The Atacama Large Millimetre Array

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1. Introduction

The Atacama Large Millimetre Array (ALMA) is one of the highest priority projects in astronomy today, combining the aspirations of scientists in Europe, the U.S. and elsewhere around the globe. The project has now reached a critical milestone: this is the year when the project officially enters the construction phase. It has already been approved for construction funding by the U.S., and the European decision to approve the construction phase is expected later this year.

ALMA will image the Universe at millimetre and submillimetre wavelengths with unprecedented sensitivity and angular resolution. This frequency range is unique in providing access to the lowest transitions from most simple molecules, and in its sensitivity to the thermal emission from cold gas and dust in the clouds where stars are forming. The expansion of the universe also brings the mid-infrared peak of emission from active star-forming galaxies into this frequency domain for redshifts larger than 3.

Progress in mm receiver performance, which now approaches quantum limits, in fast digital electronics, including photonics techniques, and in antenna design coincide to make possible an order of magnitude jump in project scale for millimetre arrays. The time is ripe for ALMA to be a major step for astronomy, making it possible to study the origins of galaxies, stars, and planets. With a capability of seeing star-forming galaxies across the Universe and star-forming regions across the Galaxy, it will open new horizons in science.

ALMA will be a millimetre/submillimetre counterpart of the VLT and HST, with similar angular resolution and sensitivity but unhindered by dust opacity. It will be the largest ground-based astronomy project after the VLT/VLTI, and, together with the Next Generation Space Telescope (NGST), one of the two major new facilities for world astronomy coming into operation at the end of this decade.

ALMA will be comprised of 64 12-metre diameter antennas of very high precision, with baselines extending up to 12 km. Figure 1 shows an artist's impression of a portion of the array in a compact configuration. The array of antennas will be reconfigurable, giving ALMA a zoom-lens capability. The highest resolution images will come from the most extended configuration, and lower resolution images of high surface brightness sensitivity will be provided by a compact configuration in which all antennas are placed close to each other. The instrument thus combines the imaging clarity of detail provided by a large interferometric array together with the brightness sensitivity of a large single dish. The large number of antennas provides over 2000 independent interferometer baselines, making possible excellent imaging quality with "snapshot" observations of very high fidelity. The receivers will cover the atmospheric windows at wavelengths from 0.3 to 10 millimetres. ALMA will be located on the high-altitude (5000 metre) Llano de

Figure 1. An artist's impression of several of ALMA' s antennas in a compact configuration.

Chajnantor, east of the village of San Pedro de Atacama in northern Chile. This is an exceptional site for millimetre astronomy, possibly unique in the world.

2. Project Development

To make such an ambitious project possible, ALMA has become a joint endeavour involving many nations and scientific institutions, and it is likely that it will become the first global project in ground-based astronomy – an essential development in view of the ever-increasing complexity and cost of front-line astronomical facilities.

For years Europe has had a major involvement in millimetre astronomy, with several of the leading facilities in the world. Many institutions throughout Europe have active research programmes in this field, and several of them have developed technical expertise in this area together with European industry, so it is natural that Europe should be a primary participant in ALMA.

The idea of a large European southern millimetre array (“Large Southern Array”, LSA) has been discussed since 1991, and in 1995 an LSA project collaboration was formally established to explore the possibility in a two-year study which included site surveys in Chile and critical technical studies. A report published in April 1997 concluded this first phase.

An important step was taken in June 1997. A similar project had also been under study in the U.S. since 1984, the “Millimetre Array” (MMA), and an agreement was made to explore the possibility of merging the two projects into one. The basic principle was that of a 50-50 partnership between Europe and the U.S., with joint overall direction. Three aspects were studied in detail – scientific, technical and management – and a feasibility study was published in April 1998.

The framework for the formal European collaboration in Phase 1 of this project (the 3-year design and development phase) was established in December 1998. A European Co-ordination Committee (ECC) was created to direct the European effort, with participation and funding from the European Southern Observatory (ESO), the Centre National de la Recherche Scientifique (CNRS), the Max-Planck-Gesellschaft (MPG), the Netherlands Foundation for Research in Astronomy (NFRA) and Nederlandse Onderzoekschool Voor Astronomie (NOVA), and the United Kingdom Particle Physics and Astronomy Research Council (PPARC). In early 2000 the Swedish Research Council (VR), and the Instituto Geográfico Nacional (IGN) and Ministerio de Ciencia y Tecnología (MCYT) of Spain were added to the European collaboration.

In June 1999 a formal agreement between Europe and the U.S. regarding collaboration on Phase 1 of a bilateral project, now called the Atacama Large Millimetre Array (ALMA), was signed. The U.S. side of the partnership is led by the National Radio Astronomy Observatory (NRAO), operated by Associated Universities, Inc. (AUI) under a co-operative agreement with the National Science Foundation (NSF). Recently, Canada has formally joined the U.S. in the North American collaboration. The overall direction for the project is provided by an ALMA Co-ordination Committee (ACC), which oversees the activities of an ALMA Executive Committee (AEC) and several technical project teams, with advice from international Scientific and Management Advisory Committees.

The design and development Phase 1 of the project is being completed at present, and the construction phase (Phase 2) is scheduled to begin, pending final decisions, with completion foreseen in 2011. The total estimated cost for Phase 2 of the bilateral project is 552 million (year 2000 US$), to be shared equally between Europe and North America.

Japan has also been working towards a project of this kind, the Large Millimetre and Submillimetre Array (LMSA). The Japanese astronomical community has decided that it would be best to fully merge this project with the bilateral project. A Japanese design and development phase, which is closely co-ordinated with the European and North American efforts, will be completed in 2003. Japanese participation will provide significant scientific enhancements to the bilateral project, and this possibility has been extensively studied. If it is realised, ALMA will become a truly global project, the first ever in ground-based astronomy.

3. Science with ALMA

3.1 Introduction

The scientific case for ALMA is overwhelming. The main science drivers are the origins of galaxies, stars and planets: the epoch of first galaxy formation and the evolution of galaxies at later stages including the dust-obscured star-forming galaxies that the VLT and HST cannot see, and all

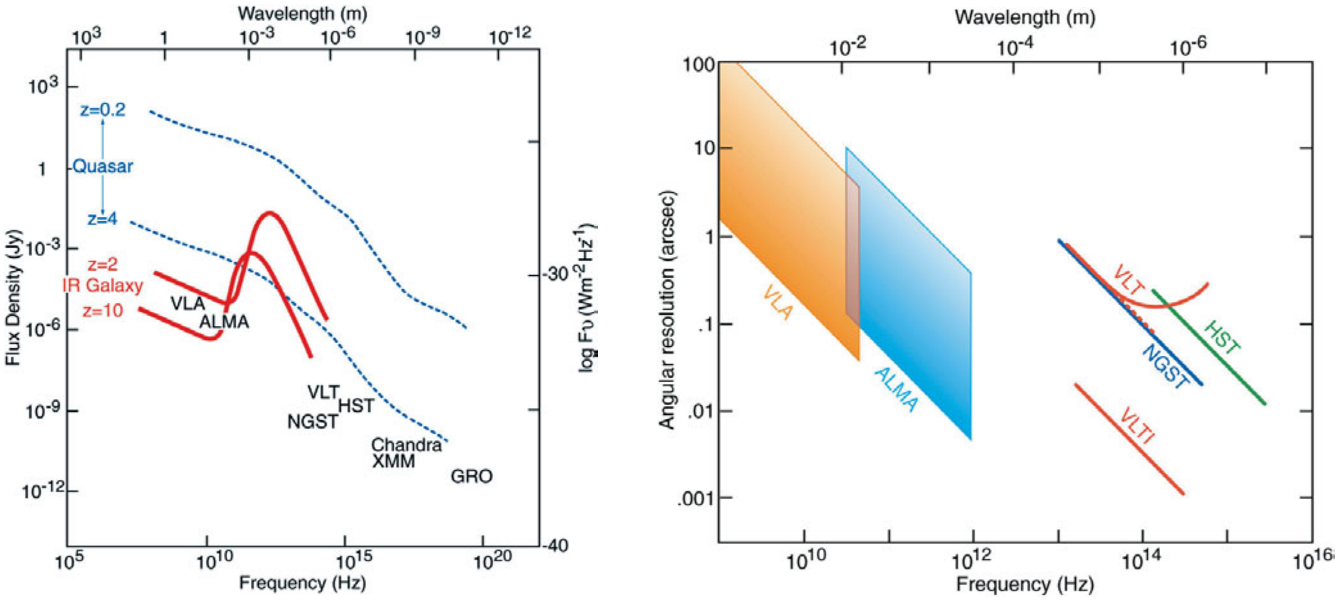

Figure 2: Left: Sensitivity of ALMA, compared with some of the world’s other major astronomical facilities, for typical integration times of several hours. Right: Angular resolution of ALMA, compared with other major telescopes. The top of the band shown for ALMA corresponds to the compact 150-m configuration, and the bottom corresponds to the large array with 12 km baselines. For the VLT, the solid line corresponds to the seeing-limited case, and the dashed line to the diffraction-limited case with adaptive optics.

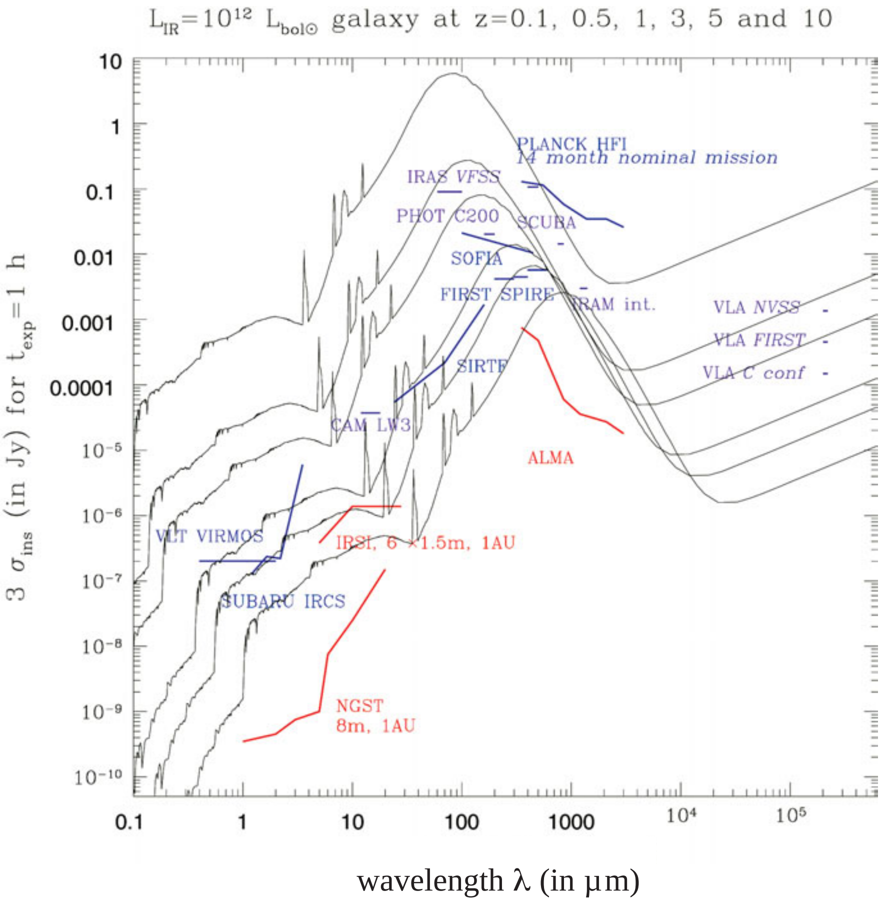

Figure 3: A detailed view of the typical spectral energy distribution of a star-forming galaxy at redshifts of 0.1 to 10. In the millimetre and submillimetre bands the observed flux is almost independent of redshift, and ALMA will be sensitive to such objects out to redshifts well beyond 10 (Guiderdoni et al., 2001, in "The Birth of Galaxies", eds. B. Guiderdoni et al., The Gioi Publ., p. 95).

phases of star and planet formation hidden away in dusty cocoons and protoplanetary disks. But ALMA will go far beyond these main science drivers – it will have a major impact on virtually all areas of astronomy. It will be a true mm/submm counterpart of the other major facilities for world astronomy, as illustrated by its relative performance in Figure 2.

3.2 Galaxies and Cosmology

Three dramatic events over the last decade have spectacularly opened up the mm/submm wavebands to the distant Universe: the discovery of CO emission in a z = 2.3 ultraluminous infrared galaxy, the discovery of the far-infrared background radiation, and the discovery of a large population of star-forming galaxies that probably dominate the luminosity of the Universe at high redshift. The most remarkable discovery is that large amounts of dust and molecules were present already at z = 4.7. This redshift corresponds to a look-back time of 92% of the age of the Universe and shows that enrichment of the interstellar medium occurred at very early epochs.

It is now clear that the mm/submm wavebands are exceptionally well suited for the study of the distant Universe. Whereas the broadband flux from distant galaxies is diminished in the UV and optical due both to the redshift and obscuration by internal dust, the same dust produces a large peak in the rest-frame far-infrared, which, when redshifted, greatly enhances the millimetre and submillimetre emission from these objects. Thus, ALMA may provide one of the best ways to find the first galaxies that formed after the "dark ages".

Current studies are limited to the very brightest objects. ALMA will make it possible to detect objects one hundred times fainter, and will make a decisive contribution to one of the key questions in current astronomy: the origin of the infrared background and the star-formation history of the Universe. The "ladder" of molecular transitions essen-

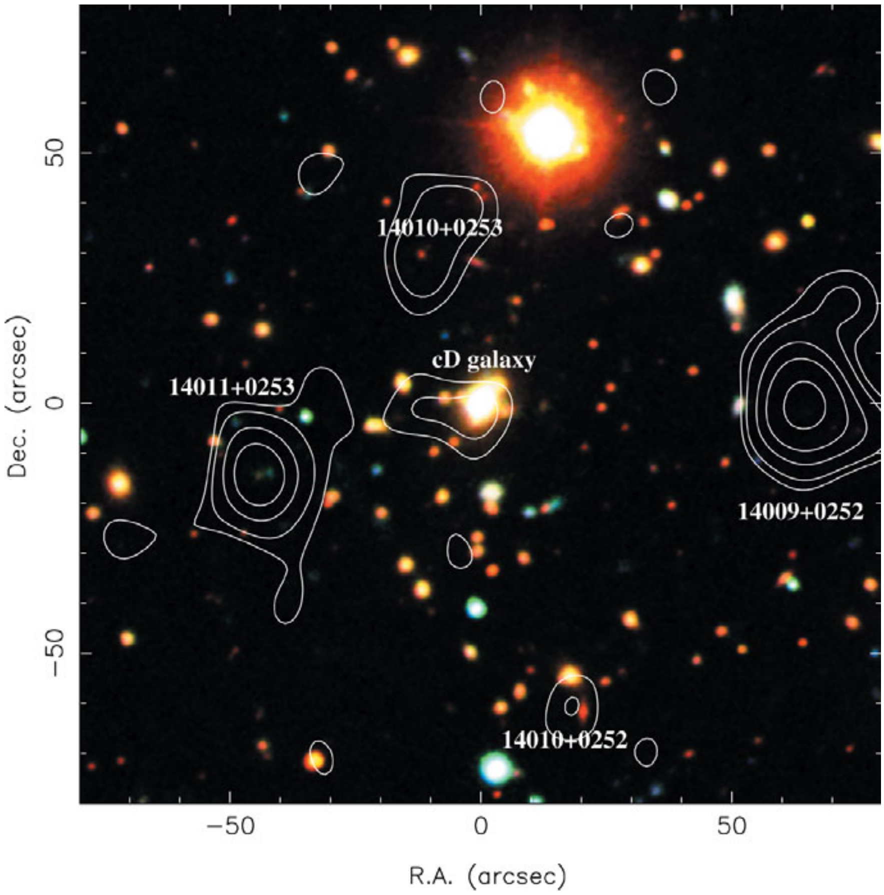

Figure 4. The submillimetre and optical wavebands provide complementary views of the Universe. This figure shows submillimetre contours superimposed on an optical image of the galaxy cluster A1835 (Ivison et al., 2000, MNRAS 315, 209). It is clear that the submillimetre sources are very faint optical objects, while the red cluster galaxies are not prominent submillimetre sources. The mm/submm wavebands are particularly sensitive to the most distant galaxies; the source 14011+ 0253 is at a redshift of 2.55, as determined directly from CO line observations. ALMA will provide submillimetre images with much finer resolution than the optical image

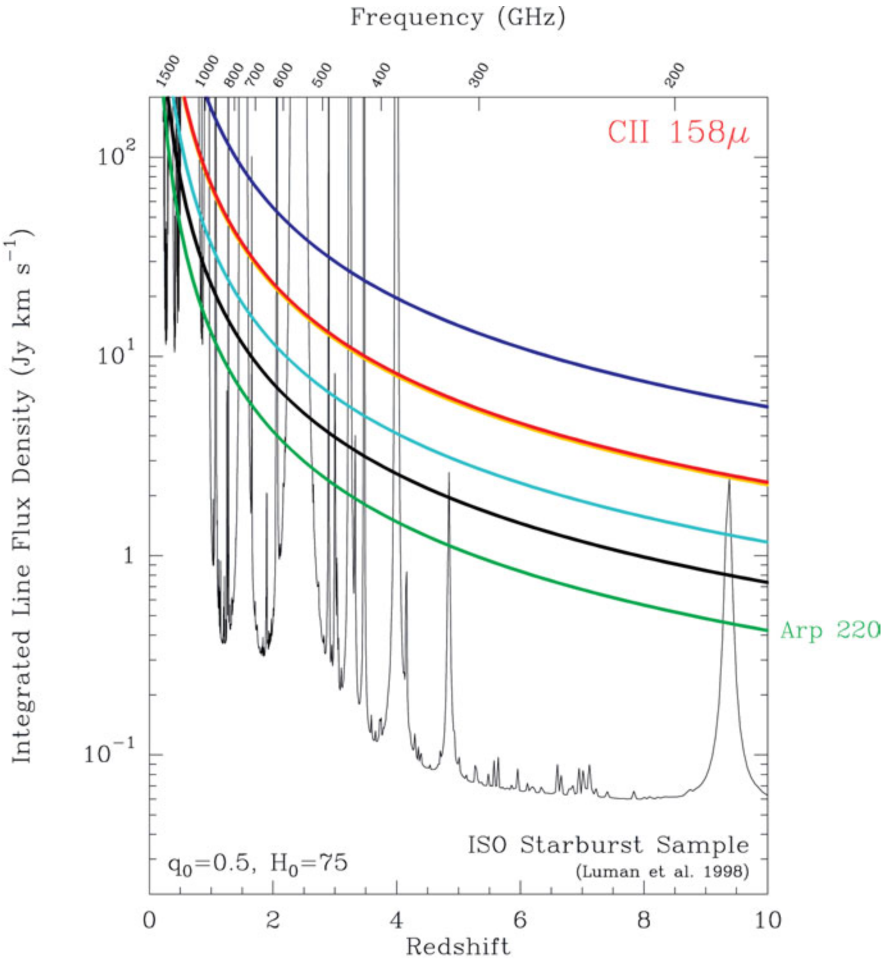

Figure 5. The detectability of the powerful [C II] line by ALMA. The coloured lines represent the integrated line flux densities one would observe for the 158 mm C II fine structure line from the sample of ultraluminous infrared galaxies observed by Luhman et al. (1998, ApJ 504, L11) using the ISO satellite if those galaxies were at the redshifts indicated by the abscissa. The thin line indicates the typical 5-sigma noise level of ALMA in two hours of integration, for a velocity resolution of 300 km s^{-1}, and assuming the precipitable water vapour content of the atmosphere is 0.8 mm.

tially guarantees that a redshifted spectral line will appear in one of the observing bands. ALMA will be thus able to obtain the redshifts of distant galaxies, and study their detailed morphology and kinematics. It will be able to detect not only molecular lines from these objects, but potentially also the atomic fine-structure lines of carbon, oxygen, and nitrogen, which, at high-z, are redshifted into the submm bands.

At present, even the strongest submillimetre sources are very difficult to identify. Most of them are not associated with previously known bright objects, yet this population probably dominates the luminosity of the distant Universe. With ALMA's high angular resolution, precision and sensitivity, it will be possible to accurately locate such sources in minutes, and measure their redshifts through the detection of CO lines in less than an hour. ALMA may also detect a population of more distant, optically obscured, objects that would escape detection at other wavelengths.

The study of the early epochs of galaxy formation is one of the main goals of ALMA, and one of the main reasons for a very large collecting area.

Many gravitational lenses will be found by ALMA, possibly more numerous and at higher redshifts than in the optical or radio wavebands because of the very steep source count. Gravitational arcs will be mapped in molecular lines.

Molecular absorption lines will be observed in the spectra of many quasars. This is a new field with great potential. Already, in the few sources bright enough, over 30 transitions from 18 different molecules have been observed in absorption systems up to $z = 0.9$. This opens up the study of detailed chemistry at cosmological distances, and makes possible direct measurement of the cosmic background temperature at high redshifts. Thousands of sources will be accessible to ALMA.

Active galactic nuclei can be studied in depth at millimetre wavelengths because of the low synchrotron and dust opacity and the unprecedented angular resolution of millimetre VLBI. The optically-obscured molecular tori and the circumnuclear starbursts of nearby galaxies can be resolved with linear resolutions of a few parsec. ALMA will be able to map both the gas and the dust that obscure the nuclei. The presence of central black holes can be studied kinematically in a large number of galaxies. The centre of our own Galaxy can be observed free of obscuration, in particular the gas dynamics of the 1-pc circumnuclear disk around the galactic centre source Sgr A*.

ALMA will make observations of normal galaxies at $z = 1$–2 with the same detail as is presently possible in nearby galaxies. The main dynamical features of nearby spirals will be observed with enough resolution and sensitivity to constrain theoretical scenarios of galaxy evolution. The mass spectrum of molecular clouds in galaxies of different types will be determined. Detailed studies of nearby mergers and IR luminous galaxies will be important to serve as templates for objects found at high redshifts. In the Magellanic Clouds, star-formation processes can be compared with those in our Galaxy. This would be highly interesting, because star formation is closely related to the ambient radiation field, dust content, and metallicity.

3.3 The Formation of Stars and Planets

A major astronomical goal of the 21st century is an understanding of how stars and planets form. Studying star- and planetary-system formation requires very high angular resolution, because protoplanetary disks are small (100–500 AU) and the nearest star formation regions are ~ 100 pc away. ALMA will provide a linear resolution as fine as 1 AU at these distances.

Because it can observe at wavelengths free of extinction, ALMA will be the premier instrument for studying how gas and dust evolve from a collapsing cloud core into a circumstellar disk that can form planets. The array will be able to directly observe astrophysical phenomena that have until now only been conjectured in theoretical models of the early stages of star formation. ALMA will yield new unique information on the gravitational contraction of protostellar cloud cores, with accurate kinematics and mass distributions inside the cores and their envelopes. It will give new clues on the role of the magnetic field in the cloud cores, the circumstellar envelopes, and the accretion disk. Observations of high-excitation submm lines of various molecules will allow us to study the physics and chemistry of the shocks in the ubiquitous outflow jets that carry away the original angular momentum.

For the later stages, when the newly-formed stars are surrounded by protoplanetary disks, imaging the gas and dust on scales of several AU will be

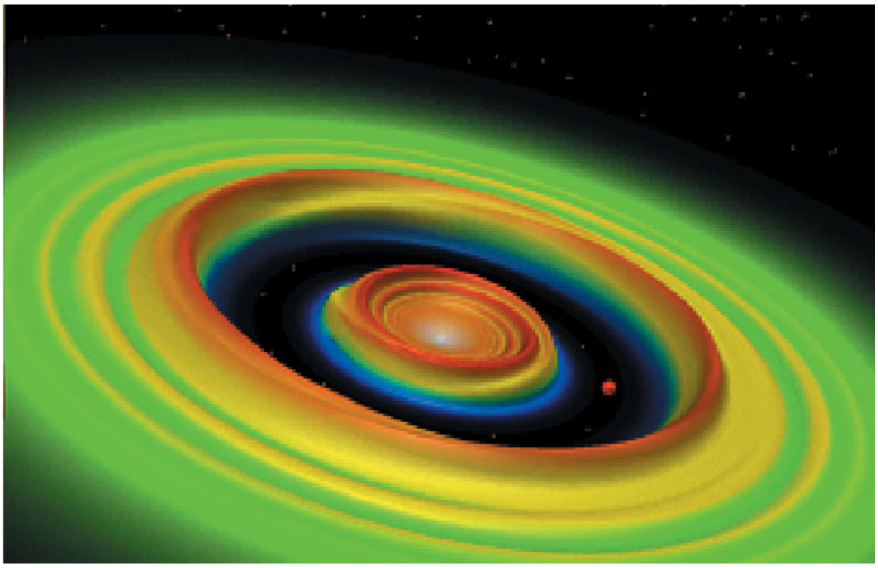

Figure 6. ALMA will reveal the details of planet formation. The figure shows a hydrodynamic model of a protostellar accretion disk in which a giant protoplanet is forming (Bryden et al., 1999, ApJ 514, 344). The newly-formed protostar resides (invisibly) at the centre of the accretion disk and a Jupiter-mass protoplanet orbits around it at the Jupiter–sun distance. A gap in the disk is cleared out by the protoplanet. Using ALMA it will be easy to image such gaps in protostellar disks in nearby star-forming regions. In this plot surface density is coded as "height".

the only way to study the earliest stages of planet formation. Current mm arrays have revealed large (hundreds of AU) rotating disks around single T Tauri stars, but the angular resolution necessary to resolve the inner regions, where planets are expected to form, will only be provided by ALMA. ALMA will be able to reveal, within protoplanetary disks, the gaps that are tidally cleared by Jovian sized planets at distances of a few AU from their young, central stars. Multi-wavelength studies of such objects will be powerful tools for analysing the dust and gas properties on the scale of the Solar System. Maps of dust and optically thin molecular lines with 0.1″ to 0.05″ beams will provide crucial data on the chemistry, the reservoirs of the biogenic elements, and the timescales on which planets form. ALMA will provide the masses of the pre-main-sequence stars through the measurement of the Keplerian motion in the protoplanetary disks.

The high sensitivity of the array will allow us to make unbiased surveys of pre-main-sequence stars to obtain the statistics of disk properties and frequency of protoplanetary systems in different star-forming regions. Comparison between isolated star formation and dense clusters will become possible. ALMA will also address the high-mass star-formation problem. Dense, hot cores are known to exist around massive (proto)-stars, but the existence of circumstellar disks analogous to those found around low mass star remains uncertain.

The study of star and planet formation is another major goal of ALMA, and one of the drivers for the highest angular resolution.

3.4 Stars and their Evolution

With its coverage of the millimetre and submillimetre ranges, ALMA will greatly expand the field of stellar astronomy. It will detect tens of thousands of stars over the entire H-R diagram. It will cover the full life cycle of stars. ALMA may provide the *only* way to observe some massive stars that spend their entire brief lives hidden by dust in their parent molecular clouds. It will provide unique information on the winds of hot stars, novae, the photospheres of giants and supergiants, and non-thermal processes in flare stars, Be stars, and dust formation in supernovae and in the outflows of planetary nebulae. It will resolve the photospheres and chromospheres of giant and supergiant stars within a few hundred parsec.

ALMA is designed to be able to observe the nearest star, our sun. This is a challenging problem because of the thermal constraints on the antenna and receiver design. If successful, ALMA could address two of the most interesting solar physics problems: the acceleration of the highest energy electrons in flares, and the thermal response of the low chromosphere to waves and shocks from the interior.

ALMA will yield fundamental knowledge for our understanding of the dynamics and chemistry of the envelopes of evolved, oxygen-rich and carbon-rich stars, where important scientific goals are the understanding of dust formation and the enrichment of the interstellar medium with heavy elements. The winds of these red giant stars rapidly remove the outer layers, terminating further evolution. The winds have low outflow speeds and high densities, so that matter easily condenses into dust grains. ALMA will image the distribution of matter in the outflows at distances of a few stellar radii, to solve the longstanding problem of dust formation and study the interaction between stellar pulsations and wind acceleration. It will be possible to study such objects across the Galaxy, and even in the Magellanic Clouds

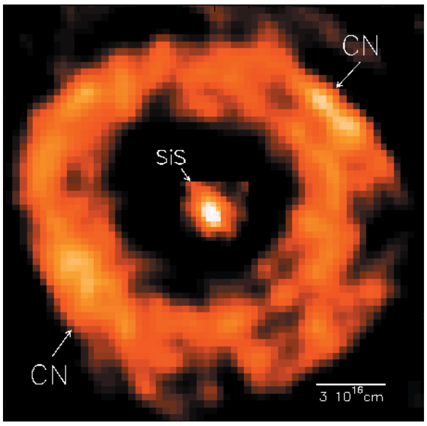

Figure 7. Distributions of the SiS and CN 3-mm emission in the CSE IRC+10216. The colours represent the line intensities integrated in a narrow velocity interval centred on the systemic velocity of the star (Guélin et al., 1996, in "Science with Large Millimeter Arrays", ed. P. Shaver; Springer Publ., p. 276).

Supernovae and gamma-ray bursts will both be important targets for ALMA. In both cases mm and submm observations provide unique and important information. Radio supernovae first appear at these wavelengths, where the flux is relatively unaffected by free-free and synchrotron self absorption. SN 1987A in the LMC will be a prime target for ALMA. In the case of gamma-ray bursts, mm/submm observations provide unique information on the peak of the burst and important constraints on the physical parameters. ALMA will allow detection of all GRBs detectable in the optical.

3.5 The Solar System

Because of its high angular resolution, its fast imaging capabilities, and its wide instantaneous bandwidth, ALMA will represent a major step forward in the study of comets, asteroids and planets. ALMA's highest angular resolution at a distance of 1 AU corresponds to a linear resolution of less than ten kilometres.

Observations of comets with ALMA will greatly increase our understanding of their nature and origin, and complement the planned space probes that will be able to sample only a few comets. Over 20 molecular species have so far been discovered in comets. ALMA will make it possible to search for less abundant molecules, radicals, and new ions, and to investigate isotopic ratios in several species. Such studies will provide key information on the origin of comets and the formation of the Solar System. It will be possible to detect molecules in distant comets and study the evolution of their outgassing as they approach the Sun. The fast high-resolution imaging capability of ALMA will allow us to study structures in the inner coma of comets, and maps of the distribution of rotational temperatures of different molecular species will help us study the thermodynamics, excitation processes, and physical conditions in these objects.

Asteroids and cometary nuclei of small sizes, and even distant objects such as Centaurs and trans-Neptunian objects, will be detectable in the mm and sub-mm continuum. Together with observations in other wavebands, ALMA will allow us to probe the temperature of these objects at various depths and to measure their albedo and size. Imaging thermal emission from the planetary satellites, the Pluto/Charon system and the largest asteroids will provide clues to their thermal properties and the degree of heterogeneity of their surface.

ALMA will be able to map planetary atmospheres on short timescales. Maps of CO and HDO in Mars and Venus will give data on wind, temperature, CO and water distribution, and atmospheric dynamics on spatial scales comparable to regional weather scales. The analysis of meteorological and climatic variations in the atmosphere of Mars will be a valuable complement to future space missions. Searching for molecular trace species likely to be present in these planets, such as sulfur-bearing compounds in Venus and organic species in Mars, will become possible. Wide bandwidth capabilities will allow us to probe the deep atmosphere of Venus. Mapping HCN and CO, and searching for other nitriles on Neptune, will provide information on whether the origin of such molecules is internal or external. It will be possible to detect and map tropospheric species such as PH_3 in the Giant Planets. During very dry conditions at the high-altitude site proposed for ALMA, the mapping of H_2O and HDO on the four giant planets will provide clues on the origin of water.

ALMA will also observe the atmospheres of Pluto and the satellites of the giant planets. ALMA will be able to detect SO_2 and SO in the plumes of the volcanoes on Jupiter's moon Io and may discover other trace constituents. Mapping the millimetre lines of CO, HCN, HC_3N, and CH_3CN in the stratosphere of Titan with high spectral resolution will provide the vertical and latitudinal distributions of these constituents, giving better constraints on the photochemistry that occurs in Titan's atmosphere and its response to seasonal effects. ALMA will have sufficient sensitivity to detect and map CO, and perhaps other species, such as HCN, in the tenuous atmospheres of Pluto and Triton. This will provide clues on the nature of the interaction between their icy surfaces and their atmospheres.

The scientific reach of ALMA thus extends from the most distant objects in the Universe to details of the nearest objects in our solar system. It will be one of the major astronomical facilities of the 21st century.

4. Scientific and Technical Requirements

High angular resolution is of great importance both for observations of the distant Universe and for detailed studies of the processes of star and planet formation nearby in our own Galaxy. It is clear from HST observations that an angular resolution of at least 0.1″ is needed for high-redshift studies. Similarly, an angular resolution of 10 milliarcsec or better is required to resolve the gaps in protoplanetary disks created by forming planets, and such resolution should be achieved at least at the shorter (submillimetre) wavelengths accessible to ALMA. Both requirements imply baselines of 10 km or greater.

Such high angular resolution cannot be exploited without adequate sensitivity. The noise in brightness temperature increases as the square of the baseline. However, millimetre astronomy is the domain of *cold* matter, so the brightness temperatures to be observed are low. In the case of spectral lines, bandwidths are limited by the line widths, so increasing detector bandwidth does not help. Furthermore, modern receiver performance is approaching quantum limits and/or the atmospheric noise limits. Therefore, the only way to increase the sensitivity is to increase the collecting area of the array. An angular resolution of $< 0.1''$ can only be achieved for thermal lines with a collecting area approaching 10^4 square metres. The other main driver for very high sensitivity is the detection of the most distant galaxies in the Universe. If galaxies formed by successive mergers of sub-galactic objects, the highest possible sensitivity will be needed to detect the first luminous objects.

The large size and collecting area can only be achieved with a large array of antennas. The collecting area of an array can be enhanced by increasing the number of antennas, their size, or both. There were thus several trade-offs to be considered. Small antennas have higher precision and give better wide-field imaging. The use of large antennas maximises the collecting area, and reduces the number (and therefore cost) of receivers and the demands on the correlator. In view of the supreme importance of high sensitivity, the largest possible antenna size was chosen. The combination of pointing and surface accuracy required for efficient operation at submillimetre wavelengths (respectively 0.6″ and 25 μm rms or better) is difficult to achieve for antenna diameters greater than about 12 metres, so this determined the antenna size. An array of 64 12-metre diameter antennas provides a total collecting area of over 7000 square metres, satisfying the sensitivity requirements given above. This large number of antennas also provides excellent high-resolution imaging capability, which will be very important for the science objectives of ALMA. The 2016 independent baselines remove the need to use Earth rotation to provide aperture synthesis, and allows high resolution "snapshot" images of high fidelity.

Thus, the angular resolution and sensitivity requirements are satisfied by ALMA, an array of 64 12-metre diameter high-precision antennas extending over a region up to 12 km across. The receivers should provide complete wavelength coverage of the atmospheric bands over the range 0.3 to 10 mm; the dewars will be built to accommodate all ten receivers needed, and will be populated initially with the four of highest priority. Other requirements include wide instantaneous bandwidth (16 GHz per antenna), a flexible correlator system allowing spectral resolution as high as 5 kHz (0.01 km s^{-1} at 100 GHz), and a complete polarisation capability providing all Stokes parameters. The site must obviously be large, flat, and very high (to minimise the atmospheric attenuation at these wavelengths), and the 5000-metre high Llano de Chajnantor in the Atacama desert region of northern Chile is ideal. Even on such an exceptional site, atmospheric pathlength fluctuations are critical for imaging performance, and ALMA is designed with water vapour radiometers to compensate for these variations, as well as a fast switching capability to "freeze" the atmosphere.

More information on the ALMA project can be found in earlier issues of *The Messenger* (March 1996, March 1998; December 1998; and June 1999), and on the following websites:

http://www.eso.org/projects/alma/
http://www.alma.nrao.edu
http://www.nro.nao.ac.jp/~lmsa/index.html.