ALMA at 10 years: Past, Present, and Future

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Chapter 1

Invited talks

1.1 Category: Cosmology and the high redshift universe

Unveiling the Cosmic Mysteries: A Decade of ALMA Discoveries Redefining Galaxy Evolution

Aravena, Manuel[1]

[1]Universidad Diego Portales, Chile

Since the start of observations in 2013 [and also through the testing commissioning phase], ALMA has transformed our understanding of the physical processes that shape galaxies and cosmic structures through cosmic time. The ever-increasing and -improving capabilities (sensitivity, bandwidth, observing modes and frequency bands) have enabled us to observe the very stellar nurseries and feedback processes in distant galaxies, even deep into the epoch of cosmic reionization. In this talk, I will review some of ALMA's main galaxy evolution studies, including a brief look into the transformational science enabled by the high-redshift ALMA large programs and the synergies with other key space and ground-based observatories.

Gas and Dust in distant galaxies seen by ALMA

Inami, Hanae[1]

[1]Hiroshima University, Japan

TBD

What truncates star formation in early massive galaxies? New insights revealed about their cold ISM using ALMA.

Williams, Christina[1]

[1]NOIRLab, USA

Quiescent galaxies are the massive remnants of both rapid star-formation in the early Universe, and powerful feedback mechanisms that may truncate star-formation. Understanding these "quenching" processes has been a major challenge to building a complete picture of galaxy evolution. I will overview recent results based on ALMA data that seek to characterize the cold ISM of massive quiescent galaxies in the distant Universe, during the first few billion years after the Big Bang. ALMA is revealing an emerging picture of a diversity of evolutionary pathways among galaxies that are ceasing their star-formation at this early epoch, which our theoretical formulations of quenching processes must accommodate. Looking forward, I will discuss future directions where ALMA can further our understanding in its second decade.

1.2 Category: Galaxies and galactic nuclei

The ALMA view of the gas cycle in nearby AGN

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The availability of high-resolution (<10-100pc) images of the distribution and kinematics of molecular gas in the circumnuclear disks of nearby AGN is key to decipher the mechanisms regulating the feeding and feedback cycle of nuclear activity in galaxies. These observations have started to be accessible for an increasing number of targets thanks to the advent of ALMA. We describe how detailed studies conducted by our group have underlined the potential pivotal role of radio jets and AGN winds in launching molecular outflows in a number of AGN. We have also searched for the 'relic' imprint left by AGN feedback on the radial distribution of molecular gas using high-resolution ALMA images from >70 nearby AGN in 3 CO lines obtained in the context of the NUGA, GATOS, WISDOM and LLAMA projects. Using different prescriptions for the normalised distribution of molecular gas we find evidence of enhanced nuclear-scale molecular gas deficits in the most extreme AGN. We also detect molecular outflows in the sources that show the most extreme nuclear-scale gas deficits. This suggests that AGN feedback can be 'caught in the act' more frequently among the higher luminosity and/or higher Eddington ratio sources. We discuss possible avenues to validate this evolutionary scenario using high-resolution numerical simulations of the feeding and feedback cycle in galaxy disks.

ALMA studies of host galaxies of extragalactic transients

Hatsukade, Bunyo[1]

[1]NAOJ, Japan

Over the past decades, the improving depth and sky coverage of modern telescopes have opened a window to the transient universe and uncovered new classes of exotic variable phenomena. Among them, long-duration gamma-ray bursts (LGRBs), superluminous supernovae (SLSNe), and fast radio bursts (FRBs) are the least understood populations. Because the link between progenitors and specific galactic environments is expected, observations of host galaxies are essential to understanding their nature. We have conducted observations of molecular gas, the fuel for star formation, in the host galaxies of LGRBs, SLSNe, and FRBs. We constructed the largest sample of these transients with molecular gas information. We found that the hosts of LGRBs and SLSNe follow the same molecular gas scaling relations (among the gas mass, stellar mass, and SFR) as other star-forming galaxies, suggesting their progenitors exist in similar environments to other star-forming environments. On the other hand, the FRB hosts have diversity in molecular gas properties (gas mass, gas fraction, gas depletion time). Moreover, they are offset from the scaling relations of star-forming galaxies, which contrast with the hosts of LGRBs and SLSNe, suggesting different origins of FRBs than LGRBs and SLSNe. These findings indicate that FRBs arise from multiple progenitors or single progenitors in a wide range of galaxy environments.

Young, massive, embedded star clusters and their feedback revealed by ALMA

Levy, Rebecca[1]

[1]University of Arizona, United States

The cycle of star formation governs the evolution of galaxies. In some local galaxies, the star formation rates in their centers are much higher than other normally star-forming galaxies and may be more similar to galaxies at earlier cosmic times. I will present observational results from the archetypal nearby starburst galaxy NGC253. First, I will discuss how gas flows to the center of NGC253 along its bar to fuel the extreme burst of star formation. Using very high spatial resolution data from ALMA tracing emission from dust and dense molecular gas, we find that the massive, compact, very young "super" star clusters (SSCs) in the center of NGC253 are arranged in a ring. The SSCs have stellar masses $\sim 10^4$-10^6 $M_\odot$, gas masses $\sim 10^{3.5}$-$10^{5.5}$ $M_\odot$, and radii ~ 0.5 pc. Next, I will discuss the detection of massive outflows of molecular gas detected from three of the SSCs in

NGC253. These outflows carry a substantial fraction of the gas mass away from the clusters and may stop these clusters from growing even larger. The precise physical mechanism powering these outflows is uncertain, but winds from massive stars and dust-reprocessed radiation pressure are the best candidates - different from lower mass, less extreme star clusters. Currently, only ALMA has the capabilities to reveal these heavily embedded clusters in the nearest external galaxies, but upgrades to ALMA, JWST, and future facilities such as the ngVLA and SKA will enable these kinds of observations out to the Virgo cluster.

1.3 Category: Star formation and the interstellar medium

The Statistics of Star Formation

Battersby, Cara[1]

[1]University of Connecticut, USA

Large programs with ALMA enable apples-to-apples statistical studies of star formation on scales never before possible. I present two ALMA large programs designed to study how stars form and to measure the gas flows that feed them. These programs bring together the high resolution and sensitivity that make ALMA so extraordinary with large statistical sample sizes to revolutionize our understanding of star formation in the Milky Way Galaxy, from large Galactic radii to the very center. The ALMAGAL large program has observed more than 1,000 dense clumps across the disk of our Galaxy at 1000 AU resolution in 1mm dust continuum and spectral lines. With these data, we can measure the basic outcomes of the star formation process across the Galaxy and search for variations as a function of Galactocentric radius, spiral arm association and as a function of clump properties, such as surface density and evolutionary stage. The ACES large program focuses on the innermost region of our Galaxy, the Central Molecular Zone (CMZ) to measure the star formation process in this extreme environment, which is often considered a proxy for high-redshift galaxies in its gas properties. ACES makes a contiguous map of the entire CMZ at 3mm in dust continuum and spectral lines with better than 0.1 pc resolution. ACES can connect the complex gas flows in this central region with a complete sample of star-forming cores to understand the mysteriously under-efficient present-day star formation in this region. With these surveys combined, we measure star formation across the entire Galaxy, with statistics to perform apples-to-apples comparison across its environments.

Investigating the origin of stellar masses with ALMA-IMF

Motte, Frederique[1]

[1]CNRS, France

The main goal of the ALMA-IMF Large Program (Motte et al. 2022) is to determine if and how the origin of the stellar initial mass function (IMF) depends on cloud characteristics and evolution. We surveyed 15 massive protoclusters, including W51 and W43, and covering a wide variety of Galactic environments and evolutionary stages (Motte et al. 2022; Galvan-Madrid et al. in prep.). ALMA-IMF provides the community with an unprecedented database (Ginsburg et al. 2022; Cunningham et al. 2023, see http://www.almaimf.com) with high legacy value for protocluster clouds (60 pc^2 covered at 2000 AU resolution, Diaz-Gonzalez et al. subm.), cores (about 1000 cores with 0.15-200 $M_\odot$, Louvet et al. resubm.), and filaments (hundreds of star-forming filaments, Baug et al. in prep.). Many ALMA-IMF cores qualify as protostellar as they drive outflows (hundreds of outflows, Nony et al. 2020, 2023; Towner et al. subm.) and hot cores (several tens of hot cores, Brouillet et al. 2022; Bonfand et al. subm.). ALMA-IMF regions display a wide range of dynamical events as currently investigated toward cores and along filaments (Cunningham et al. 2023, in prep.; Stutz et al. in prep.).

I will present ALMA-IMF results, obtained from our homogenous sample of cores, that indicate that the mass distributions of cores (CMFs) in these massive environments of the Milky Way present an excess of high-mass cores (Motte et al. 2018a; Pouteau 2022; Louvet et al. resubm.) with respect to the canonical IMF (e.g., Kroupa et al. 2013). We propose that the CMF deviates from the canonical IMF form when and where a burst of star formation develops (Nony et al. 2023; Pouteau et al. 2023; Armante et al. subm.). Based on the combined analysis of the core distribution (CMF, mass segregation) and cloud structure (PDF), we propose an evolutionary sequence of massive protoclusters, which is in line with the dynamical scenarios of cloud and star formation (e.g., Motte et al. 2018a; Vazquez-Semadeni et al. 2019).

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1.4 Category: Circumstellar disks

Astrochemistry of disks around low-mass young stellar objects

Aikawa, Yuri[1]

[1]University of Tokyo, Japan

I will cover three astrochemistry topics in disks around (i) Class II (ii) FU Ori object, and (iii) main-sequence stars (i.e. debris disks). So far, more than 50 molecular species (including isotopologues) are detected in protoplanetary disks. Combinations of line observations suggest that the elemental abundances of Class II disk gas are different from those in molecular clouds; the C/O ratio tends to be high, and the C/H ratio could be low. Theoretical studies show that such fractionations can be caused by molecular freeze-out onto dust grains, conversion of CO to less volatile molecules, and dust-gas decoupling. In contrast to Class II disks, observations of younger disks show that dust grains are well coupled with gas and CO depletion is less significant. The elemental fractionation thus would proceed rapidly in the transition from Class I to Class II. In order to fully understand the disk chemistry, we also need to know ice chemical composition. While the JWST is making progress in ice observation, ALMA observation of disks around FU Ori objects can be a powerful alternative option. Since the duration of the luminosity outburst (~ 100 yr) is shorter than the typical gas-phase chemical timescale, the gas should reflect the ice composition before the outburst. I will report the results of our Band 3 observation of FU Ori object, V883 ori. ALMAs high sensitivity has also been beneficial for observations of debris disks. CO and CI lines are detected in some debris disks. The gas could be a remnant of protoplanetary disk (i.e. primary origin) or produced via collisions comet-like objects (i.e. secondary origin). From the astrochemical point of view, the major difference between the two scenarios is metallicity, i.e. C/H. The secondary origin could be further divided to a steady state and a transient event. We propose to distinguish between these scenarios by comparing C/CO ratio with the steady state PDR model with various metallicity.

The structure of exoKuiper belts as seen by ALMA

Marino, Sebastian[1]

[1]University of Exeter, United Kingdom

Planetary systems are made of planets, but also of minor bodies in a wide size distribution from dust up to km-sized planetesimals, typically found in discs analogous to the Solar System's Kuiper belt. These debris discs or exoKuiper belts provide unique constraints to the architecture, dynamics and formation of planetary systems and ALMA has revolutionised their study in the last 10 years thanks to its unique sensitivity and flexible resolution. In this talk, I will review how ALMA changed the way we study this ubiquitous component of planetary systems. I will show how ALMA has revealed its sizes by imaging the dust and also how it has revealed an unexpected gaseous component, whose origin is still debated. Finally, I will present preliminary results of ARKS, the first ALMA large program dedicated to their study to resolve their detailed dust radial and vertical structure, as well as their gas distribution and kinematics.

ALMA's Revelations: Dynamic Structures at the Beginning of Low-Mass Star Formation

Okoda, Yuki[1]

[1]RIKEN, Japan

Exploring the earliest stage of low-mass protostellar evolution is of crucial importance in order to elucidate star and planet formation and eventually the origin of the solar system. Fundamental questions are: how the youngest protostar grows, when the disk formation starts, and how the disk structure evolves as the growth of the protostar. Thanks to the advent of ALMA, our understandings of these issues have made a great progress for the last decade. Indeed, recent ALMA studies have found the intriguing features of the earliest stage, such as an early disk structure, a drastic change in outflow directions, accretion shocks, and so on. Thus, the protostellar evolution is much more complex than ever thought. I am going to present recent ALMA findings on the physical structure of low-mass protostars at the early stage, mainly focusing on IRAS 15398-3359 and B335. Studies of this field will contribute to a basic understanding of the physical and chemical evolution to planetary systems and their diversity.

Hunting for the youngest exoplanets with exoALMA: First Results

Teague, Richard[1]

[1]MIT, USA

ALMA has unequivocally demonstrated that protoplanetary disks are highly structured objects, exhibiting stunning gaps, rings and spirals. Young, still-forming exoplanets are an exciting possibility for the cause of these structures, however direct detection of these exoplanets remains a challenge. With the development of new analysis techniques, it is now possible to measure extremely subtle variations of the gas velocity structure due to embedded planets within these disks, providing a new tool in our planet hunting repertoire. The exoALMA Large Program was designed to capitalize on this new technique to conduct the first sub-mm planet hunting campaign. In this talk I will present the first results from the exoALMA program, spanning from the detection of embedded planets to studies of the turbulent state of stellar accretion disks.

1.5 Category: Solar system

Unlocking the Secrets of the Solar System at mm/sub-mm Wavelengths

Cordiner, Martin[1]

[1]NASA Goddard Space Flight Center, USA

Millimeter and submillimeter-wave heterodyne observations provide unique insights into thermal (continuum) emission of Solar System bodies from gas-giant planets to asteroids, while spectral line observations of rotationally excited molecules allows us to probe the detailed chemistry and dynamics of planetary and cometary atmospheres. However, prior interplanetary missions (apart from the Rosetta comet mission) have lacked dedicated mm/sub-mm spectroscopic capabilities. Due to its unprecedented sensitivity and angular resolution, the Atacama Large Millimeter/submillimeter Array can therefore reveal the objects of our Solar System in a new light. In this talk I will highlight some of the most important discoveries in planetary science over the last 10 years using ALMA, including maps of Io's volcanic plumes, the atmospheric properties of Venus and Pluto, and the composition of the first interstellar comet. I will also describe key results from our group's ongoing campaign to characterize the physical and chemical evolution of Titan's atmosphere, and will highlight the importance of ALMA observations in synergy with past, present and future interplanetary missions.

1.6 Category: Stars, Sun, and stellar evolution

ALMA's transformative impact in transient science

Coppejans, Deanne[1]

[1]University of Warwick, England

ALMA observations have enabled significant progress in the field of transients. In particular, the high sensitivity and wide frequency coverage of ALMA have helped shed light on the shock physics, outflow physics, environments and progenitors of transients. In this talk I will outline some of the key physics that we can uniquely probe using high-sensitivity millimeter/submillimeter observations, and will discuss a selection of the most exciting recent results based on ALMA observations. As increasingly more sensitive and higher-cadence transient surveys come online we will a) find new classes of transients, and b) identify transients at earlier times. Rapid multi-wavelength follow-up of these new and young transients, especially with ALMA, will be key to answering important outstanding questions in the field. To conclude my talk, I will outline key ways in which ALMA will contribute to future transients research.

Unveiling the secrets of evolved stars: Insights from the ALMA Observatory

Decin, Leen[1]

[1]KU Leuven, Belgium

The ALMA observatory has revolutionized our understanding of the universe by providing unprecedented insights into the hidden world of evolved stars. This invited talk explores the remarkable discoveries made possible through ALMA's advanced capabilities in observing the emission from dust and molecules in the circumstellar environments of these aging celestial objects.

Evolved stars, such as red giants and asymptotic giant branch (AGB) stars, play a crucial role in the cosmic ecosystem. They are not only responsible for enriching the interstellar medium with heavy elements but also serve as cosmic laboratories for studying fundamental astrophysical processes. ALMA's unique ability to peer through the thick shrouds of gas and dust surrounding these stars has allowed us to uncover their well-guarded secrets.

In this presentation, we will delve into the diverse range of phenomena associated with evolved stars. From the exquisite morphological details of dusty envelopes to the chemical complexity of circumstellar molecules, ALMA has provided unparalleled insights. We will discuss the intricate interplay between stellar evolution, mass loss, and the formation of complex organic molecules in these environments.

Furthermore, ALMA's ability to capture high-resolution spectral data has opened new windows into the kinematics and dynamics of evolved star systems. We will showcase how these observations have challenged existing models and expanded our comprehension of the physical processes at work.

Additionally, we will highlight key ALMA studies that have shed light on the fate of evolved stars, including their role as progenitors of planetary nebulae, supernovae, and even the survival potential of planetary systems. These findings have profound implications for our understanding of cosmic evolution and the origins of life-enabling elements. To summarise, this invited talk will emphasize the indispensable role of the ALMA observatory in advancing our knowledge of evolved stars and the profound implications they hold for the broader field of astrophysics.

Observing the Sun with ALMA

White, Stephen[1]

[1]AFRL, USA

Solar observations with ALMA have been possible since Cycle 4. This review will describe how solar observations differ from regular ALMA observations, describe the solar science that ALMA can do, and provide examples from data taken so far. In particular, ALMA wavelengths are sensitive to thermal emission from the solar chromosphere, the complex layer just above the photosphere that produces solar UV emission. ALMA data offer a perspective on the chromosphere that is quite different from other wavelengths, since ALMA measures temperatures directly while other diagnostics, such as UV lines, are not formed in local thermal equilibrium. ALMA has proven to be particularly sensitive to unexpected cool regions in the solar chromosphere and has changed our picture of this layer.

1.7 Category: ALMA operations, observing modes, and instrumentation

The ALMA Wideband Sensitivity Upgrade

Carpenter, John[1]

[1]Joint ALMA Observatory, Chile

The Wideband Sensitivity Upgrade (WSU) is the top priority initiative for the ALMA2030 Development Roadmap. The WSU will initially double, and eventually quadruple, ALMA's system bandwidth and will deliver improved sensitivity by upgrading the receivers, digital electronics and correlator. The WSU will afford significant improvements for every future ALMA observation, whether it is for continuum or spectral line science. The continuum imaging speed will increase by a factor of 3 for the 2x bandwidth upgrade, plus any gains from improved receiver temperatures. The spectral line imaging speed will improve by a factor of 2-3. The improvements provided by the WSU will be most dramatic for high spectral resolution observations, where the instantaneous bandwidth correlated at 0.1-0.2 km/s resolution will increase by 1-2 orders of magnitude in most receiver bands. The improved sensitivity and spectral tuning grasp will open new avenues of exploration and enable more efficient observations. In this talk, I will summarize the status of the WSU and highlight key science drivers. The gains enabled by the WSU will further enhance ALMA as the world leadingfacility for millimeter/submillimeter astronomy.

ALMA Status

Dougherty, Sean[1]

[1]Joint ALMA Observatory, Chile

TBD

Chapter 2

Contributed talks

2.1 Category: Cosmology and the high redshift universe

The dust properties of galaxies in the early Universe as revealed by ALMA

Algera, Hiddo[1]

[1]Hiroshima University, Japan

After 10 productive years surveying the distant Universe, ALMA has detected (sub-)millimeter continuum emission from dozens of galaxies at z > 6.5. These observations clearly establish that dust is already an essential component of the ISM of high-redshift galaxies, and suggest a scenario whereby the build-up of dust rapidly follows that of stars. However, a single-band ALMA detection is insufficient to accurately measure the dust masses, temperatures and obscured star formation rates of distant galaxies, which instead require detailed knowledge of the underlying infrared spectral energy distribution (SED). In this talk, I will present new multi-band ALMA observations of normal star-forming galaxies at z$\sim$7, which reveal massive dust reservoirs of $> 10^8$ $M_\odot$ only 700 Myr after the Big Bang. Such high dust masses are difficult to assemble through supernovae alone, and likely require additional dust production mechanisms. Next, I will present new measurements of the infrared SED of a galaxy at redshift 7.3, which has been meticulously constrained through ALMA observations in six distinct bands. As a result, its dust emissivity index (beta) has been measured with great precision, suggesting a steeper value than what has typically been observed in local and intermediate-redshift galaxies. I will discuss this intriguing finding in detail in the context of the physical properties and production mechanisms of dust in high-redshift galaxies.

A new window to reveal the magnetised early Universe

Chen, Jianhang[1]

[1]ESO, Germany

Magnetic fields arguably play the least understood role in our general paradigm of galaxy evolution but are undeniably crucial. They have been proposed to moderate gas inflow and outflow, star-formation rates, galactic morphology, and the initial mass function. Well-ordered micro-Gaussian galactic magnetic fields have been found in nearby galaxies using radio and far-IR polarimetry. However, we have essentially zero knowledge of magnetic fields in galaxies beyond z$\sim$2. In this talk, I will present a new window with ALMA to study the magnetic fields in distant dusty star-forming galaxies based on the full-polarisation observations of dust. I will first report the detection of dust polarisation in two starburst galaxies at z=2.6 and z=5.6, indicating that the galactic ordered magnetic fields have been developed much faster than model predictions. The detected polarisation fraction is similar to that in local star-forming galaxies, providing new constraints on the amplification processes of primordial magnetic fields. Furthermore, I will show that by combining the sub-arcsec resolution of interferometers with the strong lensing techniques, it is also possible to recover the magnetic field structures even in distant galaxies, which opens a new perspective to study the magnetised Universe and the effects of magnetic fields on the general evolution of the galaxies.

ALMA [OIII] 88 um observations of galaxies in the reionization epoch and follow-up observations with JWST

Hashimoto, Takuya[1]

[1]University of Tsukuba, Japan

Understanding properties of galaxies in the epoch of reionization (EoR) is a frontier in the modern astronomy. With ALMA, it has become possible to detect far-infrared fine structure lines (e.g., [CII] 158 um and [OIII] 88 um) and dust continuum emission in star-forming galaxies in the EoR. In this talk, first we will show the [OIII] 88 um line observations in a galaxy at $z = 9.11$, MACS1149-JD1, one of the most distant galaxy so far reported (Hashimoto et al. 2018, Nature, 557, 392). Follow-up high-angular resolution observations ($\sim$300 pc) of MACS1149-JD1 shows a hint of systematic rotation at $z = 9$, demonstrating the power of the combination of ALMA and gravitational lensing effect (Tokuoka et al. 2022, ApJL, 933, 19). Secondly, we will present the results of detailed spectral energy distribution modelling that shows some [OIII] 88 um emitters have matured stellar populations at $z > 6$, implying early star formation activity at $z > 10$. Finally, we will show our initial results of JWST follow-up observations of the ALMA [OIII] 88 um emitters (GO-1840, PIs: J. Alvarez-Marquez & T. Hashimoto). In the most distant galaxy overdensity, A2744-z7p9OD at $z = 7.88$, we successfully confirmed four galaxies at $z = 7.88$ within a small area of $\sim$ 11x11 kpc. Remarkably, three member galaxies are detected by ALMA in dust continuum, which is consistent with their red UV continuum colors. The results imply that environmental effects are already at work 650 Myr after the Big Bang.

The CRISTAL ALMA Large Program: a survey of gas, dust, and stars when the Universe was ∼1 Gyr old

Herrera-Camus, Rodrigo[1]

[1]Universidad de Concepción, Chile

In this talk I will present the main results of CRISTAL, a Cycle 8 ALMA Large Program led from Chile. CRISTAL, combined with observations from JSWT, is producing the first systematic census on $\sim$kpc scales of the multi-phase gas, dust, and stars of typical star-forming galaxies at $z\sim$4-6. While the range of scientific areas covered by CRISTAL is wide, in this talk I will focus on: 1) Morpho-kinematic classification: combining the [CII] kinematics and the morphology from JWST/NIRCam images, we find that an important fraction of CRISTAL galaxies are experiencing interactions with nearby companions. Only a handful of CRISTAL galaxies show evidence for regular rotating disks. For these systems, we measure high intrinsic velocity dispersions, consistent with model predictions and observations of similar type of galaxies. 2) Outflows: based on deep [CII] line spectra, we find strong evidence for outflowing gas in the massive CRISTAL galaxies. These outflows have velocities of $\sim$300-500 km/s, and are consistent with expectations given the level of star formation activity present in these galaxies. 3) Sizes: we find that the multi-phase gas traced by the [CII] line is much more extended than the star-coming disk traced by the rest-frame UV (HST), stellar (JWST) and dust (ALMA dust continuum) emission. This extended [CII] emission is commonly referred as "[CII]-halo". I will discuss the relevance of all these results in the context of our current galaxy evolution models.

10 and 9 at 2: An ALMA/Band 9 Survey of [C II] in Distant z=2 Galaxies

McKinney, Jed[1]

[1]University of Texas at Austin, USA

Ten billion years ago, the star-formation rate density of the Universe peaked and individual galaxies were forming more stars than at any other time. The majority of star-formation at this epoch, "cosmic noon" (z∼2), was obscured by dust and happened within the most infrared-luminous galaxies. At this redshift, bright far-infrared fine structure lines like [C II] at 157.7um can be measured by ALMA in Band 9, providing a powerful window into the dynamics and properties of cold gas to study why star-formation rates were high. In this talk I will present new results from a Cycle 9 program measuring [C II] emission in z=2 luminous infrared galaxies, doubling the number of galaxies detected in [C II] at z∼2. We find a diverse range of dynamical properties traced by the [C II] emission, ranging from mergers to rotationally supported disks. Combined with mid-infrared spectroscopy we test the photoelectric heating efficiency of dust using the ratio of [C II] to Polycyclic Aromatic Hydrocarbon emission and compare against z=0 galaxies. The dynamics and conditions of cold gas in our sample support a fuel-limited scenario for the high star-formation rates at cosmic noon. Finally, we use this sample to statistically test [C II] at cosmic noon as a tracer of star-formation rates and gas masses, a critical test for the >100 [C II] measurements at z>4 which currently rely on z=0 calibrations.

The ALPAKA sample: a zoom in view on the CO morpho-kinematics of z=0.5-3.5 star-forming galaxies

Rizzo, Francesca[1]

[1]Cosmic Dawn Center, Niels Bohr Institute, Denmark

Spatially-resolved studies of the kinematics of galaxies provide crucial insights into their assembly and evolution, enabling to infer the properties of the dark matter halos, derive the impact of stellar and AGN feedback on the interstellar medium, measure and characterize the outflow motions. To date, most of the kinematic studies at z>1 have been obtained using emission lines tracing the warm, ionized gas (e.g., Halpha, [OIII]). However, whether these provide an exhaustive or only a partial view of the dynamics of galaxies and of the properties of the ISM is still debated.
In this talk, I will present ALPAKA, a project aimed at gathering high-resolution ALMA observations of CO emission lines of star-forming galaxies at z=0.5-3.5. With ∼ 147 hours of total integration time, ALPAKA assembles ∼0.25" observations for ∼30 massive star-forming galaxies, the largest sample with spatially-resolved molecular gas kinematics at z=0.5-3.5. By complementing the dynamical analysis of the ALPAKA targets with the analog analysis on [CII] high-resolution observations at z>4, I will show the first clear evidence demonstrating that there is no evolution of turbulence with redshift and that dynamically cold disks are surprisingly ubiquitous, challenging current galaxy evolution models. Finally, by complementing the ALPAKA datasets with HST+JWST observations, I will show preliminary results aiming at constraining the role played by dark matter in the build-up of early structures.

Monsters with empty bellies? A new chapter in studies of dense gas at the Cosmic noon

Rybak, Matus[1]

[1]Delft University of Technology, the Netherlands

The cosmic star-forming activity peaked between redshifts z=1-4, in the so-called "Cosmic Noon". This vigorous star production is driven mainly by galaxies with star-formation rates (SFRs) 100-1000x higher than the Milky Way. However, it has long been unclear what causes these immense SFRs: are high-redshift galaxies somehow able to form stars very efficiently, or are they simply more gas-rich than present-day galaxies?
Over the last decade, extensive surveys of the total molecular gas in high-z galaxies (via CO, dust, and [CII] emission) have established that they are indeed very gas-rich. However, recent resolved studies have shown that

a significant fractionof the molecular gas resides in diffuse, extended halos, contributing little to the observed SFR. Maybe high-z galaxies have significantly enhanced star-forming efficiency after all?
To answer this question, we need to study the dense gas (n=10^4 cm^{-3} and above) from which stars form. As the low-J CO and [CII] emission trace gas down to densities of $\sim 10^2$ cm^{-3}, we need to rely on fainter emission lines such as HCN, HCO^+, and HNC. Unfortunately, as these lines are 10-100x fainter than CO or [CII], they have been detected in only a handful of high-z galaxies.
The superb sensitivity of ALMA - recently enhanced by the addition of Band 1 - has opened the way to studying the dense-gas tracers in high-z galaxies en masse. I will showcase the results of PRUSSIC: a concerted survey of dense-gas tracers in high-z galaxies with ALMA, NOEMA, and JVLA. By combining targeted observations and archive mining, we have built the most comprehensive sample of high-z galaxies detected in dense gas tracers.We find that high-z galaxies contain surprisingly little dense gas and have an enhanced star-forming efficiency. Moreover, we have obtained the first measurements of the HCN/HCO^+/HNC ladders in high-z galaxies, allowing us to constrain the physical conditions (temperature, mechanical heating) of their dense-gas phase.

Dusty quasars eject star-forming gas from galaxies at cosmic noon

Stacey, Hannah[1]

[1]ESO, Germany

The canonical picture of galaxy evolution invokes strong feedback from active galactic nuclei (AGN) to reduce the star formation efficiency of massive galaxies. This process can explain their observed scaling relations, which were already established by cosmic noon (z = 2 - 3). However, the physical channels that allow energy and momentum released on sub-pc scales to affect gas on galactic scales are largely unconstrained. In this presentation, I show a direct link between quasar dust-reddening and molecular outflows at z $\sim$ 2.5. By examining the dynamics of warm molecular gas in the inner regions of galaxies as probed by ALMA, we detect outflows from within the galactic bulges with short timescales of 0.05 Myr that are due to ongoing energy output from the AGN. We observe outflows only in systems where quasar radiation pressure on dust is sufficiently large to expel their obscuring column densities, indicating that radiative feedback regulates gas in the nuclear regions of galaxies. This is in agreement with theoretical models that predict radiation pressure on dust in the vicinity of the black hole as a major driving mechanism of galactic-scale outflows of cold gas. Our findings show that quasar radiation ejects star-forming gas from nascent stellar bulges at velocities comparable to those seen on larger scales in ionised gas, and that molecules survive in outflows even from the most luminous quasars. I will detail how our results inform models and observations of feedback.

High-angular resolution imaging of the Sunyaev-Zel'dovich effect with ALMA

Ueda, Shutaro[1]

[1]ASIAA, Taiwan

We have observed the Sunyaev-Zel'dovich effect (SZE) towards 4 galaxy clusters with high signal-to-noise over a wide redshift range from z=0.45 to 1.1 at 5-arcsec resolution. Measuring the Sunyaev-Zel'dovich effect (SZE) towards galaxy clusters provides us with a powerful and unique probe to explore the thermodynamic properties of the intracluster medium (ICM) and the dynamical states. The SZE results from the inverse Compton scattering of cosmic microwave background (CMB) photons by hot electrons in galaxy clusters, with the SZE signal being proportional to the pressure of the ICM. Therefore, SZE observations are complementary to X-ray observations that are highly sensitive to the electron density of the ICM. ALMA offers us to achieve first high-angular resolution and high sensitivity SZE observations of galaxy clusters, allowing us to make a direct comparison with Chandra's high-angular resolution X-ray observations. In this talk, we will present our SZE measurements for massive galaxy clusters using our combined X-rays and SZE analysis. The results include the following: (1) constraining the equation of state for gas perturbations shown in both sloshing and merging regions in RXJ1347.5-1145, (2) detecting a large amount of exceptional low-temperature ICM in the center of the Phoenix cluster, and (3) studying the dynamical states of high-z massive galaxy clusters.

Accelerated massive galaxy formation along the cosmic web filaments at z=3

Umehata, Hideki[1]

[1]Nagoya University, Japan

The SSA22 proto-cluster, located at z=3.1, is among the most extensively studied areas in the first decade of ALMA, in conjunction with other cutting-edge telescopes such as VLT/MUSE. The ALMA Deep Field in SSA22 (ADF22) has been established and explored at the proto-cluster core, resulting in one of the deepest and widest Band3/Band6 contiguous mosaics. A co-spatial MUSE mosaic has revealed Lyman-alpha filaments that stretch over 4 comoving Mpc. The area hosts a plethora of active galaxies at spec-z=3.1, including 16 ALMA-identified gas-rich, dusty star-forming galaxies (SFR 200-2000 $M_\odot$/yr) and 8 X-ray AGNs (Lx$\sim 10^{44}$ erg/s), with 6 overlapping galaxies. This suggests that the growth of galaxies and black holes is being accelerated simultaneously at the core of the protocluster along the gas flow of the cosmic web. Recent [CII] and CO observations have revealed that these galaxies generally have rotation-supported gas disks, and the rotation curves show that the DSFGs reside in very massive halos (up to $\sim 10^{13}$ $M_\odot$). High-resolution imaging in dust and [CII]/CO has also exposed internal structures such as nuclear starbursts and spiral arms. Therefore, we are witnessing a rapid growth and transformation of massive galaxies within the cosmic web where fuels and angular momentum are provided via the filaments. We will discuss how ALMA has revolutionized our understanding of massive galaxy formation in the early universe, as well as prospects for the upgrades of ALMA.

Identifying and characterizing high-redshift dusty star-forming galaxies with ALMA and JWST

Zavala, Jorge[1]

[1]NAOJ, Japan

After a decade of the submillimeter/millimeter revolution sparked by the ALMA telescope, the presence of dust-enshrouded star formation activity has been confirmed in galaxies spanning a wide range of redshifts, reaching up to z = 8.5 - a few hundred million years after the Big Bang. During this talk, we will present new results on the identification and characterization of high-redshift dusty star-forming galaxies by combining our ALMA 2mm MORA survey with JWST observations taken under the COSMOS-Web project (plus other multi-wavelength extragalactic surveys). We will also present updated constraints on the dust-obscured star formation rate density up to z = 8, suggesting that the presence of dust-obscured star formation activity is not negligible even at this early epoch. Finally, we will present new results that stress the importance of submillimeter/millimeter observations when characterizing high-redshift galaxies, particularly for JWST-selected sources.

2.2 Category: Galaxies and galactic nuclei

ALMA Observations of the Rare Relativistic Tidal Disruption Event AT2022cmc

Alexander, Kate[1]

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Supermassive black holes (SMBHs) lie at the centers of most galaxies, but the processes by which SMBHs accrete material and launch outflows that shape the galaxies around them remain poorly understood. Transient accretion onto a SMBH through the tidal disruption of a stray star offers a unique opportunity to probe the environment around quiescent galactic nuclei and to map the lifecycle of relativistic jets and outflows. In 2011, radio and millimeter observations of the tidal disruption event (TDE) Swift J1644+57 revealed that these dramatic events can power luminous relativistic jets. Nevertheless, powerful jets in TDEs are extremely rare; despite over a decade of searching, a second relativistic TDE was not promptly identified until 2022. I will present ALMA observations of this new transient, AT2022cmc: the first TDE observed to launch a powerful relativistic jet in 11 years and the first jetted TDE discovered in the ALMA era. In combination with centimeter-band data, our observations track the peak of the spectral energy distribution (SED) as it evolves through the millimeter band and determine the spectral index of the optically thin portion of the SED, which allows us to (1) determine the properties of outflowing material (energy, size, expansion velocity), and (2) trace the ambient density profile around a previously-dormant SMBH on scales of a few light years. AT2022cmc is also the most distant TDE discovered to date, at z=1.193; the exquisite sensitivity of ALMA thus allows us to realize the potential of TDEs to probe the evolution of SMBHs across cosmological distances.

Star Formation and Gas Properties of Local Luminous and Ultra Luminous Infrared Galaxies

Barcos-Muñoz, Loreto[1]

[1]NRAO, US

Luminous and Ultra Luminous Infrared Galaxies (LIRGs and ULIRGs) provide a unique laboratory to study star formation in extreme conditions. They are mainly interacting, or merging, gas-rich systems that can host massive starbursts and powerful Active Galactic Nuclei (AGN) activity. U/LIRGs show star formation rates (SFR) of up to a few 100 solar masses per year concentrated into their central kpc. Due to the large amounts of gas and dust surrounding their central regions, direct observations of the nuclei are often impossible at many wavelengths. Radio and sub-mm emission are key to study their star formation and ISM properties. I will share results from high angular resolution observations with the radio telescopes VLA and ALMA of a sample of local U/LIRGs from the Great Observatories All-sky LIRG Survey. I'll talk about how combining both telescopes we can estimate whether these systems are forming stars near their maximum capacity as predicted by theoretical models for star-forming disks supported by radiation pressure on dust. I will finalize by highlighting synergies between ALMA, VLA, and recent JWST observations of a couple of local U/LIRGs.

Future Science from the Event Horizon Telescope

Bower, Geoffrey[1]

[1]ASIAA, US

The Event Horizon Telescope (EHT) is a global submillimeter-wavelength very long baseline array that produces the highest angular resolution images of black holes. The EHT Collaboration has produced images of two black holes, the supermassive black hole in the elliptical galaxy M87 and the Galactic Center black hole, Sgr A*. In this talk, I will describe the techniques and technology behind these measurements, including the essential role that ALMA has played. Both images images have a ring-like morphology consistent with predictions of general relativity and the Kerr metric. Comparison with an unprecedented library of GRMHD simulations provides insights on the accretion and outflow properties. These results confirm that the gravitational lensing feature is a universal property of black holes, establishes the consistency of general relativity over three orders of magnitude in mass, and opens the door for future tests of gravitational physics, accretion, and jet formation through experiments in the coming years.

Failed AGN feedback? – Molecular reservoirs are not severely affected by extremely fast, kpc-scale AGN ionized-wind in ULIRGs at z∼0.5

Chen, Xiaoyang[1]

[1]NAOJ, Japan

Large-scale outflows are generally considered as a possible evidence that active galactic nuclei (AGNs) can severely affect their host galaxies. Recently several ultraluminous IR galaxy (ULIRG) selected from AKARI FIR catalog was found to have galaxy-scale [OIII] 5007 outflows with extremely high energy-ejection rates compared to active galaxies at z<2. However, the latest ALMA follow-ups of these galaxies reveal that the molecular reservoirs are not severely affected by the fast ionized AGN wind. The velocity of the molecular outflow is slower by one order of magnitude than that of ionized-wind, indicating that the outflowing molecular gas could not escape from the gravitational potential of these galaxies. The finding suggests that the feedback effect on star-forming clouds in hosts could be limited even with extremely fast and powerful AGN ionized-outflows, which is consistent with the vigorous starbursts in the galaxies, i.e., with SFR of 1000 $M_\odot$/yr.

Resolving the star formation cycle from GMCs to star clusters in lensed galaxies at cosmic noon

Dessauges-Zavadsky, Miroslava[1]

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Galaxies at z>1 show increasingly higher gas fractions and SFRs, in the form of rotationally-supported turbulent disks. Their morphology is characterised by UV-bright clumps. Deep HST and now JWST observations of strongly lensed galaxies has enabled us to resolve these clumps down to tens of parsecs, revealing they are young, massive (10^6-10^8 $M_\odot$) and dense star cluster complexes, significantly contributing to the recent star formation of the host galaxy and the build-up of its stellar mass. They are believed to be formed from the fragmentation due to gravitational instability of the galaxy disks, which at high z can fragment at larger scales than in local disks because of their gas-rich and turbulent nature. Our recent detection of giant molecular clouds (GMCs) in two strongly lensed clumpy galaxies at z=1, observed with ALMA in CO down to 30 pc resolution, reveals also more massive and denser (∼10^3 $M_\odot$/pc^2) GMCs than the local GMCs. They point toward an evolution in their physical properties, reflecting the overall evolution of the ISM conditions (disk hydrostatic pressure, turbulence, density, radiation field) of galaxies across cosmic time and suggesting that GMC properties are adjusted to the ambient ISM where they form. The comparison between the mass distribution of GMCs and stellar clumps hosted in the same z=1 galaxies, moreover, evidences a much higher star formation efficiency (∼30%) than observed in nearby galaxies (<6%). Our JWST IFU observations will enable us to confirm the possible fundamental increase of the efficiency of high-z GMCs in forming stars thanks to the spatial cross-match of GMCs with very young star-forming regions (<10 Myr) as traced by the Ha emission. These first studies demonstrate that multi-wavelength observations of strongly lensed high-z galaxies can probe the star-formation cycle from the collapse of transient GMCs to the formation of stars in clustered and hierarchically organised star-forming regions at <100 pc scales.

CHILES+ALMA: A first look at combining resolved atomic and molecular hydrogen beyond z=0.1

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Understanding the relationship between the gas reservoir of galaxies and the change in their star formation rate with cosmic time is a major goal of galaxy evolution studies which (will) combine observations from ALMA with the SKA and its precursors to study the total gas content beyond the local Universe. We present results from the highest redshift sample of galaxies with both spatially resolved molecular and atomic gas measurements to date, derived from the full CHILES 1000-hour HI survey with the Very Large Array, and targeted follow-up of HI detected galaxies with ALMA in CO (1-0) at z > 0.1. The HI detected parent sample span a range of stellar masses, star formation rates, and environments while we only directly detect CO in the highest stellar mass galaxies. The CO distributions are centrally concentrated, and spatially coincident with the highest stellar mass surface density region of the galaxies. In only one galaxy is the CO peak outside the galaxy center, with the suggestion of an offset CO hole. This is also the only CO detection in a galaxy group while the rest are isolated. The HI detections show a range of morphology, but the HI reservoir is more extended than the CO when both are detected. In addition we stack the CO non-detections, and we combine the total gas fraction and H_2-to-HI ratios as a function of redshift for CHILES with other samples to search for evidence of evolution in the gas reservoirs. Finally we compare the gas content with measured star formation rates to estimate the star formation efficiency with respect to each gas component. This study provides the first resolved look at atomic and molecular hydrogen beyond the local Universe, and a view of what is to come with SKA, its precursors, and ALMA in its next decade.

Radio jets expanding in the cold molecular ISM: what ALMA has told us in the past 10 years

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Radio jets are a spectacular manifestation of the nuclear activity in galaxies.
In the past 10 years, ALMA has been instrumental in showing us how they can play a crucial role in affecting the presence, kinematics and conditions of the surrounding cold medium, therefore being more relevant for galaxy evolution than previously assumed. Thanks to key and representative objects observed with ALMA, we can quantify the impact of jets during their evolution from the initial, pc-scale phase to their growth to galactic scales and beyond. ALMA's high spatial resolution and the possibility of observing multiple transitions of CO and other molecules have been crucial for this.
This talk will summarise some of the more important results obtained by discussing a number of key objects, such as IC5063, PKS1549-79 and PKS0023-26. In these objects we have been able to map the impact of the jet on the kinematics of the gas and on the line ratios. This allows to map how the radio jets affect the physical conditions of the gas. The agreement between these results and predictions of state-of-the-art numerical simulations of jet-cloud interactions have led to a better understanding of the impact of newly born ($< 10^6$ yr) radio jets entering the ISM and driving gas outflows. IC5063 represents a reference case for the many similar studies done with ALMA.
The outflows are, however, limited to the sub-kpc regions and likely short-lived and the mode of interaction must change as the jets expand. In this talk we will present new ALMA observations confirming that this change is indeed occurring. When reaching larger (kpc) scales, the jet appears to have a gentler interaction with the ISM, pushing the gas aside, and limiting its cooling. This creates cavities devoid of cold molecular gas which wrap around the radio lobes. This evolutionary sequence of the effect of the radio plasma changing as the jet expands provides a new important ingredient for more realistic cosmological simulations.

Fate of Cold Gas Accretion in a Brightest Cluster Galaxy: The Case of Perseus/NGC1275

Nagai, Hiroshi[1]

[1]NAOJ, Japan

Recent ALMA observations have revealed that cold and massive gas filaments are ubiquitous around the central galaxy of cool-core clusters. These cold gas filaments are probably infalling to the central galaxies since the gas motion is slower than the escape velocity, and therefore they can be a dominant channel of gas feeding to the central super massive black holes (SMBHs). This picture is also supported by recent numerical simulations of cold chaotic accretion that is triggered by the non-linear growth of thermal instability in the cluster gas. However, little is known about the observational property of cold gas within the host galaxy and its connection with the kpc-scale filaments. NGC 1275 is the nearby representative of the central galaxy of cool-core cluster / brightest cluster galaxy. Using ALMA data, we revealed the presence of circumnuclear molecular disk (CND) with a radius of 100 pc of NGC 1275 and possible gas streams that connects between the CND and kpc-scale filaments (Nagai et al. 2019). We also detected low-frequency radio continuum emission over the CND and interpret that the emission is starburst origin (Nagai et al. 2021). The observed velocity dispersion of the CND gas is consistent with the turbulent velocity that is expected from supernova (SN)-driven turbulence model. This indicates that the gas accretion from CND scale to further inner region can be enhanced by the SN-driven turbulence. Interestingly, the CND rotation axis is approximately parallel to the sub-pc jet axis observed by VLBI observations (Nagai et al. 2014). This might indicate that the angular momentum of black-hole accretion disk is largely affected by that of the CND. In this presentation, we also plan to report some new results from more recent ALMA long baseline data that can nearly resolve the Bondi radius of NGC 1275 and will discuss the fate of cold accretion within the gravitational influence by the SMBH.

Dust polarization in nearby galaxies observed with ALMA

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ALMA unprecedented resolution and sensitivity, together with the high polarization accuracy, allow a previously impossible experiment: mapping the magnetic field structure at cloud scales in the cold gas of nearby galaxies. Observations tracing the magnetic field across the hierarchy of spatial scales involved in star formation and through the multiple phases of the interstellar medium are key to understanding the importance of magnetic fields in galaxies, and constraining the latest generation of models.

To date, large-scale magnetic fields in external galaxies have mostly been probed through observations of polarized synchrotron radiation, but reflect the average field structure over the full scale height explored by cosmic-rays, rather than the dense, star-forming material at the disk mid-plane.

On smaller scales, many observations of dust polarization are now available for Milky Way giant molecular clouds, but these studies, hampered by our location inside the Galaxy, have difficulty linking the cloud-scale field structure to the galactic context.

Studying the magnetic field structure on scales that resolve the turbulence coherence length in the cold ISM of external galaxies can provide first answers.

This talk will give a brief overview of the available ALMA full polarization observations of nearby galaxies, with a particular emphasis on the first parsec-scale map of the magnetic field structure in the dense gas at the heart of the nearby starburst galaxy NGC253.

The relation between ionised outflows and molecular gas content in nearby X-ray AGN

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An open question in extragalactic astronomy is what is the extent to which the Active Galactic Nuclei (AGN) affect the evolution of their host galaxies. Proper characterization of the AGN influence becomes necessary for cosmological hydrodynamical simulations that invoke feedback from these AGN to realistically simulate galaxy growth and evolution. AGN-driven outflows are frequently detected in low-redshift and high-redshift galaxies across a wide range in luminosity and multiple gas phases. However, most of the samples considered by these studies are incomplete as often only bright AGN are considered and the samples are biased against absorption in the optical/soft X-ray band. In this study, we present recent MUSE and ALMA CO (2-1) observations of nearby hard X-ray selected AGN. The AGN sample covers a large range in bolometric luminosity, black hole mass, Eddington ratio and obscuration and therefore, allows us to perform an unbiased statistical study of outflows and their impact on host galaxies. We find kpc-scale ionized outflow signals in all galaxies and substantial amounts of molecular gas in their central regions distributed in a compact disk or ring-like structure. We will show if the presence of AGN results in a negative or positive feedback. We will conclude by presenting relations between the AGN luminosity, outflow power with molecular gas content and star formation rate of the host galaxy determined using ancillary multi-wavelength data and advanced SED models.

The WISDOM project: constraining the properties of (active) SMBHs using ALMA observations

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Observations have demonstrated that the mass of super-massive black holes (SMBHs) correlates with a number of properties of their host galaxies, implying a self-regulated SMBH-host galaxy co-evolution. Our understanding of this process, however, is still incomplete. The unprecedented resolution and sensitivity provided by ALMA is revolutionising the study of co-evolutionary processes, enabling - among others - accurate dynamical studies of molecular gas at the centre of galaxies and thus allowing us to obtain very accurate determinations of the SMBH mass. In this talk, I will first discuss the successful application of this technique in the context of the mm-Wave Interferometric Survey of Dark Object Masses (WISDOM) project. I will review how we in WISDOM have used the power of ALMA to measure SMBH masses for galaxies across the Hubble sequence. I will illustrate this technique using recent results obtained from ALMA CO(2-1) data of two objects with very different types of nuclear activity and SMBH masses (NGC 1574 and NGC 4261), showing the enormous potential of this technique in underpinning our understanding of the SMBH-host galaxy scaling relations. Within the same context, I will also present the recent discovery by WISDOM of a tight correlation between the nuclear ALMA mm luminosities, dynamical SMBH masses, and 2-10 keV X-ray luminosities that is found to hold for both low-luminosity active galactic nuclei (LLAGN) and high-luminosity (quasar-like) AGN. This has been dubbed as the "mm fundamental plane of BH accretion". Crucially, spectral energy distribution (SED) models for advection-dominated accretion flows (ADAFs) seem to naturally explain the existence of the relation, which is not reproduced by the standard torus-thin accretion disc models usually applied to radiatively-efficient AGN. I will discuss the implications of this discovery for our understanding of BH accretion, as well as its potential as rapid method to (indirectly) estimate SMBH masses.

2.3 Category: Star formation and the interstellar medium

A step back in space and time: the impact of infalling envelopes and massive streamers on planet formation

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[1]ESO, Germany

Protoplanetary discs orbiting evolved, Class II young stellar objects have long been considered as isolated cradles of planet formation, but recent observations are challenging this paradigm.
Protostellar envelopes infalling onto Class 0/I discs are characterized by low opacity indices, resembling disc properties rather than ISM ones and indicating early dust growth at scales of a few hundred astronomical units. This large envelope grains would collapse faster than the surrounding gas, increasing the dust-to-gas ratio of young discs, and triggering streaming instabilities therein, a condition to form planetary cores. Moreover, the dust masses of young discs have also been shown to be much higher than evolved Class II discs, suggesting early growth of dust into planetesimals that are undetectable for radio-interferometers. Recent studies have also revealed large-scale channeled streamers falling onto protoplanetary discs, influencing their mass budget to form planets, and altering their chemical conditions via hot shocks.
These findings raise questions about planet formation that only ALMA is ready to tackle. Is dust starting to coalesce into larger pebbles at earlier stages than previously thought? Are these large grains really triggering the formation of early cores in discs? And to what extent can late infall of material influence the evolution of a forming planetary system?
We will present a multi-scale, multi-wavelength approach to measure dust properties in the envelopes of Class 0/I objects, using L1527 IRS as a testbed and presenting chances to enlarge this approach to a statistical framework. Furthermore, we will present new ALMA observations of a dusty streamer, the only one known so far, of comparable mass to the disc onto which it is infalling, thus likely strongly altering the history of its forming planetary system.

Modeling the initial conditions of collapse in a dense prestellar core

Friesen, Rachel[1]

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We present Atacama Large Millimeter/submillimeter Array (ALMA) continuum and NH_2D, N_2D^+, and H_2D^+ line emission at matched, ∼100 au resolution toward the dense star-forming cores SM1N and N6 in Ophiuchus A filament, within the Ophiuchus molecular cloud. We determine the density and temperature structure of SM1N based on radiative transfer modeling and simulated observations of the multi-wavelength continuum emission at 0.8 mm, 2 mm, and 3 mm, with additional constraints from the line analysis. We show that SM1N is best-fit by either a broken power-law or Plummer-like density profile with high central densities ($n \sim 10^8$ cm^{-3}). The inner transition radius between shallow and steep radial density profiles is only ∼80-300 au, similar to the Jeans length and in agreement with some models of contracting cores. The continuum modeling rules out the presence of an embedded, warm object, such as a first hydrostatic core or protostar. The free-fall timescale of the inner region is only a few times 10^3 years, making SM1N a dynamically unstable but still starless core. We furthermore show evidence for depletion in NH_2D (and hence NH_3) toward the continuum peak, in agreement with chemical models of complete molecular depletion in dense cores prior to protostar formation, but observed directly in only one other core. The measured non-thermal velocity dispersions are subsonic, and show evidence of greater magnitudes at higher densities that may trace increasing (but still subsonic) infall speeds, constraining models of starless core contraction. Toward N6, we confirm the previous ALMA detection of a faint, embedded point source in 0.8 mm continuum emission, with very low luminosity and no large-scale molecular outflow. All dense gas tracers avoid the N6 point source within ∼ 100 au, consistent with heating by a young warm object, possibly a first hydrostatic core.

Complex Organic Molecules in Protostars with ALMA Spectral Surveys (COMPASS)

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The emergence of complex organic molecules in the interstellar medium is a fundamental puzzle of astrochemistry. Targeted observations with ALMA have opened the door to high-sensitivity spectral surveys over wide bandwidths to elucidate the chemical complexity of young stars in a systematic manner. We will present the first results of our ALMA Large Program "Complex Organic Molecules in Protostars with ALMA Spectral Surveys (COMPASS)". The aim of the program is to perform unbiased line surveys of 11 nearby Solar-type protostars. The targeted protostars are known hosts of complex organic molecules and sample different natal environments and evolutionary stages. The concerted effort will provide a deep understanding of the complex organic inventories and isotopic ratios depending on the physical environment and evolutionary past. This will ultimately address how much diversity in organic inventories we can expect for emerging planetary systems.

Linking the large scale core magnetic field with the subsequent evolution of protostars in Orion

Le Gouellec, Valentin[1]

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Class 0/I protostars vigorously accrete from their collapsing envelope, such that most of the future star mass is built during this evolutionary stage. The magnetic field is thought to play a key role in the regulation of the angular momentum available for disk formation and in the infall dynamics of the inner core. In the past 10 years, ALMA dust polarization observations have revealed different types of magnetic field morphologies in protostellar envelopes, like magnetic field lines aligned along outflow cavity walls, and filamentary structures that are potentially accretion streamers. For the first time, the ALMA B-field Orion Protostellar Survey (BOPS) analyzed the magnetic field in an homogeneous sample of ∼60 protostellar cores in the Orion molecular cloud, targeting scales of 400 to 2000 au. CO(3-2) outflows are used to establish the angular momentum axes of the protostars. These observations reveal a myriad of envelope density structures and polarization dust emission morphologies that we attempt to characterize with respect to the large scale (∼10 000 au) magnetic field observed by SOFIA and JCMT. The large scale magnetic field direction is found not to be correlated with the angular momentum of the protostars' inner envelope. However, we explore the misalignment between these two quantities with respect to the structures of the envelope and the multiplicity. More especially, we investigate whether we can identify the respective role of the magnetic field in a statistical way, between a "strong" field case, where the core angular momentum direction has been dictated from the core initial magnetic field orientation, the envelope structures are organized and the multiplicity is low; to the "weak" field case, where the memory of the large scale field is lost, the envelope structures is chaotic and the multiplicity is higher.

Is it magnetic ? ALMA measures for the first time the gas ionization in a young protostellar analog

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Whether or not magnetic fields play a key role in dynamically shaping the products of the star formation process, and the first steps of planet formation, is still largely debated.
For example, in magnetized protostellar formation models, magnetic braking plays a major role in the regulation of the angular momentum transported from core scales to the stellar embryo, and is expected to be responsible for the resulting disk sizes around solar type stars, where planets form.
However, non-ideal magnetohydrodynamic effects that rule the coupling of the magnetic field to the gas also depend heavily on the local physical conditions, such as the ionization fraction of the gas.

Using ALMA, we have been able to measure, for the first time, the ionization fraction, chi(e), and the cosmic-ray ionization rate, ζ(CR), around a young protostar aged <100.000 yrs old, at radii <= 1000 au.
We find unexpectedly large fractions of ionized gas, χ(e) $\sim$ 1-8 $\times$ 10^{-6}, and high ionization of the gas that increases at small core radii, reaching values up to ζ(CR) $\sim$ 10-14 s^{-1} at a few hundred astronomical units (au) from the central protostellar object.
We show that this extreme ζ(CR) (two orders of magnitude larger than usually adopted values) can be attributed to the cosmic rays accelerated close to the protostar.
Our ALMA observations, finding remarkably high values of CR ionization fraction suggest that local acceleration of cosmic rays, and not the penetration of interstellar Galactic cosmic rays, may be responsible for the gas ionization, down to disk-forming scales. If confirmed, our findings imply that protostellar disk properties may be determined by the efficiency of magnetic processes, which are set by local conditions, to solve the angular momentum for star formation. We stress that the gas ionization we find with our ALMA observations is unique yet significantly stands out from the typical values routinely used in state-of-the-art models of star formation and evolution.

Insights into High-Mass Star Formation: Statistical Study of Cores in Infrared Dark Clouds

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Physical properties in infrared dark clouds (IRDCs) provide insights into how high-mass stars and stellar clusters form. We present the results of the ALMA Survey of 70 m Dark High-mass Clumps in Early Stages (ASHES) conducted on thirty-nine clumps that exhibit characteristics such as darkness at 24 m and 70 m, low temperatures, high masses, and density, making them ideal for investigating the earliest stages of high-mass star formation. Through high-resolution (~1."2) and high-sensitivity observations conducted by ALMA, we have uncovered the internal structure of IRDCs, revealing an unprecedented number of 839 cores. Our analysis reveals that less than 1% of the cores possess masses exceeding 27 $M_\odot$, all of which are gravitationally bound and associated with molecular outflows. There is no high-mass (>27 $M_\odot$) prestellar core; all most massive cores have outflows and line emission consistent with warm gas. Furthermore, 90% of our sample (35/39) only hosts low- to intermediate-mass cores, indicating the need for additional mass feeding for high-mass star formation. The prestellar core mass function (CMF) follows a power-law slope similar to Salpeter's IMF, but the CMF of protostellar cores has a shallower slope, possibly resulting from core growth.
By investigating the relationship between clump mass and maximum core mass, we find a weak correlation that contradicts the strong correlation typically observed in stellar clusters. This suggests that, at least in the very early stages traced in ASHES, the maximum core mass is not solely determined by the natal clump mass. While no preferred locations for the formation of the most massive cores are observed, we discover a segregation of denser cores from less-dense ones. This density segregation may potentially trace future mass segregation if efficient gas feeding successfully forms high-mass cores from denser regions. Our findings provide valuable insights into the very early stage of high-mass star formation.

The role of hub-filament systems in forming the most massive stars there is in the Galaxy: 10 years of ALMA observations

Peretto, Nicolas[1]

[1]Cardiff University, United Kingdom

As a result of the unequalled sensitivity and angular resolution of ALMA, our understanding of massive star formation has made tremendous progress in the past decade. It allowed researchers to peer into the massive and dense dark clouds in which massive stars form, characterise their density structures and fragmentation properties down to hundreds of AU scale, map the kinematics of the gas at the earliest phases of massive stars formation, or even constrain the complex physico-chemistry that takes place during that process. In this presentation I will focus on the role that hub-filament systems (HFSs) have on the formation of some of the most massive stars in the Galaxy, an area where ALMA had a significant impact. HFSs are small networks of filaments that converge towards sites of active star formation. The most luminous protostars in the Galaxy are systematically associated to HFSs which clearly suggests a tight link between massive star formation and HFSs. However, the physical connection between the filaments and the central hub, and the role they play in gathering the required mass for the formation of massive stars at their centres is still a subject of debate. However, ALMA observations over the past 10 years are drawing a picture of massive star formation within HFSs that is becoming ever clearer. I will review our contribution to the field by presenting: i. some of the very first cycle 0 ALMA observations of the prototypical SDC335 HFS (Peretto et al. 2013); ii. a recent study of 6 infrared dark HFSs mapped during cycle 3 and 4 (Anderson et al. 2021 and in prep); iii. and our cycle 9 LAGAF project that is currently mapping ∼140 star-forming clumps with the goal of resolving the time evolution of HFSs.

Spirals and Streamers observed towards proto-brown dwarf candidates

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Prestellar cores may not be described by a perfectly spherical shape and may be submerged into a varying density environment characterized by gas flows with varying angular momentum. This external infall may cause disk fragmentation, and the process is evidenced through the observations of bright spirals, streamers as well as multiple fragments of sub-stellar/planetary masses.
We present ALMA observations in multiple high-density molecular lines that have revealed the formation of candidate proto-brown dwarfs via disk fragmentation triggered by external infalling material in a low-density environment. At least three candidate proto-brown dwarfs are detected in molecular lines and continuum images, with gas+dust masses of ∼4-20 M_{Jup}. Prominent, asymmetric spiral and streamer structures are also seen on a scale of ∼1000 au, which are connected to the pseudo-disk of the brightest proto-brown dwarf candidate. The observed velocity structures along the spiral/streamer suggest an infalling and rotating gas stream toward the disk. I will present a comparison with numerical hydrodynamics simulations on the gravitational collapse of prestellar cores of subsolar mass embedded into a low-density external environment, which are able to reproduce the observed structures. These ALMA observations provide a unique insight into the early formation and evolution of brown dwarfs and to understand the effects of accretion from low-density external environment.

Non-equilibrium chemistry in the diffuse ISM revealed by ALMA

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[1]University of Wisconsin-Madison, United States

The diffuse interstellar medium (ISM), where the first stages of molecule formation occur, harbors a surprisingly rich chemistry, with the column densities of key species over an order of magnitude higher than can be explained by UV-dominated, steady-state chemical models. Dynamical events like shocks that drive non-equilibrium chemistry are likely important in explaining this discrepancy, but direct tests for shocks and an understanding of the environments where equilibrium models fail has been lacking. Sensitive molecular absorption measurements from ALMA have now made it possible to trace the chemistry, dynamics, and evolution of diffuse molecular gas, probing this important regime between atomic gas and star-forming molecular clouds. With the ALMA-SPONGE project, we observed HCO^+, HCN, HNC, and CCH in absorption with ALMA in directions where the properties of HI were well characterized by the 21-SPONGE project using the Very Large Array. Comparing the HI and molecular gas properties along 20 lines of sight, we established the atomic gas criteria necessary for the formation and survival of molecules in the diffuse ISM. We then demonstrated that molecular column densities were inconsistent with equilibrium model predictions where the gas is warmer than 40 K, implying non-equilibrium chemistry in the diffuse ISM in these regions. Indeed, follow-up observations of SiO at 3mm are now revealing shocks in the diffuse ISM, including in two directions where models imply non-equilibrium chemistry. The sensitivity enabled by ALMA has also allowed us to detect a broad, extremely faint component to the HCO^+ absorption that spans most velocities where HI absorption is observed. This gas has a low cold neutral medium fraction, and archival observations from ALMA and other observatories show that this molecular gas is not visible in CO absorption or emission, revealing "CO dark" gas.

The Power of Molecular Outflows in Low-metallicity Star Formation

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Massive stars play essential roles across cosmic history, making the understanding of their formation processes in various metallicity environments essential. Star formation dynamics at sub-pc scales could differ markedly in environments with significantly reduced metal abundances. For instance, theoretical models predict catastrophic instability in protostellar disks and enhanced ionization feedback in extremely metal-poor environments of « 0.1Zsun (e.g., Tanaka et al. 2014, 2018; Matsukoba et al. 2022). However, observational studies have primarily focused on individual star formation within the solar-metallicity Galactic disk. To address this, we launched a new ALMA survey, the "MAgellanic Outflow and chemistry Survey (MAGOS)," targeting 40 massive protostars in the Large and Small Magellanic Clouds (LMC and SMC; ∼0.5 and 0.2Zsun) to explore low-metallicity star formation dynamics and chemistry. We have detected molecular outflows and hot molecular cores in both the LMC and SMC (e.g., Shimonishi et al. 2023). Interestingly, while the CO outflow properties of LMC protostars align with those of Galactic protostars, they are considerably weaker in high-luminosity SMC protostars with $>=$ $10^{4.5}L_\odot$ (Tanaka et al., in prep.). This suggests the possibility of either deactivated outflow-driven mechanisms or efficient CO molecule dissociation around these high-luminosity protostars. Astrochemically, hot molecular cores are commonly found around massive LMC and SMC protostars, similar to their Galactic counterparts. However, the abundance of complex organic molecules varies by more than two orders of magnitude among LMC and SMC hot cores (Shimonishi et al. 2023). The MAGOS project offers valuable insights into low-metallicity star formation dynamics and chemistry, bridging the gap between present-day and early universe studies.

A Comprehensive Characterization of Protostellar Multiplicity in the Solar Neighborhood

Tobin, John[1]

[1]NRAO, United States

The advent of efficient surveys at high resolution and sensitivity with ALMA (and the VLA) has enabled a comprehensive and robust characterization of protostellar multiplicity in the solar neighborhood (within 500 pc). We will present a characterization of multiplicity statistics for ∼600 systems, comprising Orion, Serpens-Aquila, Perseus, Ophiuchus, and Taurus, representing the majority of low- to intermediate-mass protostars in the solar neighborhood. We have measured the separations of companion protostars from 1000s of au down to ∼30 au. The distribution of separations typically exhibits two peaks, one at ∼100 au and another at ∼3000 au, and these peaks thought to result from disk and turbulent fragmentation, respectively. We compare the separation distributions between regions and to more-evolved samples, finding that protostars in the nearby star-forming regions are statistically indistinguishable from each other, but statistically inconsistent with more-evolved populations. Furthermore, there is tentative evidence for changes in multiplicity statistics as a function of evolution (i.e., protostellar class). Molecular line observations of close ($<$ 500 au) multiples points to ∼50% of close multiples forming within rotationally-supported structures, consistent with disk fragmentation, and outflows tend to be driven orthogonal to the projected plane of close companion sources. Finally, observations of close multiples at ALMA's highest available resolutions find correlated alignment of circumstellar disks around each protostar, further pointing to disk fragmentation for multiples with separations $<$ 100 au.

2.4 Category: Circumstellar disks

Witnessing the formation of giant planets: the first discovery of a circumplanetary disk in molecular line observations

Bae, Jaehan[1]

[1]University of Florida, USA

Young stars harbor a disk of gas and dust orbiting them. Similarly, young planets are surrounded by a circumplanetary disk (CPD). CPDs supply gas and dust to the growing planet. They are also the birthplace of moons. If we are to understand how forming planets accrete materials, what chemical compositions atmosphere-forming gas has, and how and under which environments moons form, it is crucial to study CPDs. Despite the importance, observing CPDs has been very challenging due mainly to their small sizes - for a Jupiter-mass planet orbiting a solar-mass star at 100 au as an example, the diameter of the CPD is about 5 AUs, corresponding to only 0.03 arcsecond at the distance of nearby star-forming regions ($\sim$140 pc). Thanks to the angular resolution and sensitivity it offers, ALMA has been rapidly changing the situation and providing exciting opportunities to directly detect and characterize CPDs. In this talk, I will present the first discovery of a CPD in molecular line observations, around a young, forming exoplanet AS 209b. These observations provide solely needed observational constraints on the thermo-physical properties of CPD for the first time. I will conclude by discussing the potential formation mechanism of AS 209b in the framework of two main channels of giant planet formation, namely gravitational instability and core accretion.

Betelguese after the great dimming - 8mas images with ALMA

Dent, Bill[1]

[1]Joint ALMA Observatory, Chile

In early 2020 Betelguese underwent a so-called 'great dimming' event, where the drop in brightness by a factor of 2 was thought to be caused by a giant starspot or obscuration by an intervening dust cloud. We present early results from the 2023 long-baseline project to image Betelgeuse after this event. Continuum and lines in 3 bands were observed, with a spatial resolution down to 8mas. The images show hotspots over the photosphere and extended gas clumps to 2-3 stellar radii from the surface, and we compare with pre-dimming images. Astrometric results were also obtained in preparation for the December 12 2023 occultation.

The first ALMA survey of protoplanetary disks in Band-8 (410 GHz)

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Our current understanding of planet formation theories tells us that planet formation begins in gas-rich protoplanetary disks. The aim to place the Solar System in the extrasolar context needs a clear understanding of the distribution of disk architectures and their implications for the formation of terrestrial and giant planets. Post several ALMA surveys in Bands 3, 4, 6, and 7 to study the disk demography, we present the first ALMA survey of protoplanetary disks in Band-8 (410 GHz). As an extension of the ODISEA survey (Ophiuchus DIsk Survey Employing ALMA) to higher frequencies, we will present the Band 8 data of the 45 brightest disks in the cloud at an angular resolution of 0.2" (28 au). Taking advantage of the very high S/N ratio provided by the Band-8 data, we will use the Frankenstein (frank) tool to obtain the radial profiles, measure disk sizes, and identify disk substructure at the highest possible resolution for the given set of visibilities. We will also compare the Band-8 disk sizes to those obtained at lower frequencies (100 GHz and 140 GHz) and investigate the results in the context of grain growth and radial drift. This high-frequency survey will contribute to the statistical knowledge needed to understand the distribution of disk properties in nearby young star-forming regions, which is a stepping-stone for exoplanet modelers to make advancements in the field of planet population synthesis.

Polarization in the GG Tau Ring-Confronting Dust Self-Scattering, Dust Mechanical and Magnetic Alignment, Spirals, and Dust Grain Drift

Koch, Patrick[1]

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We report Atacama Large Millimeter/submillimeter Array (ALMA) polarization observations at 3 and 0.9 mm toward the GG Tau A system. In the ring, the percentage is relatively homogeneous at 3 mm, being 1.2%, while it exhibits a clear radial variation at 0.9 mm with a mean increasing from 0.6% to 2.8% toward larger radius (r). The polarization orientation at r > 1.85" appears nearly azimuthal at both wavelengths. At r < 1.85", the pattern remains azimuthal at 3 mm but becomes radial at 0.9 mm. The dust self-scattering model with amax of 1 mm could reproduce the observed polarization orientation and percentage at 0.9 mm, but the expected polarization percentage at 3 mm would be 0.2%, much smaller than the detected 1.2%. Dust alignment with poloidal magnetic field could qualitatively reproduce the flip in polarization at r < 1.85" and also the detected polarization percentage. A closer inspection of the nearly azimuthal pattern reveals that polarization orientations are systematically deviating by -9.0deg ± 1.2deg from the tangent of the orbit ellipses. This deviation agrees with the direction of the spiral pattern observed in the near-infrared, but it is unclear how dust grains could be aligned along such spirals. For the scenario where the -9 deg deviation (-7.3 deg after considering the inclination effect) measures the radial component of the dust drift motion, the expected inward drifting velocity would be ∼12.8% of the Keplerian speed, a factor of 2.8 larger than the theoretical predictions. Possible additional interpretations of the polarization are discussed, but there is no single mechanism that could explain the detected polarization simultaneously.

A Decade of Complex Organic Molecules in Protoplanetary Disks with ALMA, and an Even Brighter Future

Loomis, Ryan[1]

[1]NRAO, United States of America

11 years ago, HC_3N had just been detected for the first time in protoplanetary disks with the IRAM 30m. Over the following decade, ALMA has thoroughly revolutionized our understanding of disk chemistry, especially regarding complex organics (COMs). These observations continue to push us ever closer toward filling in the chemical 'missing link' between the comparatively well-characterized protostellar and cometary stages, shedding light on the molecular inheritance of our own Solar Nebula.
In this talk, I briefly review the progress ALMA has made in these 10 years, highlighting the molecular detections made, the astrophysical and chemical insights gained by using COMs as tracers, and the techniques developed to achieve this progress. I then discuss the current state of the art, focusing on recent surveys, new detections, and deep observations investigating isotopic fractionation in COMs. Finally, I turn toward the future and briefly explore the bright prospects for COM observations at low frequencies with the advent of both Band 1 in the near term and the higher spectral resolution and sensitivity of the ALMA Wideband Sensitivity Upgrade (WSU) in the longer term.

First results from the ARKS Large Program: CO gas in debris discs in unprecedented detail

Mac Manamon, Sorcha[1]

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Belts of exocomets, also known as debris disks, are extrasolar Kuiper belt analogs. They are ubiquitous around nearby stars, particularly young main sequence stars at a few 10s of Myr (∼75% occurrence rate). Emission from collisionally-produced dust has long been observed in these belts, but until recently these belts were thought to be gas free. One of ALMA's greatest discoveries, enabled by its unprecedented sensitivity, has been the presence of gas in now over 20 exocometary belts. This is likely a product of exocometary release, giving us access to the volatile composition of exocomets for the first time.

In this talk, I will present the first gas results from the ALMA survey to Resolve exoKuiper belt Substructures (ARKS) ALMA Large Program, aimed at characterising 18 exoKuiper belts at unprecedented sensitivity and resolution. I will present the ^{12}CO and ^{13}CO spectrospatial distribution for all detected systems, and the deepest upper limits constraining the CO release and photo-destruction mechanism, as well as a comparison with substructure as observed in dust continuum. The spectrospatial resolution (down to 13 m/s) achieved by ARKS will also enable the first kinematics study of gas-rich debris disks, enabling a search for substructures produced by the interaction between CO gas and adolescent planets.

10 years of debris disc science with Beta Pic

Miley, James[1]

[1]Joint ALMA Observatory, Chile

The first observation of Beta Pic with ALMA was made in 2012. 10 years later ALMA's antennas turned to observe Beta Pic once again, hoping to learn more from this fascinating system.
Here I will present a multi-wavelength analysis of THE archetypal debris disc, Beta Pic, using new and archival observations made with ALMA over the years. Hosting two confirmed exoplanets and a secondary gas disc released from collisions in the planetesimal belt, Beta Pic acts as a testing ground for debris disc theory and for our observational capabilities.
I will show new ALMA Band 3 observations that trace larger 'pebbles' in the disc and detect the CO(1-0) transition. Detecting multiple transitions of the CO molecule in the disc has enabled the breaking of a degeneracy that obstructed a full quantitative analysis of the secondary gas phenomenon, where large amounts of molecular gas has been detected in systems that are significantly older than typical protoplanetary disc lifetimes.
The study of Beta Pic over a decade of ALMA operations perfectly demonstrates how the observatory's unprecedented sensitivity and angular resolution have enabled new understanding of a nearby planetary system and of planet hosting systems in general.

Observations of the earliest stage of planet formation using ALMA

Ohashi, Nagayoshi[1]

[1]ASIAA, Taiwan

The ubiquitous detections of substructures, particularly rings and gaps, in protoplanetary disks around T Tauri stars raise the possibility that at least some planet formation may have already started during the embedded stages of star formation. In order to address exactly how and when planet formation is initiated,
We have carried out the ALMA large program "Early Planet Formation in Embedded Disks (eDisk)", focusing on searching for substructures in disks around 12 Class 0 and 7 Class I protostars in nearby ($<$ 200 pc) star-forming regions through 1.3 mm continuum observations at a resolution of $\sim$7 au (0.04"). The initial results show that the continuum emission, mostly arising from dust disks around the sample protostars, has relatively few distinctive substructures, such as rings and spirals, in marked contrast to Class II disks. On the other hand, a large fraction of the disks shows brightness asymmetry along their minor axes, suggesting that dust grains in these disks are not settled in their midplane yet as contrasted with Class II disks. These dramatic differences between embedded and more-evolved disks may suggest that planet formation progresses rapidly when embedded protostars evolve into Class II sources. Kinematic information obtained through CO isotopologue lines and other lines reveals the presence of Keplerian disks around protostars, providing us with crucial physical parameters, in particular, the dynamical mass of the central protostars. In my talk, I will describe the background of the eDisk program, the sample selection and their ALMA observations, and I will also highlight representative first-look results with an emphasis on the 1.3 mm continuum emission, though I could briefly touch results of molecular line emissions if I have time.

Revealing a New Window into Protoplanetary Disk Evolution via Polarization Observations

Stephens, Ian[1]

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A primary focus of ALMA's polarization capabilities has been to resolve the polarized dust emission in circumstellar disks. Once thought to only trace the magnetic fields in disks at (sub)millimeter wavelengths, ALMA has revealed that the polarization rarely traces magnetic fields. Instead, polarized emission from grains is primarily from scattering, which is most apparent at shorter wavelengths, or from grains aligned with something other than magnetic fields, which is most apparent at long wavelengths. These polarization mechanisms allow us to uniquely constrain dust properties, such as size and grain elongations, to constrain dust evolution during planet formation. In this presentation, I will summarize the history of observing dust polarization and show how ALMA has completely transformed the field. Particular focus will be on HL Tau, as it has been the most well-studied disk for polarization. I will focus on multi-wavelength observations and the highest resolution image of HL Tau yet, which has more independent polarization measurements than any other disk by an order of magnitude. I will also summarize the current contention that exists with the current theoretical development in the field.

Observing Time Variable Chemistry in Protoplanetary Disks with ALMA

Waggoner, Abygail[1]

[1]University of Virginia, United States

T Tauri stars are incredibly variable in the X-ray regime, where they regularly undergo X-ray flaring events that can temporarily enhance gas-phase cations, such as HCO^+ and $N2H^+$. Models suggest that strong flares (i.e., a flare that increases X-ray ionization rates by a factor of 100) can increase the disk averaged abundance of HCO^+ by several factors for up to approximately two weeks. Thanks to the sensitivity of ALMA, we are able to efficiently observe molecular emission from disks, opening up the possibility of exploring time domain physics and chemistry at time scales relevant to stellar variability. Through repeat observations with ALMA, it is now possible to trace chemical variability in disks on timescales spanning days to years, Short term variability would enable the determination of important physical quantities, such as disk electron fraction. . Additionally, these observations will shed light on the efficiency of the magneto-rotational instability in disks, which guides disk gas evolution and the planet formation process more broadly. In this contribution, we present models and observations demonstrating how ALMA can be used to 'catch' chemical variability and provide insight on key planet formation physics and chemical processes.

2.5 Category: Solar system

ALMA's detailed insight on the source and distribution of volatiles in cometary comae: The Case of Comet 46P/Wirtanen

Milam, Stefanie[1]

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Cometary activity is primarily driven by the sublimation of volatiles either directly from the nucleus or icy grains in the inner coma. Additionally, photochemical processes can occur within coma altering the composition and distribution of some species. ALMA's combined power of angular resolution, spectral capabilities, and sensitivity enables detailed studies on the distribution of cometary species throughout the coma to disentangle their source. This insight provides fundamental compositional details on the native composition of volatiles during planet formation in the solar system as well as the level of processing endured by these icy relics. Here we present observations of six molecular species observed towards comet 46P/Wirtanen with ALMA during the comet's unusually close ($\sim$0.1 au) approach to Earth in December 2018, providing spatial scales of 25 km across the coma. HCN, CH_3OH and CH_3CN spatial distributions are consistent with the production from direct outgassing from (or very near to) the nucleus, with a significant proportion of the observed CH_3OH originating from sublimation of icy grains in the near-nucleus coma. On the other hand, H^2CO, CS and HNC originate primarily from distributed coma sources, the identities of which remain to be established.

ALMA Observations of the DART Impact: Characterizing the Ejecta at Sub-Millimeter Wavelengths

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We report observations of the Didymos-Dimorphos binary asteroid system using the Atacama Large Millimeter/Submillimeter Array (ALMA) and the Atacama Compact Array (ACA) in support of the Double Asteroid Redirection Test (DART) mission. Our observations on UT 2022 September 15 provided a pre-impact baseline and the first measure of Didymos-Dimorphos' spectral emissivity at $\lambda = 0.87$ mm. Our post-impact observations were conducted using four consecutive executions each of ALMA and the ACA spanning from T+3.52 to T+8.60 hours post-impact, sampling thermal emission from the asteroids and the impact ejecta. We scaled our pre-impact baseline measurement and subtracted it from the post-impact observations to isolate the flux density of mm-sized grains in the ejecta. Ejecta dust masses were calculated for a range of materials that may be representative of Dimorphos' S-type asteroid material. We will present ALMA images of the ejecta, calculated ejecta dust masses, and upper limits on gas-phase ejecta along the line of sight. We will discuss our results in the context of planetary defense, the overall asteroid population, and observations of the DART ejecta at other wavelengths. Our results provide the most sensitive measure of mm-sized material in the DART ejecta and demonstrate the power of ALMA for providing supporting observations to spaceflight missions.

2.6 Category: Stars, Sun, and stellar evolution

Explore the unexplored in pulsar spectrum with phased ALMA

Liu, Kuo[1]

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Pulsars are fascinating celestial laboratories that have allowed for some of the most exciting astrophysical experiments. However, the millimeter wavelength part of the pulsar spectrum, remains barely investigated mainly because of the steep radio spectrum of pulsars. This potential "hidden gem" in pulsar studies, can only be explored with highly sensitive instruments. The phased ALMA has a diameter equivalent to a 75-m dish, providing unparalleled sensitivity and the best opportunity on Earth to observe pulsars in this spectral window. In this talk, I will introduce the very first batch of pulsar studies using the phased ALMA capability. I will first present the commissioning observation of the phased-array mode, which was on the Vela pulsar in ALMA Band 3. This has led to the first "pulsar" detection with ALMA. I will discuss the emission properties the Vela pulsar, including its pulse profile, flux density and polarizations, within a frequency range up to 100 GHz. Additionally, I will present an overview of the currently ongoing pulsars searches towards the Galactic Center with ALMA. These have provided a brand-new opportunity to find a pulsar in close orbit with the supermassive black hole, Sgr A*, a venue that would deliver some unprecedented gravity experiments in the strong-field regime.

High resolution ALMA imaging of H_2O, SiO, and SO_2 masers in the dynamical atmosphere of the AGB star W Hya

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The mass-loss mechanism in asymptotic giant branch (AGB) stars is not yet fully understood. It is of paramount importance to spatially resolve the region within several stellar radii, where dust formation takes place and the stellar wind accelerates. We present 20-milliarcsecond resolution ALMA imaging of the well-studied AGB star W Hya in molecular lines of SiO, SO_2, H_2O, SO, HCN, AlO, and AlOH at 250–269 GHz, including masers from SiO, H_2O, and SO_2. The spatial resolution is three times finer than the W Hya's millimeter continuum angular diameter of $\sim$60 mas, allowing us to spatially resolve the emission extending to $\sim$100 mas ($\sim$5 stellar radii) as well as inhomogeneous absorption over the stellar disk. The emission is irregularly shaped with a plume extending in the NNW, a tail extending in the SSE, an extended atmosphere elongated in the ENE-WSW direction, and many clumpy structures. The spatially resolved spectra of some lines show outflow velocities close to the local escape velocity.

Surprisingly, we detected prominent emission over the stellar disk–instead of pure absorption as expected–in the $Si^{17}O$, ^{30}SiO, H_2O, and SO_2 lines. The surface emission seen in the $Si^{17}O$ and vibrationally excited H_2O (v_2=2, 268 GHz) lines is particularly strong, indicating maser actions. The H_2O masers are confined within $\sim$50 mas (2.4 stellar radii), and the spatially resolved maser spectra are very broad, ranging from about -10 to 14 km/s. This is can be explained by outflowing and infalling motion induced by the stellar pulsation. The 268 GHz H_2O masers require an H_2O density higher than $\sim 10^4$ cm^{-3} and kinetic temperatures lower than 700-1000 K with the presence of dust at 900–1300 K. Therefore, it traces cool and dense pockets. The visible polarimetric images taken contemporaneously with our ALMA data reveal good agreement in the spatial distribution between the H_2O maser emission and clumpy dust clouds, indeed lending support to this picture.

Probing the dusty extended atmosphere of IRC+10216: ALMA high-resolution observations unveil atmospheric blobs

Velilla-Prieto, Luis[1]

[1]Institute of Fundamental Physics, Spain

Asymptotic Giant Branch (AGB) stars undergo a thermally pulsing phase (TP) during which they eject material, giving rise to extended dusty envelopes. Previous studies have provided evidence of inhomogeneous molecular gas and clumpy dust clouds in the vicinity of oxygen-rich AGB stars. However, the distribution of molecular gas and its expulsion in the stellar atmosphere of carbon-rich AGB stars remains poorly understood due to limited spatial resolution observations. In this study, we present ALMA high spatial resolution observations, comparable to the size of the stellar radius, of the recently formed dust and molecular gas in the atmosphere of IRC+10216, a prototypical carbon AGB star. These observations reveal intricate anisotropic structures within the extended atmosphere, shedding light on the dynamics and morphology of the system. Our observations show distinct regions of HCN, SiS, and SiC_2 emission at different radii, suggesting the presence of large convective cells that modulate the stellar wind formation. The coalescence of these convective cells with pulsations generates anisotropies that, together with companions, contribute to shaping the circumstellar envelope. These findings provide valuable insights into the complex mechanisms governing the distribution and expulsion of molecular gas in AGB carbon stars, contributing to our broader understanding of stellar evolution during the late AGB phase. These results have recently been published in Nature (Velilla-Prieto et al., 2023, Nature, Volume 617, Issue 7962, p.696-700).

2.7 Category: ALMA operations, observing modes, and instrumentation

The ALMA North American Development Programme

Brogan, Crystal[1]

[1]NRAO, USA

The Wideband Sensitivity Upgrade (WSU) is the top priority initiative for the ALMA2030 Development Roadmap. This upgrade aims to initially double, and eventually quadruple, ALMA's system bandwidth together with delivering improved sensitivity. The ALMA Partnership is contributing to advance the technologies needed to achieve this and to deliver the requested components: receivers, digital signal and correlator.
In this talk I will discuss the development programme in North America in general and its contributions to the WSU in particular.

The ALMA European Development Programme

Díaz Trigo, María[1]

[1]ESO, Germany

The Wideband Sensitivity Upgrade (WSU) is the top priority initiative for the ALMA2030 Development Roadmap. This upgrade aims to initially double, and eventually quadruple, ALMA's system bandwidth together with delivering improved sensitivity. The ALMA Partnership is contributing to advance the technologies needed to achieve this and to deliver the requested components: receivers, digital signal and correlator.
In this talk I will discuss the development programme in Europe in general and its contributions to the WSU in particular.

The ALMA East Asian Development Programme

Hatsukade, Bunyo[1]

[1]NAOJ, Japan

The Wideband Sensitivity Upgrade (WSU) is the top priority initiative for the ALMA2030 Development Roadmap. This upgrade aims to initially double, and eventually quadruple, ALMA's system bandwidth together with delivering improved sensitivity. The ALMA Partnership is contributing to advance the technologies needed to achieve this and to deliver the requested components: receivers, digital signal and correlator.
In this talk I will discuss the development programme in East Asia in general and its contributions to the WSU in particular.

The Impact of Weather on ALMA Operations

Nowajewski, Priscilla[1]

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ALMA, located in the Chilean Altiplano at the Atacama Desert, faces significant challenges due to extreme weather conditions and seasonal and daily variations. Besides the impact of winds and PWV, the observatory is subject to weather phenomena associated with ENSO, including the Altiplanic winter during the southern hemisphere summer and the Chilean winter during the winter hemisphere. These seasonal variations introduce additional complexities for observatory operations.
This research characterizes the past ten years' weather and climate at the Atacama Large Millimeter/submillimeter Array (ALMA) observatory and their impact on radio astronomy operations. The characterization considers the El Nio-Southern Oscillation (ENSO), and its impact on the intensity of both Altiplanic and Chilean winter. The

methodology involves the analysis of in-situ weather station data, numerical forecasts, and considerations for optimizing observatory operations.
In particular, we examine the role of precipitable water vapor and phase rms as crucial factors affecting radio astronomy observations.
In conclusion, this study emphasizes the impact on operations due to weather variables and the climatology of Altiplano. Considering ENSO, Altiplanic, and Chilean winters, the changes in Phase RMS and the amount of precipitable water vapor add further insights into the complexities faced by ALMA in optimizing observatory operations. The findings from this study can aid in developing strategies to mitigate the effects of daily and seasonal variations of weather variables, ensuring optimal performance and data quality in radio astronomy observations at the ALMA observatory.

CARTA: Cube Analysis and Rendering Tool for Astronomy - what CARTA can help to your ALMA projects

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CARTA is the Cube Analysis and Rendering Tool for Astronomy, a new image visualization and analysis tool designed for the ALMA, the VLA, and the SKA pathfinders, as well as future telescopes such as ngVLA and SKA. As the image size increases drastically with modern telescopes in the past decade, viewing an image with a local image viewer or with a remote image viewer via the ssh protocol becomes less efficient. The mission of CARTA is to provide usability and scalability for the future by utilizing modern web technologies and computing parallelization. On behalf of the CARTA development team, I will introduce the CARTA project and key features to the community. Current status and future perspective will be presented. The development of the CARTA project is a joint effort from (in alphabetical order): Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA), Inter-university Institute for Data Intensive Astronomy (IDIA), National Radio Astronomy Observatory (NRAO), and Department of Physics, University of Alberta.

Chapter 3

Posters

3.1 Category: Cosmology and the high redshift universe

Hidden Below the Dust: Serendipitous Discovery of a Strongly Lensed High-z Galaxy Behind Milky Way C

Alcalde Pampliega, Belén[1]

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We present the exciting discovery of J1545, an exceptionally bright and massive extragalactic source at redshift z∼6, serendipitously detected behind the Lupus1 local molecular cloud. Our ALMA high-resolution observations revealed an arc-like elongated shape overlapping with the coordinates of an earlier galaxy/brown dwarf candidate, confirming that J1545 is a strongly magnified SMG at redshift z»4. J1545 represents an extremely rare and elusive object, providing a unique opportunity to study the most extreme phases of galaxy formation in the early Universe.
Through extensive modeling we reconstruct the source plane and fitting of the data, we have obtained the photo-z distributions (z = 4.7-6.5), its high luminosity (uLIR = 9×10^{13} - 3×10^{14} $L_\odot$), and a dust temperature of Tdust = 40-55 K. Scheduled follow-up observations/spectral scans will confirm the redshifts of both the lensing galaxy and the background galaxy, providing further insights into the nature of this rare and intriguing object. Our findings shed light on the cosmic evolution and rapid mass build-up of galaxies during the epoch of cosmic dawn and highlight the importance of serendipitous discoveries and gravitational lensing in uncovering hidden cosmic treasures. We also emphasize the key role of spectroscopy and follow-up observations in confirming the redshift and nature of these objects, showcasing the power of cutting-edge observational techniques in advancing our understanding of the distant Universe.

The extreme state of the circumgalactic medium gas in a low-redshift and in a high-redshift galaxy cluster and the implication for star formation.

Andreani, Paola[1]

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In the past decade advances in observing techniques and in galaxy formation simulations drew the attention to the role of the circumgalactic medium (CGM) as a key ingredient to understand how material is exchanged between galaxies and their environment.
In Galaxy Clusters the CGM is expected to be different from the Interstellar Medium inside galaxies because of the presence of bright cluster galaxies (BCGs). The BCG powerful AGN induces pressure gradients across the CGM and its radio jets reach out to the Intercluster Medium and the hot X-ray gas surrounding the H_2 gas reservoirs. The resulting thermal and ionisation states is maintained not by star formation-generated FUV/optical photons, but by highly energetic particles (HEP).

Observations show indeed that the thermal, dynamical and ionisation state of the CGM gas shows extreme thermal decoupling of gas and dust reservoirs, where large amounts of lower-density, galaxy-expelled, molecular gas and dust are detected. In such environments very efficient CO destruction is predicted, leaving large swaths of CO-poor/-rich and warm H_2 gas surrounding 'islands' of denser, cooler, and still CO-rich, gas where CO molecules survive the HEP onslaught. The latter can be detected using the standard low-J CO lines and/or the CI[1-0] line, while the CO-poor, warmer gas mass will be targeted with direct observations of the rotational H_2 lines.

We present CO(1-0) CO(3-2) CO(4-3) CO(7-6) CI[1-0] CI[2-1] single dish (ALMA TP, APEX, NRO45m) and ALMA interferometric observations towards 2 clusters at low-z and high-z.

These data, combined with upcoming (approved cycle 2) JWST MIRI direct detections of H_2 lines, will be used to examine possible extreme gas-dust thermal decoupling over large H_2 and dust mass reservoirs.

These observations are important because the traditional way to estimate the amount of molecular gas and the initial conditions of star formation might be different impacting the type of the resulting stellar IMF.

Boosting ALMA's efficiency in two key science drivers towards the next decade

Bakx, Tom[1]

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ALMA has fundamentally improved the quality and resolution of studies of galaxies in the early Universe. Its spectroscopic capabilities reveal the properties of the gas inside and surrounding galaxies from low to very densest environments. I improve the efficiency of two key science drivers of ALMA (and other interferometers); 1. ensuring robust spectroscopic redshifts with minimum observation time and 2. providing hyper-efficient snapshot observations of spectral lines. Even Cycle 0 demonstrated ALMA's power as a redshift hunter, exploiting a full coverage of band 3 to detect at least a single CO line of high-redshift galaxies, however often one has to rely on photometric redshifts. Using public code, I provide a method to determine the quality of redshift identifications and use this to optimize future observations to robustly identify redshifts through multiple lines. This simple method enables twice as efficient observations as previous band 3 redshift studies. Meanwhile, follow-up of galaxies with robust redshifts have revealed the internal gas properties of galaxies across cosmic time. However, often such observations require re-tuning, leading to overheads that fundamentally limit ALMA's spectroscopic capabilities to several tens of sources per project. Instead, I explore a method to use fixed spectral windows that include as many lines as possible. Within six hours, we detect over sixty spectral lines in sixteen sources at 0.1 arcseconds, a five-fold increase in efficiency of previous surveys, and the first step in Big Data science with Herschel - an ongoing $\sim$100 source project targeting $>$ 350 lines probing the ISM of the most violent star-forming events in the Universe.

The Evolution of the Molecular Gas Mass Budget in the Universe

Bollo, Victoria[1]

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The cosmic history of star formation in the Universe indicates a peak two billion years after the Big Bang, followed by a sharp decline to the present day. To understand galaxy evolution, a full description of the role of cold gas as the primary fuel for star formation is essential. The amount of cold gas in galaxies and the efficiency with which it is converted into stars determine many galaxy properties. Observations of molecular gas, in particular through CO emission, provide a direct link to star formation over cosmic time.

ALMA has made significant progress in this field, but small survey sizes and the potential cosmic variance effects have limited the accuracy of cosmic gas mass density measurements to date. This project addresses these limitations by using ALMACAL, a large untargeted survey based on ALMA calibrator data, covering many fields across the southern sky and exceeding any previous survey by a factor of 10 in volume.

We present preliminary results on the molecular gas budget of the Universe and its implications for star formation history. We have developed automated algorithms to construct ALMA image cubes, run source-finding algorithms, and evaluate the CO-luminosity function for a subsample as a function of redshift to estimate the total cosmic molecular gas mass density. We discuss the implications of our work to understand of the role of cold gas in the baryon cycle in galaxies.

Studying a Highly Magnified Lensed Galaxy at z∼2.8 with ALMA

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The nature of star formation in high-z galaxies and the physical properties of the interstellar medium in which it is taking place are not very well understood as yet. Observations have shown that high-z star-forming galaxies often exhibit turbulent, clumpy, rotating discs. However, current telescopes lack the spatial resolution and sensitivity required to study the individual star-forming regions in these galaxies. Nevertheless, when taken to the extreme, gravity can create remarkable visual mirages through the significant bending of light by high mass concentrations, as observed in the core of massive galaxy clusters. This phenomenon, known as strong gravitational lensing, magnifies background galaxies located behind these dense structures, providing an excellent opportunity to study distant sources with enhanced resolution and flux. We took advantage of the strong lensing to conduct deep ALMA observations of the Cosmic Seagull, the brightest lensed submm galaxy at z∼2.8 behind the massive Bullet Cluster. ALMA's high sensitivity and resolution of subarcsec make it an ideal instrument for studying dust and molecular gas in lensed galaxies. The Cosmic Seagull splits into four distinct images with differential magnification up to 50. The high amplification rates, combined with a 0.2"-resolution submm imaging from ALMA Band-3 (2018.1.01754.S, PI: Vernica Motta), enable us to resolve the source at a sub-kpc scale, allowing a detailed examination of the galaxy internal structures and dynamics. This poster presents the data reduction and preliminary analysis of the new ALMA observations of the Cosmic Seagull, including the ∼4.6 kpc reconstructed source. We also present the local improvement of the Bullet Cluster lens model, which contributes to a better understanding of the distribution of dark matter and its role in galaxy cluster evolution.

z-GAL - A NOEMA Redshift Survey of Bright Herschel Galaxies

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The Herschel surveys have enabled the detection of numerous dusty luminous sub-millimetre galaxies (SMGs) in the early universe. Follow-up observations of these sources are essential to determine their nature and the physical properties of their interstellar medium; reliable redshift measurements are therefore crucial to explore the molecular and atomic gas of these objects.

We will here present the results of a recent Large Program, z-GAL, using NOEMA, aimed at a comprehensive 3 and 2-mm spectroscopic redshift survey of a large (137 sources) sample of the brightest SMGs selected from the Herschel H-ATLAS, HerMES and HerS surveys. Robust redshifts were derived for all sources but two, based on the detection of at least two emission lines, making it the largest sample of high-z galaxies with unambiguous redshifts to date, and are centred on the peak epoch of galaxy evolution.

We will describe the main results of the z-GAL survey, highlighting the physical properties of the SMGs derived from the molecular and atomic emission lines and the underlying dust continuum, and comment on the nature of the sources, that include lenses and hyper-luminous galaxies, as well as binary and triple systems. Complementary data, including HST, Keck and ALMA data, will also be presented. Comparisons with other recent spectroscopic surveys of high-z galaxies (in particular, BEARS and the SPT surveys done with ALMA) will be presented, showing their complementarity, commenting on some key technical aspects, and outlining future prospects, including follow-up observations based on these redshifts measurements.

IFU Trio of JWST x ALMA x MUSE: Diving into an Early Galaxy at z=6 Down to 20-80pc Scales In and Out

Fujimoto, Seiji[1]

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Detailed characterizations of low-mass galaxies in the Epoch of Reionization (EoR) are essential as they dominate the mass budget in that epoch and represent the closest analogous of first galaxies. But such studies have been difficult due to their faint and compact nature. The gravitational lensing is a promising way to overcome the difficulty, and a total of ~120 hrs unique ensemble of deep, high-resolution IFU observations have been ongoing with JWST/NIRSpec, ALMA, and MUSE, which all target a strongly and multiply magnified ($\mu \sim$20-160) low-mass ($\sim 10^9 M_\odot$) star-forming galaxy at z=6.07. In this talk, I will present initial outcomes from these ongoing deep IFU observations to characterize three fundamental properties of 1) chemical enrichment, 2) mass (star, dust, and gas) assembly, and 3) kinematics. The initial data already unveils the presence of unambiguous outflow and inflow signatures from the 3D views, and I will also present the interplay between the galaxy and surrounding gas reservoirs. This talk will overview how the first galaxy looks like from inside to outside the galaxy down to physical scales of ~20-80 pc at EoR.

ALMA reveals resolved gas and dust at 100 pc resolution in the most gas-rich, starbursting galaxies

Harrington, Kevin[1]

[1]ESO, Chile

The combination of high-spatial resolution ALMA observations and strong gravitational lensing has yielded an unprecedented view into the heart of the star-forming gas and dust in the interstellar medium of some of the most IR-luminous galaxies at cosmic noon. Here I will present results from the largest spatially resolved multi-J CO/[CI] line study for starbursts at cosmic noon. These systems, selected from the Planck all-sky sub-mm survey, have apparent IR luminosity greater than $10^{13.5-14}$ $L_\odot$, however the ratio between high-to-low-J CO line emission and other properties indicates a widely varying set of gas excitation conditions on global scales – which persists to the sub-kpc environments. I will present key thermodynamic and kinematic properties and discuss the implications for the rapid evolution of these active dusty star-forming galaxies at high-z.

Powerful radio galaxies at high redshift with ALMA.

Hedge, Alexander[1]

[1]Curtin Institute for Radio Astronomy, Australia

The first year of JWST results has seen a large number of faint type-1 active galactic nuclei (AGN) at high redshifts (z greater than 4) discovered from deep spectroscopic measurements. However in the broader population of high redshift AGNs, the obscured yet radio-loud types (such as COS-87259 at z=6.8; Endsley et. al. 2023, MNRAS, 520, 3) remain largely undetected. A new sample of 51 such obscured/NIR-ultra-faint but radio-loud AGN hosted by candidate high-redshift radio galaxies (HzRGs) was presented by Broderick et al. 2022 (PASA, 39, e061), based on a pilot study which found the second-most distant radio galaxy known at the time at z=5.55. These candidates with NIR fluxes similar to COS-87259, but with radio luminosities orders of magnitude higher, are seeding the potential to study an unprecedented population of HzRGs that push into the Epoch of Reionisation (EoR) at $z > 6.5$.
The 14 K-band faintest sources were recently observed with ALMA at 85-115 GHz to confirm their redshifts using emission lines. A handful of them have a single, very high S/N CO line which constrains their redshifts to several possible values at z less than 4, but more interestingly we confirm one target at z=3.878 via matching a pair of low S/N CO emission lines with the same pair of lines at higher S/N in a companion galaxy ~15" away in the field-of-view. Several of the targets with no features detected could lie at even more extreme redshifts ($z > 6$), but even if the sources were to lie at lower redshifts, they would represent an unprecedented sample of

radio-loud AGN in host galaxies of extremely low stellar mass (i.e. black hole masses 1-30% of the host), so the sources are inherently interesting at either low or high redshifts.
Further multi-wavelength follow-up is being pursued to estimate their redshifts and to better understand these rare sources.

Discovery of a massive, highly star-forming and morphologically complex ULIRG at z = 7.31 with ALMA

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A key question in astrophysics is understanding the emergence of the first galaxies: the transition from the Cosmic "Dark Ages", through the Epoch of Reionization at $6 < z < 11$. A recent analysis of the history of the infrared (IR) luminosity function by Zavala et al. (2021) suggests that obscured star formation is dominated by so-called ultra-luminous infrared galaxies (ULIRGs) at high redshift. Such sources have, however, proven difficult to find at the highest redshifts. I will present ALMA [Cii] and 158 um continuum observations of REBELS-25, a massive, morphologically complex ultra-luminous infrared galaxy at z = 7.31, spectroscopically confirmed by the Reionization Era Bright Emission Line Survey (REBELS) ALMA Large Programme. I will present a characterisation of this galaxy derived from the ALMA observations in combination with complementary multi-wavelength observations. I will present the [CII] kinematics, which exhibits a velocity gradient consistent with disc rotation, but given the current resolution more complex velocity structure such as a merger cannot be ruled out. The spectrum exhibits excess [Cii] emission at large positive velocities, which can be interpreted as either a merging companion or an outflow. In the outflow scenario, a lower limit of the mass outflow rate is derived that is consistent with expectations for a star formation-driven outflow. Given its large stellar mass, SFR and molecular gas reservoir at roughly 700 Myr after the Big Bang, I will explore the future evolution of REBELS-25. Considering a simple, conservative model assuming an exponentially declining star formation history, constant star formation efficiency, and no additional gas inflow, I will present the results of an investigation of whether REBELS-25 has the potential to evolve into a galaxy consistent with the properties of high-mass quiescent galaxies recently observed at z$\sim$4.

The CRISTAL Survey: Study of individual [CII] sizes and haloes of star-forming galaxies at z=4-5

Ikeda, Ryota[1]

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One of the major achievements in extragalactic studies with ALMA is the discovery of an extended feature of the [CII]158um line emission around young star-forming galaxies before and after the Epoch of Reionization. The [CII] line in those galaxies is spatially extended than rest-frame UV and FIR emissions, which suggests an efficient metal enrichment up to $\sim$10 kpc scale. Nonetheless, previous studies have mostly been conducted with stacking analysis or low-spatial resolution data, which limited our interpretation of this phenomenon. We here present the initial result of the ALMA Cycle8 Large Program, CRISTAL Survey, which provides a census of [CII] line and dust continuum emissions in a kpc scale for more than 20 individual galaxies at z$\sim$4-5. We have successfully obtained an individual size of [CII] line by modeling visibilities for all galaxies including mergers, where about half of them were not measured with the low-resolution data alone. The [CII] line emission is extended than rest-UV and FIR emissions by up to a factor of $\sim$4, but no evidence of a "halo" structure was found individually. To assess the distinct existence of the extended "halo" component, which we assume to be separable from the central disk component, we will present the result of the stacking analysis in the visibility plane and discuss the physical origin of the extended [CII] line emission.

Exploring 10kpc-scale cosmological matter density fluctuations with gravitational lensing

Inoue, Kaiki[1]

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The matter density fluctuations on scales below 10 kpc are extremely important for understanding the nature of dark matter and the early Universe. A powerful tool for directly investigating these small-scale matter distributions is galaxy-scale strong gravitational lensing. Recent theoretical studies suggest that the anomalies observed in flux ratios of certain quadruple lens systems are primarily caused by small-mass haloes and voids in the intergalactic space, rather than subhaloes associated with the dominant lensing galaxy. However, empirical evidence supporting this theory is still limited. Since the gravitational effects of small-mass structures along the line of sight are roughly proportional to the distance to the gravitational lensing source, we expect a positive correlation between the gravitational effects of small-mass structures and the redshifts of the gravitational lensing source. On the other hand, if the anomalies are mainly caused by substructure within the dominant lensing galaxy, such a correlation would not exist due to a large distance between the source and the lens. I will review some recent relevant works and then comment on our ongoing ALMA project. Finally, I will discuss the future prospect of this research, emphasising its potential for advancing our understanding of small-scale cosmological matter density fluctuations.

ALMA and Gamma-ray bursts: a decade of rapidly accelerating discovery

Laskar, Tanmoy[1]

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As the most energetic explosions in the Universe, gamma-ray bursts provide a unique opportunity to explore physics at extreme energy scales that are otherwise impossible to investigate in Earth-bound laboratories. In this review, I will describe how unleashing ALMA's unparalleled sensitivity for photometric and polarimetric observations of transients over the past decade has yielded new insights into the structure, composition, and magnetization of gamma-ray burst jets. I will conclude by discussing the future role of millimeter-band observations at the interface between millimeter astronomy and multi-messenger extragalactic time-domain astrophysics.

Neutral gas content in the ISM at the cosmic noon: a millimeter assessment

Messias, Hugo[1]

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One of the revolutionary results enabled by ALMA in its first 10 years of operation was measuring the evolution of the molecular gas mass density (ρ_{H2}). Between targeted observations and deep surveys, it is now clear that ρ_{H2} peaks between redshift 1 and 3. This is very much in line with the evolution observed for the star formation rate density. However, the same is not seen for the neutral Hydrogen (HI) mass density (ρ_{HI}) which is observed to be constant throughout most cosmic time (as estimated via [sub-]Damped Lyman$_{alpha}$ systems). Linking these two results has been a difficult task, partially related to the different scales probed by different techniques, but it is mostly due to the fact that detecting HI in the inter-stellar medium (ISM) of galaxies has mostly been limited to within the last 4.3 Gyr of cosmic time. Here, we give a step toward solving this problem. We make use of the empirical relation between dust continuum and ISM gas mass proposed in Orellana et al. (2017) to extract the HI content in the ISM of galaxies. This statistical study puts together a large sample of mm-continuum- and CO-selected galaxies extracted from ALMA, VLA, and NOEMA surveys. Such sample already shows that, overall, the depletion times commonly quoted in the literature considering molecular gas alone in mm-selected galaxies are underestimated by factors of 1.5 to 4. Specifically focusing on the sample reported by ASPECS and Birkin et al. (2021) we also show that this technique already points to mm-selected galaxies comprising 20% to 50% of the HI cosmological content at redshifts between 1 and 3. Also, the major difference in HI content is seen at the massive end when comparing the mass functions with those found in the local Universe. This archival statistical study thus shows the immense legacy value of ALMA even to prepare the community to HI-survey machines such as SKA and ngVLA.

Turbulence and dynamics of z $\sim$ 4.5 disc galaxies

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Early galaxies are expected to be turbulent and unlikely to host dynamically cold discs over many dynamical time scales. Following up on the growing number of regularly rotating discs observed at z $>$ 4, we have analysed ALMA [CII] emission-line observations of a sample of four gas discs in galaxies at z $\sim$ 4.5. We present the rotation curves obtained from the gas kinematics of the discs decomposed into their different mass components to derive properties of the dark matter halo and baryons in the inner 3 to 5 kpc. We also show that the turbulence in the discs can be fed by the intense stellar feedback without the need for large-scale gravitational instabilities and we explore the local stability in the discs by deriving the Toomre Q parameter for the disc. Finally, we characterise a central outflow observed in one of the galaxies likely driven by an active central black hole. Overall, our study provides insights into how these discs, which seem to be a common occurrence at massive galaxies in the Early Universe, can remain dynamically stable over long periods.

Constraining the galaxy assembly in the early Universe with the ALPINE-ALMA [CII] survey: the importance of major mergers

Romano, Michael[1]

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Current galaxy evolution models suggest two major drivers of the galaxy mass build-up in the early universe, i.e., the accretion of cold gas from the circumgalactic/intergalactic medium, and the galaxy major mergers. Recent works have found a possible increase in the major merger fraction at early epochs, reviving the debate on which of the two processes dominates over the other.

We investigated the importance of major mergers in this context by using the data collected by the ALPINE-ALMA [CII] survey. This project took advantage of the ALMA capabilities to observe the rest-frame far-infrared [CII] 158 um line and continuum emission in a hundred of star-forming galaxies one billion years after the Big Bang. Along with ancillary multi-wavelength data and spectroscopic observations, ALPINE allowed us to conduct the first panchromatic study of such a large statistical sample of primordial galaxies, and a robust characterization of their morphology and kinematics.

We used the morpho-kinematic information provided by the [CII] line to identify major mergers in the distant universe. We obtained the first constraint on the major merger fraction from [CII] at z$\sim$5, finding that $\sim$40% of normal galaxies was already undergoing a merging at that epoch. By combining our results with studies at lower redshift, we computed the cosmic evolution of the fraction and rate of merging galaxies, confronting them with predictions from different cosmological simulations. Finally, we compared the processes of merging and star formation as responsible for the growth of galaxies across cosmic time, finding that the contribution of major mergers to the star-formation rate density at z = 4-6 could range from 5% to nearly 30%, depending on different assumptions on the merger timescale. Our results reveal a significant merging activity in the early Universe, suggesting that major mergers could have had an important role in the overall process of the galaxy mass-assembly back in time.

Molecular outflow in the quasar J2054-0005 at z=6.04 revealed by ALMA OH 119 um observations

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Molecular outflows are expected to play an important role in galaxy evolution at high redshift owing to their ability to quench star formation. However, direct evidence of such outflows at redshift z$>$6 (epoch of reionization) has been limited to a handful of sources. To search for outflow feedback at z$>$6, we performed ALMA observations of the OH 119 um doublet toward J2054-0005, a dusty quasar at z=6.04. The OH line is detected and exhibits a P-Cygni profile with a broad, blue-shifted absorption feature and an emission feature at near-systemic velocity. The blue-shifted absorption yields unambiguous evidence of outflowing molecular gas. To study the outflow properties, we fitted the OH profile with two double-gaussians. The mean and terminal outflow velocities obtained from the fits are found to be ∼670 km/s and ∼1500 km/s, respectively. The mass outflow rate, calculated using an expanding-shell model and assuming LTE and optically thin line, is found to be comparable to the star formation rate. The depletion time for the outflow is found to be $\sim10^7$ yr, implying efficient quenching of star formation in the host galaxy. The high outflow velocity implies that the outflow may be AGN-driven. From a simple estimate of the escape velocity, we find that up to ∼50% of the outflowing molecular gas may be able to escape from the gravitational potential well of the host galaxy and rich the intergalactic medium.

High noon for cosmic giants: beacons for massive galaxy formation from South Pole Telescope protocluster cores

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The most massive local galaxies sit in the centers of galaxy clusters, surrounded by red early types. While these dense environments are well studied out to redshifts 1-2, the formation process in the first two billion years remain enshrouded in cosmic history. Contrary to the successful hierarchical structure formation scenario, giant elliptical galaxy precursors are observed in compact groups of vigorously star-forming, dust obscured galaxies. Characterized by enormous molecular reservoirs, protocluster cores show correlated star-formation on the scales of the emerging cosmic web. Moreover, they represent the sites for energy injection and enrichment of the intracluster medium around the brightest cluster galaxies (BCGs) observable already by cosmic noon.
Selected from the 25000 deg^2 large South Pole Telescope (SPT) survey, the sensitivity and angular resolution of ALMA is instrumental to characterize physical conditions of the cold, star-forming medium of protocluster cores. Guided by 870um APEX/LABOCA maps, the redshift determination to the eight brightest cores is now completed.
Strikingly, SPT2349-56, at z=4.3, is the record holder for the highest star-formation surface density known, with 15 ULIRGs within only 50 kpc in projection. The majority of core galaxies sit on the same cluster caustic in phase space, hinting at a core-wide collapse process caught in action. A beacon of this 'mega merger' are bright, massive tidal gas streamers, serendipitously discovered with ALMA. Clumpy ionized carbon [CII]158 arcs extend over 50 kpc, connecting individual galaxies to the larger collapsing core. Numerical simulations suggest that this is a signpost event for the formation of a red proto-BCG with ten times the Milky Way's halo mass, completed within the next few 100 million years.
In this talk, I will present the collapse of SPT2349-56's exceptional core, and explain why characterizing the full sample will allow to test the paradigm of massive galaxy formation.

ALMA Lensing Cluster Survey: Joint exploration with JWST into NIR-dark, Intrinsically Faint ALMA Sources at z=2-5

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Since the advent of ALMA, explorations in the early Universe have extended beyond extreme star-forming galaxies (classical SMGs) to include much fainter sources ($S_{1.2mm} < 1$ mJy), which overlap main-sequence galaxies selected in optical/near-infrared (NIR) observations. However, some of these faint ALMA objects are undetectable in deep NIR imaging due to strong dust attenuation. They are referred to as NIR-dark sources and have been overlooked in previous single-dish SMG surveys and Lyman-break selections. Although this population is thought to play a significant role in understanding the formation of massive galaxies, their physical characterization has been hindered due to the difficulties of observations, which in turn obscures our understanding of the physical origin of the strong dust attenuation.
We performed ALMA follow-up line scan observations toward four triple-lensed, NIR-dark faint ALMA sources which are discovered by ALMA Lensing Cluster Survey, a 1.2 mm survey covering 33-lensing cluster regions. We successfully detected CO/[CII]158um emission lines and identified their spectroscopic redshifts to be z=2.4-4.8. We constrained their physical parameters such as stellar mass, star formation rate, gas depletion time, and the

size of dust-emitting region. Three of the sources have compact dust-emitting regions (Re=0.5-0.6 kpc) and high star formation efficiency, similar to classical SMGs. In contrast, one source exhibits an extended dust emitting region (Re∼1.5 kpc), typical star formation efficiency, and an elongated projected axis ratio. These results suggest that normal dusty star-forming galaxies with edge-on disks can be NIR-dark and may have been missed in previous observations. We will also incorporate insights from the forthcoming publicly released JWST/NIRCam observations into our ongoing research discussions.

Disk-driven galaxy transformation at redshift 4: insights from spatially resolved ALMA data

Tsukui, Takafumi[1]

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Recent observations from ALMA and JWST have revealed numerous disk galaxies with redshifts from z=4 to z=6. Archaeological studies of the Milky Way suggest its disk may have formed as early as z∼4. ALMA observations provide detailed kinematics and energetics of the interstellar medium, allowing us to directly probe galaxy formation in the gas-rich early universe. We present new findings from high-resolution ALMA data on BRI 1335-0417 at z∼4.4, the brightest unlensed galaxy in the submillimeter. Our results include the identification of a bulge-disk structure with bar spirals, evidence of seismic ripples on the disk that show similarities to those seen in Milky Way simulations, and a star formation law after correcting for a central AGN based on spatially resolved dust modelling and point source decomposition. Such detailed investigation at this epoch has only become possible by the spatially resolved data. By studying the brightest galaxies, we can overcome the interferometer's inherent poor sensitivity, providing a unique benchmark for our understanding and numerical simulations.

Radio Polarimetry of Gamma-Ray Bursts Afterglows

Urata, Yuji[1]

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Gamma-ray Bursts (GRBs) are highly energetic explosions in the universe and are currently being exploited as probes of first-generation stars and gravitational wave transients. Although the energetics of GRBs are fundamental physical parameters that reveal their progenitor systems, the total energies have been estimated so far without considering non-energized, cool electrons at the relativistic collisionless shock that do not emit observable radiation, while the existence of such cool electrons is well studied for supernova remnants and solar winds. As the first coincident multi-frequency polarimetry between radio with ALMA and optical with VLT was successfully managed, linear polarizations in radio band are essential for discovering these non-energized electrons, because the Faraday depolarization caused by the non-energized electrons suppress the linear polarization degree at a frequency of 100-1000 GHz. Further coordinated multi-wavelength polarimetric campaigns would improve our understanding of the total jet energies and magnetic field configurations in the emission regions of various types of GRBs, which are required to comprehend the mass scales of their progenitor systems and the physics of collisionless shocks.

An ALMA+ACA+ACT view on the z=2 galaxy cluster, XLSSC 122

van Marrewijk, Joshiwa[1]

[1]ESO, Germany

Since the first ALMA memo (Owen et al. 1980), detecting the thermal Sunyaev-Zeldovich (SZ) effect has been an important science driver for ALMA. However, detecting and characterizing the hot intracluster medium (ICM) via the SZ effect is only beginning in earnest with the introduction of Band 1. With 13 times the collecting area and a larger FOV while sampling similar spatial scales as the ACA in Band 3, we can start to resolve the ICM in the most distant clusters of galaxies with only a fraction of the integration time.

The formation and evolution of the ICM across cosmic time are thought to be driven by the continuous accretion of matter from the large-scale filamentary surroundings and dramatic merger events with other clusters or groups. However, which mechanism is the dominant one is unknown. In this talk, I will show a detailed analysis of the ICM of the most distant galaxy cluster found in current SZ-cluster catalogs, namely XLSSC 122. Through modeling ALMA+ACA Band 3 and ACT observations jointly in the uv-plane, we tentatively detect an infalling group previously undetected in competitive X-ray observations. With more observations of the first galaxy clusters now coming through and as future single-dish telescopes start finding more and more high-z clusters, we can begin building a statistical sample of resolved observations to understand ICM heating, cluster growth, and evolution.

Resolving the environments of dusty star-forming galaxies

Wardlow, Julie[1]

[1]Lancaster University, UK

Measuring the environments of galaxies gives crucial insights into their evolution and the mass of their dark matter halos, and halo mass can connect galaxy populations at different redshifts. For example, dusty star-forming galaxies (DSFGs) and submillimetre galaxies (SMGs) have long been hypothesised to be progenitors of local massive elliptical galaxies, though this requires that they commonly reside is protoclusters and over densities with high dark matter halo masses. Studies to date have been limited by the use of statistical counterpart identification, a lack of spectroscopic redshift, or focusing on sources a prior selected based on environmental indicators. I will present new work resolving the environments of ALMA-identified, spectroscopically-confirmed, SMGs using wide-field ESO/HAWK-I narrowband data to pinpoint companions in an unbiased sample of SMGs. Our results show that whilst most SMGs are in protoclusters, up to $\sim$30% may be in field environments. I will also show how (sub)millimetre data can be used to measure the environments Submillimetre-faint objects and apply the method to massive radio-quiet galaxies.

How well can we determine the kinematics of high-z galaxies?

Yttergren, Madeleine[1]

[1]Chalmers University of Technology, Space, Earth and Environment, Sweden

The resolution and sensitivity of ALMA allows us to see more details, structures, and emission lines in distant ($z>1$) galaxies than ever seen before. But the interpretation of the galaxy kinematics is not straight forward and the available resolution for distant galaxies still pose a limitation.
What are the effects of the limited resolution and sensitivity on our understanding of the kinematics and evolution of distant galaxies? Can we, with the current available resolution and tools, separate an outflow from a rotating component, from a merger?
To answer these questions we combine simulation and modelling tools to carry out an extensive investigation on the effects of the limitations of the data and the abilities of 3D-kinematical tools.
Here I present my simulations of a $z=5$ rotating disk galaxy with and without a biconical outflow, "observed" with the ALMA observation simulator and fitted with the 3D-kinematical fitting tools Qubefit, GalPaK-3D and 3D-Barolo. I discuss the impact of the presence of the outflow on the observables and the fitting results, exploring how well we can determine the kinematics of high-z galaxies in the absence and presence of outflows.

3.2 Category: Galaxies and galactic nuclei

Constraining the Impact of Circumnuclear Disk Warping on Black Hole Mass Measurements With ALMA CO Imaging

Boizelle, Benjamin[1]

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Circumnuclear disks (CNDs) are found at the centers of ∼10% of all nearby, massive early-type galaxies (ETGs), with radii spanning a few x100 pc to a few kpc. Recently, high angular resolution CO imaging with the Atacama Large Millimeter/submillimeter Array (ALMA) have revealed these molecular gas disks to be in dynamically cold rotation. Despite the apparent morphological roundness of these dusty disks, CO kinematics show a near ubiquity of either small (5-10 degree) or moderate (10-30 degree) kinematic warping across the disk extent. Ongoing gas-dynamical modeling of these ALMA emission-line cubes now produce reliable black hole (BH) mass measurements, including a few highly precise BH masses. However, these current modeling efforts have primarily targeted mildly warped disks where the CNDs are treated as geometrically flat. In the one such modeling case to date, inclusion of a more general disk structure did not greatly impact the BH mass measurement. To explore the impact of moderately warped CNDs on BH mass measurement, we present detailed gas-dynamical modeling of the CNDs in NGC 3268, NGC 3557, and NGC 4697 using ALMA CO(2-1) imaging. To account for disk warping, we employ a fully-free tilted-ring model during the modeling process. Using this tilted-ring formalism, we determine best-fitting BH masses ranging from about (0.7-1.6)x10^9 solar masses for these three ETGs, with modeling error budgets of about 15-20%. While warped-disk modeling requires significantly greater computation time, the addition of a tilted-ring model greatly improves the fit of the model kinematics to the data. In the worst case, we find that using a flat-disk model systematically biases the BH mass upward by about ∼16%, which is larger than any other systematic effect identified in the modeling process.

Sulphur-bearing species in NGC 253: what do they trace?

Bouvier, Mathilde[1]

[1]Leiden Observatory, Leiden University, The Netherlands

Sulphur-bearing species are known to be highly reactive in the gas phase of the interstellar medium. Their abundance highly depends on the thermal and kinetic properties of the gas (Viti et al. 2004), making sulphur-bearing species extremely useful in reconstructing the chemical history and dynamics of the studied objects. Various processes can enhance the abundance of sulphur-bearing species in the gas phase, such as (i) thermal evaporation and (ii) sputtering and/or shattering of dust grains in shocked regions. As a consequence, in our Galaxy, Sulphur-bearing species are relatively ubiquitous and detected in various environments, from diffuse clouds to star-forming regions.

What do sulphur-bearing species trace in nearby external galaxies? What is their sulphur budget? What are the main processes at the origin of S-bearing species emission? Thanks to the advent of powerful interferometers such as ALMA, it has now become possible to address such questions by performing molecular line surveys of nearby galaxies with a resolution down to scales of Giant Molecular Clouds (GMCs; i.e. tens of pc). In particular, the ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI) is the first ALMA large programme which provides a most complete unbiased molecular survey towards the nuclear region of the starburst galaxy NGC 253 (Martín et al. 2021) at an unprecedented angular resolution of 1.6" (∼27pc).

In this context, we investigated the origin of the emission of several Sulphur bearing species towards the CMZ of NGC 253 to understand which processes dominate in a star-bursting region, where both thermal evaporation and shocks highly compete for the release of sulphured species in the gas phase. Following a detailed radiative transfer analysis, we could extract the various physical conditions associated with the CMZ of NGC 253 and compare them to those found in the Milky Way and other external galaxies.

Isotopologue Ratios Through the Eyes of ALMA: Do They Measure Starburst Age or IMF?

Butterworth, Joshua[1]

[1]Leiden Observatory, Netherlands

Enhanced isotope ratios (in particular $^{13}C/^{12}C$ and $^{18}O/^{16}O$) may be an indication of a top-heavy IMF in distant star forming galaxies. However, the possibility has not been ruled out that the same effect can be produced by a very young starburst.
Until the advent of ALMA the ability to probe and analyse multiple Super Star Clusters (SSCs), in order to investigate this, in a single galaxy was unfeasible. Now, however the high resolution achievable by ALMA allow us to probe the varying behaviour of these isotope ratios at parsecs scale in nearby starburst galaxies.
The ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI) Large Programme is a wide ranging spectral scan of the Central Molecular Zone of the nearby starburst galaxy NGC253 covering bands 3 to 7. Through the plethora of data available of various molecules and their isotopologues (primarily, CO, HCN and HCO^+) we have put to the test the capability of these isotope ratios to trace the SSC age by taking a number of star clusters with well-determined ages and determine the corresponding isotope ratios from the ALCHEMI data. In this talk I will present the correlation between isotope ratio and cluster age that we have found, and whether this correlation supports the theory that ages drive the abundance ratios.

Recovering Intrinsic Molecular Disk Properties in ALMA Imaging of Massive Galaxies: Precision Measurements of CO Hole Radii

Camacho, Conner[1]

[1]Brigham Young University, United States

With its unparalleled sensitivity and angular resolution capabilities, the Atacama Large Millimeter/submillimeter Array (ALMA) has enabled detailed mapping of the CO emission arising from circumnuclear, dusty disks in many massive nearby early-type galaxies (ETGs). At high physical resolutions, these disks typically show central holes in their CO emission-line distributions with characteristic radii of 10-60 pc from their supermassive black holes (BHs). The exact mechanism producing the central CO deficits remains unknown. Outflows, and/or molecular dissociation about an active galactic nucleus (AGN), or morphological quenching in the BH-dominated region, are plausible explanations. To explore the likelihood of either outflow or dissociation scenarios, we seek to compare AGN luminosities with intrinsic CO hole radii for a number of dust-disk ETGs. As a proof of concept, we demonstrate that gas-dynamical modeling can recover the intrinsic CO depletion radius from a suite of realistic simulations that model dusty disks with varying CO hole, synthesized beam sizes, and inclination values. We will also present early results when applying this method to high angular-resolution ALMA CO(2-1) imaging of NGC 383, NGC 524, NGC 3258, and NGC 6861, together with CO(3-2) imaging of NGC 4429. Their BH masses and host galaxy properties are well known, allowing us to more fully explore the systematics of measuring these depletion radii. We explored various functional forms to create this hole radius and statistical methods to constrain their uncertainty.

Studying the X-ray corona with ALMA in Super Massive Black Holes

Chang, Chin-Shin[1]

[1]Joint ALMA Observatory, Chile

Recent studies have proposed that the nuclear millimeter continuum emission observed in nearby active galactic nuclei (AGN) could be created by a population of electrons that also gives rise to the X-ray emission ubiquitously observed in such systems. In my talk I will present the results of the first dedicated high-resolution ($\sim$60-100 milliarcsecond) ALMA campaign that targets a volume-limited ($<$50 Mpc) sample of 26 hard X-ray selected radio-quiet AGN. We find a very high detection rate (25/26 or 94%), which shows that nuclear emission at mm-wavelenghts is almost ubiquitous in accreting SMBHs. Our sensitive observations probe physical scales between

1.5 and 23pc, and show a very tight correlation between the 100 GHz and the intrinsic X-ray emission. The ratio between the 100GHz continuum and the X-ray emission does not show any correlation with column density, black hole mass, Eddington ratio or star formation rate, which suggests that the 100GHz emission can be used as a proxy of SMBH accretion over a very broad range of these parameters. The strong correlation between 100 GHz and X-ray emission could be used to infer the column density in radio-quiet AGN from the ratio between the observed 2-10 keV and 100 GHz fluxes, up to an optical depth of one at 100 GHz ($\sim 7\times10^{26}$ cm^{-2}). Our work opens the door to using ALMA continuum observations to detect heavily obscured AGN, and to identify the precursor of gravitational waves, i.e. binary SMBHs with separations < 10-100pc.

Unveiling Sizes of Compact AGN Hosts with ALMA

Chang, Yu-Yen[1]

[1]NCHU, Taiwan

We present rest-frame far-infrared (FIR) and optical size measurements of AGN hosts and star-forming galaxies in the COSMOS field, enabled by high-resolution ALMA/1 mm and HST/F814W imaging. The sizes and SFR surface densities measured from both ALMA and HST images show that obscured AGN host galaxies are more compact than non-AGN star-forming galaxies at similar redshift and stellar mass. Moreover, most of the rest-frame FIR sizes of AGNs in our sample are similar or more compact than their rest-frame optical sizes. This result suggests that obscured accretion may compact galaxy gaseous components, linked to enhanced star formation before quenching, forming compact passive galaxies. Additionally, dusty starbursts in compact regions imply similar star formation mechanisms in AGN host regions as in ALMA-observed star-forming galaxies.

The last and the next decade of ALMA observations of radio galaxies around Cosmic noon

De Breuck, Carlos[1]

[1]ESO, Germany

Radio galaxies at z>2 are the most massive galaxies known, allowing more detailed studies than any other objects. They are ideal laboratories to see AGN feedback in action, but also accretion of gas from cosmic filaments in the Circum Galactic Medium. As type II AGN, the dusty torus allows us to observe the host galaxy, without being blinded by the bright AGN.
Before ALMA, radio galaxies were thought to have extreme star-formation rates around 1000 $M_\odot$/year, based on single-dish measurements. However, the exquisite spatial resolution of ALMA has shown that the star-formation heated dust emission is rather coming from nearby merging companion galaxies, while most of the AGN host galaxies are already quenched and relatively gas poor (though with several notable exceptions). On larger scales, ALMA has uncovered large streams of gas, and intriguing alignments with the radio jets.
In the next decade, ALMA will provide the only data of matching (or even better) spatial resolution than JWST. I will present early results from joint JWST+ALMA observations of four radio galaxies at z=3.5. We reach the inner 100s of pc scales where we notice ALMA dust and [CII] emission spatially coincident with an absorption line in the [OIII] 5007 ionization cone, suggesting we have finally pierced the inner regions of these massive AGN galaxies, detecting the dusty torus with ALMNA and the ionization cone with JWST.

Giant molecular clouds and their Type classification in M74

Demachi, Fumika[1]

[1]Nagoya University, Japan

Giant molecular clouds (GMCs) are the main star formation sites in galaxies and the GMC evolution is important in driving the galaxy evolution. Fukui et al. 1999 found GMCs are classified into three Types according to their associations with HII regions and young clusters using the resolved GMC samples in the Large Magellanic Cloud (LMC) and interpreted that the Types indicate an evolutional sequence of GMCs. Kawamura et al. 2009

estimated a GMC lifetime of 20-30 Myr in the LMC, and Corbelli et al. 2017 obtained a similar GMC lifetime in M33. Until recently it has been difficult to extend Type classifications to other galaxies beyond the Local Group because of the limited resolution. Most recently, ALMA is resolving GMCs in more than 70 spiral galaxies up to 10-20 Mpc (especially by PHANGS).
For a face-on spiral galaxy M74 at 10 Mpc, we identified GMCs and applied them to the Type classification as follows; Type I 'without star formation', Type II 'with Ha luminosity (LHa) smaller than $10^{37.5}$ erg/s', and Type III 'with LHa greater than $10^{37.5}$ erg/s', using the PHANGS CO and Ha images. As a result, we identified 65 Type I, 203 Type II, and 164 Type III GMCs. We show Type III has lower virial parameters of the three Types. We find clusters younger than 4 Myr and HII regions are concentrated within 150 pc of Type III, and LHa and cluster mass show more tight correlation for Type III than Type II. For these results, we interpreted GMCs to evolve from Type I to III, and Type III are the most gravitationally relaxed and active star-forming sites among the three Types. Then, assuming a steady state evolution, we estimate the timescales as follows; Type I is 2 Myr, Type II is 6 Myr, and Type III is 4 Myr, which are to be considered as the lower limits. In the presentation, we will argue that transition mechanisms between GMC Types, such as cloud-cloud collisions triggering high-mass star formations, and summarize the results of the evolution of several more galaxies.

The molecular gas content of the highest redshift galaxy imaged in HI: resolving the bar in a z=0.376 CHILES detected galaxy

Donovan Meyer, Jennifer[1]

[1]NRAO, USA

I will present ALMA followup of the highest redshift HI detection in the COSMOS HI Large Extragalactic Survey (CHILES) made with the first 178 hours of observing. Though the HI distribution of this system indicates a potential interaction due to the asymmetric and extended nature of the neutral hydrogen, the galaxy is a barred, starbursting, luminous infrared galaxy (LIRG) at z = 0.376. The star formation rate of this galaxy is typical of star-forming galaxies at z$\sim$1 and ULIRGS at z=0, and its HI mass is high for its stellar mass compared to samples at z=0 but comparable to the HI richest systems at z=0-0.2. The previous CO (1-0) single dish spectrum indicates a richness in molecular gas. However, our CO (3-2) observations with $\sim$2 kpc resolution primarily trace the bar. I will discuss the implications of this detection in the context of high redshift stacked and resolved HI detections, as well as the impact that including molecular gas has on our understanding of galaxy evolution since z$\sim$1, where the co-evolution of atomic and molecular gas mass densities diverge.

Supermassive Black Hole Pairs at separations <1 kpc and their role in black hole growth

Droguett, Macarena[1]

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While not very frequent, major galaxy mergers play a critical role in our understanding of galaxy formation and evolution. In spite of this, we still do not understand the key connection between these events and the rapid growth of the central supermassive black holes (SMBHs) during them, mainly because the latter likely happens during the most obscured phases.
In this talk, I will present a study of a population of dual AGN candidates near coalescence, all of them with nuclear separations below one kpc. This is only now possible, thanks to Atacama Large Millimeter Array (ALMA)'s high-resolution, sensitivity, and the ability to observe in the millimeter regime, which is relatively unaffected by dust obscuration.
By taking advantage of the observed correlation between x-ray and mm-emission in AGN, now well-established for isolated sources, we can first confirm or unveil the presence of dual AGN in a sample of local major galaxy mergers with archival ALMA observations, including IR-luminous systems from the Great Observatories All-Sky LIRG Survey (GOALS) sample. With these data, we can then measure their individual luminosities, and hence the associated SMBH accretion rates. Our preliminary results indicate that already confirmed dual AGN follow this correlation as well. We will present a study of the 100 GHz continuum morphologies and in-band spectral

indices for the systems in our sample, which will allow us to identify non-thermal emission, unveiling the presence of an AGN.
Finally, I will present preliminary results from our long baseline ALMA Cycle 9 observations of 12 Swift-BAT AGN in the local Universe hosted by late-stage major galaxy mergers, allowing us to significantly expand the sample of known dual AGN at small nuclear separations, to hence do a more robust statistical study of the incidence of dual AGN in these systems.

Kinematics of the molecular torus in NGC 1068

Gámez Rosas, Violeta[1]

[1]Leiden Observatory, Leiden University, Netherlands

NGC 1068 is one of the most studied AGN all across the electromagnetic spectrum. It is a nearby barred galaxy (d=14.4 Mpc) considered to be the prototypical Seyfert 2. Analyses of molecular lines in the millimeter and submillimeter wavelength range have given insight on the complicated kinematics of the gas at parsec scales from the black hole in the "molecular torus". Some of the conclusions include descriptions like "enhanced turbulence", "non-circular motions", "high-velocity outflows", and, most puzzling of all, "misaligned counter-rotating disks". Other works have explained the latter as only an apparent counter-rotation that results from instabilities in the torus. In this talk I will present our interpretation of new ALMA Band 7 observations with the highest spatial resolution achieved so far that aim to shed light on this disagreement.

Tracing the shock history of the molecular gas in nearby galaxies with ALMA

Huang, Ko-Yun[1]

[1]Leiden Observatory, Netherlands

Starburst activities and Active Galactic Nuclei (AGN) feedback are both important agents in influencing the interstellar medium (ISM) and the evolution of galaxies. For example, the massive molecular outflow in the composite galaxy NGC 1068 is considered as a manifestation of on-going AGN feedback, while outflows from the nucleus of the galaxy NGC 253 is believed to be starburst driven. These large-scale outflows have been suggested to induce a rich shock chemistry in the surrounding ISM.
High spatial resolution multi-line molecular observations are an ideal tool for a systematic study of these physico-chemical processes in the ISM, given the wide range of critical densities associated with different molecules and its transitions, and the dependencies of chemical reactions on the energy budget of the system. In our recent works (Huang et al. 2022, 2023; Huang et al. in prep.), we were able to characterize the gas properties (such as kinetic temperature, gas density) probed by the shock tracers- SiO, HNCO, and CH_3OH - in the nearby starburst galaxy NGC253 and the nearby AGN-host galaxy NGC1068 with ALMA multi-line imaging at GMC-scale ($\sim$50pc). Moreover, we found that the gas traced by these species is indeed subjected to shocks with different shock strengths, and possibly with different origins. The reconstructed shock history can also be associated with the star-formation (SF) history in these regions.
In this talk, I will highlight the key results from these recent works, and the path forward in systematically characterizing the shock physics and chemistry in both starburst and AGN-host galaxies.

Resolving supermassive black hole feeding and feedback down to sub-parsec scales

Izumi, Takuma[1]

[1]NAOJ, Japan

Mass accretion is a fundamental process for the growth of supermassive black holes and activating the central engines. However, detailed accretion properties have not been observationally identified at the central $\sim$10 parsec of active galaxies due to the compactness. Here we introduce the robust and quantitative identification of a sub/parsec-scale (i.e., 0.01% scale of the host galaxy) dense molecular inflow toward the active nucleus of the Circinus galaxy, seen as a deep absorption feature. Only a tiny portion ($< 3\%$) of this inflow is consumed in the actual black hole growth but a bulk portion is blown-out by multiphase outflows: in addition to molecular and atomic phases, we successfully identified ionized outflow by using submm recombination line. The slow atomic-dominant outflow will fall back to the disk to introduce significant turbulence, which will explain the physical origin of AGN torus. The observed dense gas disk is gravitationally unstable and drives accretion down to the central ∼1 parsec. However, a complete solution to the long-standing fuel supply problem requires a further understanding of the accretion mechanisms acting at the innermost sub-parsec region, which will be tackled by future ALMA observations.

Probing AGN Molecular Torus via Emission, Absorption, and polarization

Kameno, Seiji[1]

[1]Joint ALMA Observatory, Chile

A molecular torus in the central parsec scale of active galactic nuclei (AGNs) is a key component that plays important roles of mass accretion, jet collimation, and diversity in appearance depending on viewing angles. Using ALMA and VLBI, we have tackled to unveil physical properties of AGN tori via molecular emission and absorption lines, plasma free-free absorption, and polarimetry. We will present a representative case on the nearby radio galaxy, NGC 1052. This AGN emanates a double-sided jet that casts molecular absorption and plasma free-free absorption features toward the bright synchrotron emission. It also exhibits H_2O maser emissions at 22 GHz and 321 GHz, which amplifies background continuum emission through population-inverted H_2O molecules in the torus. Abnormally high $H^{13}CO$-to-$H^{12}CO$ ratio implies high column density one order of magnitude greater than that estimated by X-ray spectroscopy and small covering factor of ∼0.17 which is consistent with spatially resolved VLBI opacity map. Sulfur-bearing absorption features indicate jet-torus interaction which generates shocks that heat dust grains. Polarimetry allows us to measure the orientation of magnetic fields inside the molecular torus. In my talk, I'll report highlights of emission and absorption studies on AGNs which would be more productive with WSU.

A Comprehensive ALMA Study of Mm-wave Continuum Emission from Hard X-ray Selected Nearby AGNs

Kawamuro, Taiki[1]

[1]RIKEN, Japan

AGNs emit radiation across a wide range of wavelengths. However, until the advent of ALMA, the AGN mm-wave emission has been poorly understood. While the mm-wave emission may be due to thermal and synchrotron components extending from the infrared and cm-wave bands, respectively, ALMA has found an excess explainable by synchrotron self-absorption (SSA) emission from the AGN X-ray corona. Thus, the mm-wave emission may provide a crucial insight into the central engine of AGNs. To study the emission in more detail, we analyzed subarcsec Band-6 ALMA data of 98 nearby AGNs ($z<0.05$) from the Swift/BAT catalog. This sample provides the largest number of AGNs with high spatial resolution sampling (∼1-200 pc), and is almost unbiased for obscured systems. We found a tight relation of 1 mm and X-ray luminosities with a scatter of ∼0.36 dex. While the mm-wave emission thus may be the SSA from the X-ray corona, we also discuss other possible origins, including dust emission, outflow-driven shock, and small-scale (<200 pc) jets. We ruled out dust emission as a dominant source, as the mm-wave slope is generally flatter than expected. Also, the lack of an increase in the mm-wave luminosity with the Eddington ratio suggests that a radiation-driven outflow is possibly not a common mechanism. We furthermore found that the mm-wave luminosity is independent of inclination-angle indicators, inconsistent with a simple jet model. Overall, our results put important constraints on the mm-wave origin.

ALMA's resolved view of molecular cloud structure beyond the Milky Way

Koch, Eric[1]

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I will discuss progress and prospects for ALMA surveys that resolve individual molecular clouds in other galaxies. The formation, evolution, and destruction of molecular clouds power the growth of galaxies across cosmic time. Resolved observations show that this evolution is dynamic, with the gas continuously reshaped by turbulence, gravity, and stellar feedback. So far, large ALMA surveys of nearby galaxies demonstrate close links between molecular gas and the local galactic environment, consistent with this dynamic picture. However, systematic extragalactic surveys still have a resolution too coarse to resolve the morphology of individual molecular clouds, leaving major questions about the physical state of clouds in other galaxies. At the same time, the discovery of massive filaments in the Galaxy and the Magellanic Clouds, as well as observations of widespread shells and bubbles driven by stellar feedback in early JWST images, show that we need to resolve the morphology of molecular clouds to achieve a picture the physics of the star formation process. I will present new Local Group studies highlighting the power of these heavily resolved observations to unveil the physics of molecular gas and star formation. Then I will discuss the next steps that ALMA can take (along with JWST, HST, and ground-based IFUs) to assemble a truly resolved, systematic, and statistically significant picture of the molecular cloud lifecycle across the Local Volume and give critical insight into the physical state (gravitational boundedness, density, turbulence) of molecular gas across galaxies, whether density and self-gravity or external factors primarily drive star formation, and how stellar feedback reshapes and destroys molecular clouds. Such a survey is achievable now and would create an invaluable link between Galactic and extragalactic studies of molecular gas. Finally, I will highlight how ALMA-2030 will enable next-generation multi-line gas and dust studies toward this goal.

Extended Thermal Bremsstrahlung in AGN Hosts as a New Probe of Negative Feedback

Komugi, Shinya[1]

[1]Kogakuin University, Japan

Our current understanding of galaxy evolution requires galaxies to quench star formation efficiently after the cosmic noon, before they quickly evolve into "red and dead" ellipticals. One of the promising ways to realize this is by negative feedback from AGN. Observations of gas outflow from the AGN have been found to expel gas from the galaxy, but simulations have shown that gas could eventually return to the disk and subsequently form stars. Alternatively, Extended Emission Line Regions (EELRs) observed in optical lines around QSOs and extending tens of kpc, are evidence of preventive feedback, where the QSO directly ionizes gas in the host and inhibits the formation of cold molecular gas. Estimating the mass of ionized gas (and thus the amount of feedback) in EELR have been difficult, however, because line excitation and dust extinction need to be assumed, and the diffuse emission suffer from the overwhelmingly bright central core.

Using ALMA, we have detected diffuse and extended millimeter continuum in the host galaxy of the prototypical QSO 3C273. The emission is cospatial with the optical EELR, could not be explained by star formation or synchrotron emission, and consistent with theoretical calculations of thermal free-free emission from host gas directly ionized by the QSO. This is the first detection of a radio counterpart to the EELR. The virtue of millimeter detection of the EELR is that no dust extinction need to be assumed, emission mechanism are simple compared to the optical, and that ALMA enables precision self-calibration reaching an image dynamic range of $>$50000, so that the contamination from the core can be overcome. The ionized gas mass in 3C273 is easily estimated to be $\sim 10^{10}$ solar mass.

This method of probing negative feedback can be applied to other QSO as well, providing a new avenue to revealing the interaction between AGN and the host galaxy.

Evidence for increased star formation in the centres of barred galaxies

Laing, Jennifer[1]

[1]McMaster University, Canada

Galactic bars play an important role in the dynamical evolution of their host galaxy, but their own evolution and impact on the local gas reservoir and star formation rate are still open questions. Recent work by the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) collaboration found higher molecular gas surface densities and velocity dispersions in barred galaxies compared to unbarred galaxies. The higher turbulence found in bars is expected to create the observed increases. In this work, I explore bar turbulence in molecular gas using published high resolution measurements of CO(2-1) from the PHANGS-ALMA survey. I compare properties of the molecular gas, such as surface density, velocity dispersion and star formation rate, in the centres of barred and unbarred galaxies. I consider the effect of galaxy environment on these properties from a local (at cloud scales, ∼100 pc) and global perspective. On global scales, I consider these properties in the context of the environment in which a galaxy lives, whether in a cluster or in the field. All three quantities are found to be enhanced in barred galaxy centres regardless of global environment.

Statistical Study of the Star Formation Efficiency in Gas-rich Bars

Maeda, Fumiya[1]

[1]University of Tokyo, Japan

The dependence of the star formation efficiency (SFE) on galactic structures-especially whether the SFE in the bar region is lower than those in other regions-has recently been debated. We report the SFEs of 18 nearby gas-rich massive star-forming barred galaxies with large apparent bar major axes (>= 75"). We statistically measure the SFE by distinguishing the center, the bar end, and the bar regions for the first time. The molecular gas surface density is derived from archival CO(1-0) and/or CO(2-1) data by assuming a constant alphaCO and the SFR surface density is derived from a linear combination of FUV and MIR intensities. The angular resolution is 15", which corresponds to 0.3-1.8 kpc. We find that the ratio of the SFE in the bar to that in the disk was systematically lower than unity (∼ 0.6-0.8), which means that the star formation in the bar is systematically suppressed. Our results are inconsistent with similar recent statistical studies, which have reported that the SFE tends to be independent of galactic structures. This inconsistency can be attributed to the differences in the definitions of the bar region, the spatial resolutions, the alphaCO, and the sample galaxies. Furthermore, we find a negative correlation between the SFE and the velocity width of the CO spectrum, which is consistent with the idea that the large dynamical effects-such as strong shocks, large shears, and fast cloud-cloud collisions caused by the noncircular motion of the bar-result in a low SFE.

Complex organic molecules at Mpc distances. Results from ALCHEMI Large Program

Martin, Sergio[1]

[1]Joint ALMA Observatory, Chile

NGC 253 is the one of the brightest molecular emitters outside the Galaxy and therefore the more suited candidate for deep molecular surveys.

Despite of being observed at every wavelengths for decades, mid through ALMA journey last decade, we pushed the limits of extragalactic astrochemistry with the ALCHEMI Large Program, the most ambitious study of the molecular content and distribution in an extragalactic object. This project has produced already about ten publications making use of different molecular tracers to peer into the physical conditions and processes ongoing within this starburst environment.

In this presentation I will focus on the unprecedented molecular richness observed outside the Galaxy, and in particular on the preliminary results on the detection and imaging of complex organic molecules. A handful of long carbon unsaturated molecules, including long cyanopolyynes are detected and its emission and abundance ratios can be directly compared to Galactic molecular clouds and star forming regions. Initial results will be presented to celebrate the 10th anniversary of this game changer observatory.

ALMA Confirmation of Millimeter Time Variability in the Gamma-Ray Detected Seyfert Galaxy GRS 1734-292

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GRS 1734-292 is a galaxy that exhibits no significant starburst or jet activities in the radio spectrum. However, Fermi-LAT detected this object in the GeV range. The source of the non-thermal activity in this Seyfert galaxy poses an intriguing question. We present observations of GRS 1734-292 using the Atacama Large Millimeter/submillimeter Array (ALMA) at frequencies of 97.5, 145, and 225 GHz. These observations confirmed the presence of excess millimeter emission in the central ∼100 pc region, and its time variability was observed over two epochs separated by four days. The timescale of variability aligns with the time it takes light to cross a compact source (<100 Schwarzschild radius). By considering the power-law synchrotron emission from the corona (i.e., the hot plasma above the accretion disk), the millimeter spectrum suggests a coronal magnetic field strength of approximately 10 G and a size of around 10 Schwarzschild radii. Another possible explanation for this millimeter emission is synchrotron and free-free emission from disk winds (i.e., fast wide-opening angle outflows from the disk) with a size of approximately 10 pc, although it may be challenging to account for the rapid variability. These two scenarios can be distinguished through future higher-resolution (<0.01") millimeter observations, which will uncover the sites of particle acceleration in the central regions of active galactic nuclei.

The molecular gas ISM properties in typical gas-rich star-forming galaxies at z∼1.5

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Around half of the stellar mass observed today on galaxies was formed in just about 3.5 Gyr between z ∼ 1 and z ∼ 3. This is the epoch when the cosmic star formation rate (SFR) density peaked, just before decreasing more than one order of magnitude to the present day values. Strikingly, at those redshifts, roughly 90% of the star-forming galaxies follow the so-called main-sequence (MS), with the bulk of the more massive ($M_* > 10^{10}$ $M_\odot$) galaxies displaying global disk-like stellar morphology and kinematics. However, most of this knowledge is based on observations targeting the ionized gas interstellar medium (ISM), with scarce evidence constraining the properties of the molecular gas ISM. By pushing ALMA to its limits, MS galaxies at z∼1–3 can be imaged in CO low-J transition emission over ∼kpc-scales, providing a resolved view high-z cold gas ISM. In this study, I will present ∼kpc-scale CO(2–1) observations of three gas-rich MS galaxies at z∼1.5. The molecular gas ISM follows regular radial profiles, and the kinematics suggests elevated degree of turbulence, in resemblance to that measured from the ionized gas component. Those findings are one of the first clues about the molecular gas ISM conditions in star-forming galaxies representative of the bulk of the galaxy population at z∼1.5.

Mm/submm Energy Diagnostics & Non-LTE Modeling of the AGN-Starburst Composite Galaxy NGC 7469 with ALMA

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Mass accretion has been considered as a promising mechanism of supermassive black hole (SMBH) growth (e.g., Alexander & Hickox 2012), which is particularly effective during mergers of gas-rich galaxies (e.g., Hopkins et al. 2007). High mass accretion makes SMBH appear as an Active Galactic Nucleus (AGN). Early stages of its evolution has been considered to be heavily obscured by dust and gas, and it is extremely difficult to identify those populations at rest-UV to optical wavelengths due to severe dust extinction.

Thus, identifying energy sources of galaxies at mm/submm (least affected by dust extinction) can be an excellent way to uncover dust-obscured AGNs, which are elusive at optical. Izumi et al. (2020) found that the AGN in NGC 7469 has a [CI](1-0)/^{13}CO(2-1) emission line ratio nearly 10 times higher than that in starburst (SB) regions.

Very high gas excitation (temperature) and dissociation of CO molecules due to intense X-ray irradiation are considered to take place in AGN and cause high CI/^{13}CO ratio.
We performed non-local thermal equilibrium (non-LTE) analysis and compare them with the chemical model in order to evaluate quantitatively the scenario above. We modeled the emission of [C I](1-0), ^{13}CO(2-1) and ^{12}CO(1-0), (2-1), and (3-2) lines under non-LTE analysis by using RADEX code (van der Tak et al. 2007) toward the AGN and SB regions in NGC 7469.
We searched for the optimal values of kinematic temperature (Tkin), [C0]/[CO] abundance ratio, and CO column density (N_{CO}) (under fixed H_2 volume density n(H2), for simplicity). We found Tkin and [C0]/[CO] are higher in AGN than those in SB while N_{CO} is lower in AGN than that in SB. That follows the trends from the X-ray Dissociation Region models (Meijerink & Spaans 2005). Details of our research will be discussed in this presentation.

Closing the feedback-feeding loop of the radio galaxy 3C 84

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Gas accretion by a galaxy's super massive black hole (SMBH) and the energetic feedback by the accreting active galactic nucleus (AGN) on the gas around it are two tightly intertwined processes. Observations of galaxy clusters have shown how plasma jets emitted by the AGN heat the intra-cluster medium, preventing cooling of the cluster gas and thus the infall of this gas onto the SMBH. However, observations of cool-core galaxy clusters have also shown that rising plasma bubbles, inflated by the jets, can also induce local cooling of the cluster gas, leading to filaments of cold gas. The fate of these filaments is unclear, but it has been suggested they may play a role in feeding the AGN activity.
We will present results of re-processed CO(2-1) ALMA observations of the molecular gas in NGC 1275, the central galaxy of the Perseus cluster hosting the radio-loud AGN 3C 84. These data show, for the first time, in great detail how kpc-sized cold gas filaments originating from jet-induced cooling of cluster gas are flowing onto the circum-nuclear accretion disc of the SMBH, showing that the cooled gas does indeed play a role in feeding the AGN activity. These results complete our view of the feedback loop of how an AGN can impact on its surroundings and how the effects from this impact maintain the AGN activity.

Tracing the Evolution of Specially-resolved Gas and Star Formation Properties along the Offset from the Star-forming Main Sequence

Pan, Hsi-An[1]

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Quenching of star formation is one of the key drivers of galaxy evolution. We use data taken from the ALMaQUEST survey (ALMA-MaNGA QUEnching and STar formation) to study the change of spatially-resolved molecular gas and star formation properties as galaxies moving away from the star-forming main sequence towards the passive regime. In particular, we are interested in investigating where and how does star formation quench in galaxies? For example, it is the amount of molecular gas (fuel) available to form new stars or the efficiency of molecular gas to form stars that controls star formation quenching in nearby galaxies. Our results show that star formation quenching can be driven by a variety of mechanisms, both within a galaxy and between different galaxies. About a third of galaxies undergoing quenching is predominantly efficiency driven, a third is fuel driven, and a third is driven equally by both across the galactic disks. Finally, some galaxies are driven by different mechanisms in different radial regime. The different driver of of star formation quenching imply the diverse evolutionary paths of galaxies. This study, as well as the ALMaQUEST survey, mark a new era of research using ALMA and its extraordinary capability for exploring cold gas properties in extreme environments and galaxy evolution.

APEX Observations of the 752 GHz water line in low redshift ULIRGs

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Using the Atacama pathfinder experiment (APEX) with the Swedish-ESO PI Instrument for APEX (SEPIA) Band-9, we report the first-ever ground-based detection of the water line p-H_2O ($2_{11} - 2_{02}$) at 752.033 GHz in three z < 0.08 ULIRGs, IRAS 06035-7102, IRAS 17207-0014 and IRAS 09022-3615. We detect the H_2O line with overall signal-to-noise ratios of 8-10 in all three galaxies, among which IRAS 06035-7102 is the first detection of this line. We estimated global infrared luminosities by fitting a model consisting of a modified black body with a power law at mid-IR wavelengths. While exploring the correlation between the p-H_2O ($2_{11} - 2_{02}$) and the total infrared luminosity LIR, our galaxies are found at the bright end of the local ULIRG population. Our spectrally resolved observations of the 752 GHz H_2O line were compared to the ALMA-detected CO(J = 4-3) line profile in two galaxies IRAS 17207-0014 and IRAS 09022-3615, finding in the later that water emission is spatially and spectroscopically offset compared to the gas traced by CO(4-3). This suggests a significant contribution of far-IR photons in the excitation of p-H_2O ($2_{11} - 2_{02}$), as H_2O is preferentially coincident to the dust continuum rather than CO. This pilot study demonstrates the feasibility of directly conducting observations towards the H_2O line from the ground, and opens the possibility for ground-based follow-up campaigns, to increase the sample or interferometric observations at higher resolution to spatially resolve the H_2O down to scales of giant molecule clouds in ULIRGs

Roadmap of ALMA in Event Horizon Telescope observations

Ramakrishnan, Venkatessh[1]

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I will present an overview of the significant findings of 2017 EHT observations and the impact ALMA has in all these results. This will include both total flux and full polarisation results of SgrA* and M87*.
Since these two targets represent only a small fraction, I will discuss how an ongoing study of more nearby targets will be fundamental in establishing a vital relation pertaining to accretion-spin-mass-distance scale. This transformative science is important to anchor several (non-)General Relativity-related models, which will also be important to place more stringent constraints on gravitational physics as we are gearing towards finding more black hole binary detections from the multimessenger era.

Observing AGN fuelling via molecular absorption lines

Rose, Tom[1]

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AGN and their jets are, to a large extent, powered by the accretion of cold molecular gas. Unfortunately, observing this gas on small spatial scales is difficult because it can normally only be seen en masse through emission lines.
I will present observations of the molecular gas in massive galaxies on scales of just tens to hundreds of solar masses. We see the gas on this incredibly small mass scale using high angular resolution observations of the galaxies' bright and extremely compact continuum sources - against which we see the shadows of gas clouds in the form of absorption lines. Our ALMA surveys of several galaxies have detected dozens of $\sim$100 solar mass molecular clouds.
The velocities of the clouds are revealed by the absorption's redshift and in many cases, they're moving towards their supermassive black hole at several hundred km/s. I will explain how these observations show the early stages of individual clouds accreting onto their host AGN.
Characteristics of the absorption lines, such as their strength and width, can then be used to infer the clouds' mass, temperature, and chemistry. Through this, we show that the gas fuelling AGN and their jets has remarkably similar properties to gas present in the Milky Way.

Negative AGN feedback in NGC 1068: The Kinematics, Chemistry, and Cloud Properties

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Based on the rich, high-quality ALMA data acquired over the past decade, for the nearby Seyfert 2 galaxy NGC 1068, we have embarked on a detailed study of the AGN feedback occurring within the central kiloparsec (kpc) of NGC 1068. In this work, we present the following findings:
(1) Kinematical properties: We observe a significant enhancement in [CI] emission within the central kpc, with a [CI]/CO ratio greater than 1. The gas exhibiting the highest [CI] enhancement (ratio > 1) displays a kpc-scale elongated structure, centered at the AGN, which corresponds to the known biconical ionized gas outflow that entrains molecular gas in the disk. We successfully reproduce the kinematics of this elongated structure using a truncated, decelerating bicone model, suggesting an interaction between the jet and the ISM.
(2) Chemical properties: Using principal component analysis (PCA) applied to 150-pc-resolution spectral scan data sets, we identify two prominent features. The first is a central concentration at the circumnuclear disk (CND), while the second consists of two peaks across the center, coinciding with the peaks of the biconical outflow. The concentrated molecular lines within the CND predominantly belong to high-dipole molecules. Line emissions from molecules known to be enhanced in an irradiated ISM show similar concentrations and extended components along the bicone. These findings suggest that molecule dissociation plays a significant role as a dominant chemical effect in the cold molecular outflow of this galaxy.
(3) Cloud properties: By extracting molecular clouds from the 55-pc-resolution [CI] and CO data, we conduct a comparative study between molecular clouds along the AGN jet and those in the spiral arms.
This presentation provides comprehensive insights into the AGN feedback mechanisms within the central kpc of this prototypical Seyfert galaxy.

Star Formation along the merger sequence in LIRGs: the case of Arp 240.

Saravia, Alejandro[1]

[1]University of Virginia, United States

We present a study of the star formation properties of the early-stage luminous infrared galaxy (LIRG) merger Arp 240. We use ALMA CO (J 2-1) and VLA radio continuum observations to measure the star formation rates (SFR), molecular mass surface density, star formation efficiencies (SFE), and linewidths at sub-kpc resolution, probing physical scales of ~ 500 pc. We used a uniform grid analysis to create maps of these properties for Arp 240, providing insights into how these quantities vary as a function of location in the merger. We examine the Kennicutt-Schmidt (K-S) empirical relation on sub-kpc scales in Arp 240, finding general agreement between the sub-kpc regions in our grid analysis and the integrated measurements of starburst galaxies. However, the slope of the relation in our data was found to be sublinear. Our observations show that Arp 240 has two distinct regimes of star-forming emission: low-surface brightness emission and the bright, compact starbursting complexes. The brightest regime exhibits a substantially steeper power law relative to the low-surface brightness regions, indicating a higher star formation efficiency in the brightest regime. In this talk, we will also show preliminary work expanding the analysis done in Arp 240 to other 20 LIRGs at different merger stages, using archival ALMA data at similar resolutions. Our work is one of the few studies of LIRGS to leverage VLA extinction-free measurements that trace SFR across the majority of the regions of molecular gas observed with ALMA at these scales.

The first joint ALMA/X-ray monitoring of a radio-quiet AGN: understanding the origin of the compact

Shablovinskaya, Elena[1]

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The origin of compact radio/mm emission observed in nearly all radio-quiet Active Galactic Nuclei (AGN) is still debated. Recent studies have proposed that it is produced by self-absorbed synchrotron emission from the accretion disk corona, which is also responsible for the X-ray emission ubiquitously observed in AGN. The detection of correlated variability between the mm and X-ray bands would be the smoking gun supporting this idea. We carried out the first joint mm (ALMA; ∼100 GHz)/X-ray (NICER/NuSTAR/XMM-Newton/Swift; 0.3-10 keV) observations of the brightest unobscured radio quiet-AGN, IC 4329A (z = 0.016). In my talk, I will present the first results of this large campaign, discussing the relation between the X-ray corona and the compact radio emission observed in radio-quiet AGN.

Interactions Between Galaxy Substructure and Highly Inclined Ram Pressure: ALMA Observations of Extreme Stripping in the Coma Cluster Galaxy NGC 4858

Souchereau, Harrison[1]

[1]Yale University, United States

Galaxies orbiting a galaxy cluster can experience ram pressure winds while moving through the intracluster medium, which can dramatically rearrange and strip away gas and dust from the galaxy disk. The geometry of the interaction can significantly modify its effects, including the overall stripping efficiency, and the morphology of the stripped tail.
Leveraging ∼1" (500pc) resolution CO(2-1) data of the Coma galaxy NGC 4858 from the ALMA-JELLY large program, with complimentary HST continuum and Subaru H-alpha data, we observe and analyze a wealth of features indicative of a galaxy experiencing a highly inclined ram pressure wind. Using a novel "quadrant" approach, we characterize the interplay between rotation and ram pressure on the molecular gas distribution and kinematics, and explore RPS-induced effects on star formation. Through structural analysis of the galaxy's prominent stripped tail, we show that the inner tail region is highly asymmetric, agreeing with predictions from galaxy "wind tunnel" simulations of highly inclined ram pressure.

High Star Formation Efficiency in Barred Galaxy Centers Revealed with a New CO-to-H_2 Conversion Factor Prescription

Teng, Eltha Yu-Hsuan[1]

[1]University of California San Diego, United States

The CO-to-H_2 conversion factor (alpha$_{CO}$) is central to studying molecular gas and star formation in galaxies, and it is known to vary with environmental conditions. In particular, alpha$_{CO}$ can drop in galaxy centers by nearly an order of magnitude. The variation of alpha$_{CO}$ causes major uncertainties in current molecular gas measurements, and it interferes with accurately measuring star formation efficiency and molecular cloud properties. Using high-resolution and sensitive ALMA observations of multiple ^{12}CO, ^{13}CO, and C^{18}O lines in several barred galaxy centers, we have found that the alpha$_{CO}$ decreases are primarily driven by CO opacity changes and thus shows strong correlations with observables like velocity dispersion and ^{12}CO/^{13}CO line ratio (Teng et al. 2022, 2023). Motivated by these results, we have constructed a new alpha$_{CO}$ prescription which accounts for emissivity effects in galaxy centers and verified it on a set of barred and non-barred galaxies with measured alpha$_{CO}$ values. Applying our new prescription to the PHANGS-ALMA Large Program dataset, we observe distinctly higher star formation efficiency in some barred centers than in non-barred centers. We will discuss how the alpha$_{CO}$ variation and current prescriptions impact star formation efficiency and molecular gas concentration in various types of galaxies and galactic nuclei, leveraging the full PHANGS-ALMA sample of ∼100 nearby galaxies.

Full SED Analysis of z ∼ 0.5-5 Lensed Galaxies Detected by Millimeter Observations

Uematsu, Ryosuke[1]

[1]Kyoto University, Japan

Sub/millimeter galaxies are a key population to elucidate galaxy evolution because the majority of star formation at high redshifts occurred in galaxies deeply embedded by dust. To search for this population, our team has performed an extensive survey with ALMA, called the ALMA Lensing Cluster Survey (ALCS). This survey covers 134 arcmin^2 and detects 180 secure sources at z∼0.5-6 with a flux limit of ∼0.2 mJy at 1.2 mm (Fujimoto et al. submitted). Here we report the results of multi-component SED analysis for the whole ALCS sample, utilizing the observed UV to millimeter photometries. We find that most of the ALCS sources are in the star-forming main sequence, while some of them show starburst activities. The ALCS sample contains extremely dusty-obscured galaxies (IRX=log LIR/LUV>5). We also confirm the cosmological evolution of dust temperature across z=1-5 as reported in previous studies. Finally, we identify 20 AGN candidates that are not detected in the archival Chandra X-ray data, utilizing the Bayesian Information Criteria. Their inferred AGN luminosity density shows an excess at z=2-3 compared with that determined from X-ray surveys by Ueda et al. (2014), suggesting that a significant fraction of AGNs in this epoch are Compton-thick and might be missed in previous X-ray observations below 10 keV.

The EDGE-ACA survey: The Star Formation Activity Across the Green Valley

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We present a survey of 60 local galaxies (including 11 green valley and 13 red clump galaxies) with integral field spectroscopy based on the CALIFA sample and using the Atacama Large Millimeter/Submillimeter Compact Array, as part of the Extragalactic Database for Galaxy Evolution (the EDGE-ACA survey). We use CO(J=2-1) and optical data to test how the star formation quenching processes affect the star formation rate (SFR) per unit molecular gas mass, SFEmol = SFR/Mmol, and related quantities in galaxies with stellar masses $\log[M^*/M_\odot] = 10\text{-}11.5$. We observe a systematic decrease of the molecular-to-stellar fraction (fmol) with decreasing level of star formation activity, with green valley galaxies having also lower SFEmol than galaxies in the main sequence. On average, we find that the spatially resolved SFEmol within the bulges of green valley galaxies is lower than in the bulges of main sequence objects when adopting a constant CO-to-H_2 conversion factor, alpha_{co}. While efficiencies in main sequence galaxies remain almost constant with galactocentric radius, in green valley galaxies we note a systematic increase of SFEmol, fmol, and specific star formation rate, sSFR, with increasing radius. Finally, we observe lower SFEmol in the central regions of AGNs when compared to their outskirts, and the magnitude of the decrease appear too large to be explained by changes in alpha_{co}. Our results suggest that gas depletion/removal does not fully explain the star-formation quenching in galaxies transiting through the green valley, and that a reduction in star formation efficiency is also required during this stage.

Study of the galactic environment with dense gas at the 60 pc resolution in the nearby Seyfert galaxy NGC 1068

Watanabe, Yumi[1]

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To understand galaxy evolution, it is important to study the active galactic nucleus (AGN), the star formation, and the state of molecular clouds for a variety of galaxies.
In this study, NGC 1068, one of the prototypes of the nearby Seyfert galaxy, was observed with ALMA at the 60 pc resolution to investigate the nature of molecular clouds around AGN typical of the local universe.
NGC 1068 has a circumnuclear disk (CND) (radius ∼0.2 kpc) of gas surrounding the AGN. The ring-like spiral arms (radius ∼1 kpc) surrounding the CND is called to be starburst ring (SBR) in which many massive stars have formed, making it ideal for studying the relationship between star formation and the parental dense gas.

We took up HCN molecule to trace high-density gases. Using the HCN (J=1-0) and molecular gas tracer CO (J=1-0) data obtained with ALMA, we have mapped the HCN/CO intensity ratio with high resolution (60 pc) and sensitivity (0.07 K).
The analysis has yielded the following preliminary results. Not only the CND, but also the region 0.3 kpc outside the CND shows high values of intensity ratios greater than unity. This is unusually high compared to the typical value of <0.1 for spiral galaxies. Possible causes of the high ratio include anomalous excitation or anomalous HCN/CO abundance ratios. This presentation will discuss the causes of the anomalous HCN/CO intensity ratios found in around the CND.

Dense gas in star forming galaxies traced by HCN and CN

Wilson, Christine[1]

[1]McMaster University, Canada

We have used archival data from the Atacama Large Millimeter Array to assess the relationship between dense gas, star formation, and gas dynamics in 10 nearby (ultra-)luminous infrared galaxies and spiral galaxy centers on sub-kiloparsec scales. We use gravo-turbulent models of star formation to measure the dense gas traced by emission from HCN. We find that the HCN/CO ratio is a good tracer of gas above densities $\log(n) = 4.5$ but that this ratio does not universally track the ratio of gravitationally-bound, star-forming gas. Models with a power-law density distribution at high densities outperform pure lognormal models in reproducing the observed trends in depletion time and efficiency per free-fall time. In addition, the data from this same sample of galaxies also shows a nearly constant CN/HCN line intensity ratio. This result conflicts with simple models of photon dominated regions, which predict that HCN emission traces shielded regions with high column densities while CN traces dense gas exposed to high ultraviolet radiation fields. We are using this strong CN-HCN correlation to extend our dense gas analysis to molecular cloud scale observations of nearby galaxies such as the Antennae merger system.

3.3 Category: Star formation and the interstellar medium

Formamide formation in Star forming regions - an updated view

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If the molecules that kickstarted biology were delivered to Earth by meteorites and comets in Earth's early history, then it is necessary to understand how these molecules form in space. Incredibly, several potential parent molecules of amino acids have been discovered around young stars in our galaxy in recent years, but even with laboratory experiments and theoretical chemistry calculations, it is not clear how these parent molecules were able to form in space. We have surveyed three star-forming regions in order to better understand how prebiotic molecules, formamide (NH_2CHO) in particular, could form and what impact the environmental conditions (gas temperature and density, and UV level) could have on the amount of the molecules produced.

A high HDO/H_2O ratio in the Class I protostar L1551 IRS5

Andreu, Audrey[1]

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Water molecules play a key role in the interstellar medium as they cool down the warm regions and boost the gravitational collapse leading to star formation. They are also very abundant and fundamental to the emergence of life. Water molecules have been detected at different stages of the star formation process from cold prestellar cores to protoplanetary disks. The deuteration of water, through both the HDO/H_2O and D_2O/HDO ratios, is a chemical tool used to characterize the formation of water and its evolution from the early stages of the star formation process up to its delivery to planets. Since then, most of the studies focused on Class 0 sources. Studies on more evolved sources are scarce but are needed to reconstruct the chemical evolution of water.
We will present here results regarding the water deuteration of L1551 IRS5, a Class I solar-type protostar and FUor-like object observed with the NOEMA interferometer. Thanks to these interferometric data, the water deuteration can be investigated in the innermost regions of the protostar at scales of about a few 100 au which is similar to the sizes of disks in which planets form. The results will be compared to previous studies on protostars and comets.

The deepest view of the molecular gas in a star-forming galaxy at cosmic noon (z∼2)

Arriagada Neira, Sebastián[1]

[1]Universidad de Concepción, Chile

About 10 Gyr ago (z∼2), typical or "main-sequence" star-forming galaxies were rich in molecular gas, feeding their star formation activity to all-time highs. I will present in this poster the latest results about the molecular gas properties of BX610, a normal, massive star-forming galaxy at z∼2, for which we have obtained the most detailed map of the molecular gas based on very deep ALMA observations (∼20 hr) of the CO(4-3) and [CI](1-0) transitions, and the dust continuum. This observation corresponds to the deepest integration on a single high-z source by ALMA so far, allowing us to study with a unique resolution the environmental properties of different regions of the galaxy. We also combine these observations with deep VLT/SINFONI Halpha observations to obtain the complete picture of the molecular gas and star-formation properties. In terms of morphology, we observe a clear offset between the peak of Halpha line emission and the dust continuum, revealing heavy extinction, especially in the nuclear region. Furthermore, this peak of Halpha is located in the same area where we observe high emission of both CO(4-3) and [CI](1-0). According to the Kennicutt-Schmidt relation, this star-forming clump is highly efficiently converting gas into stars at a rapid pace. Based on the CO(4-3)/[CI](1-0) line ratio, we find a gradient of molecular gas excitation, where the values in the central region and the outer disk are comparable to those found in local starburst and spiral disks, respectively. Most importantly, we find that the molecular gas fraction Mgas / M* drops in the nuclear region and peaks in the outer disk, providing direct evidence for the quenching of the star formation activity from the inside out. Finally, with these new ALMA data, we can determine whether this star-forming clump will remain bound within the disk due to gravity pressure generated by molecular and stellar mass or dissolve through outflows driven by stellar winds.

The potential of sulfur-bearing species to trace accretion/ejection processes in young protostars

Artur de la Villarmois, Elizabeth[1]

[1]ESO, Chile

Sulfur-bearing molecules may have played an important role in the origins of life on Earth, however, the sulfur chemistry is poorly understood in the process of low-mass star and planet formation. Dense cores are depleted in S-bearing species, in comparison with ISM abundances, while deeply embedded protostars and cometary samples show different abundances of S-molecules. Furthermore, some of the simplest S-bearing species are hardly detected toward more evolved Class II disks and they seem to be more sensitive to the accretion of the forming protostar, providing information not only about the chemical content, but also about the physical processes at play.

In this work, I will present observations of sulfur-bearing species (CS, SO, ^{34}SO, and SO_2) toward 50 Class 0/I sources that are part of the Perseus ALMA Chemical Survey (PEACHES) and compare these results with the detection of Complex Organic Molecules (COMs) and with the sulfur content of other star-forming regions (SFRs). The presence of collimated outflows (seen in CS and SO emission) is linked to the detection of multiple COMs, suggesting a high column density of warm material, and the SO/^{34}SO ratio seems to be a good tracer of the high-density envelope. Finally, we find that the sulfur content varies between different SFRs, with higher S-depletion in regions with low external UV irradiation, like Perseus.

This kind of large surveys with ALMA are essential to provide statistical results and broader conclusions regarding the poorly understood sulfur chemistry.

ALMA 3 mm spectroscopic mapping across the disk of the closest starburst galaxy NGC 253

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Star formation correlates mostly directly with dense gas (traced by, e.g. HCN), but spectroscopic tracers of dense gas are incredibly faint with low surface brightness. As a result, we still know relatively little about the resolved structure of dense gas in galaxy disks and its relation to other parts of the galaxy, particularly in extreme systems such as starburst galaxies. I present new ALMA ACA observations of 90 and 100 GHz molecular lines across the disk of the closest starburst galaxy NGC 253 at spatial scales of 300 pc. This yields continuous, uniform measurements of the dense gas abundance and efficiency spanning from the starburst nucleus across the disk environments. We find that all detected lines show enhanced emission towards the centre of this galaxy, then steeply decreases along the bar and remains continuous in the rest of the disk. Dense molecular gas gets piled up in a ring, after which it inflows to the nuclear region, and the presence of an outflow in NGC 253 impacts the dense molecular gas at these scales. In assessing the dynamics of the dense gas by using the spectral decomposition algorithm (SCOUSE), we find a strong environmental dependence on the observed spectral features. In particular, the bar and central sightlines contain complex spectra indicating the presence of multiple gas flows. Similarly, we observed environmental dependence on the observed HCN/CO (the proxy for the dense gas fraction) and the IR/HCN, which traces star formation efficiency. Dense gas fraction strongly decreases towards the outer parts of the disk of NGC 253, whereas SFE shows different behaviour for gas surface densities below and above 200 $M_\odot/pc^2$.

Our work illustrates the importance of using ALMA to push such "mm-spectroscopy" towards small spatial scales and high sensitivity in understanding dense molecular gas content across disks of extreme environments that are examples of high-redshift galaxies.

Possible episodic infall towards a compact disk in B335

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Previous observations of the Class 0 source B335 indicate active infall, identified through molecular lines such as HCO^+, HCN, and CO, with no rotational disk observed beyond roughly 12 astronomical units (au). This study investigates the early stages of protostellar evolution and disk formation in B335 by mapping the gas infall region and its kinematics.

We employed high resolution 13CO data from the Atacama Large Millimeter/submillimeter Array (ALMA), merged with archival short-baseline data, to produce a high-fidelity image of the infall in B335. Additionally, we revisited the Band 6 continuum images, to examine the distribution of dust close to B335. The continuum emission reveals an elliptical shape (10x7 au) oriented consistent with a forming disk. Infall velocities suggest asymmetric infall, mainly from the north and south, with velocities exceeding what would be expected from a free-fall scenario. Three-dimensional radiative transfer models suggest that varying infall velocities could explain for these kinematics.

The study suggests that a disk is forming in B335 with gas falling towards it. However, further kinematically resolved data is required to confirm a rotationally supported disk around this protostar. The high infall velocities we measure, complicate the straightforward application of magnetic braking theory, hinting instead to a pressure gradient allowing velocity variations in the area.

Exploring the Relationship Between Filaments and Star Formation: Insights from the INFANT Survey

Cheng, Yu[1]

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Filamentary structures are ubiquitously found in high-mass star forming clouds. The relationship between filaments and star formation is still being intensively studied (Hacar et al. 2023 and references therein). While a significant step forward, our detailed knowledge of internal filament properties is still largely limited to the solar neighborhood. In light of this we carry out the INFANT (INvestigations of massive Filaments ANd sTar formation) survey, a multi-wavelength, multi-scale survey of a sample of massive filamentary clouds with ALMA band 3/band 6 and VLA K band, aimed at investigating the relationship between filaments and star formation across a range of evolutionary stages. Here we present the ALMA Band 6 observation and discuss its implication for core growth and core mass function.

Searching for CO-Dark H_2 in a Resolved Low Metallicity Photodissociation Region

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Photodissociation Regions (PDRs) are fundamental to understanding the processes that drive the evolution of interstellar matter in galaxies. PDRs happen on the boundary of molecular clouds where the FUV radiation from massive stars heats the gas, and dust, dissociate molecular hydrogen, and ionize atomic hydrogen. We present observations of N13, a low-metallicity PDR in the nearby Small Magellanic Cloud, where we are able to spatially resolve it's four key layers (HII region, Ionization Front, Dissociation Front, and the Molecular Region) using ALMA and JWST. A key prediction of PDR models is the location of the transition from atomic carbon to carbon monoxide (C/CO) relative to the atomic to molecular hydrogen (H/H_2) transition. It is predicted that this transition occurs deeper in the PDR at low metallicity compared to higher metallicity regions, due to decreased dust shielding. This prediction is key to explaining the large amounts of 'CO-Dark H_2' at low metallicities, but it has never been directly tested due to a lack of observations that can resolve each of the individual zones of a PDR. In this poster, we investigate the locations of the boundary layers of C+/C/CO using ALMA and $H+/H/H_2$ using JWST, individually and relative to each other, and measure temperature profiles to compare them to PDR models. This work uses observations from ALMA for ^{12}CO (2-1, 3-2, 4-3, 6-5) and CI (1-0, 2-1) from the 12-meter array plus ACA, and JWST near- to mid-IR spectroscopy tracing H+, H, and H_2. This is one of the first resolved benchmarks for low metallicity PDRs.

ATOMIS, an ALMA Archive Tool for Molecular Investigations in Space

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ATOMIS (ALMA archive TOol for Molecular Investigations in Space) is a web application that is designed to search for specific molecular species in the observations of the ALMA archive. With ATOMIS, the user can select the sources and species of interest while specifying filters on the minimum and maximum Eup, Aij, the uncertainty on the frequencies of the transitions. Classic filters on observations (angular resolution, spectral resolution, sensitivity, ...) are also available. ATOMIS then lists all the spectral windows covering the transitions of the selected species. From ATOMIS, it is also possible to download the ALMA fits cubes and directly visualize them using the ALADIN (http://aladin.u-strasbg.fr/) and CASSIS (http://cassis.irap.omp.eu) softwares.

The hot corino-like properties of four FUor-type eruptive young stars

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The chemical composition of planets is determined by the material they accrete from the midplane of their parent disks. Thus, understanding the chemical evolution of protostellar/protoplanetary disks is paramount for the study of planet formation. The detection of complex molecules is attainable in the youngest protostars due to their elevated temperatures. However, as the protostars evolve and their disks become colder, the molecules freeze onto the dust grains, becoming harder to detect as evidenced by the low number of Class I and II YSOs with detections of organic molecules. Therefore, the chemical evolution of the protostar, from Class 0 to Class III, remains a mystery.
FU Orionis-type objects (FUors) are low-mass young stellar objects experiencing brief periods of enhanced mass accretion rates, which cause an increase in the disk temperature, and, thus, desorb the frozen molecules, making them easier to be detected by current facilities. FUor-type events typically occur in Class I/II objects, i.e. the evolutionary stages when planets are formed, presenting a great opportunity to analyze the chemical composition of disks as they are feeding gas and dust to the protoplanets.
Here we present serendipitous detections of complex organic molecules around four FUor-type objects: L1551 IRS 5, Haro 5a IRS, OO Ser and V346 Nor. The detected molecules, their temperatures and the size of their emitting regions indicate that all four FUors are similar to hot corinos. We calculated the abundances with respect to methanol, and compared with other young stellar objects that are not in outburst and in different stages of stellar evolution. We will discuss similarities and differences between FUors and quiescent sources to see what is the role that outbursts have in the overall picture of chemical evolution. Finally, we will show how these and other less powerful eruptive young stars can provide information on the chemical evolution of protostars.

Water masers in the ALMA era: an excellent tool to study star formation at subarcsecond spatial scales

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The water molecule is one of the most common compounds in the Universe and it exhibits several maser transitions at submillimeter wavelengths, which can be observed at ALMA. Previous studies have primarily focused on water masers at 22 GHz, which are excited in regions of high density and high temperature. These masers are typically very bright, spectrally narrow, and originate from very compact regions. Consequently, they have been invaluable for studying circumstellar structure and dynamics at sub-arcsecond spatial scales.
Different water maser transitions can be pumped over a range of astrophysical conditions. The submillimeter transitions at 321 GHz and 325 GHz, in particular, trace respectively warmer and lower density regions than the 22 GHz transition. They have been identified as tracers of disk/jet structures in a limited number of star-forming regions. This becomes especially intriguing in the context of high-mass protostars, as the presence of

disk-jet systems impact in their formation mechanism. Conversely, transitions such as the one at 183 GHz, which primarily undergo collisional pumping, can provide valuable insights on the physical conditions of the region where powerful molecular outflows interact with the material from the parental cloud.
Observations of different water maser lines need to be used to constrain the physical conditions in the masing region and they constitute excellent tools to study common phenomena associated with the star formation process at subarcsecond resolution, if observed with interferometers like ALMA.
In this poster we present the results of a survey searching for submillimeter water maser transitions at 321 and 325 GHz complemented with ALMA data from the public archive and focused on a sample of young stellar objects spanning a wide range of masses, from high to low-mass.

Classifying ALMA continuum data using machine learning

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The volume of data from telescopes stored in archives has increased rapidly over time. The ALMA archive, for instance, holds such an immense amount of information that astronomers cannot effectively access it without search tools specifically designed for this archive. These tools function by assigning each observation with keywords, allowing users to search based on these keywords. However, this system has its shortcomings. Firstly, the astronomer assigning an observation might not recognize or include all relevant keywords. Secondly, given the vast and varied phenomena in our universe, creating a comprehensive keyword list becomes a near-impossible task.
Machine learning offers enormous potential for both finding objects of interest and then interpret their morphology in terms of physically meaningful properties. In this project, we trained a convolutional neural network to detect gaussian disks with extensions in the ALMA-archive. Extensions in the dust emission perpendicular to disks could be a sign of dust leaving the disk via winds, but to date only a handful of such observations have been acquired. We want to know whether this is a common feature for young disks or not. Our data set originates from five unique observations and are used to train a neural network.
By using linear and non-linear augmentation techniques (artificially creating data), we expanded the data set and trained a neural network. Preliminary results show that this methodology can be used to find observations in the archive, that resembles the input training data. In other words, Gaussian disks with extensions can be identified. A future, and long-term, goal is to refine the approach in such a way that the code can handle data and perform morphological classification for various archives.

ALMA Observations of Starless Core Substructure

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Protostars form within the densest cores, the smallest component of the hierarchal structure which make up large molecular cloud complexes. There are many physical processes that occur in clouds that govern the density substructures within them, including turbulent motions, which are hypothesized to act over a wide range of scales, including down to within the individual dense cores. Observations should reveal the complex structures created by turbulent motions and fragmentation in general, however detailed studies on the inner structure within dense cores are relatively untested. To date, there have only been two cloud-wide studies of starless core populations (Dunham et al. 2016, Kirk et al. 2017) in order to test the predicted outcomes of the turbulent fragmentation model. This has largely been possible due to the advent of ALMA, which unlike previous facilities, have the necessary sensitivity and resolution to probe the inner structure of these types of objects. In this presentation, I will present ALMA Band 3 observations of the entire population of starless cores in Orion B North, and compare the results to synthetic observations based on turbulent magnetohydrodynamic simulations of core-formation. We find that our ALMA observations are consistent with the predicted number of starless core detections.

The transition from atomic to molecular gas with ALMA

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The formation of molecular hydrogen in interstellar medium induces the formation of other molecular species, some of which are more easily accessible from the ground than H_2. The CO ground state rotational line integrated intensity is the most common tracer of molecular hydrogen in cloud complexes because this line is easily detected over wide areas. Yet, the combination of the atomic gas directly traced by the hydrogen hyperfine transition at 21cm and molecular hydrogen traced by CO does not often account for the total gas column, traced by dust emission or by gamma rays. The dark neutral medium (DNM), also called CO-dark gas represents a significant fraction of the total mass of cloud complexes. ALMA enables to probe this gas by detecting absorption lines from molecular species, with a known abundance relative to molecular hydrogen. The ground state transition of HCO^+ at 89.19 GHz has been observed toward 46 background quasars located in the Taurus, and Chamaeleon molecular complexes. These data confirm the presence of molecular hydrogen even in sight-lines with no detectable CO emission, and show that the DNM is mainly composed of molecular hydrogen. The DNM closely relates to the cold HI phase. Overall, the total hydrogen column density (HI+2H_2) along these sight-lines is about two-third in atomic form and one third in molecular form. For sight-lines with CO emission, the CO-H_2 conversion factor can be estimated.
We show that 2/3 of the inferred H_2 occurred along sightlines with WCO >= 1 K km/s and recovering 90 % would require detecting CO emission down to 0.2 K-km/s.

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Evolutionary trends of physical properties of protostellar cores in high-mass star-forming regions revealed by ALMA

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High-mass star formation is a hierarchical process from cloud, to clump, to core scales. ALMA allows us to probe the physical and chemical properties of the gas and dust of protostellar cores (<0.1pc) in the earliest evolutionary formation phases.
We investigated how physical properties, such as the density and temperature profiles, evolve on core scales through the evolutionary sequence during high-mass star formation ranging from protostars in cold infrared dark clouds to evolved UCHII regions. For that we observed 11 high-mass star-forming regions with ALMA at 3 mm wavelengths. The temperature structure and radial profiles (T ∼ r-q) were determined by modeling molecular emission of CH3CN with XCLASS and by using the HCN-to-HNC intensity ratio as probes for the gas kinetic temperature. The density profiles (n ∼ r-p) were estimated from the continuum visibility profiles.
We find a large spread in mass and H_2 column density in the detected sources ranging from 0.1-150 $M_\odot$ and 10^{23}-10^{26} cm^{-2}, respectively. We find evolutionary trends on core scales for the temperature power-law index q increasing from 0.1 to 0.7 from infrared dark clouds to UCHII regions, while for the the density power-law index p on core scales, we do not find strong evidence for an evolutionary trend. However, we find that on the larger clump scales throughout these evolutionary phases the density profile flattens from p∼2.2 to p∼1.2.

By characterizing a large statistical sample of individual fragmented cores, we find that the physical properties, such as the temperature on core scales and density profile on clump scales, evolve even during the earliest evolutionary phases in high-mass star-forming regions. These findings provide observational constraint for theoretical models describing the formation of massive stars.

An isolated massive star formation environment

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We study the chemical complexity and diversity of the massive protostar G28.20- 0.05, which has been found to be isolated on the protocluster scale. We analyze data from the Atacama Large Millimeter/submillimeter Array (ALMA) 1.3 mm observations with angular resolutions from 0.7" ($\sim$ 4000 au) to 0.03" ($\sim$ 200 au). We detect a wide variety of molecules, including oxygen-bearing (e.g., H_2CO, CH_3OH, CH_3OCH_3), sulfur-bearing (SO_2, H_2S), and nitrogen-bearing molecules (e.g., CH_3CN, C_2H_5CN). We identify three hot cores in the central region near the protostar and discuss the chemical origins of all the species. In this poster, we present the 1.3 mm continuum of the isolated massive protostar and discuss its physical and chemical properties. Different molecules trace different environments and gas kinematics within this source which has been identified through the analysis of spatial distributions of all observed species. Our findings support the core accretion scenario for the formation of the massive protostar.

ALMA Studies of Eruptive stars

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ALMA opened a new regime for studying episodic accretion in FU/EX Ori objects. Despite becoming highly popular in the last 15 years, we are still trying to understand episodic accretion, a process relevant to forming low-mass stars, binaries, and planets. Gravitational and thermal instabilities, disk fragmentation, forming planets, and stellar encounters are some of the different proposed triggering mechanisms for the outbursts. From recent ALMA and JVLA results, it is becoming clear that the highest resolutions are needed to image the very compact disks surrounding these objects and map the instabilities driving the activity. By imaging the inner regions, we can fit the temperatures and masses to estimate Toomre's Q and check for the conditions to cause instabilities. Here we show our attempts to understand these disks with today's ALMA capabilities. Still, very high-resolution imaging at lower frequencies (ALMA Band 1 and the ngVLA) will allow us to measure and correct for non-thermal contribution from the disk winds, which is crucial for estimating the disk temperatures in the optically thick bands. We also present ALMA images of FU Ori, the eruptive class prototype, for the first time, mapping its physical structure and kinematics from thousands of AUs to a few AU scales.

Quantifying the Spatial Variation of CO-to-H_2 Conversion Factor in the Antennae - Our Closest Starburst Galaxy Merger

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Starburst mergers have been found to have significantly shorter depletion time (tdep), the ratio between molecular gas mass and star formation rate (SFR), than normal spiral galaxies, which implies real physical differences in the star formation process. However, the molecular gas mass in these starburst systems is still poorly constrained due to uncertain CO-to-H_2 conversion factors (alphaCO). I will present the first resolved alphaCO modeling results with multiple ALMA CO observations at both giant molecular cloud (GMC) and kpc scales for one of the closest starburst mergers, the Antennae. By combining our CO modeling results and dust continuum measurements, we find that most GMCs in the Antennae have alphaCO values $\sim$4 times smaller than the commonly adopted Milky Way value. By applying our modeled alphaCO to the GMC surface density calculation, we find that GMCs in the Antennae are less gravitationally bound than expected, which is more consistent with GMC dynamical states predicted by merger simulations. We also find that alphaCO at GMC scales shows a significant anti-correlation with CO(1-0) surface brightness with a power law slope of -0.3, which is in line with alphaCO prescriptions in simulations. At kpc scale, we find that alphaCO values are generally smaller than those at GMC scales, which is consistent with our expectation that the warm diffuse medium on kpc scales has a much smaller alphaCO than individual cold dense GMCs. We find a similar anti-correlation between alphaCO and CO(1-0) surface brightness at kpc scales. We also calculate SFR surface densities based on an extinction corrected PaBeta map and compare them with molecular gas surface densities using different alphaCO prescriptions. We find that the varying alphaCO at kpc scale from our modeling gives us a linear Kennicutt-Schmidt relation with tdep of 100 Myr while a constant alphaCO value gives a shallower relation with power law slope of 0.6. This analysis suggests that the varying alphaCO might be a more realistic choice in gas mass calculation.

The extremely sharp transition between molecular and ionized gas in the Horsehead nebula revealed by ALMA.

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Massive stars can determine the evolution of molecular clouds by eroding and photo-evaporating their surfaces with strong UV radiation fields. Thus, probing the fundamental structure of nearby molecular clouds is crucial to understand how massive stars shape their surrounding mediums and how fast molecular clouds are destroyed. By combining data from the 12m array, the Atacama Compact Array (ACA) and Total Power, we present CO and HCO^+ ALMA observations of the Horsehead edge at 0.5" angular resolution, corresponding to physical scales of about 200 astronomical units. We find that CO and HCO^+ are present at the edge of the cloud, very close to the ionization (H+/H) and dissociation fronts (H/H_2), suggesting a very thin layer of neutral atomic gas and almost no CO-dark H_2 gas at the molecular cloud edge. Notably, the HCO^+ emission map exhibits a bimodal behavior, tracing the cold and dense gas shielded from UV radiation and a more diffuse gas component interacting directly with the UV radiation field. Additionally, using CO as a proxy of the C^+/C/CO front, we conclude that the distances between the fronts can be reproduced by isobaric stationary models, which confirms the presence of a steep density gradient, as suggested by previous observations. Still, dynamical effects cannot be completely ruled-out, and even higher angular observations will be needed to unveil their role.

Extremely dense and enigmatic prestellar core G208.68-19.92-N2 in the Orion Molecular Cloud 3

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We present a comprehensive analysis of the starless core G208.68-19.02-N2 (G208-N2) in the Orion Molecular Cloud 3 (OMC-3) using observations from ALMA Bands 6 (1.3 mm and 1.1 mm), 8 (0.75 mm), 9 (0.45 mm), and 10 (0.35 mm), as well as ACA Band 7 (0.83 mm). The dust continuum emission reveals the filamentary nature of this core with a length of ~5000 au and a H_2 volume density of $\sim 6 \times 10^7$ cm^{-3}. At the tip of the filament, a compact "nucleus" is observed, characterized by a radius of ∼ 200 au and a mass of $\sim 0.1\ M_\odot$. The nucleus does not have a counterpart at wavelength shorter than 0.35 mm. In addition, there is no signature of outflow localized to the nucleus in the CO 2-1 image. The nucleus exhibits a central density of $\sim 3 \times 10^9$ cm^{-3}, following a radial density profile described by a power-law function with an index of -1.94. Although the power law index aligns closely with that of the singular isothermal sphere (SIS), the density of the nucleus at each radius is higher than that of SIS value by a factor of ~3.7. This indicates that the gravity is dominant over pressure across all radii within the nucleus. The complete absence of $C^{18}O$ 2-1 emission in the filamentary structure including the nucleus suggests significant CO depletion due to low temperature and high density. The filamentary structure is traced by the $N2D^+$ 3-2 and ortho-H_2D^+ emission lines, while they do not exhibit pronounced peaks towards the nucleus. Intriguingly, a very narrow (~0.2 km/s) DCO^+ 5-4 emission component is observed in the vicinity of the nucleus. . This suggests a limited release of CO from the dust, potentially attributed to the presence of an internal heating source, such as a nascent first hydrostatic core.

Tracking the decay of the January 2015 accretion outburst in the massive protostar NGC6334I-MM1B

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We will present the latest multi-epoch continuum and line observations with ALMA and VLA of the extraordinary outburst in the massive protostar NGC6334I-MM1B. In January 2015, ten maser transitions of methanol, water, and hydroxyl flared almost simultaneously, including the first appearance of 6.7GHz methanol masers toward this object in 3 decades of observations. The maser emission has declined over the past few years, but the 6.7 GHz maser appears to be restabilizing in the latest single dish light curves. Multi-epoch ALMA observations show that the millimeter continuum emission has also dropped somewhat, but remains at an elevated state corresponding to a higher protostellar luminosity than before the outburst. We compare the decay profile to the latest hydrodynamic simulations of accretion outbursts in massive protostars.

Correlation between magnetic field and core fragmentation in a massive star-forming region, G28.34+0.06

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Magnetic fields play a crucial role in the star-forming process by supporting clouds or clumps against gravitational collapse. The interplay between magnetic field, gravity, and turbulence can influence types of core fragmentation, e.g., no, aligned, and clustered fragmentations (Tang et al. 2019). G28.34+0.06 (G28.34) is a massive star-forming region which contains filamentary structures and a massive northern clump (hub). We estimate magnetic field orientations and strengths at the northern clump using dust polarization observations towards G28.34 obtained by SCUBA-2/POL2 on the JCMT. Magnetic fields in cores fragmented within clumps have been studied using ALMA observations (Liu et al. 2020). We compare magnetic field orientations at the clump and core scales. We also estimate the distribution of magnetic field strengths and mass-to-flux ratios to show relative importance of magnetic field compared to gravity within the clump. The magnetically super-critical regions in the clump are consistent with core position obtained by ALMA. Our results contribute to understanding the role of magnetic fields in core fragmentation.

Star Formation in Small Galaxies: Dwarf Galaxies in the Era of ALMA

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Dwarf galaxies are the most common type of galaxy in the Universe and play an important role in galaxy evolution, yet our understanding of the molecular interstellar medium (ISM) in these systems continues to lag behind our understanding of the molecular ISM in massive spiral galaxies. In this talk, I will share results for dwarfs my collaborators and I have observed in ^{12}CO with ALMA. Results suggest that some, but not all, stages of the star formation process proceed in a universal way across galaxy environments. I will also provide a review of what has been learned about dwarf galaxy molecular clouds in the era of ALMA and offer insights for moving forward in this field.

Spatial distribution of acetaldehyde in Orion KL: observations and chemical modeling

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Despite the chemical richness of Orion KL, acetaldehyde (CH_3CHO) – one of the most ubiquitous interstellar aldehydes – has not been firmly identified at high-angular resolution. Here we explore an extensive ALMA archive dataset covering the frequency range 142 – 355 GHz, to search for acetaldehyde and other little-investigated aldehyde species. Four emission components of acetaldehyde are clearly identified toward Orion KL, showing a main emission peak consistent with the ethanol (C_2H_5OH) peak in hot core-SW (HC-SW). This implies the chemical linkage between them.
The column densities of acetaldehyde and its kinetic temperatures are determined toward this main emission region, assuming molecular excitation under local thermodynamic equilibrium conditions. The distribution of acetaldehyde is compared with that of ethanol, as well as other molecules bearing an aldehyde (HCO) group, such as methyl formate (CH_3OCHO), glycolaldehyde (CH_2OHCHO) and formic acid (HCOOH).
Acetaldehyde presents a fractional abundance and spatial distribution similar to those of formic acid, implying a chemical relationship between them otherwise a similarity in their own independent behavior. The observational abundance ratios between the aldehyde-like species toward the ethanol peak are investigated with a chemical model. The model shows that a relatively long cold collapse timescale and a methyl formate binding energy similar to or lower than that of water are needed to explain the observations. The relative abundance ratios obtained from the model sensitively depend on the assumed kinetic temperature. This explains the high spatial variability of the aldehyde ratios observed toward Orion KL.

A high-resolution picture of spiral arms, instability and chemistry within the disk around a forming massive star

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We revisit our high-resolution (30 mas or 130 au at 4.2 kpc) ALMA 1.2mm observations of the accretion disk around the forming O-type star AFGL 4176 mm1 (Johnston et al. 2020a) to investigate the morphology and kinematics of various disk-tracing molecular lines previously detected at lower-resolution (Johnston et al. 2015, 2020b). The disk (AFGL 4176 mm1-main) has a radius of 1000au and contains significant structure, most notably a spiral arm on its redshifted side. Using local thermodynamic equilibrium modelling of the CH_3CN K-ladder, we previously determined the temperature and velocity field across the disk, and thus produced a map of the Toomre stability parameter Q, indicating that the outer disk is gravitationally unstable. This instability indicates the disk is likely to fragment further in the future, providing a possible path to companion formation. Our investigation of these molecular tracers provides one of the first looks at resolved chemistry in an unstable disk around a forming massive star, hinting at the interplay between the accretion physics and chemistry ongoing within it and allowing comparison to ALMA observations of circumstellar disks around lower-mass protostars.

ALMAGAL First Results: Robust temperatures and luminosities of cores in a thousand high-mass cluster-forming regions

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The ALMA Large Program ALMAGAL has observed over 1000 high-mass star forming clumps and unveiled the many $\sim$1000 au protostellar cores embedded within. For the first time, interferometric spectral line data is now available toward a significant fraction of the total Galactic population of high-mass star formation sites and we present the first catalogue of temperatures and luminosities for all detected cores. With a coherent data set and homogeneous analysis, we then draw statistically significant global conclusions about their physical properties.

With such a rich sample, we also explore - and quantify - the scope and limitations of several molecular temperature tracers. Degeneracies in the underlying parameter spaces that reproduce spectra are explored through massive MCMC realisations; and the effect of assumptions commonly made in spectral analysis is investigated through machine learning techniques trained with spectra of structured sources. With key parameters such as luminosity critically dependent on the temperature, we find that using only best fit temperatures may cause highly misleading conclusions. Determining the credibility range of parameters is vital to draw robust conclusions and truly understand the physical conditions leading to the formation of high-mass stars in our Galaxy.

Simulating Molecular Gas Emission in Prestellar Cores with Radiative Transfer Modelling

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Star formation is one of the main research areas in Astrophysics. Stars form by gravitational collapse of dense cores in molecular clouds. To understand the origin of stellar masses, multiple systems, and outflows, it is necessary to understand the formation and evolution of dense cores. To date, several hypotheses have described their gravitational collapse. Deriving the dynamical model that fits both the observed dust and the gas emission from such cores is therefore of great importance. The aim of this project is to simulate the molecular gas emission as predicted by three different theories of gravitational collapse: quasi-equilibrium Bonnor-Ebert sphere, singular isothermal sphere, and Larson-Penston flow using radiative transfer modelling (i.e., RATRAN). We further investigate the spatial distribution of cold gas as it would be seen by the most powerful (sub)-mm interferometric and single-dish observatories (e.g., ALMA, APEX) and what it means for prestellar core chemistry.

Star formation and molecular gas observations of NGC 5331 with ALMA and VLA

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LIRGs (Luminous Infra-Red Galaxies) make up the brightest objects in the infrared sky and represent an important population to study galaxy evolution. Models predict episodic enhancements of total star formation as the merger progresses, with the first burst of star formation happening mid-stage in the merger sequence. We conducted an in-depth gas study of the LIRG NGC 5331, a mid-stage merger, to get an insight into this critical period in galaxy evolution. At a distance of 155 Mpc, this galaxy merger has an infrared luminosity of $L_{IR}=10^{11.66}$ $L_\odot$, and it is part of the Great Observatories All-sky LIRG Survey (GOALS). Using a combination of ALMA CO (1-0) line emission data, and radio continuum observations taken with the VLA, we determined each galaxy's mass, star formation rate, velocity dispersion, and molecular gas mass, among other parameters, both as a whole and from smaller regions. We place these properties into a Kennicutt-Schmidt relation and compare with published values of other LIRGs, ULIRGs, and local circumnuclear disks (integrated values across the whole system). The selected regions in NGC 5331 show similar values of star formation rate surface density and molecular gas surface density to those in the literature. Both galaxies exhibit non-circular motions, including a potential inflow in the southern galaxy. Our final goal is to replicate this study in as many local U/LIRGs as possible, to study how star formation changes with merger state.

Building on the archives: Connecting the CN/CO intensity ratio with global properties in nearby U/LIRGs

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The Atacama Large Millimeter Array (ALMA) gives us access to the densest molecular gas on sub-kiloparsec scales, providing valuable insight into the physical and chemical processes that regulate star formation. We will present recent work on the CN (1-0)/CO (1-0) intensity ratio for a sample of nearby Ultra-Luminous and Luminous Infrared Galaxies (U/LIRGs) utilizing the power of the ALMA archive. We identify 16 U/LIRGs which have been previously observed and detected in both the CN (1-0) and CO (1-0) lines at ∼500 parsec resolution based on 16 different ALMA projects. We will discuss how the CN/CO line ratio varies both within individual U/LIRGs and between ULIRGs and LIRGs as independent samples. The CN/CO line ratio is higher in ULIRGs than LIRGs, with a larger spread in the ratio measured for LIRGs due to the variety of galaxy environments included in our sample; e.g., starburst nuclei and quiescent disks, nearby galaxy mergers, and active galactic nuclei (AGN) in Seyfert galaxies. Additionally, we will present new results correlating the global CN/CO ratio in these extreme systems with global galaxy properties of total infrared luminosity, merger stage, AGN contribution, [CII] and [OI] luminosities, and star formation rate measured from both infrared luminosity and radio continuum.

Unlocking the Potential of the Most Definitive Molecular Tracer of UV-Enhancement: l-C3H+

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The interstellar molecule l-C3H^{+} appears to be the most sensitive and definitive molecular tracer of enhanced UV-flux ever observed in the ISM. Extensive, deep searches for this species in dozens of sources show its presence nearly exclusively in UV-enhanced regions. Yet, our understanding of the spatial distribution of the molecule within these sources, and the excitation conditions (and abundances) in previously-observed regions, is sorely lacking. I will discuss recent ALMA observations of l-C3H^{+} in the Horsehead PDR region that have revealed an unexpected large-scale distribution of l-C3H^{+}. With these data we wish to better understand the spatial distribution, abundance, and excitation of this potentially transformational molecule in our ability to probe the extent of UV-enhanced flux in these and other key regions. The results will be used to refine state-of-the-art PDR chemical modeling codes.

Protostellar outbursts: Which chemistry in the envelope ?

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Episodic accretion in protostars may trigger luminosity outbursts, and therefore heat up their envelope. The sudden increase of temperature sublimates ice mantles on grains, and the release of new molecules in the gas phase may alter the long-term evolution of the chemical environment. In this study, we investigate the chemical composition of the envelope of the Class I outbursting protostar L1551 IRS 5, by performing a spectral survey with the IRAM-30m telescope. We compare the abundance ratios and isotopic fractionation ratios with quiescent protostars. Using kinetic chemical models in protostellar envelopes simulations, we aim at bringing constraints on the properties of luminosity outbursts (duration, intensity, ...).

The CoCCoA Project: Unbiased Line Surveys of Complex Molecules in High Mass Cores

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The CoCCoA Project: Unbiased Line Surveys of Complex Molecules in High Mass Cores
Complex interstellar molecules have been increasingly used as probes of both astrophysical processes and as windows into chemical evolution through the star- and planet-formation process. These interpretations rely, critically, on a foundational understanding of the underlying chemical evolution and its interplay with the physical structure and processes of the source itself. In turn, this understanding is often contingent on complex astrochemical reaction network models which have been developed over decades through comparison to the most chemically rich sources available. Because of the limitations of earlier observational facilities, these sources are among the most extraordinary in the sky ... and their chemistry is equally as extraordinary. As a result, our understanding of interstellar chemistry (and thus our interpretation of what processes they probe) is often heavily biased and not representative of a more universal chemistry.
The CoCCoA Project (Complex Chemistry in Cores with ALMA) is a first attempt to change that, leveraging the power of ALMA to observe at high spatial resolution and high sensitivity to study two dozen "ordinary" hot cores between ~1-4 kpc distance. An overview of the project, early results, and status of the observations and the efforts toward making public, science-ready data products available to the community will be presented.

Zooming in on protostellar outflows: A Combined JWST and ALMA Study of the very low mass, Class 0 protostar IRAS 16253-2429

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We present a joint ALMA & JWST study of the IRAS 16253 protostar, combining data from the eDisk & Investigating Protostellar Accretion Programs. This very low-mass protostar in rho-Oph has a mass of 0.12 $M_\odot$ & a luminosity of 0.2 $L_\odot$. With ALMA & JWST, we trace the flows of gas during the protostellar phase that drives the formation process of stars & planetary systems. During their primary accretion phase, protostars are too deeply embedded to be studied in the optical & NIR wavelengths. With JWST, we can detect these deeply embedded Class 0 protostars. Using NIRSpec & MIRI IFUs, we spectral image the 2.9-29 micron wavelength range with a resolution of 30 au at the distance of rho-Oph. While JWST can map the ionic & molecular species, including H_2, in shock-heated gas, it doesn't have sufficient velocity resolution to study the gas kinematics. Using ALMA, we can detect the cool in lines of isotopologues of CO that trace the cold gas that dominates the mass of envelopes & outflows with similar spatial resolution. Our analyses reveal a highly collimated, ~500 au long (dynamical time scale 34 yrs) jet in [Fe II], while no such collimated molecular jet is detected with ALMA. We find that the radius of this jet is about 40-50 au, comparable to the radius of the protostellar disk (50 au). The CO outflow also has a similar radius. This hints that jet & outflow originate from the entire disk surface. The absence of the molecular jet raises intriguing questions about the underlying mechanisms of launching jets & outflows from protostars. In the cavities, we find jets traced in ions but without molecules. Using JWST, we measure the velocity (~150 km/s) & the mass flow through the jet, indicating a low mass flow of $\sim 10^{-8}$ $M_\odot$/yr. We map both shocks from H_2 & entrained gas from ALMA CO lines. Together, these data show how ALMA & JWST can link the jets & winds driving the outflows to the flows of entrained gas responsible for lowering the star formation efficiency.

Diving into complex organic chemistry of protostellar systems with ALMA

Nazari, Pooneh[1]

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Planet cores are thought to start forming around protostars where many complex organic molecules (species with at least 6 atoms containing carbon) are detected. Therefore, understanding the chemistry of these molecules helps us understand the chemistry of the forming planets. As an example, Earth is deficient in carbon compared with the Sun and these molecules can be used to understand why. These molecules emit at ALMA wavelengths and during the past decade many of them were detected for the first time by ALMA. During the first years of ALMA complex chemistry was analysed toward single sources. However, a high-sensitivity statistical analysis of complex organics toward many low- and high-mass protostars was missing until only recently.
In a series of recent works we studied the complex organic chemistry around many low- and high-mass protostars with ALMA. We found that the column density ratios of complex organics are remarkably constant across low- and high-mass protostars with a small scatter around the common mean. This points to their formation in similar physical environments, most likely the pre-stellar ices. In this talk I will present these conclusions, in addition to new results on using ALMA to detect evidence of destruction of carbon grains around young protostars for the first time. This process of destruction of refractory organics is thought to be responsible for carbon deficiency on Earth.

The Rosetta Stone project: a comparison between observations and simulations to investigate the star-formation mechanisms in massive star-forming regions

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It is still debated whether massive star formation either follows a core-fed or clump-fed model. In this poster I will present the first results of the Rosetta Stone project, which has been designed to discriminate between the two scenarios. This is done by identifying the mechanisms driving the fragmentation of the condensations at parsec scales, known as clumps, into the seeds of future (high-mass) stars at thousands of AU scales, called fragments. The strategy involves comparing observations and numerical simulations. As the first case of study, 13 clumps at various evolutionary stages selected in the SQUALO project, an ALMA 1.3mm and 3mm survey, have been taken as a reference. The physical properties of the fragments identified within the SQUALO images (including number, mass, and relative distance of the fragments) have been interpreted by comparing them with those of a statistically significant sample of radiative MHD simulations of massive clumps fragmentation. Different realizations of parameters have been explored in the simulations, including some values which are representative of the observed clump properties (such as clump mass and radius), as well as others that are not accessible from the available data (such as the clump initial Mach number and the mass to magnetic flux ratio). Various time steps and 3 projections in the sky have been analyzed, for a total of 270 maps. A post-processing strategy has been developed to reproduce the features of the ALMA telescope observations, obtaining synthetic observations from simulated data. Evidences from the analysis of the fragmentation properties derived by the comparison of observations and simulations seem to favor a clump-fed star-formation model in which the fragments are not isolated from the environment. Young and massive clumps initially fragment under the influence of non-thermal motions. Then the fragments accrete mass from the parental clump, which itself acts as gas reservoir, and by merger events.

Chemical Diagnostics for Tracing the Physical Structures in Disk-Forming Regions of Young Low-Mass Protostellar Sources

Oya, Yoko[1]

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To understand the origin of the Solar system, the physical/chemical evolution along the star/planet formation is a key issue. With the advent of ALMA, extensive observational studies have revealed that both the physical structure and the chemical composition drastically change during the disk formation around protostars. Furthermore, it has been found that molecular distributions are sensitive to changes in the physical conditions. Some kinds of molecular lines are therefore prospected to work as 'molecular markers' to slectively highlight particular structures of disk forming regions.

Specifically, sulfur-bearing species seem good tracers; in a young low-mass protostellar source IRAS 16293-2422 Source A, the kinematic structures of its circummultiple structure and its circumstellar disk are traced by the OCS and H2CS emission, respectively. The gas in its circummultiple structure was found to keep falling even beyond its centrifugal radius, which is often assumed to be the outer edge of a Keplerian disk. Machine/deep learnings may help us to extract the key information of the gas dynamics from the enormous molecular line data obtained with ALMA.

Angular momentum of the gas is the essential topic to understand the structure formation. The chemical diagnostics with the aid of the molecular markers can be a helpful tool to tackle with the redistribution of the angular momentum among the disk/envelope and outflow structures. Conversely, detailed physical characterization is essential to elucidating the chemical evolution occurring there.

Dust In The Wind: An ALMA search for dust in the outflow of the HH212 class 0 protostellar system

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Perhaps the most visually striking phenomenon during star formation is the ejection of material along the direction of the protostar's rotational axis. These ejections are observed in the form of molecular outflows and/or atomic jets, and carry away mass, energy and angular momentum from the system. Given the known dust content of protoplanetary disks, and the energetics of outflows, it has been suggested that it should be possible to lift dust from disks via winds, but this has yet to be directly confirmed observationally. A detection of dust within protostellar outflows would not only put constraints on the dust content in outflows, but if a sufficient amount of dust can be removed, the mass budget for planet formation could also be affected. We present re-imaging of archival, multi-frequency dust continuum observations taken with the Atacama Large Millimeter/sub-millimeter Array (ALMA) towards the HH212 protostellar system. We detect an extension in the dust emission coincident with the molecular outflow, and using multi-frequency data in Bands 7 and 9, we estimate the spectral index of the emitting dust and the dust mass in the wind launching region. We find a small but still significant amount of dust mass coincident with the molecular outflow cavity, and we take this as evidence that the wind is indeed carrying away dust from the HH212 protoplanetary disk. (Plunkett et al. 2023, in review)

Multi-phase view of the ISM in the Carina Nebula

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The Carina Nebula Complex (CNC) is a spectacular star-forming region located at a distance of 2.3 kpc, which is close enough to observe a wide range of size scales in detail. With more than 65 O-stars and more than 900 young stellar objects identified it is also the nearest analogue of more extreme star forming regions, such as 30 Doradus. In this talk I will present the results of a major effort to study the relationship between the different gas phases in the Carina region from 100 pc to 0.01 pc using the Australia Telescope Compact Array, the Mopra telescope and ALMA. At large scales, CO image combined with far-infrared data from Herschel revealed the overall molecular mass and its distribution across the CNC. An extremely detailed map of the HI 21-cm line across the whole nebula revealed a complex filamentary structure in the atomic gas, which allowed the identification of regions where phase transition between atomic and molecular gas is happening. Most recently, we have released a 1-3 GHz radio continuum image across the whole Caria region, revealing a complete and spectacular view of the ionized gas in the region. At small scales, ALMA high spatial resolution observations of molecular line tracers and dust showed that the level of stellar feedback effectively influences the fragmentation process in clumps, and provides further evidence for a higher level of turbulence in the material with a higher level of massive stellar feedback.

Molecular gas in low metallicity galaxies

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Stars form in molecular clouds. These clouds are dense concentrations of H_2 that are traditionally traced in external galaxies using transitions of CO or other, more complex molecules. CO observations in low metallicity systems are elusive as CO emission is weak and the low abundance of Carbon and dust prevents the shielding of the molecule from photo dissociation. Tracers of recent star formation, such as Halfa or far-ultraviolet (FUV) emission, show that most dwarfs contain young stars and star clusters, but CO observations often yield only upper limits. Recent observations suggest that molecular clouds traced by CO in the metal-poor ISM are small and the intense UV interstellar radiation fields (ISRFs) these unshielded environments at least partially photo-dissociate CO, thus eroding the clouds.
Models predict that low metallicity galaxies have large reservoirs of CO-dark molecular gas and high CO-to-H_2 conversion factors to compensate for the missing CO.
We will review the latest results of the molecular cloud properties obtained with ALMA of star-forming regions at the lowest metallicities dwarf galaxies from the SMC (0.2 Zo) to WLM (0.1Zo). These studies provide key insights into the star formation process at low metallicities and are fundamental to understand the star formation at early times in the Universe.

The Formation of High-mass Binary Systems

Sanhueza, Patricio[1]

[1]NAOJ, Japan

High-mass stars (> 8 $M_\odot$) are preferentially formed in binary systems. So far, there are no definitive observational constraints to identify which are the dominant physical mechanisms explaining the binarity rate of high-mas stars. To find out if core fragmentation or disk fragmentation (or both) are responsible for the high binarity rate of high-mass stars, we carried out the Digging into the Interior of Hot Cores with ALMA (DIHCA) survey. We observed 30 high-mass star-forming regions at 220 GHz, obtaining spatial resolutions between $\sim$100 - 200 au (0.06" resolution). So far, 2/3 of the sample have been analyzed and 38 massive young stellar objects (MYSOs) have been identified. Of these, 12 MYSOs seem isolated up to $\sim$4000 au and are considered to be a single MYSO. The remaining MYSOs form 20 binary systems, including systems of only MYSOs as well as with a low-mass protostellar companion. The peak of the separation distribution shows a peak around 700 au. If disks in MYSOs are large ($\sim$1000 au) as initially thought, our finding suggests that disk fragmentation plays a dominant role. However, very recent simulations suggest that MYSOs have smaller disks ($\sim$500 au), suggesting core fragmentation would play a dominant role. Which physical process determine the binarity of high-mass stars is still matter of analysis.

The IR environment of ALMAGAL fields

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I will present results from a study of the IR environment in the vicinity of the 1017 sources from the large program ALMAGAL. The purpose is to correlate the IR content of the sources with the evolutionary stage, and to get a more complete picture of the forming clusters.

Early Planet Formation in Embedded Disks (eDisk): Constraining the chemical tracers of young protostellar sources.

Sharma, Rajeeb[1]

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Understanding the formation and evolution of molecules from protostellar cores to protoplanetary disks is crucial to form a complete picture of planet formation. In this context, a systematic examination of the morphology of molecular line emissions in high-resolution observations (∼010 - 030) is made towards 12 Class 0 and 7 Class I nearby protostars as part of the ALMA large program Early Planet Formation in Embedded Disks (eDisk). The primary goal of this study is to empirically identifying key molecular tracers of specific components of young protostars on the scales of their emerging disks. Molecular emission of ^{12}CO, ^{13}CO, $C^{18}O$, H_2CO, c-C_3H_2, SO, SiO, CH_3OH, and DCN is detected. The outflows are well-traced by the classical tracers ^{12}CO and SiO in most sources. Similarly, ^{13}CO and $C^{18}O$ trace the rotating disk and inner envelope, while c-C_3H_2 emission traces the cavity walls in some sources. Notably, some molecules such as SO and H_2CO trace different morphologies in different sources, indicating that they are likely originating from distinct processes. SO traces extended envelope in some sources while tracing outflow in others. H_2CO traces outflows and outflow cavities in some sources and also the rotating envelope in others. These results provide valuable insights on characterizing the chemical environment of young embedded disks, improving our overall understanding of the conditions governing the first steps toward planet formation and evolution in young disks.

ALMA View of Molecular Complexity in Low-metallicity Massive Protostellar Cores

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Understanding the star formation and ISM at low metallicity is crucial to unveil physical and chemical processes in the past Galactic environment or those in high-z galaxies, where the metallicity was significantly lower compared to the present-day solar neighborhood. Hot molecular cores are compact ($<$0.1 pc), dense ($\sim 10^6$ /cm^3), and hot ($\sim$100 K) protostellar sources, which appear in the early evolutionary stage of massive star formation. Hot cores are an excellent laboratory to study the molecular complexity of the ISM since a variety of molecular species, including complex organic molecules, are often detected in hot cores.

In the last decade, with the advent of ALMA, hot cores have been detected in distant low-metallicity star-forming regions such as those in nearby galaxies, the Large and Small Magellanic Clouds, as well as in the outskirts of our Galaxy (Shimonishi et al. 2016, 2020, 2021, 2023; Sewilo et al. 2018, 2023). The metallicity of these regions is lower than the solar neighborhood by a factor of about 2-10. The presence of hot cores in various metallicity environments implies that the formation of a hot core would be a common phenomenon during massive star formation throughout the cosmic history.

Chemical analyses of low-metallicity hot cores suggest that molecular abundances do not always simply scale with the metallicity of their parent environments. For example, CH_3OH, an organic molecule and classical hot-core tracer, shows a large abundance variation within low-metallicity hot cores, and it is significantly depleted beyond the level of the metallicity difference in some cases. On the other hand, inorganic molecule and another hot-core tracer, SO2, shows roughly metallicity-scaled abundances. The reason of such chemical differentiation in low-metallicity environments remains to be clarified. Here I will present recent observational progress of low-metallicity hot cores with ALMA and discuss potential future synergy with other facilities.

Probing Massive Star Cluster Formation and Feedback in an Extragalactic Central Molecular Zone with ALMA and JWST

Sun, Jiayi[1]

[1]Princeton University, United States

Central Molecular Zones (CMZs), the gas-rich central regions of galaxies, are among the most extreme star-forming environments in the local universe. Many ALMA studies have shown that CMZs often witness the formation of massive star clusters and subsequent intense feedback processes, providing critical constraints for our current star formation theories and models. In this talk, I will present parsec-scale resolution ALMA, JWST, and HST observations of infant massive clusters in a nearby galaxy with a prominent starburst CMZ. Our new ALMA observations reveal over a dozen compact sources with strong millimeter continuum emission. Each of these sources is estimated to host more than 10^5 solar masses of stellar and/or gas content, suggesting they are massive clusters in their infancy. Most of these millimeter sources lack counterparts in HST or JWST images, implying extremely high extinction and a very young age. The spatial distribution of these proto-clusters appears to favor theories of massive cluster formation due to external dynamical triggering ('pearls on a string') over those assuming formation due to random local gravitational collapse ('popcorn'). Most of the proto-clusters likely cannot convert the majority of their remaining gas reservoir into stars given the various stellar feedback mechanisms at play. These findings illustrate the immense potential of high-resolution synergistic studies of ISM, star (cluster) formation, and feedback with ALMA, JWST, and ngVLA in the future.

Network of filamentary structures and cluster formation in Corona Australis revealed with ALMA

Tachihara, Kengo[1]

[1]Nagoya University, Japan

Contrary to the understanding of isolated star formation, the initial condition of cluster formation remains poorly understood. In this study, we investigated the head region of the Corona Australis molecular cloud, which is the closest low-mass cluster-forming region. The cloud has a distinctive head-tail shape with elongated structures spanning approximately 5 pc, originating from a dense gas clump of around 400 solar masses. Our analysis utilized ALMA ACA data in the $C^{18}O$ (J=2-1) emission line, reveal complex internal structures. Applying the FilFinder algorithm, we identified a network of 91 thin filamentary structures with an average width of 0.007 pc within the observed region of approximately 0.4 pc^2. The derived line mass of these filaments ranges from 0.7 to 7 solar M_o/pc, based on the column density measurements of 0.5 to 5 x 10^{22} cm^{-2}. Notably, these values are found to be considerably smaller than the critical line mass. The typical linewidth of the filaments is ~ 1 km/s with inter-filament velocity dispersion of around 1 km/s, indicating a turbulent condition suggestive of external disturbance. Interestingly, out of the 91 identified filamentary structures, only 10 are associated with young stellar objects (YSOs), despite the presence of 50 YSOs within the cluster. This finding suggests that most of the filamentary structures are transient and do not undergo fragmentation to form stars via gravitational instability. Recent high-resolution numerical magnetohydrodynamic (MHD) simulations, incorporating filament formation by the flows along the magnetic field with ambipolar diffusion, successfully reproduced the observed cloud structure. As a result, these filamentary structures are interpreted as the result of slow shock instabilities. Additionally, this interpretation is supported by the fact that the cloud is situated at the boundary of two HI shells.

Probing Massive Star Formation with the ALMA Archive

Telkamp, Zoie[1]

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Massive stars are key contributors to the regulation and evolution of galaxy environments, but the mechanisms behind their formation are still disputed. Some theoretical models predict that they form via disk-mediated accretion (e.g., Krumholz et al. 2009). However, while many disks around low mass protostars have been observed, limited information exists on the properties of their high mass counterparts (e.g., Beltrn & de Wit 2016; Ahmadi et al. 2019, Johnston et al. 2020). We carried out a systematic archival analysis of the highest resolution (<= 50mas) Band 6 ALMA data available for tens of massive protostars to test radiative transfer model predictions of their disks. We performed a joint analysis of global MIR to FIR spectral energy distribution fitting along with analysis of the ALMA 1.3mm fluxes, disk properties obtained through 2D Gaussian fitting, and disk axis vs. outflow axis orientations to test predictions of these models. Together, these methods provide detailed constraints on the properties of massive protostars and their disks.

Massive star formation scenario in the LMC probed by the ALMA-ACA Molecular Cloud Survey: promoting synergies with X-ray Observations

Tsuge, Kisetsu[1]

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Galactic tidal interactions significantly affect gas dynamics in galaxies. In the Magellanic system, a recent close encounter between the LMC and the SMC resulted in HI gas from the SMC falling onto the LMC. The falling HI gas is colliding with the LMC disk at various locations, such as 30Dor and N159 (Fukui+17; Tsuge+19; Tokuda+19). To quantify the impact of the HI collisions, we performed an ALMA-ACA survey of ^{12}CO and ^{13}CO J=2-1 transitions, covering the massive star-forming regions N44, N11, and N79, where evidence for HI collisions has been found.
The results indicate that N44 has the highest molecular mass, velocity dispersion, and ^{13}CO/^{12}CO intensity ratio, followed by N11 and N79. Further, the collision velocities of HI gas in N44, N11, and N79 are 70, 50, and 30 km/s, respectively, with corresponding collisional compression pressures derived from Hi data of 14, 11, and 4 [10^5 K/cm^3]. Consequently, we argue that there is a correlation among the pressure, the molecular mass and the number of high-mass stars formed. These features suggest that a more intense HI gas collision possibly creates a higher-pressure environment and promotes the formation of more massive, denser molecular gas, leading to the efficient formation of high-mass stars with more developed filamentary system.
Furthermore, we note that high-velocity gas collisions impact both atomic/molecular gases and drive plasma evolution. Knies+21 proposed a 3D structure of gas collisions toward 30 Dor by using diffuse X-ray absorption and suggested its role in heating diffuse hot gas emitting X-rays. A comparison of the diffuse X-ray properties with HI/CO gas in the LMC, including N44 and N11 regions, is underway using eROSITA (Tsuge+23 in prep.). I also plan to discuss the future ALMA observations and synergies with next-generation X-ray missions (Athena, XRISM) to investigate ISM evolution birth of stars to its endpoint.

Methanol deuteration in high-mass protostars

van Gelder, Martijn[1]

[1]Leiden Observatory, The Netherlands

The deuteration of molecules forming in the ices such as methanol (CH_3OH) is sensitive to the physical conditions during their formation in dense cold clouds and can be probed through observations of deuterated methanol in hot cores. In this poster, we present methanol D/H ratios derived from ALMA data for a large sample of 99 high-mass protostars and link these to the physical conditions during the formation of methanol in the prestellar phases.
Singly deuterated methanol (CH_2DOH) is detected at the 3-sigma level toward 25 of the 99 sources in our sample of high-mass protostars. Including upper limits, the (D/H)$_{CH3}$OH$ratioinferredfromN_{CH2DOH}$/N$_{CH3}OHwasderivedfor$

- 10^{-2}. Including other high-mass hot cores from the literature, the mean methanol D/H ratio is 1.1 ± 0.7 10^{-3}. This is more than one order of magnitude lower than what is seen for low-mass protostellar systems (2.2 ± 1.2 10^{-2}). Doubly deuterated methanol (CHD2OH) is detected at the 3-sigma level toward 11 of the 99 sources. Including upper limits for 15 sources, the $(D/H)_{CH2DOH}$ ratios derived from N_{CHD2OH}/N_{CH2DOH} are more than two orders of magnitude higher than $(D/H)_{CH3}OH with an average of 2.0\pm 0.8 \times 10^{-1}$ which is similar to what is found for low-mass sources. Comparison with literature GRAINOBLE models suggests that the high-mass prestellar phases are either warm (>20 K) or live shorter than the free-fall timescale. In contrast, for low-mass protostars, both a low temperature of <15 K and a prestellar phase timescale longer than the free-fall timescale are necessary.
The results of singly deuterated methanol show that high-mass prestellar phases are either warmer or shorter lived than their lower-mass counterparts. However, successive deuteration toward CHD2OH seems equally effective between low-mass and high-mass systems, which raises the need for additional modeling and observational efforts to explain this.

An ALMA View of Dense Filamentary Fan-shaped Molecular Clouds in the Large Magellanic Cloud: Detailed Velocity Field Analysis and Comparison to an MHD Simulation

Yamada, Rin[1]

[1]Nagoya University, Japan

A supersonic collision of atomic and/or molecular clouds is a major mechanism of high-mass star formation (see Fukui et al. 2021 for review). Such a collision is numerically simulated by magneto-hydrodynamics to form the dense filamentary structures of molecular clouds (Inoue & Fukui 2013; Inoue et al. 2018), and the observational test has been an issue of keen interest. N159 in the molecular ridge region of the LMC is one of the best laboratories for this test because the 100 km/s atomic gas collision driven by the tidal interaction with the SMC has been reported (Fukui et al. 2017). Especially in N159E-Papillon and N159W-S, dense filamentary fan-shaped molecular clouds with lengths and opening angles of ∼5 pc and ∼30 deg, respectively, have masses of $\sim 10^4$ Mo (Fukui et al. 2019; Tokuda et al. 2019). However, the velocity fields of these regions have not been fully understood. We analyzed the ALMA Cycle 4 ^{12}CO and ^{13}CO data in the N159E-Papillon, N159W-S, and N159W-N regions with a spatial resolution of 0.2 arcsec, particularly focusing on velocity fields of filamentary clouds. In the position-velocity cut perpendicular to the symmetric axis of the fan-shape in the three regions, the ^{12}CO and ^{13}CO gas is distributed in an "arc-like" structure, indicating that the three-dimensional distribution of the gas is "half-cone". In addition, the arc-like structure is locally jagged with dense gas concentrated on the vertexes, which may represent gas accretion onto the dense filament along the half-cone. This velocity distribution is in good agreement with the magneto-hydrodynamical calculations with realistic initial conditions where the spherical cloud is colliding with a flat plane cloud by Inoue et al. (2018). In the presentation, we also show the velocity field analysis of 30 Dor regions and discuss the general physical properties of dense filaments formed by high-speed cloud-cloud collision.

A complete view of complex chemistry in gas and ice using ALMA and JWST

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The discovery of complex organic molecules (COMs) in solar-type protostars highlights the extensive chemical evolution at the onset of planet formation. These molecules, which are potential precursors to pre-biotic molecules, are also found in comets that contain the most pristine matter in the solar system. In recent years, the increasing detection of COMs by ALMA suggests a common presence of COMs in the early stage of star formation. However, the formation pathways of COMs and whether most protostars undergo similar chemical evolution remain open questions with incomplete observational constraints. It is thought that COMs form in the ice mantles on dust grains followed by thermal sublimation near protostars, but direct observational constraints are scarce. While ALMA provides sub-100 au resolution, a resolution necessary to resolve sites of planet formation, to characterize gaseous COMs in nearby embedded protostars, measurements of chemical composition in ices had been limited by low-resolution and limited sensitivity spectroscopy until JWST. Thus, it is imperative to probe both gas and ice chemistry related to COMs, which can only be achieved with both ALMA and JWST. In this presentation, I will present the results of gas+ice chemical analysis in a Class 0 protostar, IRAS 15398-3359, using multi-configurations ALMA observations and the JWST CORINOS program, latter of which shows potential signatures of icy COMs. I will focus on methanol production from ice to gas and discuss the implications on the COMs (or the lack of) in gas and ice phase. I will also present an overview of the ice chemistry characterized by the JWST CORINOS program and the accompanied ALMA program to test the models of COM formation.

ALMA observations of the disk-outflow system in S255IR-SMA1 at ∼15 mas (∼20 au) resolution

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The S255IR-SMA1 core harbours a 20 $M_\odot$ protostar NIRS3. Several years ago a first disk-mediated accretion burst was detected there. We have studied this object for a long time with various instruments, including ALMA. Our first ALMA observations have ∼150 mas resolution. In 2021 new observations with an order of magnitude higher resolution were performed. The main results are as follows. An emission of the ionized envelope around the NIR3 protostar is observed. A clumpy sub-Keplerian disk around the NIR3 protostar ∼400 AU in diameter with signatures of infall is observed in several molecular lines. A submillimeter emission from the jet is observed, which apparently represents a free-free emission of the ionized gas. There are several knots along the jet with the intervals between them ∼100 au. The jet orientation differs by ∼20deg from that on larger scales, which indicates a strong precession. There is velocity gradient across the jet in molecular lines. The CH_3OH 14_1-14_0 and 12_1-12_0 A-+ maser emission is detected around the jet.

3.4 Category: Circumstellar disks

Is grain growth taking place around the young Cosmic Pretzel?

Agurto, Carolina[1]

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A good constraint of when the growth of dust grains from sub-micrometer to millimeter sizes occurs, is crucial for planet formation models. This provides the first step towards the production of pebbles and planetesimals in protoplanetary disks.
Currently, it is well established that Class II disks have large dust grains. However, it is not clear when in the star formation process this grain growth occurs. In order to expand the study of grain growth in Class I disks, I decided to model the dust properties in the outer and inner regions of the Class I protostar binary BHB07-11, or better known as the Cosmic Pretzel. For this purpose, we used the multi-wavelength ∼30 AU resolution ALMA observations in Bands 3, 6 and 7 to determine whether there are spatial variations in the grain size distribution. The analysis provides physical properties for the inner and external disk, and suggests a variation in dust grain properties between disk-inner-envelope and that dust grains have grown from an initial ISM-like dust population.

Thermal and chemical changes in planet-forming environments in numerical simulations, a possible new path for planet-hunting with ALMA.

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Over the past few years, multiple protoplanets have been confirmed through direct imaging, and many other new candidates through indirect method detections such as gas kinematics with ALMA. In the planet-formation scenario with multiple planet candidates, we study the effect of accretion shocks and protoplanet thermal emission on its host disk and the surrounding planet-feeding-seed material. We show the thermal and chemical changes of protoplanetary emission and shocks in the local disk through hydrodynamical and radiative transfer simulations with chemistry. We also show its consequences and expectations for ALMA observations. In our analysis, we show the protoplanetary effect on gas composition and ALMA-relevant observables for different accretion rates and dust-to-gas ratios. Depending on the assumed regime, there will be footprints in the dust continuum emission from planet-hosting disks, along with chemical/thermal predicted signatures in line emission. The results have the potential to open new avenues for protoplanet detection through the scrapping of the rich ALMA archive and for the design of new proposed ALMA observations.

Early Planet Formation in Embedded Disks (eDisk): picture of a protostar at the low mass end revealed in IRAS16253-2429

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Disk substructures in protoplanetary disks are considered to be signs of planet formation. Meanwhile, recent survey observations have pointed out that the typical protoplanetary disks are not massive enough to form giant planets, whereas numerous giant planets are found in extrasolar systems. These results imply planet formation in an earlier, i.e., protostellar phase. To detect signs of planet formation in the protostellar stage, the ALMA large program eDisk has been carried out in Band 6 targeting 19 protostars (16 objects are newly observed). Our sample includes 12 Class 0 and 7 Class I protostars. These protostellar disks show differences from protoplanetary disks (e.g., much fewer visible substructures and more asymmetric brightness distributions along the disk minor axis). I will present the initial results mainly about a target, Class 0 protostar IRAS 16253-2429. Previous works suggested a central mass in this protostellar system close to the brown dwarf (BD) mass limit (0.08 $M_\odot$) with a large uncertainty (M^*∼0.02-0.12 $M_\odot$). Precise mass measurement is crucial to identify such a protostar that will help to approach the low mass end of star formation. The 1.3 mm continuum emission at an angular resolution of 0.08" (∼11 au) shows a disk-like structure with a radius of ∼20 au and a possible substructure. The $C^{18}O$ and ^{13}CO J=2-1 lines trace the infalling envelope, previously reported. While the ^{12}CO J=2-1 line traces the outflow perpendicular to the dusty disk, a high-velocity component (|V-Vsys|>2 km/s) of this line suggests the presence of a Keplerian disk. The SO $J_N=6_5\text{-}5_4$ line shows different velocity structures, implying the presence of a ring around the Keplerian disk and a streamer from the east. Our result may provide a typical picture of protostars at the low mass end.

Layered molecular outflows and disk substructures in YSOs: the HL Tau case

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The HL Tau young system includes the iconic ringed disk revealed by the first ALMA images, but also powerful outflows, in the form of a collimated atomic jet, a wide angle H_2 wind and a conical CO outflow. During the recent ALMA-DOT campaign, conducted at 0."25 resolution, we found that the CO outflow shows a peculiar substructure in the velocity channel maps, consistent with a flow arranged in nested, detached flow surfaces with decreasing velocity toward the outer layers. This distribution is in line with the flow being an extended, inhomogeneous magnetized disk-wind launched from a region between 4 and 40 au from the star. As such, the outflow would be responsible for the removal of the excess angular momentum from the intermediate disk portion in which the effective turbulent viscosity is suppressed. In addition, the outermost two layers appear to be launched from the regions corresponding to the first and second ring from the source. This supports recent non-ideal MHD models (e.g. Suriano et al. 2019) according to which magnetic instabilities in the disk produce at the same time inhomogeneous layered MHD winds and rings/gaps in the disk, alternatively to the action of yet elusive protoplanets. The outflow from at least three other targets show similar features to the HL Tau one. The study of such winds in the millimeter range proves therefore to be crucial for the investigation of the planet formation process.

Investigating the Origin of Gas in the Debris Disk around HD121617 using ALMA Observations

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Debris disks, which develop from protoplanetary disks when the star is approximately 10 Myrs old, were believed to be dust poor and devoid of gas. However, recent ALMA surveys have revealed that at least 20 debris disks contain gas. Due to the prevalence of gas, understanding the gas origin is crucial for studying planetary system formation and evolution, including exocomet composition and direct gas accretion onto forming planets.

This project analyzes newly obtained ALMA data to investigate the origins of gas in the face-on debris disk around HD121617, specifically focusing on the ^{12}CO J=3-2 and ^{13}CO J=3-2 emission lines. The origin of the gas remains a subject of debate, as the challenge lies in distinguishing between a secondary origin where the gas is produced by collisions within the debris disk and a primordial origin where the gas is a remnant of the protoplanetary stage. In the primordial scenario, the presence of H_2 gas is a critical factor, as it dominates the gas mass. Conversely, in the secondary scenario, the gas is thought to originate from exocometary sources with H_2 present in trace amounts, if at all. Therefore determining if H_2 gas is present (in substantial quantities) is crucial to determining the origins of gas in debris disks.

This can be accomplished by comparing the excitation and kinetic temperature. For example, if the excitation and kinetic temperature are equal the gas is in LTE, which would imply a H_2-rich scenario (primordial origin). Conversely, in a non-LTE scenario, multi-line analysis can reveal the density of the gas, and constrain or set an upper limit to the amount of H_2 present, ruling out a primordial origin. Therefore, my project aims to determine the kinetic temperature from the intrinsic Doppler width of the line and the excitation temperature from line ratios. By determining both the kinetic and excitation temperature we will resolve this uncertainty and conclusively determine if the system is in LTE.

Multi-frequency analysis of protoplanetary discs in the Ophiuchus star-forming region

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Protoplanetary discs serve as crucial reservoirs for the formation of small bodies and planets. According to the core accretion theory, initial formation stages involve the growth of interstellar dust grains into larger pebbles of sub-millimeter and millimeter sizes. Observations at such wavelengths provide vital insights into these early processes. Constraining the dust properties of planet-forming discs is fundamental to understanding how dust growth may be favored or accelerated therein. The analysis of multi-frequency data, which after 10 years of ALMA operations is now for large samples, is a powerful approach to investigating disk properties. As part of the ODISEA project (Ophiuchus DIsk Survey Employing ALMA), we are combining new Band-4 (140 GHz) observations with existing archival data in Band-3 (100 GHz), Band-6 (230 GHz), and Band-7 (350 GHz) to constrain dust properties in dozens of disks. We will estimate radial profiles for the temperature, surface density, optical depths, and maximum grain sizes to test grain growth and radial drift in dust evolution models. Our results will contribute essential benchmark information for interpreting disk demographic studies at different wavelengths and improving our understanding of planet formation.

What is the size distribution of protoplanetary disks in nearby star-forming regions?

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The size of a protoplanetary disk is a fundamental property that controls the potential architectures of planetary systems. However, protoplanetary disks seem to be significantly smaller than previously thought, and after 10 years of ALMA operations, the full-size distribution of protoplanetary disks in star-forming regions remains to be established. As part of the ODISEA project (Ophiuchus DIsk Survey Employing ALMA), we are observing 55 faint disks at 0.05" (7 au) resolution and 45 brighter disks at 0.2" (28 au) resolution in Band-8 (400 GHz) to measure the size distribution of 100 disks in a single molecular cloud. We will investigate how disk sizes vary as a function of stellar mass, SED Class, and multiplicity. Our results will serve as a benchmark for comparisons to other regions and give better context to the results from ultra-high-resolution studies of the brightest and largest disks already observed by ALMA.

Reexamination of Cosmic-ray Ionization Rate in Protoplanetary Disks with Sheared Magnetic Fields

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The magnetic fields in protoplanetary disk are stretched to the azimuthal directions due to the velocity shear. Thus, the cosmic rays entering into the disk need to detour while propagating to the midplane. However, most of the previous studies assume that cosmic rays travel to the midplane straightly from the vertical direction.

We investigate the effects of magnetic-field configurations on the ionization rate by cosmic rays in protoplanetary disks. First, we consider cosmic-ray propagation from the interstellar medium (ISM) to the protoplanetary disks in the case that magnetic fields threading the protoplanetary disk are connected to its parent molecular cloud, and show that the cosmic-ray density around the disk should be 2 times lower than the ISM value. Then, we compute the attenuation of cosmic rays in protoplanetary disks. Our result show that the detouring effectively enhances the column density by about two orders of magnitude. We employ a typical ionization rate by cosmic rays in diffuse ISM, which is considered too high to be consistent with observations of protoplanetary disks, and find that the cosmic rays are significantly shielded at the midplane.

In the case of the disk around IM Lup, the midplane ionization rate is very low for inner to $\sim$100 au, while the value is as large as a diffuse ISM in the outer radii. Our results are consistent with the recent ALMA observation

that indicates the radial gradient in the cosmic-ray ionization rate. The high ionization rate in the outer radii of disks may activate the magnetorotational instability that was thought to be suppressed due to ambipolar diffusion. These results will have a strong influence on the dynamical and chemical evolutions of protoplanetary disks.

Lines analysis in the Ophiuchus molecular cloud: Gas in the ODISEA survey.

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The characterization of the molecular gas, around young stellar objects (YSOs) and protoplanetary disks, it is very important for the understanding in the stars evolution and planetary formation at early stages. The ODISEA survey corresponds to the largest sample of low YSOs in the Ophiuchus molecular cloud, with ∼300 targets from class I to III. Here we present the line analysis at 150 au angular resolution for all the mentioned objects, including extended emission, and rotating gaseous disks. Showing the morphology, the mass and size estimation, and correlation for the gas related to the central source. This research represents one of the largest samples, for the demographic statistics of gas, asociated with YSOs in the same molecular cloud.

Early Planet Formation in Embedded Disks (eDisk): A Keplerian Disk and Streamers in the Class I Protostellar System IRAS 04169+2702

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We present the first-look results of high-resolution (0.05"; 8 au) dust continuum and molecular line observations toward the Class I protostellar system IRAS 04169+2702 in the Taurus B213 region, as part of the ALMA Cycle 7 Large Program "Early Planet Formation in Embedded Disks (eDisk)". The 1.3-mm dust continuum emission of the circumstellar disk reveals two local peaks in the central region surrounding a free-free emission dominant depression. Velocity gradients along the disk major axis are seen in emission from $C^{18}O$, ^{13}CO, and ^{12}CO lines. The position-velocity diagrams of these lines reveal a Keplerian-rotating disk around 1 solar-mass protostar as well as envelope material falling in with angular momentum conserved. In addition to the compact disk, a spiral structure is revealed in the dust continuum, ^{13}CO, $C^{18}O$, SO, and H_2CO. Notably, in the region closer to the protostar, the spatial distribution of $C^{18}O$ emission coincides with that of SO emission, implying that the presence of a shock related to accretion through the spirals.

Dynamical masses of debris disk host stars

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Gaseous circumstellar disks present a rare opportunity to test models of stellar evolution against dynamical mass measurements, by using the Keplerian motion of the gas to determine the mass of the central star. These measurements require a combination of precise distance measurements from Gaia and spatially resolved spectroscopy from ALMA. Such measurements have previously been made for pre-main sequence stars, but the older debris-disk-hosting counterparts have largely been ignored. Here we present an archival analysis that measures masses of all the gas-bearing debris disk host stars with a uniform analysis strategy. We find that the dynamical masses are in agreement with modeled masses for most systems, with a few interesting exceptions. More stringent observational constraints on stellar metallicity would provide the greatest improvement on the precision of the analysis. We also find that azimuthal asymmetries in CO are surprisingly common around debris disk host stars, occurring in at least 5/12 of the targets bright and resolved enough for modeling are asymmetric in their CO line profiles.

Unraveling the Chemical Complexity of FU Orionis-Type Eruptive Stars

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FU Orionis-type objects (FUors) are low-mass stars that experience occasional large increases in mass accretion, which affect their chemical surroundings. We investigated 11 FUors using data from the ALMA archive and found more than four species of complex organic molecules (COMs) in four FUors (Haro 5a IRS, V346 Nor, OO Ser, and L1551 IRS5 N) as well as in one nearby source (L1551 IRS5 S). Notably, we discovered a variety of oxygen- and nitrogen-bearing COMs in L1551 IRS 5 N, including multiple deuterated methanol isotopologues. We determined the temperatures and column densities of these COMs using the XCLASS package and also examined their kinematics and distribution. Our research is significant because all four FUors are in a relatively evolved stage (Class I), where detections of COMs are rare. These FUors offer valuable insights into the chemistry of Class I protostellar disks, which are typically difficult to study unless highlighted by stellar outbursts.

Probing the physical structures of streamers accreting to the disk around IRAS 16544-1604 by using various molecular lines

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We will report our latest eDisk results of the Class 0 protostar, IRAS 16544-1604. Specifically, we discuss the detailed spatial and velocity structures of the elongated gas structures connecting to the central protostellar disk. Such gas features have also been found by recent ALMA observations of protostellar sources, and thought to be trajectories of gas accretion from the envelope to the disk, called streamers.
We detected three 1500 au scale elongated structures on the northern side of the disk associated with IRAS16544. By comparing one of them with a infall model with an angular momentum conservation, the spatial and velocity structure of the observation is consistent with the model, so we found that it is a streamer. This is a structure that cannot be explained by the classical model of isotropically accretion from a spherically symmetric envelope, suggesting that IRAS 16544 may be able to reveal the difference between the streamer and uniform accretion. We further analyzed FAUST data of the same object in conjunction with the eDisk data, and identified several candidates of streamers in the entire protostellar envelope. These streamers are detected not only in $C^{18}O$ but also various molecular line such as c-C_3H_2 and DCO^+. We will discuss these results in this presentation.

Grain growth and dust segregation revealed by multiwavelength analysis of the Class I protostellar disk WL 17

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We present the results from the ALMA Band 3 and 7 archival data of the Class I protostellar disk WL 17 in the Ophiuchus molecular cloud. Disk substructures are found in both bands, but they are different: while a central hole and a symmetric ring appear in Band 3, an off-center hole and an asymmetric ring are shown in Band 7. Also, we obtain an asymmetric spectral index map with a low mean value of $= 2.28 \pm 0.02$, which suggests grain growth and dust segregation on the protostellar disk scale. Our radiative transfer modeling demonstrates that these two features are understood by 10 cm sized large grains symmetrically distributed and 10 m sized small grains asymmetrically distributed. In addition, the analysis shows that the disk is expected to be massive and gravitationally unstable. We suggest a single Jupiter-mass protoplanet formed by gravitational instability as the origin of the ring-like structure, grain growth, and dust segregation identified in WL 17. The results have been published recently: Han et al. 2023, ApJ, 956, 9.

C I Traces the Disk Atmosphere in the IM Lup Protoplanetary Disk

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The central star and its energetic radiation fields play a vital role in setting the vertical and radial chemical structure of planet-forming disks. We present observations that, for the first time, clearly reveal the UV-irradiated surface of a protoplanetary disk. Specifically, we spatially resolve the atomic-to-molecular (C I-to-CO) transition in the IM Lup disk with ALMA archival observations of [C I] 1-0. We derive a C I emitting height of $z/r \sim 0.5$ with emission detected out to a radius of 600 au. Compared to other systems with C I heights inferred from unresolved observations or models, the C I layer in the IM Lup disk is at scale heights almost double that of other disks, confirming its highly flared nature. C I arises from a narrow, optically-thin layer that is substantially more elevated than that of ^{12}CO (z/r 0.3-0.4), which allows us to directly constrain the physical gas conditions across the C I-to-CO transition zone. We also compute a radially-resolved C I column density profile and find a disk-averaged C I column density that is 3-20x lower than that of other disks with spatially-resolved C I detections. We do not find evidence for vertical substructures or spatially-localized deviations in C I due, e.g., to either an embedded giant planet or a photoevaporative wind that have been proposed in the IM Lup disk, but emphasize that deeper observations are required for robust constraints.

Probing Dust in Young Protoplanetary Disks through ALMA's High-Resolution Imaging and Polarization

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The unprecedented sensitivity and resolution of the Atacama Large Millimeter/submillimeter Array (ALMA) accompanied by improvements in radiation transfer modeling have yielded tremendous insights into the properties and distribution of dust in young protoplanetary disks. While dust disks around optically visible, Class II protostars are found to be vertically thin, when and how dust settles to the midplane is unclear. We analyze the edge-on, embedded, Class I protostar IRAS 04302+2247, also nicknamed the "Butterfly Star". By observing the 1.3 mm continuum with a resolution of 0.05", we detect an asymmetry along the disk minor axis indicating an optically thick and geometrically thick disk viewed nearly edge-on. Employing forward ray tracing through RADMC3D, we determine that the dust scale height is comparable to the gas pressure scale height. The results suggest that the dust has yet to vertically settle significantly for this Class I source. Furthermore, ALMA's capabilities extend beyond characterizing Stokes I, as it has showcased its exceptional ability to resolve continuum polarization in the rings and gaps surrounding the Class I protostar HL Tau. With a resolution of 0.03" at a wavelength of 0.87 mm, ALMA's high angular resolution polarization measurements have surpassed previous low angular resolution polarization observations, which predominantly revealed scattering-induced polarization. Instead, the finely resolved polarization pattern now reveals an elliptical orientation within the first gap, challenging existing explanations based solely on scattering. By developing polarized ray tracing that accounts for thermal emission and scattering of aligned grains, we demonstrate that the intricate polarization pattern can be explained by the optical depth effects of scattering aligned grains. These results underscore the power of ALMA in unraveling the conditions and processes that shape the formation of planetary systems.

Vortex-induced rings and gaps in a protoplanetary disk

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The co-existence of crescents and rings has been observed in protoplanetary disks in dust continuum emission. The crescents in continuum emission have been proposed to be the dust-trapping vortices generated by Rossby Wave Instability (RWI). We hypothesize that the RWI vortices could produce rings and gaps by driving density waves, analogous to planets. We study the properties of density waves and substructures induced by vortex in 2D hydrodynamic simulations for both global disks and shearing boxes performed by Athena++. In this work, we aim to find rings and gaps induced by vortices in disks comparable to observations.

Visibility-based Analyses of Non-Axisymmetric Structures of Protoplanetary Disks

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ALMA has found that protoplanetary disks have rich structures such as gaps, rings and vortices. Non-axisymmetric structures are considered to be the signature of dynamical processes occuring in protoplanetary disks and closely related to ongoing planet formation. The directly observed quantities by interferomers are visibilities, which is an incomplete set of the spatial Fourier Transform of the brightness distribution on sky. One way of analyzing the data is to reconstruct the sky-plane images using algorithms such as CLEAN. However, images reconstruction sometimes involves artificial signals due to the incompleteness of the observable visibilities. Therefore, more direct methods of analyzing the visibility is desired. Some studies assume a model of on-sky brightness distribution and find the best-fit parameters using visibility fitting. This method, however, involves a prescription of a disk model so that it has a bias. In this presentation, we show a formulation and method to extract large-scale non-axisummetric structures of the disk from direct analyses of visibility data. We formulate the problem fully in the visibility domain so the method is free of uncertainty arising from image reconstraction. We do not assume a disk model so that there is no bias in the disk structures. We apply the methods to the actual data obtained by ALMA, and show that it is possible to extract the information of the structures that are smaller than the beam size defined by CLEAN methods. The method is usedul in extracting structures that are on the scales of several to ten au at the typical distances of proplanetary disks and therefore structures of planet-forming region can be addressed.

Early Planet Formation in Embedded Disks (eDisk): A first look at the Class 0 prostostar GSS30 IRS3

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Protoplanetary disks are the places where planets are formed during the star formation process. In recent years, the focus of research efforts to better understand planet formation has been on Class II sources, identifying substructures in approximately one hundred of them. The origins of these substructures, however, remain a topic of debate. Planet formation is the leading theory among the different mechanisms proposed to explain the formation of these substructures. To investigate whether these substructures are the result of planet formation, it is necessary to study the earlier evolutionary stages of protoplanetary disks, specifically Class 0/I disks, which have not been studied in detail. The ALMA Large Program "Early Planet Formation in Embedded Disks (eDISK)" aims to systematically study the origin of substructures in Class 0/I protoplanetary disks. As part of the program, we present observations of the Class 0 protostar GSS30 IRS3, which were conducted using ALMA Band 6 (1.3 mm) at a spatial resolution of 8 au. Observation targeted continuum and several molecular lines (^{12}CO, ^{13}CO, C^{18}O, c-C_3H_2), which were all detected. While no apparent substructures such as gaps or spirals were observed, we noted a disk asymmetry. A fit in the visibility plane suggests that the asymmetry may be a sharp substructure. The ^{12}CO traces the mass loss from the protostar disk, revealing a low-velocity molecular outflow with a mass loss rate of 6×10^5 $M_\odot$ yr^{-1} and a high-velocity outflow component. Using the rotation curve analysis of the C^{18}O isotopologue, which mainly traces the Keplerian disk, we derived a dynamical mass of 0.235 ± 0.039 $M_\odot$ IRS3. A warp is detected in the C^{18}O emission line, which we interpret it as infalling gas. The gas-to-dust size ratio for IRS3 was found to be 1.64, indicating no evolution of this ratio compared to Class II sources.

Interactions between planets and debris disks: the role of disk gravity

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Planetary systems generally contain not only planets, but also belts of debris similar to the Solar System's asteroid and Kuiper belts. High-resolution observations of such exo-Kuiper belts, or debris disks, frequently reveal complex morphologies such as gaps or double-ringed structures, spirals, and warps. Most existing dynamical models for explaining such morphologies focus on the role of (invoked) massive perturbers such as planets and stellar companions, ignoring the gravitational effects of the disk itself. This assumption, however, may not always be justified, especially in view of observations that debris disks could contain tens of Earth masses in large planetesimals. Here, I will present results showing that the (self-)gravitational potential of debris disks can be important for producing some of the observed disk structures. Namely, I will demonstrate that the long-term (i.e., secular) interaction between a single planet and an external, self-gravitating debris disk can lead to the formation of a wide gap within the disk. The proposed mechanism is based on the occurrence of secular resonances within the disk, which is found to be quite robust even when the disk is less massive than the planet (contrary to what may be naively expected). I will also show that the same mechanism may lead to the launching of a long, one-armed spiral arm beyond the gap, while at the same time the planet's orbital eccentricity is damped. This circularization occurs in the absence of planet-planetesimal scattering. Applications of these results for explaining observations will be discussed at length, focusing on three systems: HD 107146, HD 92945, and HD 206893. I will also discuss the implications of these findings for inferring the dynamical masses of debris disks, as well as the orbital parameters and evolution of planets in debris disk-hosting systems.

Multi-wavelength observations of transitional disks

Sierra, Anibal[1]

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There is not a global consensus on what are the main physical mechanisms that create the inner cavities in transition disks.

Constrains on the dust properties (such as grain size or surface density) could help us to discriminate about different theories that have been proposed to explain the mm and sub-mm observations of these objects.

Using resolved ALMA and VLA observations of six transition disks (CQTau, DMTau, LkCa15, RXJ1615, SR24S, and UXTau), we model their dust continuum visibilities and obtain multi-wavelength brightness radial profiles, which are then used to constrain the dust properties as a function of radius, and where we look for signatures of the different physical mechanisms (e.g. dust traps) that could be taking place in each disk.

Kinematic signatures of gravitational instability in the AB Aurigae planet-forming disk

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If a protoplanetary disk is sufficiently massive, its own self-gravity becomes absolutely consequential to its evolution and readiness for planet formation. Such a disk is said to be undergoing gravitational instability (GI), a fundamental process that results in prominent spiral arms forming throughout the disk on global scales, which can fragment into clump-like protoplanets. Despite its importance to disk evolution and planet formation, diagnosing whether gravitational instability is at play in real disks has historically proven difficult.

In this talk, I present new ALMA Band 6 molecular line observations of the AB Aur disk taken in 2022, one of the longest ALMA gas programs toward a single protoplanetary disk to date. AB Aur is a bright and well-studied young system that has shown strong signs of GI in previous multi-wavelength observations, and has recently been discovered to host a clump-like protoplanet, AB Aur b, making it one of the handful of planet-hosting disks. I describe our discovery of clear and direct evidence of GI in the AB Aur disk, using newly developed kinematic techniques. Our work may rule GI as the likely formation pathway of AB Aur b.

eDisk Modeling of a Protostellar Disk: Dust Flaring, Viscous Accretion Heating, and Larger Gas Radius

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We will present our effort to reproduce the observational results of our ALMA Large Program; Early Planet Formation in Embedded Disks (eDisk). eDisk has observed 17 protostellar sources plus two sources from the archive at a spatial resolution of ∼5 au in the 1.3-mm dust-continuum emission, $C^{18}O$ (2-1), and the other band 6 lines. The overview paper, as well as several of the first-look papers of the individual sources has already been accepted. Three of the main observed features of eDisk are; (1) the dust emission often shows asymmetry along the minor axis of the disk; (2) the brightness temperature of the 1.3-mm dust emission is as high as >150 K; (3) the radius of the Keplerian rotating disks around the protostars are often larger than the radius of the dust disk. With our modeling, we found that the asymmetric intensity distributions along the minor axes can be interpreted by the dust flaring coupled with the optically thick 1.3-mm emission. Incorporation of viscous accretion heating is required to reproduce the high dust brightness temperature. The gas radius is indeed larger than that of the dust radius, suggesting the presence of dust migration. We will introduce these results in our presentation.

Constraints on planet formation from observations and models of disk populations

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The initial stages of planet formation involve the growth of dust particles from submillimetre sizes to pebbles and planetesimals. In this contribution I will discuss our current understanding of grain growth and trapping in disks as a function of the mass of the central star from solar type stars to brown dwarfs. I will show the combined result of multi-wavelength and spatially resolved observations of the protoplanetary disk populations in Ophiuchus, Lupus, Chamaeleon and Upper Scorpius regions, as well as of selected disks at very high angular resolutions. The data are analysed in the framework of a disk population synthesis modelling which incorporates the effects of the main physical mechanisms that govern disk evolution, and compared with numerical simulations of disks produced by the collapse of magnetised clouds. In our analysis we properly take into account the fraction of optically thick emission as a function of wavelength, age and disk properties, we derive solid constraints on the level of dust processing in the disk, on the mass accretion history on the central object, and on the properties of the disk/stellar winds as traced by cm-wave emission. The comparison of the observational properties of disks with the models allow us to place them in a coherent evolutionary framework in which planet formation begins in compact and massive disks formed at the protostellar collapse stage, with the subsequent disk evolution shaped by the disk-planet interaction process.

Rings or no rings, that's the question

van der Marel, Nienke[1]

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ALMA has revealed the presence of substructures in the form of rings, gaps and asymmetries in the dust distribution of many protoplanetary disks. However, mos disks observed at high angular resolution are relatively bright and large, whereas the majority of the faint, smaller disks are much less well studied. These fainter, compacter disks are of as much interest as the ringed disks, as they indicate a lack of planets above the pebble isolation mass. In such disks, radial drift transports pebbles all the way inwards, creating the possibility of forming close-in super-Earths ('Kepler planets') at sub-au orbits. Several of such disks have been resolved so far with ALMA observations at 0.04", revealing no significant substructure. Such disks are prevalent around M-dwarfs, where most of the close-in super-Earths are found according to exoplanet demographic studies. Also molecular chemistry studies suggest that icy pebbles in compact disks have drifted all the way in, sublimating their icy content. In this talk I will discuss what ALMA and Spitzer/JWST have revealed so far about these compact disks, and the implications for a new planet formation model where close-in super-Earths are formed through high pebble drift.

Probing vertical settling in protoplanetary disks

Villenave, Marion[1]

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To form giant planets in protoplanetary disk lifetime, small micron sized particles must grow rapidly to larger grains. A full understanding of that process requires a detailed characterization of the radial and vertical structure of the gas-rich disks associated with young pre-main sequence stars. Disks observed edge-on are of particular interest as they provide a unique point of view to unambiguously disentangle their vertical and radial dimensions. In this talk, I will present constraints on the vertical concentration of large dust particles in disks of different ages, obtained via radiative transfer modeling of ALMA observations. The modeling of multi-wavelength observations of such disks allows to identify high density regions, favorable for grain growth and planet formation, and to study the efficiency of planet formation in protoplanetary disks.

First detection of HC_5N in a protoplanetary disk

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Since ALMA's first light in 2011, the molecular inventory of protoplanetary disks has dramatically increased, including the detection of complex organic molecules (COMs) such as CH_3CN, HCOOH, and HC_3N. These COMs not only present an opportunity to investigate the prebiotic chemistry of forming planetary systems, but they also act as valuable physical tracers of fundamental disk properties. Continuing to expand this molecular inventory to more complex species both allows for refinement of chemical models and adds new tracers of disk physics to our toolbox.
Here we present the first detection of HC_5N toward the nearest protoplanetary disk TW Hya; the largest species detected thus far in disks. With such a high molecular mass, HC_5N has very little thermal broadening. This combined with its low optical depth provides a chance to probe turbulence within the planet and comet forming midplanes of protoplanetary disks. We discuss these possibilities within the context of the increased sensitivity and spectral resolution of ALMA's upcoming Wideband Sensitivity Upgrade and the ngVLA.

Providing Evidence of Gravitational Instability on planetary scales in an FU Orionis Disk

Weber, Philipp[1]

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The categorization of giant planet formation has traditionally revolved around two pathways: core accretion and gravitational instability. However, in recent years, gravitational instability has received less support primarily due to the lack of observational evidence showcasing fragmenting protoplanetary disks around young stars.
In our study, we present evidence supporting the occurrence of planet formation via gravitational instability. We observed the system surrounding a young outbursting protostar in polarized light using SPHERE/IRDIS. Our observation unveiled an expansive structure of scattered light, intricately shaped into multiple spiral arms.
Furthermore, through a thorough re-analysis of archival ALMA band 6 data, we made an intriguing discovery. We identified several clumps of continuum emission aligning precisely with a spiral arm that coincides with the aforementioned scattered light structure. Based on our analysis, we interpret these localized emissions as disk fragments that formed as a result of the gravitational collapse of the spiral arm.
Notably, we estimated the mass of solids within these clumps to be on the order of several Earth masses, providing first evidence of gravitational instability acting on planetary scales. This significant finding potentially represents the first real-time observation of planet formation, marking a remarkable milestone in our understanding of the process.

Dust properties from multi-wavelength ALMA observations: single sources and disc demographics

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In planet-forming discs, knowledge of the properties of dust grains (size, density, temperature and composition) is key to understand how planets form. Attempts to observationally infer these quantities rely on collecting interferometric data in the dust continuum at different wavelengths to study the spectral behaviour of the disc emissivity (a function of dust properties). ALMA has been transformational in this context, providing high sensitivity and resolution images that allowed to study solids on planet-forming scales. Because obtaining such high-quality data at several wavelengths is challenging, grain size, density and temperature have been conclusively characterised only in few cases. I plan to present preliminary results in the case of CI Tau, whose high-resolution data cover a waveband wide enough (0.9 mm to 9.0 cm) to assess its dust properties on global and local scales. However, only targeting few bright sources is not informative of how planet-formation takes place in populations of (mainly faint, compact) discs. A recent work targeted a family of Lupus discs, observed with ALMA at medium resolution between 0.9 and 3.1 mm, suggesting that grains could be (much) larger than few mm in these sources. I plan to discuss how these results change when dust self-scattering is considered, showing that more conservative estimates can be obtained. I will also discuss the role of ALMA Band 1 data to answer the open questions on disc solids.

Heterogeneity and metal content of 3 main-belt asteroids from high-resolution ALMA data

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ALMA is able to spatially resolve main-belt asteroids at millimeter wavelengths, which allows for detecting surface heterogeneity via spatial variations in thermal properties across their surfaces. Resolving these 0.1-0.2" objects at thermal wavelengths is not possible with infrared telescopes today but is now possible with ALMA. In this work, we have obtained 1.3 mm thermal emission data from ALMA for three asteroids at $\sim$30 km resolution (the asteroid diameters are 200-250 km): a stony (S-type) asteroid (15) Eunomia, and two metal (M-type) asteroids (16) Psyche (de Kleer et al. 2021) and (22) Kalliope. Studies of thermal emission of asteroids are relevant for understanding the regolith properties and composition, from which we can infer the nature and evolutionary processes occurring on the underlying body. Comparing the spatial variations in thermal and dielectric properties of the stony and metal asteroids can provide insights into how regolith properties relate with compositional variations arising from formation and/or differentiation of the parent planetesimal. We have applied a thermophysical model to ALMA 1.3 mm thermal emission data to derive the best-fit global values as well as area-by-area fits of thermal inertia and millimeter emissivity of the three asteroids. The thermophysical model we have used is based on Delbo et al. (2015), and adapted to take into account the spatially resolved thermal emission data including subsurface emission (de Kleer et al. 2021; Cambioni et al. 2022).

Revealing the dynamics of Venus' upper atmosphere with submillimeter observations

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Venus has a thick atmosphere that extends to more than 130 km above the surface. Although attention often tends to focus on the lower atmosphere of Venus, where the atmosphere rotates around the planet at very high speed, the upper atmosphere above $\sim$80 km altitude is also a very important research target for understanding physics and chemistry in planetary atmospheres. In particular, around 90 - 110 km altitude, which can be observed with submillimeter waves, some characteristic atmospheric circulations are thought to be formed as a result of the transport of angular momentum and energy by atmospheric gravity waves propagating from the lower altitudes. Elucidating the effects of atmospheric waves on atmospheric circulation and thermal structure in a thick planetary atmosphere like Venus is important for a more universal understanding of planetary atmospheres. Submillimeter Heterodyne observations enable us to visualize Venus' upper atmospheric circulations by means of observing the Doppler-shift of CO lines. Here we present observational insights into the atmospheric dynamics of Venus' upper atmosphere obtained from observations with ALMA and other submillimeter telescopes.

3.5 Category: Stars, Sun, and stellar evolution

DEATHSTAR - A new hope for accurate mass-loss-rate estimates for nearby AGB stars

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Mass loss via a stellar wind is a critical process that governs the later phases of stellar evolution. Through this wind, Asymptotic Giant Branch (AGB) stars are major contributors of newly synthesized elements and dust to their host galaxy. Accurate characterization of this phenomenon is therefore key to advancing our understanding of the Galactic chemical enrichment and evolution. The Deathstar project aims to provide a definitive description of AGB gas mass loss by mapping the winds of 69 nearby AGB stars in the southern hemisphere using ALMA observations of CO lines. Leveraging ALMA ACA's capabilities, we directly and systematically measured the sizes of the CO envelopes created by the winds, eliminating a major source of uncertainty from wind property estimates. By incorporating these size measurements and utilizing our newly-calibrated distance measurements from Gaia and VLBI parallaxes, we further refine our calculations of mass-loss rates for AGB stars. In this talk, I will present the estimated sizes of the CO envelopes of these nearby AGB stars and compare them with predictions from photodissociation theory. Additionally, I will present our much-improved mass-loss rates constrained by ALMA observations, demonstrating the profound impact of ALMA on our understanding of AGB outflows.

An ACA spectral survey at 3 and 1.3 mm in a sample of AGB/post-AGB stars

Cerrigone, Luciano[1]

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The circumstellar envelopes of stars in transition from the Asymptotic Giant Branch (AGB) to the planetary nebula phase are known to be dusty and rich in molecules. While much of the current knowledge in terms of spectral-line emission from AGB/post-AGB stars is based on spectral surveys of a handful of objects, we have carried out a spectral survey of 17 AGB/post-AGB stars and potential candidates with the Atacama Compact Array, to pave the way for further detailed studies at higher spectral and angular resolution. All targets were located between ∼22 and ∼09 hours of right ascension and were observed in Band 3 (85–116 GHz); a subset of targets was also observed in Band 6 (211-272 GHz). Continuum emission was detected in 10 targets, allowing us to estimate the spectral index across the band and thus distinguish radiation from dust, stellar wind, or ionized shell. Although some objects do not display any or very few spectral lines, probably due to the specific evolutionary stage or mass of the central star, lines of molecules such as CS, SiS, HCN, SiO, CO as well as CN and CCH were detected in several sources. In particular, in V510 Pup, a high-velocity molecular outflow previously seen in CO is confirmed and detected in several other molecules. The observations were approved as an ALMA Observatory Project, aimed at providing data to the general community.

Probing the inner winds of oxygen-rich evolved stars with ALMA observations of mm-wavelength SiO masers

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SiO masers are useful tracers for studying the innermost regions of circumstellar envelopes (CSEs) of evolved stars where convection and pulsation shocks are damped and dust formation commences. We present results from ALMA Band 6 observations (213-270 GHz) of mm-wavelength (i.e. high-rotational transition number J) SiO masers towards 17 oxygen-rich AGB and red supergiant stars, carried out as part of the ATOMIUM Large Programme (PI: L. Decin) in 2018-2020. We found that most of the targets exhibit high-J ^{28}SiO, ^{29}SiO, or ^{30}SiO masers, with ^{28}SiO v=1 J=5-4 being the most abundant line. 2D Gaussian component fitting of the

ALMA extended-configuration data revealed that the distribution of high-J SiO maser components does not usually follow the ring structure seen in the best-studied 43 (v=0 J=1-0) and 86 (v=1 J=1-0) GHz SiO masers. Instead, they trace more complex irregularities in the inner wind e.g. elongated structures, streamers, infalls, velocity-position gradients, and partial ring structures. Although a correlation between mass-loss rates and flux-weighted mean angular separations from the star is suggested by linear regression models, we cannot rule out the possibility of the correlation existing by chance without multi-epoch observations.

Water masers map the complexity of mass loss from evolved stars

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Ten years of ALMA imaging of evolved star winds show that the rate, composition and dynamics of mass loss are changeable, inhomogenous and asymmetric. Water masers, in energy states from 200-6000 K, trace the wind from the pulsation-dominated radio atmosphere, to acceleration through escape velocity, out to regions where the molecules are photo-dissociated or freeze out. Dozens of transitions are accessible to ALMA, of which at least 7 have been imaged. Maser beaming allows the wind structure to be mapped from the radio atmosphere to hundreds of stellar radii (R*) at an order of magnitude higher resolution than is possible with thermal lines. Applying recently-developed models to the overlap or segregation of water (and OH and SiO) maser transitions reveals the local density, temperature and other physical conditions on R* scales. Many water masers are concentrated in dense clumps whilst the less dense surrounding gas is traced by masers such as at 183-GHz and OH lines. These measurements provide input to constrain chemical and kinematic models of thermal lines and dust.
Only 22-GHz masers have been monitored long-term, showing variability linked to the stellar phase but too far from the star to be explained directly by pulsation shocks, suggesting heating stimulates their collisional pumping. Large variations, sometimes localised, are seen on other timescales, perhaps due to a companion, variable or episodic directed mass loss – or simply cloud overlap. High-resolution observations can reveal shocks, since shocked masers can appear almost as large as the emitting region, in contrast to the usual shrinking due to maser amplification. Shocks may explain the location of some high-energy transitions at tens R*, further than expected from the star.
We present studies of VY CMa (RSG) and R Hya (AGB). The former has been mapped in the most water transitions; the CSE of the latter bears the scars of a recent thermal pulse and suggested companion interaction.

ALMA observations of Titanium and Aluminium bearing species in Mira

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AGB stars are among the main sources of dust production in the Galaxy. However, the condensation of inorganic dust grains in the outflow of AGB stars is largely unknown. From theoretical studies, aluminium oxides, titanium oxides, and silicon oxides are considered as the main candidates of condensation cores of dust particles in M-type AGB stars. In this poster, we present the preliminary results of our ongoing work on studying the dust in the outflow of the well-studied nearby AGB star, Mira.
We used spatially resolved observations with the Atacama Large Millimeter Array (ALMA) and identified multiple rotational transitions of 46,48, 49, 50TiO, 46,47,48,49,50TiO2, AlO, AlCl, $Al^{37}Cl$, AlF, SO, SO_2, SiO, and SiS lines. We aim to more precisely constrain the aluminium and titanium budget in the inner wind of Mira, with the ultimate goal of shedding light on the intricate processes governing dust formation in Mira.

An ALMA zoomed-in journey to explore the emerging ionized regions of pre-Planetary Nebulae

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In this presentation, I will report on recent results from our successful and pioneering observational program with ALMA to study emerging ultracompact Hii regions of pre-Planetary Nebulae (pPNe). By utilizing mm-wavelength recombination lines (mm-RRLs) as novel tracers, we're able to delve deeper than ever before into the inner workings of these fascinating objects. I will focus on our study of two poster-child pPNe, namely, M2-9 and CRL618. We unveil the structure and kinematics of the elusive inner nebular regions of these objects with an unprecedented angular resolution of 20-30mas (i.e., down to ∼15-30AU linear scales). For both targets, the ionized central regions are elongated along the main symmetry axis of the large-scale nebulae, consistent with bipolar winds, and show notable axial velocity gradients with expansion velocities of up to ∼200km/s. The intensity and width of the H30alpha profiles are found to be
time variable, denoting changes on scales of a few years of the physical properties and kinematics of the on-going post-AGB ejections. We have modelled our observations using the 3D non-LTE radiative transfer code co3RaL (by D. Tafoya). This has allowed us to describe with unparalleled detail the physical conditions in the inner layers of these iconic pPNe, which are key to understand the development of multi-scale asymmetries in these stages.

A Close-Up View of the Most Recent Common Envelope Systems

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Common envelope evolution (CEE) is a critical phase in the life cycle of binary stars. It occurs when two stars are engulfed in a mutual envelope as a result of one of them growing in size at the end of its life. Drag forces in the companion and on the core of the giant transfer angular momentum and energy to the envelope gas, leading to orbital decay until either the envelope is ejected, leaving a tight orbiting system, or the two stars merge. Systems experiencing CEE are believed to play a role in forming cataclysmic variables, low-mass X-ray binaries, double white dwarf systems causing Type I supernovae, and systems with double neutron stars emitting gravitational waves. Despite their significant astrophysical relevance, CEE systems in their initial phases remain elusive, and direct measurements of the physical parameters of the ejected gas are rare.
Water fountains (WFs) are evolved low-mass stars (less than 8 solar masses) characterised by high-velocity water masers (>100 km/s), faster than the OH masers tracing circumstellar envelopes from the asymptotic giant branch phase. Recent ALMA observations of their molecular gas indicate that WFs most likely binary or multiple systems that entered the CEE phase less than 200 years ago, offering a unique opportunity to explore this phase in its earliest stages. ALMA has captured the sharpest images of these systems, unveiling equatorial torii, collimated fast jets, expanding bubbles, and more. The analysis of the physical parameters of these components, alongside numerical simulations, is enabling us to determine the astrophysical conditions under which CEE occurs.

Charting Circumstellar Chemistry of Carbon-rich AGB stars with ALMA

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Asymptotic giant branch (AGB) stars contribute substantially to the chemical enrichment of galaxies. They produce heavy elements through nucleosynthesis and release them to the interstellar medium through stellar winds. The chemical characterisation of the latter is crucial for understanding the astrochemical networks that lead to the formation of complex molecules and dust. However, the chemistry in circumstellar envelopes (CSE) of carbon-rich AGB stars remains poorly constrained and is currently almost exclusively based on observations of a single star, IRC +10216. The high sensitivity and angular resolution of ALMA have now made it possible to

probe into the CSEs of farther away AGB stars as well, opening up the possibility to finally determine whether IRC +10216 is indeed an archetype carbon-star as conventionally assumed.
In this talk, I will present high angular resolution ALMA Band 3 spectral-line surveys of three carbon-rich AGB CSEs. With more than 200 emission lines detected per source, this survey offers one of the best tools for the detailed study of the molecular richness in C-star CSEs. The three stars, with similar outflow properties and brightness, have been chosen for sampling a broad range of mass-loss rates and 12C/13C ratios. These indicate differences in their physical evolution and nucleosynthetic histories, making them ideal candidates for a comparative study of variations in circumstellar chemical evolution.
I will give a comprehensive overview of the molecular content, chemical structure, and observed complex morphology of the CSEs, as revealed by ALMA in great detail. I will present abundance estimates obtained using detailed non-LTE radiative transfer modelling, based on ALMA, APEX, and Herschel-HiFi data. I will discuss in detail the observed similarities and differences, both among the stars in the sample, and with IRC +10216. I will also provide an outlook of future work, including updates to the existing chemical models for AGB CSEs.

Nonthermal radio variability in protostars with the VLA, ALMA, and the VLBA

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Low-mass young stars and protostars are known to be highly variable and magnetically active. Their intense magnetic fields are responsible for high-energy processes in their immediate vicinity as revealed through X-ray and radio observations. The revolutionary development of radio facilities in the last decade has made possible to narrow the gap against the extensive X-ray studies in this field. Radio variability in protostars at centimeter and millimeter wavelengths is associated with nonthermal (gyro-)synchrotron emission from magnetospheric activity. Here I will present a radio variability study for an unprecedented sample of Young Stellar Objects (YSOs) at centimeter and millimeter wavelengths at high spatio-temporal resolution with the VLA, ALMA, and the VLBA. I will first describe our results from a systematic search for intense centimeter radio flares towards the Orion Nebula Cluster (ONC) using the VLA. These results together with the few serendipitous discoveries of strong millimeter flares in the literature, has motivated us to conduct a systematic search for mm-variability in the ONC using ALMA. This later study sets the first systematic constraints on the occurrence of such events in a large YSO sample, finding a wide range of mm-variability on timescales of minutes to days, including a strong mm-flare from a YSO at 8-second time resolution. Finally, I present a multi-epoch VLBA survey of nonthermal emission from YSOs towards the ONC. This dataset provides a more efficient method for the assessment of nonthermal radio variability at high time resolution compared to methods required for other interferometric datasets (e.g., VLA and ALMA) towards complex regions. This dataset will provide the largest sample of VLBA light curves of protostars at high time resolution from seconds to years.

3.6 Category: ALMA operations, observing modes, and instrumentation

ALMA Array Operation process overview

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ALMA Science operations activities in Chile are responsibility of the Department of Science Operations, which consists of four groups, the Array Operations Group (AOG), the Program Management Group (PMG), the Data Management Group (DMG) and the Array and Operations Performance Group. The AOG includes the Array Operators and have the mission to provide support for science observations operating safely and efficiently arrays of antennas. The poster describes the AOG process, management and operational tools.

ALMA High Frequency Long Baseline Capability Tests in Bands 8-10

Asaki, Yoshiharu[1]

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The Atacama Large Millimeter/submillimeter Array (ALMA) was used in 2019 and 2021 to undertake High-Frequency Long Baseline Campaign (HF-LBC-2019 and HF-LBC-2021) in ALMA observing Bands 8-10 (397-908 GHz) in array configurations including 16 km baselines. These campaigns are divided into two parts: (1) observations were arranged using close calibrators between 0 and 4 deg from the target point-source quasars (QSOs) to also explore subtle effects of calibrator separation angle; and (2) imaging validation tests targeting the evolved star R Lep were arranged for phase calibrations using band-to-band (B2B) phase referencing with a close phase calibrator to achieve the highest angular resolution at each of the high frequency Bands. In the first part, a total of 13 observations were made, five using standard in-band observations and eight using the band-to-band (B2B) observing mode, where phase solutions are transferred from a lower frequency band. At bands 9 and 10, image angular resolutions as high as 7 and 5 mas were achieved, respectively. In the second part, R Lep images of the continuum emission and the hydrogen cyanide (HCN) maser line at 890.8 GHz, from the J=10-9 transition between the (1110) and (0400) vibrationally excited states, achieved angular resolutions of 13, 6, and 5 mas in Bands 8-10, respectively. We have successfully make verification of the high frequency long baseline capabilities with B2B, parts of which have been provided to Users from Cycle 9, starting from 2022 October.

The Science Case for the Atacama Large Aperture Submillimetre Telescope

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ALMA has revolutionised (sub-)millimetre astronomy and will continue to provide exciting discoveries at the cutting edge of astronomy research for many decades to come, particularly with the advancements provided by the development roadmap. In order to make the most of the detailed imagery and spectra that ALMA can provide, we need the next generation of large scale observations to find the best targets for high resolution follow-up. To get there we need a dedicated, new facility with a large throughput to systematically sample the sky. The AtLAST Consortium is currently building the science and technical case for this facility. Here I'll present a sample of the detailed science case studies that we are currently developing in order to define the telescope requirements. As a 50m single dish telescope with a 2-degree field of view, the strength of AtLAST will be cases where a large field of view and/or sensitivity to large-scale structure is crucial, including imaging our own Sun, mapping the dynamics of the galactic plane and conducting deep surveys of high redshift galaxies. The huge advances AtLAST will provide over current facilities will result in a fundamental change to our understanding of the submillimetre sky whilst also ensuring that ALMA does not become source starved.

The elusive baryon cycle and prospects for future ALMA and AtLAST observations

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The baryon cycle drives the formation and evolution of structures from stellar core on sub-pc scales to the largest overdensities in the Universe on Mpc scales. This implies that all these physical scales are connected and linked physically to each other, and such link extends over different time scales and multiple gas phases. However, all the manifestations and observables of such baryon cycle, from star forming filaments in the ISM, to the massive molecular outflows and accreting filaments enriching the circumgalactic medium and, possibly, the intergalactic medium, are: 1) diffuse and low surface brightness in nature; 2) extended on large angular scales (arcmin/degrees), and 3) multi-phase, with a crucial role of gas phases (molecular, atomic) that are not visible in the optical/IR but require sensitive sub-mm instruments. These characteristics make it very challenging to observe the baryon cycle with current or planned telescopes. This issue motivates, among other science drivers, the construction of a new, sensitive, large-aperture (50 meter), wide field of view (1-2 deg), single dish telescope on the Chajnantor plateau: the Atacama Large Aperture Submillimeter Telescope (AtLAST). AtLAST will obviate the technical limitations of interferometers and will be a fundamental complement to ALMA, by providing the much needed coverage of short UV baselines needed for ALMA+single dish data combination, as well as the high mapping speed and throughput to survey large areas of the sky and so discover new targets for ALMA follow ups. After an introduction on the crucial discoveries relevant to the baryon cycle enabled by ALMA, I will outline the main results of the EU-funded AtLAST design study, which will be completed in August 2024. The study is investigating all aspects of building such new international research infrastructure such as the selection of the optimal site, the power supply through renewable energy, and the governance and operations models.

The ALMA Program Management Group and the ALMA Data Acquisition Process.

Cortes, Juan[1]

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The ALMA Program Management Group (PMG) bears the responsibility for daily observation execution, ALMA program status tracking, data quality control, and coordinating these tasks with staff at the three ALMA Regional Centers (ARCs). The PMG comprises a Program Manager and eight Data Analysts, supplemented by around thirty Astronomers on Duty (AoD) who conduct ALMA observation executions in service mode at both the Operations Support Facility (OSF) and Santiago Central Offices (SCO). In this presentation, we outline the mission, core operational tasks, deliverables, and activities of the ALMA Program Management Group. Additionally, we provide a detailed overview of the ALMA Data Acquisition Process and an analysis of its recent cycle performance based on the ALMA Key Performance Indicators (KPIs).

A BRAIN study to tackle imaging with artificial intelligence in the ALMA2030 era.

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An ESO internal ALMA development study, BRAIN is addressing the ill-posed inverse problem of image analysis employing astrostatistics and astroinformatics [1]. These emerging fields of research offer interdisciplinary approaches at the intersection of observational astronomy, statistics, algorithm development, and data science [2]. In this study, we provide evidence of the benefits in employing these approaches to ALMA image analysis for operational and scientific purposes. We show the potentials of two techniques (RESOLVE [3,4] and DeepFocus [5]), applied to ALMA calibrated science visibilities. Significant advantages are provided with the potential to improve the quality and completeness of the data products and overall processing time. Both approaches evidence the logical pathway to address the incoming revolution in data analysis dictated by ALMA2030 [6]. Moreover, we bring to the community additional products through a new package (ALMASim) to promote advancements in these fields, providing a refined ALMA simulator usable by a large community for training and/or testing new algorithms.

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This work is in collaboration with Michele Delli Veneri (UniNa), Lukasz Tychoniec (ESO), Eric Villard (ESO), Ivano Baronchelli (INAF), Andrea Dosi(UniNa), Jakob Roth (MPA), Torsten Ensslin (MPA), Giuseppe Longo (UniNa)

Initial Concept and Roadmap of the Band-4+5 Receiver Upgrade of the Atacama Large Millimeter / Submillimeter Array (ALMA)

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The Band-4+5 receivers of the Atacama Large Millimeter / Submillimeter Array (ALMA) is proposed for the upgrade after 2030. The new receiver will cover the RF frequency of the original Band-4 (125 - 163 GHz) and Band-5 (163 -211 GHz) with continuous frequency tuning over dual polarizations, dual sidebands with instantaneous intermediate frequency (IF) bandwidth up to 16 GHz per sideband and per polarization.

To fulfill the ALMA2030 upgrade schedule, Band-4+5 receiver development is aiming to have the prototype receiver ready around 2028. Both the high-electron-mobility-transistor (HEMT)-based receiver and superconductor-insulator-superconductor (SIS)-based receiver schemes will be considered.

To avoid the possible interference between LO and IF signals, considering the possible 16 GHz IF bandwidth over 2 - 20 GHz, the LO fundamental frequency will be chosen in 24- 32 GHz, followed by an active frequency tripler and a directional coupler to form the phase-lock loop. The 72 - 96 GHz frequency tuning range of the LO-PLL output is sufficient to cover the required LO frequency range of the subharmonic diode/transistor mixers for the HEMT-receiver scheme. For the SIS-receiver scheme, the 72- 96 GHz LO signal requires a WR-10 vacuum feedthru and stainless waveguide section to fed into a cryogenic frequency doubler to 144 - 192 GHz, then distribute to the four SIS mixer chips via WR-5.1 waveguide dividers and couplers.

To avoid the development risks, commercially available components with qualified performance will be used for the prototype cartridges. The key components with 51.2% relative bandwidth to be developed in-house are (i) RF InP HEMT LNAs, (ii) Nb SIS mixers, (iii) waveguide 3-dB hybrid, (iv) orthomode transducers, (v) corrugated horn, (vi) optics mirror pairs. For (iv) and (v), since the waveguide components with same relative bandwidth have need developed in other frequency bands, the development will be started from scaled models of the previous results.

ALMA ACA Spectrometer

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The ACA Spectrometer (ACASPEC) is a new spectrometer developed for science observations on the Total Power Array (TP Array) in the Atacama Compact Array (ACA). Led by KASI in collaboration with NAOJ, the ACASPEC replaces the functionality of the ACA Correlator (ACACORR) for the TP array. It utilizes general-purpose graphics processing units (GP-GPUs) to process signals in software. The ACASPEC enables independent operation of the TP Array, bringing improved observing efficiency, higher spectral dynamic range, and expandability for the upcoming Wideband Sensitivity Upgrade. Installed in February 2022 at ALMA Array Operations Site, ACASPEC achieved the first light, confirming that all the signal paths from the antennas to the archive were well-connected and processed. Following that, commissioning and science verification (CSV) activities were conducted. Consistency between the ACASPEC and the ACACORR was verified for various spectral setup parameters, the Jy/K conversion factor, and spectral shapes and intensity of emission lines. The spectral dynamic range better than 10000 has been confirmed using the CO line. In addition, the ACASPEC showed enough performance for calibration observations, such as pointing and focus using the cross-correlation products. Finally, end-to-end testing was conducted to verify all processes of TP observations, including connections with other ALMA subsystems. Data processing by the CASA Single-Dish pipeline worked properly for the ACASPEC data in standard On-the-fly mapping and TP spectral scan modes. Detailed comparisons for intensity using data cubes taken by the ACASPEC and the ACACORR also showed good agreement, with more than 85% of data points matching within 20% for both data sets. Following this success of the CSV testing, the ACASPEC will be offered to ALMA science operations in Cycle 11. In this poster, we will present the development of the ACASPEC system and the CSV results.

On Operational Aspects of ALMA Flux Density Calibration

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The Atacama Large Millimeter-/submillimeter Array (ALMA) uses models of planetary objects, primarily Uranus, and quasars, as secondary calibrators, for the absolute calibration of the flux density, while direct methods using the calibration devices (SEFD) have been explored. Recently ALMA Science Operations improved the procedure for quasar flux density monitoring in terms of observational efficiency and calibration accuracy. A special scheduling algorithm, termed Per-Source Observing (PSO), was implemented in mid-2022 to allow updates of the quasar flux densities as needed per source and per band, as conditions allow. Frequently used flux and bandpass calibrators are monitored with high cadence (3-5 days) and up to Band 9, significantly improving specifically high-frequency flux calibration. In accordance, the Flux (estimation) Service of the ALMA Calibrator Source Catalogue (SC) introduced a fitting algorithm on well-sampled quasars for the queries run by the Pipeline during data reduction, which is being extended from linear to quadratic terms in log frequency for specified bands, for example towards ALMA Band 1 observing. In this presentation we describe the new methods and their evaluation in the contest of efficiency of observational procedures and the ALMA flux calibration accuracy, giving reference also to related conference contributions with further details.

Baseline position measurements during Cycle 7 Long Baseline

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The accuracy in the positions of the ALMA antennas is relevant for making interferometry observations, especially for high frequencies (>300 GHz) with a large separation between target and phase-calibrator (>5 deg).
In 2021, antenna position calibrations were made in ALMA with the 16 km long baseline configuration at Chajnantor Plateau. In total there are 119 observations using more than 40 antennas, consistent of pointing toward 5 sources (unresolved quasars) three times.
Using ALMA standard baseline fit tool, tc_{antpos} in CASA TELCAL software, that includes a PWV correction in delay, we fitted the antenna positions trying to obtain zero delays in observations made at different elevations and azimuths.
The errors in the antenna position observed in this campaign can break down into three components: 1) geography, 2) turbulence, and 3) temporal. The strongest geography dependency is Cerro Chascón between P-branch and S-branch that is producing the highest errors to antennas near this mountain, where Z axis is the most affected with a maximum error of $\sim$3 mm. The turbulent component is following an power slope where the error increases with baseline distance, b, as $b^{0.4}$, $b^{0.3}$, and $b^{0.4}$ for X, Y, and Z axes respectively. And the temporal component, measured as a maximum of 100 days, is correlated with each P, W, and S array brands, and it could be associated by changes in weather conditions.

It is important to reduce the level of antenna error to be able to make high frequency and long baseline observations. In ALMA operations (data acquisition), this temporal variation will be mitigated with whole array baseline calibrations every week during long baseline configurations. This component will be also study in more detail to see it is possible to model this temporal behavior with weather parameters such as PWV, PHASE-RMS, and wind speed.

Exploiting the Fourier space: advanced usage of ALMA data

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We will present a summary of a set of advanced tools, originally developed for their use with ALMA data. We will also summarize some of the cutting-edge scientific results that these tools have provided. In particular, model-fitting techniques, able to retrieve rapid (intra-observation) source variability (also in polarization), achieve over-resolution (based on a-priori source information), and combine ALMA observations to ALMA-VLBI observables (EHT and the GMVA), among others.

Using the ESO-Allegro Phase RMS database to help push towards more High Frequency observations

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As part of an ESO internal development study we have reanalyzed over 17000 observations taken from Cycle 3 to Cycle 7 in order to specifically evaluate the phase RMS, i.e. the stability of the atmosphere, as a function of timescale and baseline length. In using the bandpass calibrator scans, we have calculated the phase RMS for timescales from 30s to 4mins relevant for phase referencing techniques, and scaled to relevant baselines of 500, 1000, 5000 and 10000m, as well as extracting various other weather condition metadata. Irrespective of the frequency band used at the time, all phase RMS values are converted to a frequency independent path length variability, easily allowing a wholistic comparison of the short term 'path length' variability over the 5 cycles. We find and show that Southern Winter months, June-July-August, particularly at nighttime offer the most stable conditions, suitable for ALMA's highest frequency bands, while such bands would not effectively be possible in Summer (December, January). The phase RMS of longer baseline can also be compensated (improved) by faster phase referencing technique, which typically would offer 'more' time in a given band, but can lower observing efficiencies. Fast switching is a requirement to enable the highest frequency observations on ALMA's longest 16km baselines. In so far, globally there are no weather-related trends although future studies are underway.

VLBI with ALMA: Past, Present and Future

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This year also marks the tenth anniversary of the VLBI effort at ALMA, so it is timely to review what has been accomplished, where we are, and what the future is likely to have in store. The ALMA Phasing System (APS) is a complex one which we attempt to describe here, its . The scientific outcome together with GMVA and EHT is well known, but aside from the noteworthy supermassive black hole images, we have also made considerable advances making use of ALMA-only interferometric data mostly due to the long full-polarization session observations during VLBI campaigns. With the recent additions of spectral-line VLBI observations and ALMA-standalone Phased-Array observations, while the wide-band sensitivity upgrade is gaining momentum, we can only expect that a great future is ahead.

The ALMA Dashboard: A web-based application to monitor the ALMA system

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The ALMA observatory is a complex system consisting of many components including 66 antennas (each of which can contain up to 10 receivers and can be placed on one of 192 pads located on the Chajnantor Plateau in Chile), two correlators, and a central local oscillator. It was recognized early on that ALMA operations needed a way of tracking the status of the system's key elements and presenting it in a simple, easy-to-read way. The ALMA Dashboard has provided such functionality during the last 10 years. It is a web application that shows in tabular and graphical form the status of each of the antennas and receivers, high-level properties of the array, as well as other information such as, for example, a map of the array, the serial number of important components, and comments from users.
Besides visually, the information in the ALMA Dashboard can be accessed via a REST API. This feature has been used, for example, to automate the array creation process by Array Operators, to avoid including in science observations antennas that are, say, out of service or requested for other activities such as Engineering maintenance. The Dashboard has become a useful tool for the coordination of activities on the ALMA array.
In this poster, we show the main features and tools of the ALMA Dashboard application, describe its usage in ALMA operations, present the latest improvements, and discuss possible ideas for future development.

Key Performance Indicators of the ALMA Program Management Group: A Pathway to Enhanced Efficiency and Effectiveness

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In line with the core goal of ALMA, the mission of the Program Management Group (PMG) is defined as: "To efficiently and effectively manage ALMA programs and assure the quality of data acquisition". It is within this framework that we have developed our high-level Key Performance Indicators (KPIs), with an aim to create a team driven by efficiency and effectiveness. This poster outlines the various metrics and goals associated with our higher-level KPIs, which measure the efficiency and effectiveness of our use of ALMA resources. These include observing and operations efficiency, total accumulated QA0 Pass, downtimes, failure rates, idle time, and more. The development of these KPIs has prompted a comprehensive review of procedures and logging policies during science operations. As a result, we now have a more precise log and description of activities affecting efficiency and effectiveness. Moreover, these KPIs aid us in setting and maintaining realistic goals over time, while also aligning our efforts across the different sectors of the observatory.

ALMA spectrum management and synergies with other entities in Chile

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An overview of the activities of the ALMA Spectrum Management Office and the synergies with other entities engaged in similar scientific research activities in Chile or that develop actions aimed at the control and regulation of radio frequency emissions.

ALMA's search for clean OFF positions for TP projects

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Composed of 4 12-m antennas (named as PM antennas), ALMA's Total-power (TP) array complements 7-m and 12-m Array's coverage, by using single dish and ON+OFF switching observing mode. These OFF (on-sky) positions are used for baseline subtraction on the ON (on-target) positions, so they need to be free from emission, at the science representative frequency. Since Cycle 5 we have been providing clean OFF positions for all science projects. For extragalactic projects, an offset of 10arcmin in horizontal coordinates is suggested. For Galactic projects, a specific position is provided, within 5deg from target for projects in Bands 3 through 6, and within 3deg for projects at higher bands. This last case involves a dedicated observing campaign, per cycle, to search for clean OFF positions for those science Galactic projects that require one. These observations are done mainly in Band 3 at 115.3 GHz, looking for CO(1-0) emission, although dedicated observations at higher frequencies can be done for cases where no CO-clean positions are found within the closeness criteria. Every newly found clean position is added to ALMA's calibrator catalog, enriching it more and more after each cycle. To this date we have a total of 171 clean positions in our catalog, spread out through our Galactic plane, and also covering some nearby GMCs, like Orion, Lupus, Taurus and Ophiucus, and the Magellanic Clouds