Astro2020 APC White Paper:

A Science-Driven Vision for ALMA in the 2030s

Type of Activity:
☐ State of the Profession Consideration ☑ Ground Based Project ☐ Space Based Project
☐ Technology Development Activity ☐ Infrastructure Activity ☐ Other

Panel: Radio, Millimeter, and Submillimeter Observations from the Ground

Thematic Areas:
☑ Planetary Systems ☑ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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1 Introduction: ALMA Today

The millimeter/submillimeter wavelength regime accounts for the second largest peak in the electromagnetic spectrum of the Universe and is comprised of emission from intrinsically cool objects ($10 - 200$ K), as well as radiation from warmer sources that is absorbed and re-radiated. Thus, observations in this wavelength regime are critical to the understanding of our cosmic origins. As early as 1980, building on the unparalleled success of the Very Large Array interferometer in providing high angular resolution in the centimeter-wavelength regime to address broad scientific topics, it was becoming clear that a complementary millimeter/submillimeter interferometric array could address key questions in modern astrophysics from the origins of stars and planets to galaxy evolution. The Atacama Large Millimeter/submillimeter Array (ALMA) project was first conceived as smaller individual millimeter array projects (the Millimeter Array of the United States, the Large Southern Array of Europe, and the Large Millimeter Array of Japan) by what would eventually become the primary ALMA partners in the mid-80s to mid-90s. However, by 1997 it was clear that a truly transformational instrument could only be realized through a world-wide partnership. After two decades of design and development, ALMA began early science operations in 2011, with full science operations commencing in late-2013. Today, ALMA is a partnership of ESO, NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile – 22 countries in total, while the Joint ALMA Observatory is operated by AUI/NRAO, ESO and NAOJ, the three ALMA executives.

Located at 5000m elevation in the Atacama Desert of northern Chile (one of the driest sites on Earth), ALMA is comprised an array of precision antennas in order to provide high fidelity images at (sub)millimeter wavelengths across a broad range of angular scales (Wootten & Thompson, 2009). A 50-element main array of 12 m antennas operates in configurations ranging from 150 m to 16 km in extent, while a compact array of twelve 7 m antennas plus four additional 12 m antennas (total power array) provide short spacings for projects on the main array, as well as standalone studies. ALMA's broad frequency range required the construction of multiple bands of cryogenic receivers (currently 8 bands covering 84-950 GHz, or 3.6-0.3 mm), with each band individually upgradeable. As a result of its large collecting area ($>$6600 m^2) and instantaneous spectral bandwidth (8 GHz in dual polarization), ALMA provides astronomers with vastly improved spectroscopic sensitivity over previous (sub)millimeter telescopes. The transformative nature of ALMA is evidenced by the 1434 refereed publications produced in less than a decade of operation, on diverse topics ranging from high resolution imaging of objects in our own Solar System to detections of gas and dust in galaxies near the dawn of time. At the last proposal call (Cycle 7), ALMA received 1785 proposals from astronomers all over the world, for an over-demand of nearly 5 times for the 50-element main array. It is also notable that $\sim 30\%$ of the Astro2020 science white papers mention ALMA. ALMA has been a resounding success by any measure (also see Figs. 1-4).

ALMA's design was governed by the three "Level-One" science goals described below. All of these goals have now essentially been met as demonstrated by Figures 1-3.

(1) Detect Gas in Distant Galaxies: The ability to detect spectral line emission from CO or [CII] in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours of observation. N.B. This goal has been achieved in spirit, though not in detail – indeed, a major achievement of modern astrophysics is the realization that 'Milky-way'-like galaxies do not exist at z=3.

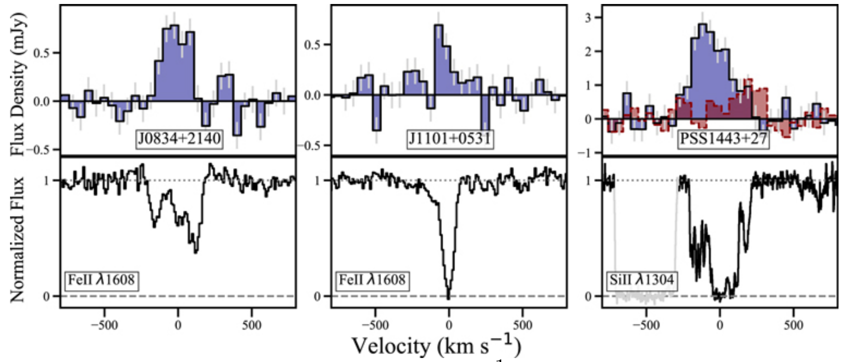

Figure 1: *ALMA [CII] spectra of three damped Lyα absorber galaxies at $z \sim 4$ are shown in the top panels from Neeleman et al. (2019, the bottom panels show metal absorption lines for comparison). The luminosities of these galaxies are (0.36-30)$\times$ 10^8 $L_\odot$ and the star formation rates are 7-110 $M_\odot$ yr^{-1}.*

(2) **Image Protoplanetary Disk Structure and Kinematics:** The ability to image the gas kinematics in a solar-mass protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal structures created by planets undergoing formation.

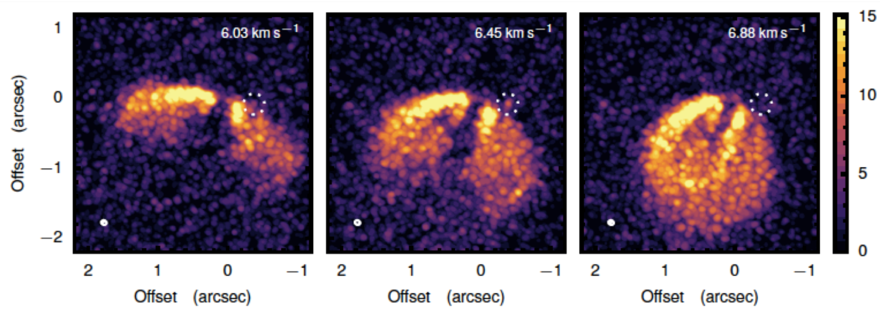

Figure 2: *ALMA ^{13}CO(3-2) images revealing the kinematics of the protoplanetary disk PDS 70 (d=113.4 pc), which harbors a planet imaged in the near-IR (PDS 70b) (Keppler et al., 2019). In addition to detecting gaps in the dust and gas emission at the location of PDS 70b, these data also reveal the presence of a weak point source that deviates from Keplerian rotation that may represent another planet.*

(3) **Provide Precision Images:** The ability to provide precise images at an angular resolution of $0.1''$.

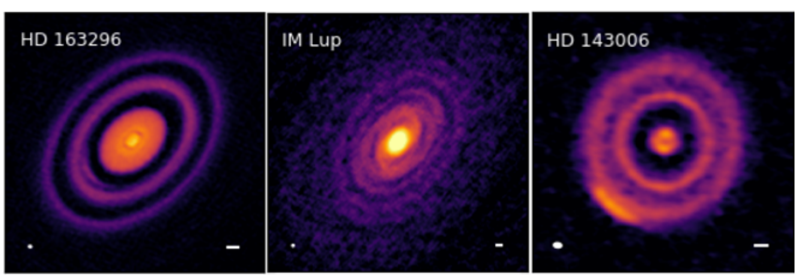

Figure 3: *Stunning ALMA 0.87 mm dust continuum images at 35 mas (5 au) angular resolution of protoplanetary disks from the Cycle 4 large program DSHARP (Andrews et al., 2018). The DSHARP disks are at distances of 100-160 pc.*

The purpose of this white paper is to describe a vision for ALMA in the 2030s that continues to deliver on the scientific promise of this remarkable instrument. We hope this information will both inform the 2020 Decadal Survey of the goals that we are working towards in the next decade, and as a preview of future efforts that will be required to make the next giant leaps in the study of our cosmic origins. First, we briefly describe the ALMA development program, then present the ALMA Development Roadmap outlining ALMA's new ambitious science goals for the next decade along with the development activities that will begin to enable them. Finally, we describe the longer-term priorities for ALMA to fully realize its potential in the 2030s. This submission seeks support for continued investment in ALMA's future.

2 The ALMA Development Program

One of the key innovative aspects of the ALMA operations plan is that a vigorous development program should be included in Observatory operations funding from the beginning, in order to keep ALMA, envisioned as a 30-yr+ endeavor, at the forefront of scientific discovery over the long-term. The primary tenets of the ALMA development program are that it will (1) be driven by scientific requirements as identified by the community, embodied in the ALMA Science Advisory Committee (ASAC), and supported by independent peer-review; (2) be comprised of both short-term *development studies* to facilitate technology readiness/proof of concept for subsequent longer-term *development projects*; and (3) require development projects to undergo rigorous technical and scientific design review and approval from the ALMA Board (which includes representatives from the executives and funding agencies, advised by ASAC). The initial priorities of the ALMA development program were clear: to complete the original ALMA design capabilities for those items that had to be de-scoped during the baseline construction project due to cost constraints.

Calls for studies and/or projects have been issued approximately yearly to the ALMA/NA partnership. Since 2011, twenty-nine study proposals and eleven project proposals from investigators within the ALMA/NA community have been funded (see reports from NA partnership community activities at ALMA/NA Development Reports). These community-based NA-funded studies and projects provide critical avenues for innovation, collaboration, training, and investment for NA universities and research groups. To date, the international ALMA Development Program has delivered a wide range of new ALMA science capabilities including Solar observing (Loukitcheva, 2019), Band 5 receivers (165-211 GHz; Belitsky et al., 2018), and Very Long Baseline Interferometry (VLBI) via the ALMA Phasing Project in collaboration with the Event Horizon Telescope (Event Horizon Telescope Collaboration et al., 2019). A few of the remarkable science discoveries enabled by these development projects are shown in Figure 4. Community-based ALMA studies and projects have also delivered a broad-range of new data analysis tools, for example the NA-led ALMA Data Mining Toolkit (ADMIT; Teuben et al., 2015) and the Total Power to Visibilities software for data combination (TP2VIS; Koda et al., 2019).

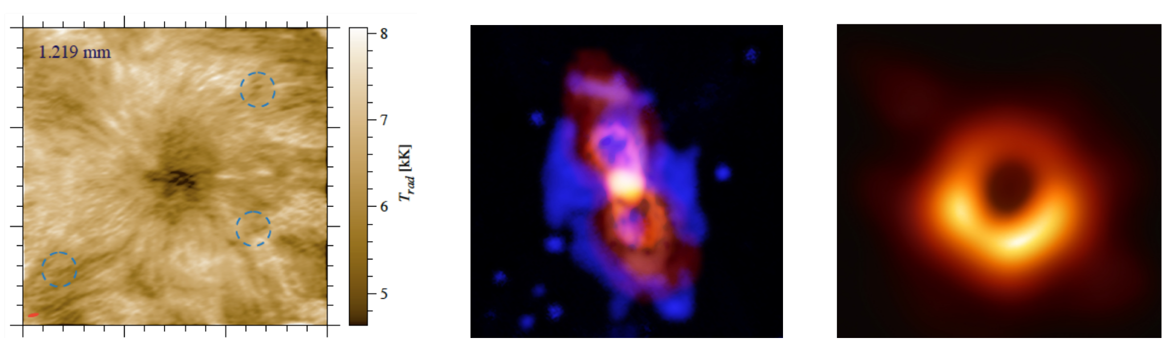

Figure 4: **Left:** *ALMA 1.2 mm brightness temperature image of a sunspot (Jafarzadeh et al., 2019).* **Middle:** *Composite image of CK Vulpeculae, the remains of a double-star collision imaged at Band 5: red=aluminum monofloride (main isotope ^{27}AlF), blue=1.5 mm dust continuum (Kamiński et al., 2018, image credit: ALMA (ESO/NAOJ/NRAO), T. Kamiński; Gemini, NOAO/AURA/NSF, B. Saxton).* **Right:** *Image of the event horizon of the black hole at the center of the M87 galaxy (Event Horizon Telescope Collaboration et al., 2019).*

3 The ALMA Development Roadmap

By 2015, the steady progress of the ALMA Development Program along the path to restoring capabilities descoped from the original design encouraged the international ALMA community to consider longer term goals and to identify the key upgrades that would sustain its scientific productivity into the 2030s and beyond. The recommendations of the ASAC were summarized in a series of studies known collectively as the *ALMA2030 Report* (Bolatto et al., 2015). The *ALMA2030 Report* includes studies of which receiver bands should be upgraded based on expected scientific impact, as well as input on the scientific value of expanding to longer baselines and attacking new ambitious top-level science goals (§3.1). Guidance for these studies arose from materials developed, in part, by the ALMA development program, which has funded studies and projects that have examined possible upgrades to receivers, correlators, extended baselines, and the archive. These studies were complemented by regional development workshops and summary discussions at major ALMA meetings.

Subsequently, the ALMA Development Working Group, comprised of members of the ASAC, regional ALMA program scientists, and Executives, was established to hone the recommendations into a plan which has recently culminated in the *ALMA Development Roadmap* (Carpenter et al., 2019, also see the summary booklet[1]). The final prioritization and recommendations were split into two categories: (1) near- to mid-term goals for the next decade that are near-technology readiness (§3.2); and (2) longer term goals for the 2030s that are required to fully attain the new science goals but still need significant research and development (§3.3). Provided that the ALMA executives continue to see stable funding levels for ALMA that support the Development Program, it is envisioned that the near- to mid-term developments can occur in a staged fashion throughout the next decade within the budget of the current Development Program. In contrast, the more ambitious 2030 development priorities will require additional investment.

Implementation of the ALMA 2030 vision is critical to continue the essential multi-wavelength synergy of ALMA with other new and planned large facilities in space: the *James Webb Space Telescope (JWST), Wide Field Infrared Survey Telescope (WFIRST), the Large UV Optical Infrared Surveyor (LUVOIR), Lynx X-ray Observatory, Habitable Exoplanet Survey (HabEx), Origins Space Telescope (OST)*, and on the ground: the Large Synoptic Survey Telescope (LSST), the US Extremely Large Telescope (ELT) Program, the Next Generation Very Large Array (ngVLA), and the Square Kilometer Array (SKA).

3.1 New Ambitious Key Science Drivers for the Next Decade

As outlined in the *The ALMA Development Roadmap* (Carpenter et al., 2019) the new primary ALMA science drivers for the next decade are described below. Since they were developed by the astronomical community, these new science goals are naturally extensively represented in the Astro2020 science white papers (SWPs). For each new ALMA goal, we first list key supporting Astro2020 SWPs by number and first author, followed by the new capabilities that will be needed in the coming decades to accomplish these science goals. In what follows, "spectral grasp" is shorthand for the ability to tune to a wide range of diagnostic spectral lines within a single receiver band in a single observation, while "spectral range" indicates the need to access the full (sub)millimeter

[1] https://www.almaobservatory.org/en/publications/the-alma-development-roadmap/

frequency range visible from the ground, such as to accommodate a particular source's redshifted spectral emission or the rest frequency of a unique diagnostic line transition.

(1) Origins of Galaxies: Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2-4) by imaging their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.

Astro2020 SWPs: 52, 236, 248, 308, 419, 444, 446, 488, 608
(Carilli et al., 2019; Casey et al., 2019; Pineda et al., 2019; Mantz et al., 2019; Clark et al., 2019; Smith et al., 2019; Kohno et al., 2019; Walter et al., 2019; Geach et al., 2019)

+ Spectral line sensitivity

+ Spectral grasp

+ Spectral range

+ Continuum sensitivity

(2) Origins of Chemical Complexity: Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (∼10-100 au) by performing full scans of a whole frequency band at a rate of 2-4 protostars per day.
Astro2020 SWPs: 95, 186, 210, 254, 258, 259, 262, 417, 433, 473
(Cleeves et al., 2019; Öberg et al., 2019; Savin et al., 2019; Pontoppidan et al., 2019; McGuire, 2019a,b,c; Heiles et al., 2019; Matra et al., 2019; Remijan, 2019)

+ Spectral line sensitivity

+ Spectral grasp

+ Spectral range

+ Increased angular resolution

(3) Origins of Planets: Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (∼1 au) in the dust continuum at wavelengths shorter than 1 mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.
Astro2020 SWPs: 95, 145, 186, 195, 270, 273, 386, 464, 491, 550
(Cleeves et al., 2019; Lyra et al., 2019; Öberg et al., 2019; Isella et al., 2019; Sheehan et al., 2019; Stephens et al., 2019; Jang-Condell et al., 2019; Su et al., 2019; Weinberger et al., 2019; Monnier et al., 2019)

+ Continuum sensitivity

+ Increased angular resolution

These ambitious goals, while far reaching from a science perspective, are unified by a relatively small number of required upgrades: spectral line and continuum sensitivity, increased spectral grasp and spectral range, and enhanced angular resolution. As proven by the original Level One science goals, the *capabilities* driven by these goals will enable a vast range of new discovery space beyond these specific goals. The science white papers listed above, and many others on diverse science topics, also exemplify ALMA's unique synergy with other new and planned facilities.

3.2 Near to Mid-term Development Priorities (the 2020s)

In order to achieve the new science goals listed in §3.1, the ALMA Roadmap places top near- to mid-term development priority on expansion of the bandwidth of the receivers and digital processing system, which includes the correlator. The current ALMA system is limited to 16 GHz of instantaneous bandwidth (8 GHz per polarization). However, the 8 GHz instantaneous frequency coverage per polarization covers a small fraction of the available atmospheric windows. Therefore, blind redshift programs and astrochemical surveys currently need multiple tunings to cover an appreciable range of redshifts or to obtain a basic chemical inventory. Because the new science goals require these observing modes, an expansion of throughput by a factor of at least two is needed to achieve them, as it will reduce the time to conduct such spectral surveys by at least a factor of two, reaching even higher factors (8-16) for high spectral-resolution spectral scans. Wider throughput also increases the ability to observe critical molecular transitions simultaneously, promotes spectral serendipity, and improves the continuum sensitivity, which is particularly useful at high spatial resolution where calibration can be challenging. Thus, the scientific thrust of bandwidth expansion will offer broader benefits, including an improved understanding of protoplanetary disks, galaxy assembly, and chemistry of star-forming regions. Besides a bandwidth increase, all science goals will further benefit from improvements in receiver performance and in digital processing efficiency. A new international working group – the ALMA Front-end & Digitizer Specification Upgrade Working Group – was recently convened to explore the current state of the art in bandwidth and performance of receiver and digital processing systems in order to set new system specifications that are ambitious but feasible on the 2030 timescale. For example, improvements to the receiver performance are possible in many of the ALMA bands (see Figure 5). One key component needed is an upgrade of the efficiency and processing power of the current ALMA correlator.

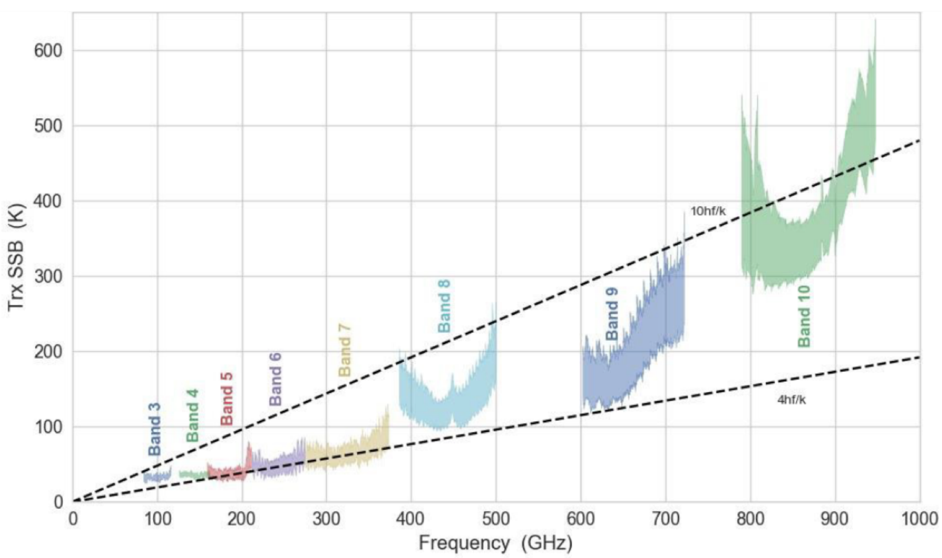

Figure 5: *Current ALMA receiver temperature T_{rx} (i.e. sensitivity, single sideband) vs. sky frequency, colored by band. The two dashed lines indicate 4× and 10× the quantum limit.* **Improvements are possible in the bands that have T_{rx} above the lower line.**

3.2.1 ALMA Correlator Upgrade Project (CUP)

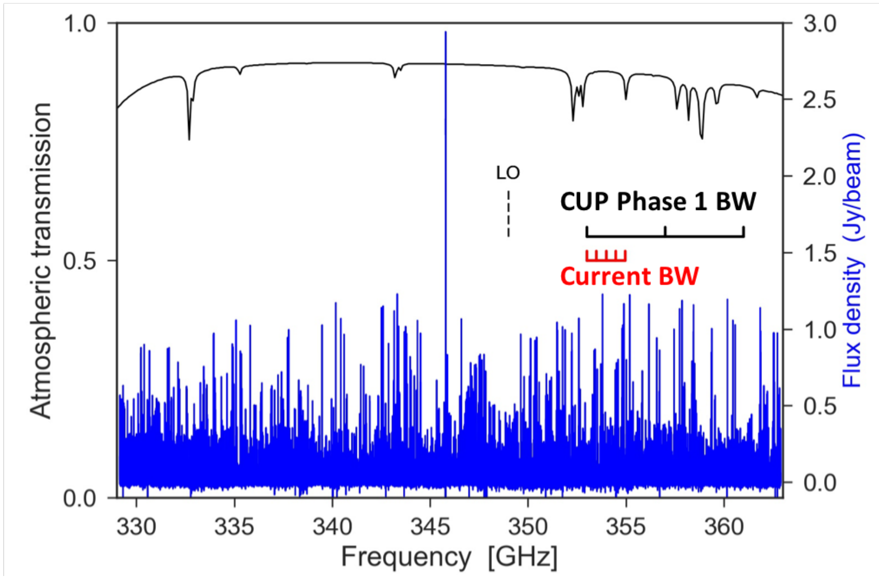

Figure 6: *ALMA Band 7 spectral scan of the complex molecular emission toward protostar IRAS 16293 with 0.2 $\mathrm{km\,s^{-1}}$ velocity resolution (Jørgensen et al., 2016). The red line ('Current BW') shows the bandwidth available per tuning for these observations, while the black line ('CUP Phase 1 BW') shows the 8x larger usable bandwidth after CUP Phase 1; allowing such a spectral scan to be observed in half the time.*

A correlator upgrade is under development. It will enlarge the number of channels and increase the resolution by 8x, while also improving spectral sensitivity by employing more bits, providing the equivalent of adding 6 antennas to a 48-antenna array. When complemented with an upgraded digitization and frequency distribution system, now under study, the correlation capacity may be doubled to 16 GHz per polarization in a subsequent upgrade. Some ALMA receivers present more bandwidth to the correlator than it can currently process; the workhorse Band 6 receiver (211-275 GHz) provides 11 GHz of spectral bandpass per polarization, though only 8 GHz of that can be processed until the current correlator upgrade is complete.

3.2.2 ALMA Band 1 Receiver

ALMA Band 1 covers 35-50 GHz with 8 GHz of instantaneous bandwidth and is currently under construction, with the goal of being available for science observations in the first part of the next decade (Huang, 2019). Di Francesco et al. (2009) provides an overview of the many areas of science that this band can uniquely address, including the primary Band 1 science goals:

- Detail the evolution of grains in protoplanetary disks by following the transition of dust grains from mm-size to cm-size pebbles in protoplanetary disks (Origins of Planets)
- Characterize molecular gas in high-redshift galaxies through detection and imaging of low-J rotational transitions of CO (from J=1-0 to J=6-5), including detection of CO J=3-2 at the epoch of reionization (z$\sim$6-9) (Origins of Galaxies)

3.2.3 ALMA Band 2 Receiver

The Band 2 (67-90 GHz) prototype provides two broad sidebands over an expanded frequency range of 67-116 GHz (Yagoubov et al., 2018), with each sideband offering an instantaneous bandwidth of at least 12 GHz. When deployed, this receiver will fulfill the complement of receiver bands in the original ALMA design and provides another step toward the near-term goal of doubling ALMA's bandwidth. There are several primary science goals for the Band 2 receiver including:

- With its wide spectral grasp, Band 2 will improve the efficiency of high-redshift and other spectral surveys, which will be especially important for studying the Origins of Galaxies.

- The Origin of Chemical Complexity can be explored by probing widely spaced molecular transitions of what are thought to be the building blocks of life. Observations with this receiver can probe all four main carbon and oxygen isotopologues of CO in one wideband spectral setup covering 109.5 to 115.3 GHz. Additionally, molecules that have a high critical density are less susceptible to freeze-out in protoplanetary disks and may be simultaneously investigated in Band 2. Such molecules include HCO+, HCN, HNC, and N_2H^+ and their deuterated isotopologues (DCO^+, DCN, DNC, and N_2D^+) (e.g. Öberg et al., 2019). Furthermore, studies of deuterated molecules provide observational probes of star-forming material, tests of ion-molecule chemistry, and tracers of Big Bang nucleosynthesis (Wilson 1999).

3.2.4 Technical Studies Underway

In order to increase the system bandwidth of ALMA, the throughput upstream of the correlator must also be expanded. An ALMA Study now in advanced stages will present an analysis and trade-off study of an ALMA Digital Front-End system, which includes the digitizers and digital processing in the ALMA receiver cabin, and the digital transport system between the antennas and the centrally located correlator (Baryshev, 2019; Baudry, 2019; Quertier, 2019).

A number of studies are also currently underway to improve the performance of ALMA Bands 3, 6, 7, and 9 (see Fig. 5). At NRAO, we are focused on upgrading Band 6 (211 to 275 GHz). Band 6 is the most heavily sought of the eight operating bands on ALMA. While the performance of the Band 6 receivers is generally superb, there are now several possible improvements which would increase the sensitivity and bandwidth in that band (Mangum, 2019). Flattening the receiver noise to a value of $\sim$40 K across the receiver band will improve the sensitivity by more than a factor of two for projects targeting widely-separated line frequencies and their accompanying continuum emission. Science goals which will be realized by this upgrade include:

- Origins of Planets, via simultaneous and sensitive measurements of isotopic ^{12}CO, ^{13}CO, and $C^{18}O$ in circumstellar disks, and

- Origins of Galaxies, via high redshift studies of [CII], CO, and other species

3.2.5 Software and User Support Activities Underway

A number of activities are also being pursued to improve and extend data reduction capabilities, data analysis, and the archival research experience. For example an NA-funded study is doing algorithm development to permit full primary-beam polarization mapping (mosaicing; Bhatnagar et al., in prep.), while the ESO-led *Additional Representative Images for Legacy* project (ARI-L; Massardi, 2019) will utilize the ALMA pipeline to image and archive ALMA data prior to when the imaging pipeline was available (mid-Cycle 4). NRAO has also launched the Science Ready Data Products initiative designed to improve the user experience for radio interferometry data by providing science quality data, as well as tools for data processing and discovery through an updated archive interface (see NRAO APC WP, Beasley et al.).

3.3 ALMA in the 2030s: Longer Term Goals

To fully realize the new ALMA science goals (§3.1) there are two challenging top priority requirements: (1) extend the maximum ALMA baseline length (and hence improve the angular resolution) by 2-3 times; and (2) increase the collecting area by at least a factor of 3. **Together with the advances afforded by the near- to mid-term goals, these improvements will result in a factor of 10x and 6x increase in continuum and spectral line sensitivity, respectively.** These two capabilities are coupled: with 50 12m-antennas the surface brightness sensitivity of ALMA is already quite limiting for the longest baseline configurations, restricting current studies to only the brightest continuum and spectral line sources at the highest angular resolutions. Thus, only increasing the baseline lengths will not suffice – breaking new science frontiers in the (sub)millimeter at high angular resolution will only be possible if additional collecting area is also added, especially for spectral line studies. For example, while the DSHARP ALMA images of 20 protoplanetary disks (Fig. 3) are extraordinary, these disks lie at distances $< 160\,\mathrm{pc}$ and sample a small fraction of star forming environments. As described in Cleeves et al. (2019), extending the scope of this research to a more representative sample, and hence larger distances is critical to both the Origins of Chemical Complexity and the Origins of Planets, but requires greater resolution and sensitivity.

A promising study for the first step in doubling the baseline lengths is already underway (Phillips, 2019) that investigates the addition of five new more distant antenna locations that still lie within the Chajnantor Science Preserve. A simulation of what might be possible with this extension *for very bright continuum objects* and long integrations for uv-coverage is shown in Figure 7.

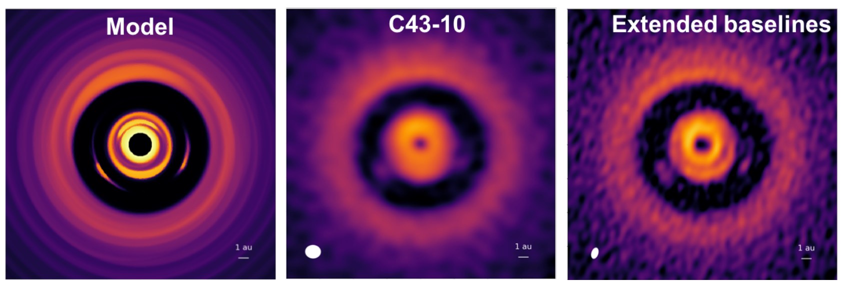

Figure 7: **Left:** *Model of Jupiter-mass planet orbiting at 5 au in an evolved disk analogous to TW Hya (d=50 pc) at 0.87 mm.* **Middle and Right:** *Simulation observed for 8-hrs with the current longest baseline configuration and with the Phillips (2019) extended configuration. The dust traps induced by the planet are considerably more apparent at the higher angular resolution (courtesy L. Ricci).*

Achieving high fidelity images at higher angular resolution for weaker thermal continuum sources, and almost any thermal line emission, will require additional collecting area. The original 12 m ALMA antennas were expensive, more than $10M per antenna fully outfitted, due to the need to be quite rigid to support precise observations at the highest frequencies of ALMA. Furthermore, this cost was during an era in which steel and carbon fiber were more affordable compared to today. Substantially increasing the collecting area of ALMA will require new design concepts and approaches to operations. This will include significant research and development to design a new, more affordable antenna that can operate up to at least 370 GHz with good surface and pointing performance (at minimum commensurate with current specifications). It may also be necessary to leave the new collecting area in fixed locations to reduce operations cost. In the next decade we will be working to move these two longer term development priorities into concrete designs that can be presented to the Astro2030 decadal survey. In this endeavor, we will be able to leverage a wide range of activities that are underway in the current decade including the ngVLA (see Murphy et al. APC WP), which must overcome similar issues, albeit with somewhat less restrictive antenna performance requirements. In the 2030s ALMA will also be able to take advantage of algorithm development that will enable efficient processing of data from large numbers of antennas from projects like the ngVLA and SKA.

Additional long-term goals focus on increasing the mapping speed by implementing: (3) focal-plane arrays in one (or more) strategically chosen receiver bands (Knee, 2019); and (4) a 25 m-class single dish (sub)millimeter antenna (see AtLast APC WP, Klassen et al.). By the mid-2030s, it is likely that many of the current (sub)millimeter single-dish and small antenna-size interferometers will be decommissioned (a trend that is already well underway in the US, but see Large Millimeter Telescope, APC WP, Schloerb et al.). **Without investment in the capabilities to study larger-scale emission in our Universe, our understanding of star and galaxy formation and evolution will be severely hampered.**

4 Summary and Conclusions

In the less than ten years since the first science observations on ALMA, the original "Level One" science goals have been largely met. A major reason for the success of ALMA has been the commitment by the ALMA partners to a robust and ongoing Development Program that sustains the investment and allows the observatory to advance along with science and technology. To date, the ALMA Development Program has allowed the observatory to complete nearly all the capabilities descoped from the original ALMA reference plan during the construction project for budgetary reasons. In addition, the Development Program has provided numerous capability enhancements to ALMA, including a phasing system essential for the recent Event Horizon Telescope black-hole imaging project, and additional value-added tools for users to promote archival research and image analysis, among several others.

For the next decade, ALMA has defined an ambitious 2030 Development Roadmap based on new, key science drivers: Origins of Galaxies, Origins of Chemical Complexity, and Origins of Planets. The technology priorities to achieve this plan to at least double the processing bandwidth of ALMA, which requires upgrades to receivers, the digital system, and the correlator. The plan also calls for studies for longer-term initiatives planned for future decades. The first steps in this plan are already underway, including receiver and correlator upgrades and specification studies for the digital processing system. The bandwidth expansion and study programs for the longer-term initiatives may be accommodated within the projected Development Program funding profile over the next decade.

Beyond 2030, a significant upgrade to ALMA is envisioned that would result in a factor of 2-3 improvement in angular resolution, a factor of 10 improvement in continuum sensitivity, and a factor of 6 improvement in spectral sensitivity. A capability enhancement of this order would allow breakthroughs in numerous areas including the kinematic detection of forming planets in a large sample of protostellar disk systems. A practical implementation of the expansion in collecting area necessary for this increase will require significant research and development into affordable antenna designs, and new approaches to operation. These efforts will have much synergy with the ngVLA project. Other long-term goals include increases in imaging speed through focal plane arrays and the inclusion of a large single dish as part of the array. Investigations for these longer-term efforts will be undertaken in the coming decade, with a design proposal anticipated at the Astro2030 decadal survey.

References

Andrews, S. M., Huang, J., Pérez, L. M., et al. 2018, ApJL, 869, L41, link
Baryshev, A. 2019, ALMA Development Workshop, 5, link
Baudry, A. 2019, ALMA Development Workshop, 6, link
Belitsky, V., Bylund, M., Desmaris, V., et al. 2018, A&A, 611, A98, link
Bolatto, A.D., Carpenter, J., Casassus, S., Iono, D., Ivison, R., Johnson, K., et al. 2015, ALMA2030 Report, link
Brogan, C. 2019, ALMA Development Workshop, 11, link
Carilli, C., Casey, C., Narayanan, D., et al. 2019, Astro2020 White Paper 52, BAAS, 51, 41, link
Carpenter, J., Iono, D., Testi, L., et al. 2019, ALMA Memo 612, arXiv:1902.02856
Casey, C., Capak, P., Staguhn, J., et al. 2019, Astro2020 White Paper 236, BAAS, 51, 212, link
Clark, C., Bianchi, S., Bot, C., et al. 2019, Astro2020 White Paper 419, BAAS, 51, 378, link
Cleeves, I., Loomis, R., Teague, R., et al. 2019, Astro2020 White Paper 95, BAAS, 51, 81, link
Di Francesco, J., Johnstone, D., Matthews, B., et al. 2009, arXiv e-prints, arXiv:0910.1609
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019, ApJL, 875, L1, link
Geach, J., Banerji, M., Bertoldi, F., et al. 2019, Astro2020 White Paper 608, BAAS, 51, 549, link
Heiles, C., Araya, E. D., Arce, H., et al. 2019, Astro2020 White Paper 417, BAAS, 51, 376, link
Huang, Y. D. 2019, ALMA Development Workshop, 23, link
Isella, A., Ricci, L., Andrews, S., et al. 2019, Astro2020 White Paper 195, BAAS, 51, 174, link
Jafarzadeh, S., Wedemeyer, S., Szydlarski, M., et al. 2019, A&A, 622, A150
Jang-Condell, H., Brittain, S., Weinberger, A., et al. 2019, Astro2020 White Paper 386, BAAS, 51, 346, link
Jørgensen, J. K., van der Wiel, M. H. D., Coutens, A., et al. 2016, A&A, 595, A117
Kamiński, T., Tylenda, R., Menten, K. M., et al. 2018, Nature Astronomy, 2, 778
Keppler, M., Teague, R., Bae, J., et al. 2019, A&A, 625, A118
Knee, L. 2019, ALMA Development Workshop, 28, link
Koda, J., Teuben, P., Sawada, T., et al. 2019, PASP, 131, 054505
Kohno, K., Tamura, Y., Inoue, A., et al. 2019, Astro2020 White Paper 446, link
Loukitcheva, M. 2019, Advances in Space Research, 63, 1396
Lyra, W., Haworth, T., Bitsch, B., et al. 2019, Astro2020 White Paper 145, BAAS, 51, 129, link
Mangum, J. 2019, ALMA Development Workshop, 31, link
Mantz, A., Allen, S. W., Battaglia, N., et al. 2019, Astro2020 White Paper 308, BAAS, 51, 279, link
Massardi, M. 2019, ALMA Development Workshop, 33, link
Matra, L., Kral, Q., Su, K., et al. 2019, Astro2020 White Paper 433, BAAS, 51, 391, link
McGuire, B. 2019a, Astro2020 White Paper 258, BAAS, 51, 233 link
McGuire, B. 2019b, Astro2020 White Paper 259, BAAS, 51, 234, link
McGuire, B. 2019c, Astro2020 White Paper 262, BAAS, 51, 236 link
Molter, E. M., de Pater, I., Roman, M. T., et al. 2019, arXiv e-prints, arXiv:1905.12566
Monnier, J., Rau, G., Bermudez, J. S., et al. 2019, Astro2020 White Paper 550, BAAS, 51, 498, link
Neeleman, M., Kanekar, N., Prochaska, J. X., Rafelski, M. A., & Carilli, C. L. 2019, ApJL, 870, L19
Öberg, K., Bergin, E., Andrews, S., et al. 2019, Astro2020 White Paper 186, BAAS, 51, 165, link

Phillips, N. 2019, ALMA Development Workshop, 38, link
Pineda, J. L., Goldsmith, P. F., & Langer, W. D. 2019, Astro2020 White Paper 248, BAAS, 51, 223, link
Pontoppidan, K., Banzatti, A., Bergin, E., et al. 2019, Astro2020 White Paper 254, BAAS, 51, 229, link
Quertier, B. 2019, ALMA Development Workshop, 39, link
Remijan, A. 2019, Astro2020 White Paper 473, BAAS, 51, 428, link
Savin, D. W., Babb, J. F., Bellan, P. M., et al. 2019, Astro2020 White Paper 210, BAAS, 51, 96, link
Shan, W. 2019, ALMA Development Workshop, 42, link
Sheehan, P., Tobin, J., Stephens, I., et al. 2019, Astro2020 White Paper 270, BAAS, 51, 244, link
Smith, J. D., Armus, L., Davé, R., et al. 2019, Astro2020 White Paper 444, BAAS, 51, 400, link
Stephens, I., Li, Z.-Y., Yang, H., et al. 2019, Astro2020 White Paper 273, BAAS, 51, 246, link
Su, K., Ballering, N., Ertel, S., et al. 2019, Astro2020 White Paper 464, BAAS, 51, 419, link
Teuben, P., Pound, M., Mundy, L., et al. 2015, Astronomical Data Analysis Software an Systems XXIV (ADASS XXIV), 305
Walter, F., Carilli, C., Decarli, R., et al. 2019, Astro2020 White Paper 488, BAAS, 51, 442, link
Weinberger, A., Turner, N., & Hasegawa, Y. 2019, Astro2020 White Paper 491, BAAS, 51, 445, link
Wootten, A., & Thompson, A. R. 2009, IEEE Proceedings, 97, 1463
Yagoubov, P., Mroczkowski, T., Testi, L., et al. 2018, arXiv e-prints, arXiv:1812.03575