Major Science Themes in the 2020-2030 Decade

Executive Summary

ALMA was designed to address many science questions in the broad area sometimes bundled under the umbrella question: “How does the Universe work?” This includes areas in which the submillimetre band has traditionally advanced knowledge, such as the physics and chemistry of the ISM, the formation of stars and disks, the structure and evolution of galaxies and AGN. ALMA also has the potential to contribute to the highest profile areas of astrophysics, namely the search for life elsewhere, and placing constraints on fundamental physics.

Introduction

The purpose of this document is to serve as a reference for future discussions of science priorities for the ALMA Development Plan. We examine the outstanding science questions in a number of sub-fields, and consider the landscape of likely advances from other observatories in the near future. The potential contribution of ALMA to each of these science areas is laid out. The emphasis is on the science questions to be addressed, rather than the details of how data can be utilized to answer those questions, i.e. there is no discussion of data volumes or visualization/analytic tools to use to answer the questions.

[The primary audience for this document is a set of future ALMA bodies faced with ranking options, in which science prioritization plays a role. However, it is expected that the document may be read more widely.]

There can be little doubt that two areas of modern astrophysics grab the most headlines: studies of extrasolar planetary systems, leading towards the goal of searching for signs of life elsewhere; and investigation of fundamental physics using astrophysics in order to understand the composition and origin of the Universe. ALMA can contribute to both of these areas.

However, a third research area is also highlighted in most planning exercises (see Appendix A), namely “How does the Universe work?” This is the “bread and butter” of a very large fraction of ALMA observations, directed towards understand the life cycles of stars, the evolution of galaxies and the relationship between stars and disks and between galaxies and black holes.

These research areas are directly linked to the “level one science goals” that motivated the construction of ALMA in the first place, namely:

- the ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation;
- the ability to image the gas kinematics in a solar-mass protostellar/ 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 gaps created by planets undergoing formation;
- the ability to provide precise images at an angular resolution of 0.1″.

ALMA’s range of capabilities enables it to contribute to a wide range of the astronomical sub-fields within the general “how does the Universe work?” unifying theme.
We discuss each of these areas below, within separate sections in which are described: (1) outstanding science questions or goals; and (2) how ALMA can contribute. We divide astrophysics topics into the following areas, stepping generally from the largest scales of the universe down to the smallest ones:

- Cosmology
- High redshift galaxies
- AGN and Black holes
- Nearby galaxies
- Origin of stars and planets
- Astrochemistry and Astrobiology
- Stellar evolution
- Solar System

Cosmology

Outstanding Science Questions/Goals

1. Constrain theories of modified gravity and dark energy, measurement of H(t), w(z), BAO, growth rate, etc.
2. Constrain inhomogeneities as a function of scale and redshift.
3. Measure shift of absorption lines in real time.
5. Probe the re-ionization history of the Universe and find the first objects.
6. Investigate the SZ effect at high resolution in order to understand details of the physics of galaxy clusters.

How ALMA Can Contribute

ALMA can contribute to an improved understanding of Galactic dust polarization to help with foreground removal for detecting CMB primordial B-modes. ALMA's high angular resolution capabilities reveal small-scale CMB anisotropies, and high resolution observations of the SZ effect in clusters can be used to accurate derivations of cosmological parameters.

High redshift galaxies

Outstanding Science Questions/Goals

1. Examine cold gas and dust at high-z without optical/IR detection in proto-galaxies
2. Probe the role of molecules in galaxy evolution (and metallicity evolution) through constraints on cooling and star formation rates.
3. Examine galactic dynamics at high-z.
4. 'See' large scale structure (clusters) in formation between proto-galaxies
5. Quantify obscured star-formation through cosmic time.
6. Determine the progenitors of present day elliptical, red and dead galaxies.
7. Establish the molecular and dust properties of galaxies in the very high redshift Universe (z = 6 and above).
8. Measure the evolution of the galaxy gas fraction through cosmic time

How ALMA Can Contribute

The well-known negative K correction effect at mm/sub-mm wavelengths give this region of the electromagnetic spectrum an advantage to studying objects from the distant universe. Higher survey speeds with ALMA would provide valuable contributions. Spectroscopy provides redshift determination, given a wide enough bandwidth to capture at least two adjacent CO rotational transitions. Therefore fast coverage of large portions of the spectrum is important (large bandwidths, multi-frequency observations) as is high sensitivity receivers. This is particularly true for the higher frequency windows of ALMA, which provide access to FIR fine-structure transitions near the peak of star formation history of the universe. Focal Plane arrays (with good bandwidth per pixel) may be also advantageous for surveys of galaxy clusters or deep fields, but the degree to which this technology helps and the tradeoff between bandwidth and number of pixels depends on the particular shape of the source galaxy counts.

AGN and Black holes

Outstanding Science Questions/Goals

1. What are the size and dynamics of the black hole in our own Galaxy?
2. What are the physical properties of AGNs in the local group, and can they be used to extrapolate to higher redshifts?
3. How do relativistic jets form, and what controls the magnetic activity in the inner regions of the accretion disk?
4. Understand accretion in AGNs, the formation of non-relativistic outflows (BAL winds), extent, geometry, whether they are ubiquitous in all AGNs.
5. Prove black holes and the (non)existence of singularity.

How ALMA Can Contribute

VLBI with ALMA will probe the conditions around the event horizon of the black hole in our Galaxy. This is the equivalent of the study of our Sun to understand stellar physics/evolution. The combination of high angular resolution and spectroscopy with ALMA combine for a powerful probe of the kinematics of circumnuclear regions. The dynamics and physical state of the gas can be probed with a combination of spectral lines tracing different densities. Black hole masses can be measured from ALMA observations of nuclear molecular gas.

Nearby galaxies and the Galaxy

Outstanding Science Questions/Goals

1. What is the physics and chemistry of the lifecycle of baryonic matter in galaxies (including our own)?
2. How do baryons cycle in and out of galaxies, and what do they do while they're there?
3. What is the effect of metallicity on the evolution of early galaxies? Is the mode of star formation the same as on later galaxies?
4. How does large scale feedback occur?
5. What are the gas flows within galaxies?
6. What are the relative roles of star formation and AGN feedback? What is the relative importance of AGN feedback vs. (for example) stellar feedback on its AU/pc/kpc/Mpc scale environment?
7. How do black holes grow, radiate, and influence their surroundings?
8. How do Giant Molecular Clouds form and evolve?
9. What determines the efficiency of the star formation activity across galaxies?

How ALMA Can Contribute

ALMA can contribute to answering these science questions by adding to the detailed inventory of baryons in nearby galaxies: cold gas, dust, molecules (clouds, continuous). In the past, people compartmentalized in wavelength regimes, focusing on a single ISM phase. In the future, simultaneous multiphase and multiscale studies will be the manner in which such questions are addressed. What is necessary is to link the large scales where accretion is happening, with the small and intermediate scales where star formation and feedback occurs. Multi-scale, high angular resolution mapping of entire galaxies (or the MW plane) in spectral line and continuum is needed. The multi-scale approach is key to connect the gas from kpc scales down to Giant Molecular Cloud (~100 pc) scales down to clump (few pc), core (~0.1 pc) and accretion disk (<1000 AU) scales. Full ALMA can do this in relatively small areas in the 12m+ACA+TP mode (which avoids spatial filtering), but large area surveys at < 1” resolution, without spatial filtering and in multiple tracers (of different ionization state, densities, temperatures) would be a task for Focal Plane arrays.

Origin of stars and planets

Outstanding Science Questions/Goals

1. Is the IMF Universal?
2. What is the life cycle of the ISM?
3. What are the properties of disks that form planets?
4. When does planet formation first take place? How is it affected by the transition from proto-planetary disk to debris disk?
5. How do the structure and evolution of debris disks constrain the architectures and evolution of planetary systems at late stages of their formation and beyond?

How ALMA Can Contribute

ALMA can sample many well-studied disks, which will enable the diversity and similarities of disk properties to be explored. Studies which connect the large scales of molecular clouds and star forming regions to the smaller scales of single star+disk/planets systems will follow the flow of mass and energy and enable studies of turbulence. Large fields of view with high spatial resolution and multiple tracers (e.g., lines, dust emission etc.) are necessary. Multi-wavelength coordinated studies including diagnostics of the UV radiation field are important.

ALMA can detect stellar photospheres and track stellar positions with sub-mas accuracy. ALMA should demonstrate its capability to supplement radial velocity characterizations of exoplanets with barycentric motion characterization so that the planetary contingent of e.g. Pollux may be better defined.

Astrochemistry and Astrobiology

Outstanding Science Questions/Goals

1. How do pre-biotic molecules form?
2. When do the first complex organics form in the Early Universe?
3. What is the pathway from complex molecules to life?
4. How do early solar system dynamics shape planetary systems?
5. What is the chemical composition in (exo-)planetary atmospheres?
6. What molecules can be used to trace life in other planets/moons/asteroids?

How ALMA Can Contribute

ALMA enables the detection of complex organic molecules (COMs) with abundance levels down to <10^{-11} or even down to a few 10^{-12}. This applies to both pre-stellar cores and protoplanetary disks. The high angular resolution of ALMA will help protoplanetary disk chemistry studies because cold disks show typical sizes from some tens to hundred of AU (angular scales of <1” at distances of 100-200 pc). For pre-stellar cores, the development of Band 2 would be useful because the beam would match the region where the emission of complex organics (a few 1000 AU at a distance of 100-200 pc) is expected to be found. An increase in the sensitivity of ALMA would allow the detection of the simplest COMs in the Early Universe providing constraints on when COM chemistry becomes active and on how efficient this process is at high redshift. Radio Recombination Lines could be useful as well since they have the potential to probe the densest, and innermost regions of ionized winds.

Stellar evolution

Outstanding Science Questions/Goals

1. What drives stellar mass loss? What is its role in star formation, galactic enrichment, and feedback?
2. What is the contribution of dust from supernovae and evolved stars?
3. How do the extremes of matter constrain fundamental physics?
4. What is the role of binarity in stellar evolution?
5. How do stars interact with their environment?
6. What is the structure of the outer solar atmosphere? How important are shocks and dynamics to maintaining the observed temperature profiles?

How ALMA Can Contribute

ALMA can probe stars at differing evolutionary stages, from those which are forming to those which have already expired. ALMA’s ability to study the Sun and solar-like stars using essentially the same instrumentation makes it unique, and eliminates some of the instrumental issues surrounding solar/stellar studies. ALMA’s studies of the Sun can provide simultaneous constraints on the co-location of cool and hot gas above the visible solar surface. Stellar astrometry can be used for proper motion measurements, important for dynamical constraints on binarity. Line surveys of evolved stars (including the rich molecular diagnostics available in the mm and sub-mm) probe the conditions of mass loss at various stages of stellar evolution. Continuum measurements constrain dust production in different stellar sources. Pulsar observations with ALMA enable the possibility to probe strong gravity and provide tests of fundamental physics. Enabling

VLBI capabilities with ALMA can probe the influence of compact objects on their environments.

Time domain studies are important to several areas of study in stellar evolution, both periodic/stochastically occurring phenomena, and transient/triggered transient objects. Central to this theme is an examination of the time-varying millimeter sky, something probed only cursorily with previous generations of millimeter and sub-millimeter telescopes. This requires transient follow-up capabilities in general, both for something like gamma-ray burst follow-up as well as other transient phenomena. What ALMA needs is fast reaction time and flexible scheduling capabilities. ALMA could be an extremely powerful tool, if it were able to react to science alerts from other facilities (satellite or ground-based), autonomously and on the order of hours.

Solar System

Outstanding Science Questions/Goals

1. Is there life in the Solar System and how do we find it?
2. How did the Solar System form and evolve?
3. How does giant planet composition vary with altitude and latitude?
4. What are the dynamics of planetary and satellite atmospheres?
5. What do the composition of comets reveal about conditions in the primitive solar system?

How ALMA Can Contribute

ALMA's ability to perform high resolution mapping in a number of spectral lines is key to making advances on several of these solar system questions. High resolution spectroscopy elucidates velocity fields, and the abundance of spectral lines present from molecular rotational transitions of these generally cold objects provides a wealth of information about the chemistry of solar system objects. Objects such as comets change in real time, requiring repeat observations, and non-sidereal tracking requirements.

Appendix A: Existing plans

The selected themes for the ESA Cosmic Vision 2015-2025 (http://sci.esa.int/cosmic-vision/38542-esa-br-247-cosmic-vision-space-science-for-europe-2015-2025/) were:
- What are the conditions for planet formation and the emergence of life?
- How does the Solar System work?
- What are the fundamental physical laws of the Universe
- How did the Universe originate and what is it made of?

The 2013 NASA "Astrophysics Roadmap" (http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf) lists three fundamental questions for the science-driven 30-year vision of space astronomy:

- *Are we alone?*
- *How did we get here?*
- *How does the Universe work?*

At the next level of detail in NASA's Roadmap, seven out of nine of the bullets in the report have relevance to ALMA:

- Probe the origin and ultimate fate of the Universe, and determine the forms of matter and energy that govern it, by mapping the growth of cosmic structure through its history.
- Unveil the chaotic flows of superheated gas swirling around black holes that fuel the most powerful engines in the Universe.
- Use telescopes as time machines to map the full history of galaxy formation and assembly, from the birth of the first stars through the turbulent epoch of rapid growth to the galaxies we see today.
- Make star-by-star maps of nearby galaxies across the full range of observed galaxy types to decode their histories and understand how and when they acquired their present-day forms.
- Characterize the evolution of planetary systems like our solar system by understanding the nature of newborn stars, the evolution of disk around protostars, the process of planet formation around them, and the crucial transport of water to inner planets. Study debris disks around main sequence stars to study the evolution of planetary systems in the late stages of their formation and beyond.
- Complete the reconnaissance of planets and planetary systems, including gas giants, rocky planets like Earth and Mars, ocean-covered water worlds, planets close to and far from their parent stars, and even free-floating planets that have been ejected to interstellar space by gravitational interactions with their siblings.
- Directly image the planets around nearby stars and search their atmospheres for signs of habitability, and perhaps even life. (define the signatures for life).

ALMA's grasp of the cosmos extends from the solar system outward, and addresses key themes brought up in the recent planetary decadal survey ("Visions and Voyages";http://www.nap.edu/download.php?record_id=13117). Three cross-cutting themes were identified:

Building new worlds – understanding solar system beginnings
Planetary habitats – searching for the requirements of life
Workings of solar systems – revealing planetary processes through time

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Appendix C: Brainstorming ideas

This is a very valuable list of ideas/questions contributed by several people to this document. Some are developed in the broader topics developed above, some are too specific to be included in those topics, except in the broadest sense. We list them here to preserve these ideas and individual questions.

* What is the astrochemistry of the universe?
    - how/when/where did the cosmos become populated with the heavy elements?
    - what is the pathway from simple molecules to complex molecules?
    - what is the pathway from complex molecules to life (e.g. astrobio, comets?)
    - How dust grains are formed?
    - how can molecular lines be used to constrain the physics of the cosmos?
    - how can the physical environments in the cosmos be used to inform chemical models (metallicity/alpha element dependant chemistry),
* What are the properties of proto solar systems (individual planets)?
* What physical conditions drive the most extreme star formation in the cosmos?
* What regulates star-formation? Is environment important?
* Better tracers of H2 and/or better understanding of the CO X-factor
    - improved tracers of non-molecular, non-ionized gas? ("CO-dark gas")
* Merger sequence (major and minor) over redshift and environment: tracing star formation etc.
* Galaxy centres- AGN fueling, black hole masses (w/ molecular gas at ALMA, stars/ion. gas and masers at other facilities), dusty torii (AGN unification), non-relativistic winds, link to megamasers, geometric distances, cosmology
* How does gas turbulence behave on many scales: Galaxy Disks/Centres, ISM, protoplanetary disks, our own atmosphere? [what questions will we be asking about turbulence in 20 years? Maybe all the same?] - on protoplanetary disks: which part of the disk is actually turbulent? (assuming we will have a good tracer for turbulence by that time). Also a relevant question is, what drives (replenish) turbulence in the ISM?.
    - turbulence in ISM requires large-area, multiscale: multi-beam receivers, OTF maps in the Galaxy
* What does the time-varying millimeter sky look like?
* Molecular outflows (SF or AGN driven, gas entrained or line driven, mass loading, extent, effect on environment). Maser proper motions may be observed in nearby Sf regions.
* Dust: Grain size distribution, grain shapes, different grain species. What effect do

these have on our inferences about mass of clumps? high redshift galaxies? What heats dust in different types of galaxies- star formation, old stars, AGN
* What drives “anomalous microwave emission”? (spinning dust? important at small scales?)
* Gas in galaxies of different types, spiral, starburst, early-type, dwarf - differences and similarities
* Is intra-cluster dust (in galaxy clusters) significant ?
*Biomarkers, is there an specific molecule that we could use to trace life in other planets/moons/asteroids.
*Gas kinematics in galaxies as a mass tracer - Tully Fisher, Dark Matter vs MOND (etc), maximal disks [CO as a high resolution and accessible tracer at all redshifts]
* Can we track infall into Sgr A*, e.g. if a G2-like event happens but *really* happens? What opportunities shouldn’t we miss?
*Exoplanets in evolved stars. There are observations of planets around WD and also around NS, do they form in the PN/SN phase respectively? or are they captured? Observations of a second generation planet formation can open up a whole new window.
* Can ALMA detect globular clusters forming ? Proto globular cluster clouds. There are a few candidates of proto massive clusters in our own Galaxy. But the question here is whether we can really detect and characterize these at cosmological distances.
* We haven’t found yet very young planetary systems - maybe a few? - RV surveys are hard on young stars due to activity (<100Myrs). The number of young stars hosting planets might increase thanks to a future NIR spectrograph (NTT or/and CRIRES+. added in proof :-) the number of transiting planets will increase by a lot thanks to the future missions/facilities. It is not clear the role of ALMA in characterising the planets themselves (not sure about the sensitivity to do direct imaging). For sure their circumstellar environment is of interest.
* Galaxy Clusters - evolution of molecular gas, fueling of stellar mass loss
* What is overall morphology of the magnetic field throughout the ISM? Its relevance for molecular cloud and star formation? How is magnetic flux lost during star formation? Magnetic field relevance to the ubiquitous filaments seen in the ISM? Does magnetic braking solves the star formation angular momentum problem?
Does the magnetic field collimate bipolar outflows from proto-stars?.
How is the magnetic field morphology in accretion disk around supermassive black holes? ALMA will require wide field mapping in full polarisation mode for some of these to happen, as well as very high angular resolution in full pol.
High sensitivity mapping of the CMB polarisation in bicep2 like fields.
Understanding of the sun magnetic field, specially magnetic reconnection in sun spots or/and coronal mass ejections, sun flares.
* Linking dynamics of the outer Solar System with composition and origin of TNOs: How

the primordial TransNeptunian disk formed and evolved to the current day? In particular, how dominant was dynamical instability versus smooth migration in moving Neptune from its formation location? How could the low-inclination/low-eccentricity TNOs population survive the planetary migration?
* Astrometry in the mm regime: relatively unexplored territory
* Study the origin of second generation gas in debris disks, is it related to late stages of planet formation? What about gas in Gyr old systems?
* Can ALMA contribute on the study of the Sun, Sun-Earth connection, climatology in planetary system and finally on global warming
* Mass measurements of multiple Trans-Neptunian systems through mutual orbit determination in order to constrain the origin of TNOs. (need for higher angular resolution ~5 mas, preferentially in band 7, in order to resolve ~25 known binary systems)
* Can ALMA help solving the Li puzzle in K-giant stars?