ORIGINS OF THE ALMA PROJECT IN THE SCIENTIFIC VISIONS OF THE NORTH AMERICAN, EUROPEAN, AND JAPANESE ASTRONOMICAL COMMUNITIES

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ABSTRACT

ALMA is a worldwide project, the synthesis of early visions of astronomers in its three partner communities, Europe, North America, and Japan. The evolution of these concepts and their eventual merger into ALMA are discussed, setting the background for the papers which follow on the scientific requirements and expected performance of ALMA for extra-galactic, galactic, and solar system research.

Key words: ALMA, millimeter, submillimeter, interferometers, instrumentation, history.

1. INTRODUCTION

The Atacama Large Millimeter Array (ALMA) is a fusion of ideas, with roots in the conceptual projects of three astronomical communities: the Millimeter Array (MMA) of the United States, the Large Southern Array (LSA) of Europe, and the Large Millimeter Array (LMA) of Japan. ALMA has a large collecting area of 7238 m^2 provided by 64 antennas of diameter 12m. ALMA is very flexible. Its antennas can be placed in configurations with sizes from 150 m to 14 km, providing a range of angular resolution of nearly a factor of 1000 at fixed observing frequency. It has the potential to cover all ten frequency bands from 30–950 GHz where the earth's atmosphere is reasonably transparent, with an initial set of receivers that covers the four of these bands. It has a powerful and flexible signal correlator that can process 2016 baselines with 16 GHz of bandwidth per antenna. In addition, it has been agreed that ALMA include the Atacama Compact Array (ACA), an array of 12 antennas of diameter 7m (with 4 additional 12m diameter antennas for single dish observations and calibration purposes), equipped with the same receivers as the large array, and equipped with its own signal correlator of similar power as the large array, as well as three additonal receiver bands for all 80 antennas. The ACA provides data on spatial frequencies between the compact configuration of the large array and a single (12m) antenna. ALMA with the ACA and additional receiver bands is known as "Enhanced ALMA". These specifications are those necessary to meet scientific requirements. They also reflect the union of visions for the three earlier conceptual projects now realized in ALMA.

2. THE ROOTS OF ALMA

2.1. Millimeter Array

The origins of the Millimeter Array (MMA) are found in the pioneering science of the NRAO 36-Foot Telescope (later known as the 12-Meter Telescope), soon followed by the 4.9m telescopes at the University of Texas and Aerospace Corporation, the 14m telescope at the Five Colleges Radio Astronomical Observatory, and the 7m telescope at AT&T Bell Labs. The millimeter interferometers of the University of California (Berkeley) at the Hat Creek Observatory (later the Berkeley-Maryland-Illinois Association, or BIMA) and the California Institute of Technology at the Owens Valley Radio Observatory demonstrated the power that comes with high angular resolution for studying the sources found with the single dishes. The experience of using a powerful, flexible array that was provided by NRAO's Very Large Array (VLA) at longer wavelengths was also very influential — the prime characteristic of the MMA was the ability to obtain rapid high-quality images at 230 GHz, that is, the MMA was to be a millimeter version of the VLA. The science targets of the MMA included the same broad range of topics seen at the VLA: sun, solar system, stars, galactic interstellar medium, external galaxies, and cosmology.

In 1982 an NSF committee appointed to make recommendations for the future of millimeter-wavelength astronomy in the United States called for the development of an interferometer with a collecting area of 1000–2000 m^2 capable of working at 1mm wavelength with $1''$ resolution at 115 GHz. The first concept for this interferometer was presented in MMA Memorandum #1 [1], where an array of 15 antennas of diameter 10m at the VLA site in New Mexico was proposed at an estimated cost of $36M(US). The proposal to build the MMA, submitted by Associated Universities, Inc. (AUI) to the National Science Foundation (NSF) in July, 1990, called for an array of 40 antennas of diameter 8m, with four receiver bands covering the atmospheric windows from 30–350 GHz, configurable in four arrays of size 70–3000 m, with a correlator capable of processing 2 GHz per antenna [2]. The proposal discussed two possible sites for the MMA, both in the southwestern United States. Studies of the atmopheric transparency and phase stability at these sites led to similar studies on Mauna Kea, in Hawaii. Extensive atmospheric monitoring was also conducted there. Concerns with the limited size of the area available to the MMA on Mauna Kea and with potential environmental problems prompted a search for potential sites in Chile. The Goddard Institute for Space Studies (later, Harvard-Smithsonian Center for Astrophysics (CfA)) survey of galactic CO emission using 1.2m telescopes, one in each hemisphere, had experienced excellent observing conditions at Cerro Tololo. In April of 1994 the observatories at Cerro Tololo, ESO La Silla and Paranal, Las Campanas, and high-elevation sites further inland, including sites previously identified as possibilities for the Sub-Millimeter Array (SMA) of the CfA, were visited. This search followed by nearly 10 years the first suggestion, in MMA Memorandum #25 [3] that the MMA be built in the Southern Hemisphere. The quality of the sites prompted an extension of MMA capability to the submillimeter [4]. The site in Chile selected for the MMA, not one of the sites considered for the SMA, was to the east of the village of San Pedro de Atacama in the Andean altiplano at an elevation of 5000m. This site, named Llano de Chajnantor, is shown in Fig 1. It was formally proposed to the NSF by AUI as the MMA site in 1996. The estimated cost of the MMA was $120M(US).

2.2. Large Southern Array

As in the United States, a broad science program in millimeter wavelength astronomy had developed in Europe, centered around the two telescopes of IRAM, a 30m single dish and an interferometer of three (now six) 15m antennas, the 14m telescope of the Onsala Space Observatory (OSO), and the submillimeter capability of the 15m James Clerk Maxwell Telescope. The group at the University of Bordeaux were pioneers in millimeter wavelength interferometry. The first concept for a millimeter interferometer in the Southern Hemisphere came in the late 1980s out of OSO following the success of the Swedish-ESO Submillimetre Telescope (SEST), and called for an array of 10 antennas of diameter 8m to be located near ESO's Very Large Telescope on Cerro Paranal in northern Chile [5]. The estimated cost was $50M(US). An array in the Southern Hemisphere became the hallmark of the European array for scientific reasons (the Galactic Center, Magellanic Clouds, etc.) and because ESO, the natural organization for a European astronomical project, had its telescopes there.

The discovery of CO emission in a galaxy at a redshift of $z = 2.3$, had a profound influence on the size of the LSA. In recognition of the possibility that this galaxy was either atypically luminous or, more likely, gravitationally lensed, it was argued [6] that a collecting area of at least 10 times that of the IRAM Interferometer on the Plateau de Bure, that is, an unprecedented 10000 m^2 of collecting area, was required to be able to observe the entire (unlensed) population of such galaxies. These ideas were incorporated in the thinking for the Large Southern Array (LSA); it's concept proposal (1995) called for a 10000 m^2 collecting area provided by 50 antennas of diameter 16m or 100 antennas of diameter 11m. The LSA was to work at frequencies of 350 GHz and below and be equipped with state-of-the-art receivers and signal correlator. To obtain angular resolution of $0.1''$ at a wavelength of 2.6 mm, configurations of size $\sim$ 10km were contemplated. Because its highest operating frequency was 350 GHz, the LSA did not require a site as high as that picked for the MMA, and sites at lower elevations of 3300m and 3750m were studied. The estimated cost of the LSA was about $250M(US).

2.3. Large Millimeter Submillimeter Array

In Japan, plans for a large millimeter wavelength array grew naturally out of a desire to expand the Nobeyama Millimeter Array. The Large Millimeter Array (LMA) was discussed in 1983, just following the dedication of the NRO, and in its first form expanded the five 10m diameter antennas of the NRO interferometer to 30, working to a maximum frequency of 230 GHz on baselines up to 1 km. It was decided in 1987 to expand the concept to 50 antennas of diameter 10 m working at frequencies of 35–500 GHz with the possibility of going to submillimeter frequencies, in configurations of size 20–2000 m [7]. Japanese university groups established a small, automated submillimeter telescope on Mt. Fuji and a small millimeter telescope in Chile. The site of the NRO precluded observations in the submillimeter, and sites on Mauna Kea and in North Africa and Chile were considered as possibilities. Serious site studies in Chile began in 1992 with a survey of 20 possibilities.

As the quality of the sites in Chile became apparent, consideration of Mauna Kea was dropped and the prospects of observing in the submillimeter band became the focus of the LMA program, leading to the change in project name to the Large Millimeter/Submillimeter Array (LMSA). In 1995 a memorandum of understanding between the NOAJ and NRAO was signed whereby the two groups agreed to work cooperatively on site studies. Sites at Pampa la Bola and Rio Frio received intensive study, with Pampa la Bola to the north-east of Llano de Chajnantor site becoming the site of choice in 1997; the importance of 10 km baselines to a combined MMA+LMSA had become clear in a workshop held in Tokyo on submillimeter astronomy at 10 milliarcseconds resolution. The Pampa la Bola site showed excellent phase stability and is now the location for a long arm of ALMA antenna pads that stretches northeast of the Llano de Chajnantor. In 1994 the LMSA received high-level governmental endorsement as a top-priority project for new ground-based astronomical facilities. Proto-planetary disks and high-z galaxies were considered to be the main scientific targets of the project. The frequency range of the LMSA was expanded to include 650 and 900 GHz bands in the submilllimeter [8].

3. CONCLUSION

Few of the participants in the MMA, LSA, and LMSA projects were entirely comfortable with the prospect of building three separate large millimeter/submillimeter arrays in Chile, even if each satisfied to a significant extent the particular wishes of its community. Working groups were established in the General Assemblies of URSI (1993) and the IAU (1994) to study potential partnerships and discussions on the subject occured frequently. The major breakthrough occured with the signing of a resolution between ESO and NRAO on June 26, 1997, whereby the two parties agreed to pursue a common project that merged the MMA and LSA into what would eventually be named ALMA. The merged array combined the sensitivity of the LSA with the frequency coverage and superior site of the MMA [9]. The merger was made official in June 1999 with the signing of the Phase 1 ALMA Agreement. ESO and NRAO worked together in technical, science, and management groups to define and organize a joint project between the two observatories with participation by Canada and Spain. A flurry of resolutions and agreements ensued, including the choice of "Atacama Large Millimeter Array", or ALMA, for the name of the new array in March of 1999. This effort culminated in the signing of the ALMA Agreement on February 25, 2003, between the North American and European parties.

Following mutual discussions over several years, the ALMA Project received a proposal from the NAOJ whereby Japan would provide the ACA and three additional receiver bands for the large array, to form Enhanced ALMA. Further discussions between ALMA and the NAOJ led to the signing of a high-level agreement on September 14, 2004, that makes Japan an official participant in Enhanced ALMA. Final negotiations on an operations plan for Enhanced ALMA are expected to be concluded by the end of 2005. ALMA is budgeted at $552M(Y2000US), shared 50:50 between North America and Europe. The value assigned to the Japanese contribution to Enhanced ALMA is $180M(Y2000US).

In 2004, the last of a number of steps was completed in the long process to secure long-term (50 year) access to the ALMA site with the issuance of three decrees by the Republic of Chile and signing of two contracts. This process included the establishment of AUI in Chile with the same rights and priviledges as ESO, securing by AUI of exploratory mining rights for the site, establishment by Chile of a Science Reserve that includes the site, permission for ESO to open a new observing site, approval of an environmental impact study, purchase of land for the mid-level operations facility, lease and right-of-way agreements for the site and access road, approval of a quiet/coordination zone around the site to protect against radio frequency interference, an agreement with the regional government concerning support of cultural and educational activities, and an agreement with CONYCIT concerning the share of observing time on ALMA for Chilean astronomers and support for the development of astronomy in Chile. More than 14 government agencies in Chile were involved in the negotiations.

Assuming all three partners are able to meet their commitments, the final project will be cost-shared 37.5%/37.5%/25% between North America, Europe, and Japan, respectively. The observing time, after a 10% share for Chile, will be shared accordingly. When Enhanced ALMA, to be known as the Atacama Large Millimeter/Submillimeter Array, with the same acronym ALMA, comes into full operation it will truly be a world millimeter/submillimeter array.

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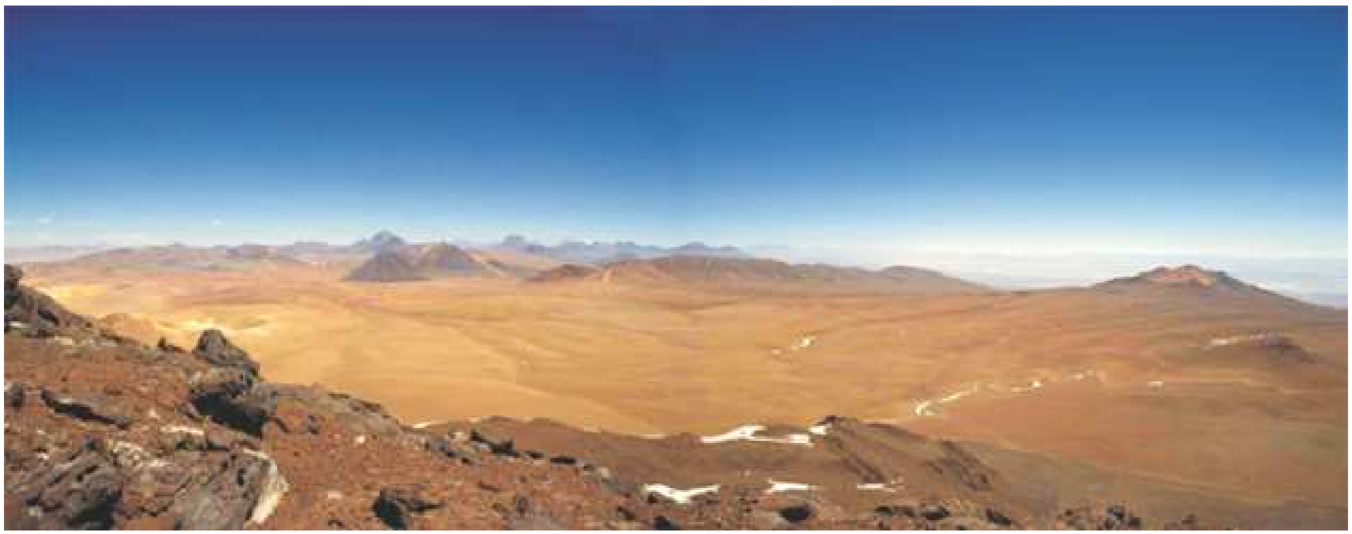

Figure 1. The ALMA site on the Llano de Chajnantor, elevation 5000m, as seen from Cerro Chajnantor (S. J. E. Radford).

SCIENTIFIC REQUIREMENTS OF ALMA, AND ITS CAPABILITIES FOR KEY-PROJECTS: EXTRAGALACTIC

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ABSTRACT

The Atacama Large Millimeter Array (ALMA) consists of 64 antennas of 12 m diameter that will initially observe in 4 frequency bands between 84 and 720 GHz with spatial resolutions down to 0.″01 and velocity resolutions as fine as 0.05 km/s. These technical requirements are based on three primary science goals. We illustrate two of these requirements: (i) the ability to detect spectral line emission from a Milky-Way type galaxy at z=3, and (ii) the ability to provide precise images at an angular resolution of 0.″1. Finally, we present a possible large extragalactic project with ALMA: molecular line studies of submm galaxies.

Key words: ALMA; instrumentation.

1. PRIMARY SCIENTIFIC REQUIREMENTS

ALMA will be a flexible observatory supporting a breath of research in the fields of planetary, galactic and extra-galactic astronomy. The three primary science requirements have been defined as:

1. The ability to detect spectral line emission from CO or CI in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.
2. The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc, enabling one to study their physical, chemical and magnetic field structures and to detect the gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0.″1. Here, the term precise images means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20°.

We now concentrate on the two requirements important for extragalactic astronomy (see J. Richer's contribution for the galactic requirements).

1.1. Spectral line imaging of normal galaxies at z=3

An estimate of the technical requirements to achieve this science goal can be made by using experience learned from existing millimeter arrays, which have collecting areas between 500 and 1000 m^2. These arrays now routinely detect CO emission from high redshift galaxies and quasars (see Carilli *et al.* , 2004a, for a review). Fainter molecular lines such as HCN (*e.g.* Carilli *et al.* , 2004b) and atomic Carbon (Weiß *et al.* , 2004a) are now also within the reach of existing telescopes. These observations take one to two days of total observing time, and are only possible for the most luminous sources and/or with the aid of gravitational lensing. In normal, unlensed galaxies, these lines would be a factor of 20 to 30 fainter.

The sensitivity of ALMA for a given integration time is essentially controlled by three major terms: (1) the atmospheric transparency, (2) the noise performance of the detectors, and (3) the total collecting area.

The location of ALMA on the Chajnantor plateau at an altitude of 5000m will minimize the contribution from the atmosphere compared to existing millimeter observatories. The noise level of the detectors can be reduced be a factor of two, and will then approach the fundamental quantum limit. An important factor of $\sqrt{2}$ will be gained by the requirement that ALMA support front end instrumentation capable of measuring both states of polarization. The remaining factor of 7 to 10 can only be gained by increasing the collecting area. Hence, an ALMA requirement is a collecting area >7000 m^2.

Table 1. Aperture efficiencies ϵ_a and estimated system temperatures $T_{\rm sys}$ for ALMA at 50° elevation.

Frequency GHz	ϵ_a	$T_{\rm sys}$ K
35	0.75	35
110	0.74	67
230	0.72	107
345	0.69	251
409	0.67	425
675	0.54	1050
850	0.45	1150

A more specific calculation of the requirement to have the ability to detect CO emission from a Milky Way type galaxy at z=3 is as follows. At cosmological distances, the 10 kpc disk of the Milky Way is much smaller than the primary beam of existing millimeter antennas, so a single observation would be sufficient. The flux density sensitivity in an image from an interferometric array can be written as

$$\Delta S = \frac{4\sqrt{2}kT_{\rm sys}}{\gamma\epsilon_q\epsilon_a\pi D^2\sqrt{n_p\frac{N(N-1)}{2}\Delta\nu\Delta t}}\ {\rm Wm^{-2}Hz^{-1}},$$

where $T_{\rm sys}$ is the system temperature, ϵ_a is the aperture efficiency, ϵ_q is the correlator quantization efficiency, D is the antenna diameter, $n_{\rm p}$ is the number of simultaneously sampled polarizations, N is the number of antennas, $\Delta\nu$ is the bandwidth, Δt is the integration time, and γ is a gridding parameter that we set to unity. For ALMA, we shall assume ϵ_q=0.95, $n_{\rm p}$=2, and $\sqrt{N(N-1)} \simeq N$ so this equation then simplifies to

$$\Delta S = \frac{2.6\times10^6 T_{\rm sys}}{\epsilon_a N D^2\sqrt{\Delta\nu\Delta t}}\ {\rm mJy}.$$

$T_{\rm sys}$ and ϵ_a vary between the different atmospheric bands of ALMA. A surface accuracy of 20 μm should be achievable, providing aperture efficiencies between 0.75 and 0.45 (see Table 1). $T_{\rm sys}$ depends on several atmospheric and instrumental parameters. Table 1 lists estimates of the achievable $T_{\rm sys}$ at an elevation of 50° using state-of-the-art receivers. With these assumptions, one can thus calculate the required collecting area parametrized by the product ND^2 to achieve a certain flux density level.

The total CO luminosity of the Milky Way in the CO(1–0) transition $L'_{\rm CO(1-0)}$=3.7×10^8 K km s^{-1}pc^2 has been estimated by Solomon & Rivolo (1989). The CO luminosities seen in higher CO transitions by COBE (Bennett *et al.* , 1994; Wright *et al.* , 1991) are slightly higher. In the following, we shall adopt $L'_{\rm CO(1-0)}$=5×10^8 K km s^{-1}pc^2. From this, we can calculate the expected received flux density following Solomon, Downes, & Radford (1992) as

$$S_{\rm CO} = 3.08\times10^{-8}\frac{L'_{\rm CO}\nu^2_{\rm rest}(1+z)}{\Delta v_{\rm rest}D_L^2},$$

where $S_{\rm CO}$ is the flux density in Jy, $\nu_{\rm rest}$ is the rest frequency of the transition in GHz, D_L is the luminosity distance in Mpc, and $\Delta v_{\rm rest}$ is the rest line width in km s^{-1}.

In the Milky Way, most of the CO emission arises in clouds of several tens of Kelvin kinetic temperature. In Milky Way-like galaxies at z=3, the gas will be somewhat warmer due to the higher background temperature from the cosmic microwave background radiation. At z=3, we can observe the J=3–2 or J=4–3 transitions, which fall inside the atmospheric transmission regions. We thus need to consider the expected luminosity of these higher order transitions, using a proper radiative transfer model that takes the higher background temperatures into account. Several such models have been proposed (Silk & Spaans, 1997; Combes, Maoli, & Omont, 1999; Papadopoulos *et al.* , 2000). However, they reach significantly different conclusions. There have also been a few observations of CO ladders in high redshift quasars (Carilli *et al.* , 2002; Bertoldi *et al.* , 2003) and Ultra Luminous InfraRed Galaxies (Weiß *et al.* , 2004b), all showing CO intensities up to the 6–5 or 7–6 transition. However, the CO emission from quasars and ULIRGs is likely to be dominated by the central component, while our requirement is to detect the outer regions in Milky Way type galaxies. In a sample of 28 nearby galaxies, Mauersberger *et al.* (1999) finds $I_{\rm CO(3-2)}/I_{\rm CO(1-0)}$ ratios between 0.2 and 0.7, very different from the ones found in the high-z quasars and ULIRGs. Given these uncertainties, we shall assume $L'_{\rm CO(3-2)}/L'_{\rm CO(1-0)}$=1.

For a standard ΛCDM cosmology with H$_0$=71 km s^{-1} Mpc^{-1}, $\Omega_{\rm M}$=0.27 and Ω_Λ=0.73, the luminosity distance at z=3 is D_L=26 Gpc. Assuming an intrinsic width Δv=300 km^{-1}, the expected flux density of the CO(3–2) line is thus 36 μJy. Requesting a 5σ detection in a 75 km s^{-1} channel in 12 hours of on-source integration time (corresponding to 16 hours of total telescope time), we thus require an ND^2 of ∼7300 m^2. This can be achieved with the ALMA array of 64 12 m antennas. Of course, larger values of ND^2 are always desirable, as they would allow one to resolve the line flux density into more pixels (higher angular or spectral resolution) or image to higher S/N more quickly.

Next to CO, ALMA should also be able to observe other lines such as CI, NII and CII lines at cosmological redshifts. These lines will provide important probes of the IMF and the Lyman continuum luminosity from the most luminous stars in early galaxies. However, because the evolution of their luminosity as a function of redshift and Hubble type is less known than for CO, we did not use them to determine the total aperture requirement of the array.

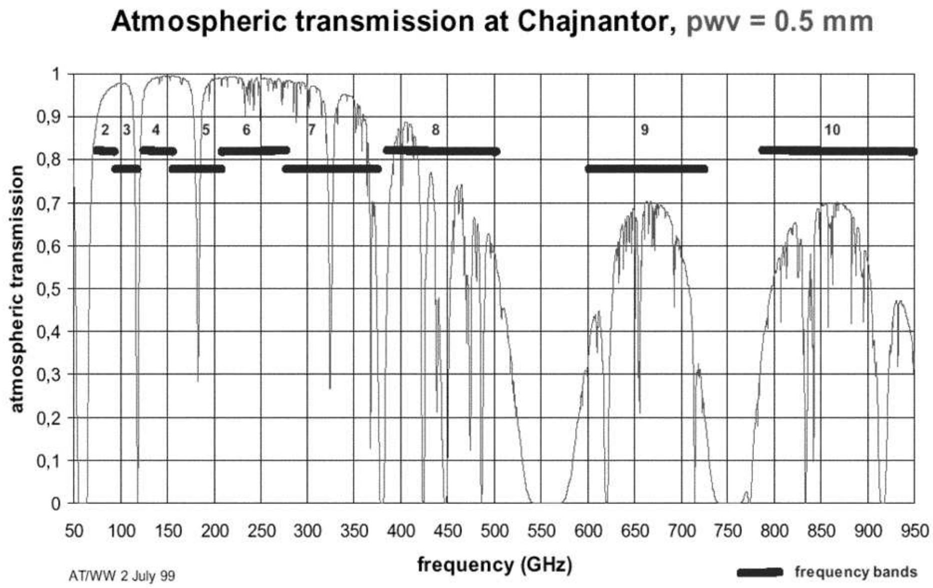

Figure 1. Atmospheric transmission at Chajnantor with the ALMA frequency bands indicated. Initially, only bands 3, 6, 7 and 9 will be used .

1.2. Precise high-resolution imaging

The requirement for ALMA to obtain precise images at an angular resolution of 0.″1 follows from the need to complement contemporary facilities such as the James Webb Space Telescope, the extended VLA, and adoptive optics imaging on large ground based telescopes.

To obtain high fidelity images with an interferometer requires a sufficient number of baselines to adequately cover the uv plane. To reach such excellent images limited by dynamic range requires that 50% of the (u, v) cells be filled (Morita, 1996). This fraction of occupied cells (FOCC) is calculated out to the longest array baselines. The FOCC is a function of hour angle coverage. Obviously, one would like to observe sources within a limited hour angle range to avoid large system temperature variations that would corrupt the images. Especially in the submillimetre windows, such variation limit the hour angle coverage to approximately 2 hours. Holdaway *et al.* (1998) presents a detailed analysis of the variation of FOCC as a function of array configuration and hour angle coverage. To achieve an FOCC>0.5 in a configuration with a maximum baseline of 3000 m in 2 hours of hour angle coverage requires a collecting length ND >560. This can be achieved with the ALMA array of 64 12 m antennas.

As for any array, ALMA will also be prone to the short spacing problem. Because one cannot measure the smallest spatial frequencies, below approximately the antenna diameter, the interferometer will not be sensitive to sources more extended than ∼2/3 of the primary beam. A key requirement of ALMA is therefore the ability to observe in total power mode. To reach a similar S/N level in total power would require 4 antennas optimized for total power measurements (using a nutating secondary), each observing 4 times longer than the array (hence only 25% of the projects will have total power information).

Even after the combination with the total power data, there will still be a gap in the uv plane, located in a ring of approximately half the antenna diameter. This gap will be filled in by the Atacama Compact Array, a set of twelve 7 m antennas.

2. DETAILED REQUIREMENTS OF ALMA

To achieve the above science requirements requires a reconfigurable array covering baselines from a few meters up to several kilometers, observing in all the millimeter and submillimeter windows (Fig. 1). The 12 m diameter of the antennas is driven by the required pointing and surface accuracy. Additionally, the ALMA antennas will be equipped with water vapor radiometers to measure atmospheric pathlength variations. Together with a fast switching technique, this will minimize the image distortions caused by phase variations.

Given the diverse scientific community to be served by ALMA, the final major requirement of is that ALMA should be an easy by non-experts. Automated image processing will be developed and applied to most ALMA data, with expert help available for intricate experiments. Table 2 summarizes the requirements of ALMA.

Table 2. Requirements of ALMA

Requirement	Specification
Frequency	all atmospheric windows between 30 and 950 GHz (Fig. 1)
Bands	10 bands; initial priority to band 3=84–116 GHz, band 6=211-275 GHz, band 7=275–373 GHz and band 9=602–720 GHz
Tunability	possible completely across all observable windows
Spectral resolution	sufficient (0.01 km/s) at 100 GHz to resolve thermal line widths
Intraband tuning	within 1.5 s
Interband tuning	within 1 minute; within 1.5 s if standby
Dynamic range	spectral: 10000:1; imaging: 50000:1
Flux sensitivity	sub-mJy point source at all frequencies within 10 min under median atmospheric conditions
Site	Llano de Chajnantor at 5000 m altitude
Antennas	64 antennas of 12 m diameter
Antenna surface	rms deviations of 25 μm from ideal
Receivers	close to quantum limited
IF bandwidth	8 GHz per polarization in continuum mode
Dynamic scheduling	optimization following scientific priority and required/current conditions
High fidelity	on spatial scales of degrees to $0\farcs01$
Total power	4 antennas equipped with nutating subreflectors
Configurations	continuous from within 150 m to maximum baseline of 18.5 km
Pointing	accurate to $0\farcs6$ using reference pointing
Antenna locations	determined to 65 μm
Phase corrections	corrected phase visibility fluctuations not to exceed 1 radian at 950 GHz
Amplitude fluctuations	$<$3% at 300 GHz and $<$5% at higher frequencies
Polarization	all polarization cross-products measured simultaneously
Polarized flux error	$<$0.1% of total intensity for V=0 source
Polarization position angle	better than 6° for linear polarization
Calibration	accurate to 3% below 300 GHz and 5% at higher frequencies. Absolute calibration to 5%.
Solar	it shall be possible to observe the Sun at all frequencies
Software	preparation, scheduling and reduction software provided by ALMA
Data reduction	pipeline with minimal input from astronomer for most projects

3. POSSIBLE EXTRAGALACTIC PROGRAMS

In order provide a set of high-priority ALMA projects that could be carried out in ∼3–4 years of full ALMA operations, a Design Reference Science Plan (DRSP) has been set up. The DRSP contains 128 projects[1] written by 43 experts in four scientific categories (Galaxies and Cosmology, Star and planet formation, Stars and their evolution, Solar system). These projects assume the full array of 64 antennas, which will be available by 2012. The scientific goals will of course evolve over time, so these projects may become slightly outdated by this time. The main goal of the DRSP is to serve as a quantitative reference for developing the science operations plan, for performing imaging simulations, and for software design. These provide a useful overview of ALMA's capabilities in these four domains. The DRSP does **not** form the basis for any definition of ALMA early science observing programs, nor for any claims on key or other projects. Here we illustrate an example extragalactic project doing molecular line studies of submm galaxies.

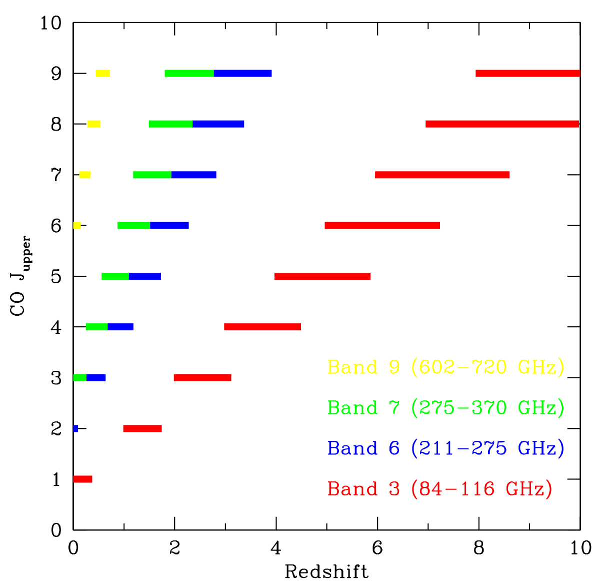

Figure 2. The redshift coverage within the initial four ALMA frequency bands of the different rotational transitions of ^{12}CO as a function of redshift. Note that at each redshift, there will be at least one CO line that can be detected with ALMA. At $z > 3$, one can even detect two transitions within band 3.

The discovery of a significant population of dusty star forming galaxies at high redshift from deep (sub)mm surveys made with the SCUBA and MAMBO bolometer arrays has transformed our knowledge of galaxy formation (*e.g.* Smail, Ivison, & Blain, 1997; Greve *et al.* , 2004). These sources make up at least half of the FIR/submm background (Hauser *et al.* , 1998). A significant fraction (of order 50%) of star formation in the cosmos occurs in these galaxies that are heavily obscured by dust. The optical/near-IR identification is extremely time-consuming, and often requires ultra-deep radio maps to narrow down the large positional uncertainty of the (sub)mm positions (Ivison *et al.* , 2002; Dannerbauer *et al.* , 2004). As a result, the redshift distribution is still not properly determined, although the median redshift is claimed to be close to $\langle z\rangle \sim 2.4$ (Chapman, *et al.* , 2003).

ALMA will not only provide sub-arcsecond resolution images of these sources, solving the optical identification problem, but will also allow to bypass the optical spectroscopy altogether. The limited bandwidth of present-day mm interferometers means that accurate optical redshifts are needed before one can confirm the redshift by observing the CO lines (Neri *et al.* , 2003). The 2×4 GHz bandwidth of ALMA allows one to detect at least one CO transition in three frequency settings between 90 and 116 GHz (Fig. 2). A second search will then be required to confirm the redshift. The two CO lines will also provide estimates of CO excitation conditions. For sources with 850 μm continuum flux densities of 1 mJy (which would be found with second generation bolometer arrays such as SCUBA-2/JCMT or LABOCA/APEX), ALMA would have a solid detection in <2 hours integration time per source, so it is feasible to observe a representative sample of 50 sources in 100 hours. These sources can the be followed up with high resolution CO images to determine their composition (many sources are expected to be in mergers), and to derive dynamical mass estimates from their velocity profiles (*e.g.* Genzel *et al.* , 2003). Such studies require only 1 hour per source, compared to 24 hours or more for brighter sources known today. Finally, the HCN line, which is typically 10× fainter than CO will be detectable in about 10 hours with ALMA. This will provide a much better tracer of the dense gas feeding the star-formation in these galaxies.

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ALMA: GALAXIES AND AGN

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ABSTRACT

With the ability to see into optically obscured regions with more than an order of magnitude better sensitivity and spatial resolution relative to current (sub)mm telescopes, ALMA will provide a unique look into the physics of galaxy formation and active galactic nuclei. In this paper I summarize the ALMA potential for studying star forming galaxies and active galactic nuclei from the nearby universe to the epoch of formation of the first luminous objects.

Key words: galaxies: radio, mm, IR; AGN.

1. INTRODUCTION

Studies of the cosmic 'background' radiation at optical through far infrared wavelengths show two peaks of roughly equal power (Franceschini 2001). This background is not a true (ie. diffuse) background, like the CMB, but arises from the summed light from galaxies throughout the universe. The optical peak corresponds to direct starlight, while the peak in the FIR corresponds to star light that has been reprocessed by dust. While such 'background' calculations compress a tremendous amount of information, the basic fact that the FIR and optical peaks are of similar strength implies that roughly half the star light in the universe is absorbed by dust and re-emitted in the infrared.

Far-IR through radio telescopes have the ability to see through the dust in galaxies, into the regions of most active star formation. An excellent example of the affect of dust on our view of 'galaxy formation' in the nearby universe is the galaxy IC 342 at a distance of 2 Mpc. Figure 1 shows an overlay of the optical, mm continuum, and CO emission from IC 342 (Meier & Turner 2004). The optical emission is dominated by a young star cluster at the galaxy center. However, the mm continuum (corresponding to thermal emission from warm dust) and molecular gas emission both peak at the ends of the inner bar, indicating the sites of most active star formation. These regions are highly obscured by dust in the optical.

Moving to high redshift, perhaps the best example of dust-obscured galaxy formation is the brightest submm galaxy in the Hubble Deep Field – HDF850.1 (Hughes et al. 1998; Downes et al. 1999). Figure 2 shows the overlay of the optical and mm images of this field. Accurate radio interferometry has shown that there is no optical counterpart to HDF 850.1 down to the limit of the HDF. Subsequent imaging in the near-IR has found a faint, red source (K = 23.5; I-K > 5.2) at the radio/mm position, likely corresponding to a $z > 3$ star forming galaxy (Dunlop et al. 2004). If so, the intrinsic IR luminosity is $\sim 7 \times 10^{12}$ $L_\odot$, with a star formation rate of a few thousand $M_\odot$ year^{-1}. Perhaps most impressively, this single source (as opposed to 10^4 optical galaxies) could potentially dominate the cosmic star formation rate density at $z > 2$ in the HDF (Hughes et al. 1998).

A complementary viewpoint of the affect of dust on our understanding of galaxy formation at high redshift is the study by Adelberger (2001) of the UV through IR SEDs of high redshift galaxies. He finds that selection at rest frame uv wavelengths (ie. uv-dropouts or Ly-break galaxies) is a very sensitive means of finding high redshift galaxies, to well below L_*. However, he finds little correlation between uv luminosity and bolometric luminosity. In other words, the higher luminosity galaxies are also more heavily dust-obscured, such that, while uv selection may find most of the star forming galaxies at high redshift, the presence of dust complicates the physical analysis of the cosmic star formation rate from uv selected samples.

2. ENABLING TECHNOLOGIES

Telescopes such as ALMA and Herschel are being designed to study dust obscured galaxy formation throughout the cosmos. What are the principle technological advances for ALMA that will lead to major advances in the study of galaxy formation?

The most important advance for ALMA will be the two orders of magnitude increase in sensitivity over existing mm arrays. Figure 3 shows the continuum spectrum of the active star forming galaxy Arp 220 in

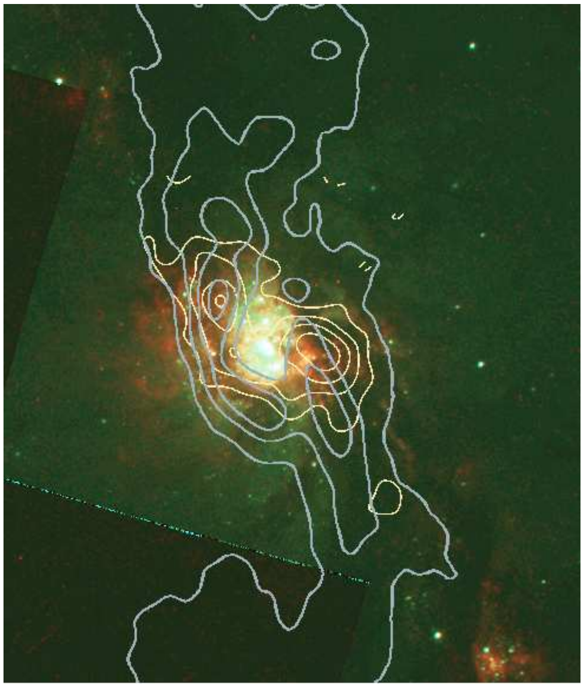

Figure 1. Images of IC342 in the optical (color), CO 1-0 (grey contours), and mm continuum (white contours; from Meiers & Turner 2004). The mm continuum peaks indicate the regions of most active star formation, at the ends of the inner bar, are optically obscured.

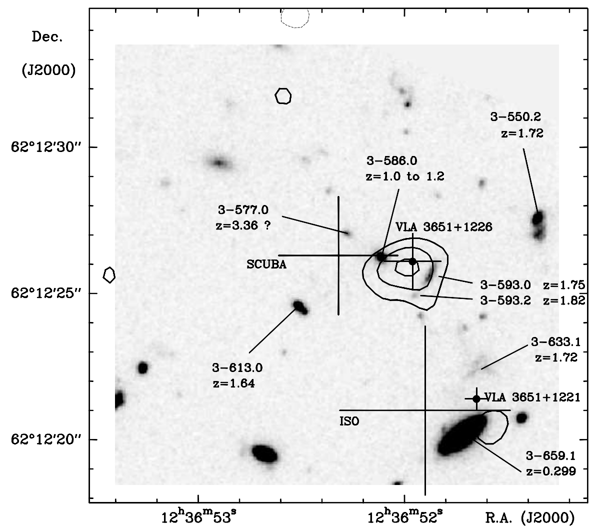

Figure 2. The contours show the PdBI image of the brightest (sub)mm source in the Hubble Deep Field, HDF850.1 (Downes et al. 1999), and the greyscale is the HST image. Accurate astrometry shows that the submm source has no optical counterpart to the depth of the HDF.

the radio through IR range, redshifted to z=2,5, and 8. Also shown are the sensitivities of some current, or near-term, instruments, as well as ALMA. Current mm arrays such as the Plateau de Bure interferometer and CARMA can, and have, detected ultra-luminous infrared galaxies (ULIRGs, $L_{IR} > 10^{12}$ or star formation rates > a few hundred $M_\odot$ year^{-1}) to very high redshifts, assisted by the large 'inverse-K' correction on the Rayleigh-Jeans side of the dust spectrum. This large inverse-K correction can be seen in the submm part of the spectrum in Fig. 3, where the flux density of Arp 220 at a fixed observing wavelength is roughly constant for redshifts from 0.5 to 8. Such ULIRGs are rare in the nearby universe, and are certainly not representative of what may be the normal star forming galaxy population at high redshift, such as the Ly-break galaxies, for which star formation rates are typically well below 100 $M_\odot$ year^{-1} (Adelberger 2001). The radical increase in sensitivity afforded by ALMA will enable study of even dwarf starbursts ($\sim$ 10 $M_\odot$ year^{-1}) out to extreme redshifts.

Figure 3 also shows the complementarity of ALMA with planned facilities at other wavebands, such as the Square Kilomter Array and the JWST. Future instruments will provide a pan-chromatic view of star forming galaxies to extreme redshifts, into the epoch of 'first light' in the universe (see section 5). Each of these wavebands provides unique probes of the galaxy formation process, from the non-thermal emission from star forming galaxies and AGN at cm wavelengths, through the dust and molecular gas at mm and submm wavelengths, to the stars, ionized gas, and AGN in the near-IR.

The second enabling technology for studying galaxy formation with ALMA is the nearly two orders of magnitude improvement in spatial resolution over existing connected-element mm arrays. Figure 4 shows the 'Walker diagram' of angular resolution vs. frequency for cm and mm arrays. ALMA will provide a resolution down to 10's of milliarcsecs at 100's GHz, with brightness temperature sensitivity below 1 K. This increase will reveal star formation on scales of Giant Molecular Clouds (GMCs) out to 200 Mpc distances.

3. SOME CURRENT EXAMPLES AND WHERE ALMA WILL TAKE US

3.1. Nearby galaxies

Consider the recent 'state-of-the-art' multi-transition study of molecular gas in the very nearby star forming galaxy IC342 by Meier and Turner (2004). Through detailed studies of both low and high density gas tracers, as well as other physical diagnostics such as photodissociation region tracers, they were able to delinate the complex star formation processes throughout the disk, bar, and nucleus of IC342 down to GMC scales. These processes include dense gas associated with the most active star forming regions at the ends of the inner bar, as traced by eg. HC_3N emission, and PDR regions associated with the central star cluster, as traced by C_2H.

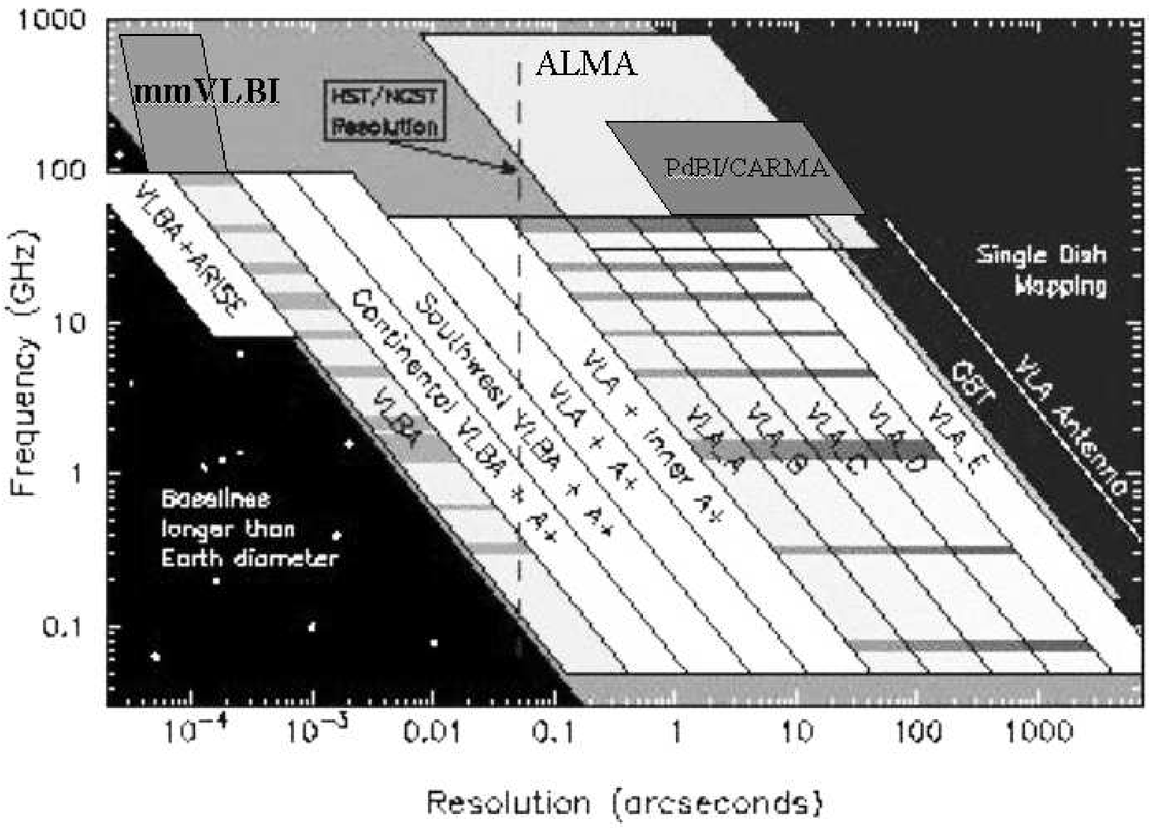

Figure 4. The 'Walker' diagram of resolution vs. frequency for current and future radio and mm telescopes.

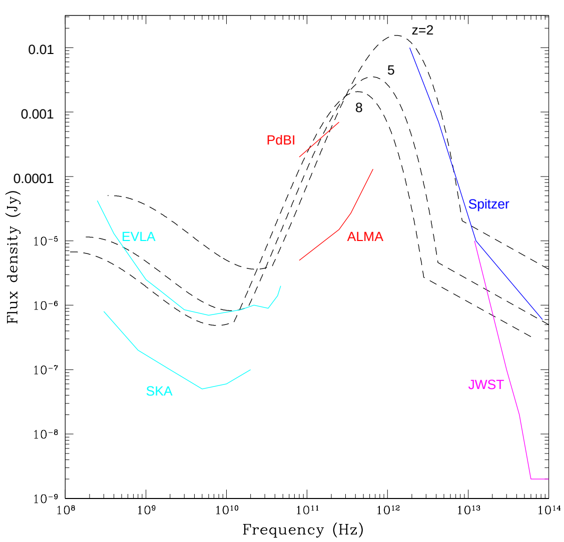

Figure 3. The dash lines show the spectrum of the active star forming galaxy Arp 220 ($L_{FIR} = 1.3 \times 10^{12}$ $L_\odot$) at three redshifts ($z = 2$, 5, 8). The solid lines show the rms sensitivity of current and future instruments (in one transit) at cm through near-IR wavelengths.

Similarly telling probes of gas dynamics on GMC scales in galaxies have been obtained by Schinnerer et al. (2004) in NGC 6946 at 5.5 Mpc distance. These PdBI observations of CO 2-1 emission at 0.5$''$ resolution show clear signatures of changing gas dynamics, and likely nuclear gas 'feeding', in the inner 10's of parsecs.

The important point is that these studies require physical resolutions on scales of GMCs, and currently we are limited to galaxies not far beyond the local group (< few Mpc). ALMA will provide the resolution and sensitivity to extend these studies out to 200 Mpc distance, encompassing rich clusters such as Virgo and Coma, as well as extreme starburst galaxies, such as Arp 220 and MRK 273, and luminous AGN, such as Cygnus A, M87, and MRK 231.

3.2. High redshift galaxies

Studies of the evolution with redshift of the cosmic star formation rate density (eg. Blain et al. 2002) show a peak in the range $z = 1.5$ to 3. One of the unanswered questions in this regard is the effect of dust on this critical inventory of galaxy formation. Unfortunately, current submm observations are limited to only the most extreme systems at these distances (Fig 3). ALMA will push down to flux densities of 10's of μJy, ie. to normal star forming galaxies at high redshift (star formation rates $\sim$ 10's $M_\odot$

year^{-1}), with sufficient resolution to avoid confusion limits that plague single dish observations (Figure 5). At this level the (sub)mm source counts are comparable to the optical galaxy density observed in the HDF (few$\times 10^6$ deg^2). The key point is that deep ALMA and optical surveys are clearly complementary, with optical surveys dominated by galaxies at lower redshift ($z \leq 1$), and ALMA surveys revealing dusty star forming galaxies at higher redshift ($z > 1$).

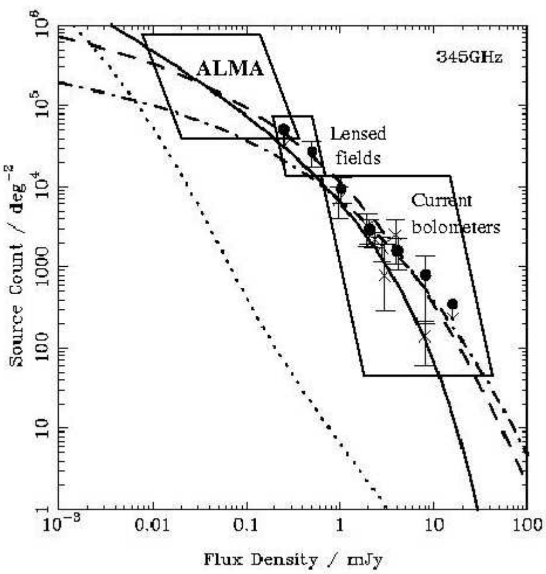

Figure 5. Source counts at 350 GHz (from Blain et al. 2002).

In terms of molecular line studies, Cox (this volume) summarizes the current situation for CO observations of low and high redshift galaxies. He shows the clear correlation between FIR luminosity and CO luminosity for low redshift galaxies, consistent with a powerlaw of index 1.7 (Gao & Solomon 2004; Beelen et al. 2004; Carilli 2004). The high redshift sources, which by necessity are also the highest luminosity, are also shown, and interestingly, the high z sources continue the correlation to higher luminosity. Most of these sources host known AGN, and yet they follow the same correlation of L_{FIR} vs. L'_{CO} as the low z star forming galaxies. This correlation could be used to argue that star formation is still the dominant dust heating mechanism in the high z sources (ie. coeval starburst and AGN).

The second strongest molecular line emission from star forming galaxies is from the HCN molecule (Gao and Solomon 2004), with the HCN emission typically being about 10% that of the CO luminosity, although this fraction increases with increasing IR luminosity. Figure 6 shows the L_{FIR} vs. L'_{HCN} correlation for nearby galaxies, plus some recent measurements of high redshift galaxies using the VLA (Carilli et al. 2004; Solomon et al. 2004). HCN is in important diagnostic, tracing dense gas directly associate with star forming regions (critical density for excitation $\sim 10^5$ cm^{-3}), as opposed to CO which traces all the molecular gas (critical density for excitation $\sim 10^3$ cm^{-3}). Interestingly, the HCN - FIR correlation is linear (power-law index = 1), unlike the non-linear CO-FIR correlation. This suggests that the FIR luminosity is linearly correlated with the dense gas mass associated with active star forming clouds. The high z sources generally fall along the linear correlation defined by the low z galaxies, again suggesting a similar dust heating mechanism (ie. star formation). However, a number of the high z sources have only HCN lower limits, which would allow for some dust heating by the AGN.

ALMA will push the studies of molecular line emission to the normal galaxy population at high redshift, probing to Milky way type molecular gas masses out to $z \sim 3$. Moreover, ALMA will provide sub-arcsec imaging of the gas, to probe dynamics and dark matter on kpc-scales. Modelling by Blain (2001) has shown that blind surveys by ALMA should detect 10's of galaxies per hour via their CO emission in the redshift range 0.5 to 2.5.

However, it should be noted that for dense gas tracers like HCN, ALMA will be forced to study the higher order transitions at high redshift (eg. a 90 GHz observing frequency corresponds to HCN 5-4 at $z = 4$). It is possible (likely?) that these transitions are sub-thermally excited due to the very high critical densities involved. In this case, study of the dense gas tracers at high redshift may be better done using large area cm telescopes working in the 20 to 50 GHz range, such as the EVLA, and eventually the SKA (Carilli & Blain 2003).

One area where ALMA will clearly make fundamental breakthroughs is in the study of the ISM submm cooling lines, such as C+ and CI (van der Werf 1999, Papadopoulos et al. 2004). This area has been dissapointing at high redshift, due to the relative weakness of the strength of the C+ line in galaxies with warm IR spectra (Malhotra this volume). This effect may be due to a decrease in the efficiency of photoelectric heating by charged grains in regions of high radiation fields (Wolfe 2004). By pushing down to normal galaxies, where the C+ line is expected to dominate ISM cooling, ALMA will open an exciting window into ISM physics in early galaxies.

4. COMPLEMENTARITY

ALMA will not work in a vacuum (unfortunately!), and it is important to recognize contributions from other telescopes. Indeed, this conference is meant to highlight the dual roles of ALMA and Hershel in the study of extragalactic astronomy, as can be seen in these proceedings. But in the mm regime itself, there will also be large single dish telescopes providing complentarity to ALMA as well, such as the LMT, GBT, APEX, ASTE...

One area where the single dish telescopes will contribute is through very wideband spectroscopy (up to 32 GHz). Such wide band spectra will have multiple

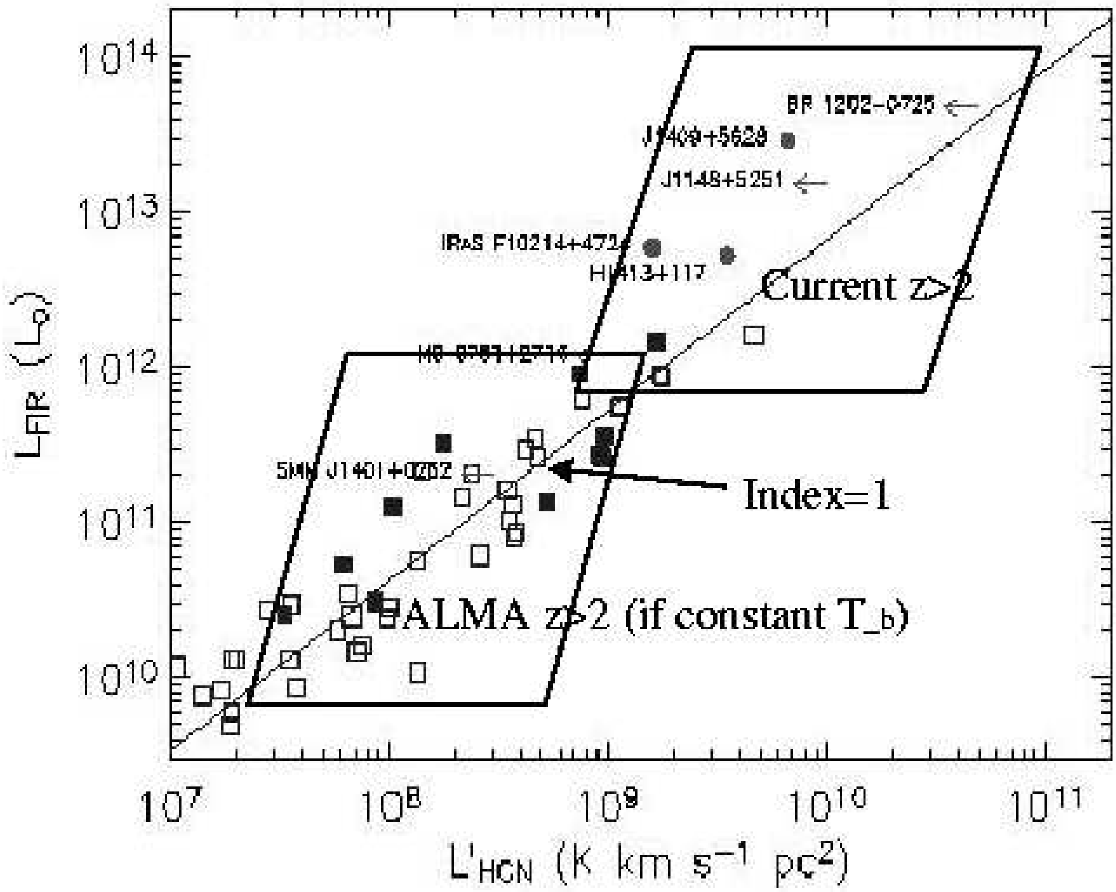

Figure 6. The correlation between FIR and HCN luminosity for low z (squares) and high z (circles) galaxies and AGN (Gao & Solomon 2004; Beelen et al. 2004; Carilli et al. 2004).

transitions of CO, C+, HCN, and other molecules in a single spectrum of a high z source, and hence provide redshifts without having to rely on optical spectroscopy.

A second area where single dish telescopes will contribute is with large format bolometer cameras doing very wide field surveys to sub-mJy sensitivity. The important point is that the small FoV of ALMA makes very wide field surveys difficult. Indeed, future bolometer cameras will be competitive with, or superior to, ALMA, in terms of survey sensitivity for fields larger that $15' \times 15'$. Hence, one can invision very wide field surveys with future sub-mm bolometer cameras, as well as with radio and far-IR telescopes, to define samples of interesting sources which can be followed-up with sensitive, high resolution observations with ALMA to study the detailed physics of the sources. Of course, for ultra-deep (μJy), narrow field studies of the submm source population, ALMA will be incomparable.

5. ALMA STUDIES OF COSMIC REIONIZATION

The discovery of the Gunn–Peterson absorption trough in the spectra of the most distant quasars ($z > 6$), corresponding to Ly α absorption by the neutral IGM, implies that we have finally probed into the epoch of cosmic reionization (EoR; White et al. 2004). The EoR sets a fundamental benchmark in cosmic structure formation, corresponding to the formation of the first luminous objects (star forming galaxies and/or accreting massive black holes). Unfortunately, G-P absorption during the EoR precludes observations of objects at wavelengths longer than 0.9 micron. Hence study of the first galaxies and AGN is the exclusive realm of near-IR to radio astronomy. The last few years has seen a revolution in the number of objects discovered at $z > 6$ using near-IR imaging and spectroscopy, including star forming galaxies (Malhotra & Rhoads 2004; Stanway et al. 2004; Hu & Cowie 2002; Kodaira et al. 2003) and AGN (Fan et al. 2003).

The recent discovery of molecular line emission, thermal emission from warm dust, and radio syncrotron

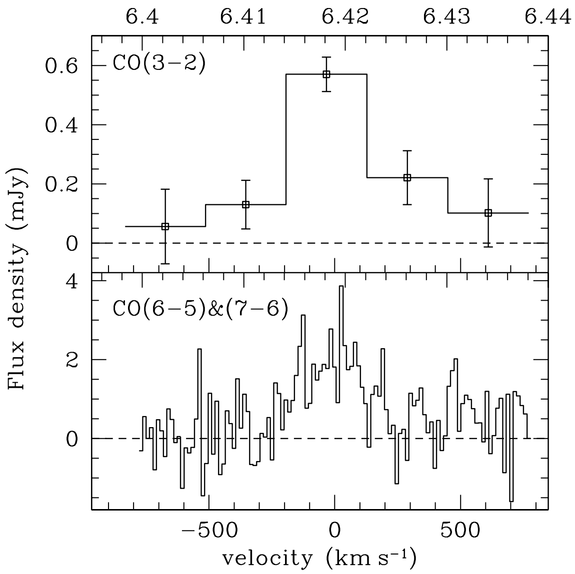

Figure 7. The CO line emission from the most distant QSO, 1148+5251 at $z = 6.42$ *(Walter et al. 2003; Bertoldi et al 2003). The 3-2 line was observed with the Very Large Array at 47 GHz, while the higher order transitions were observed with the Plateau de Bure interferometer. The implied molecular gas mass is* 2.2×10^{10} $M_\odot$.

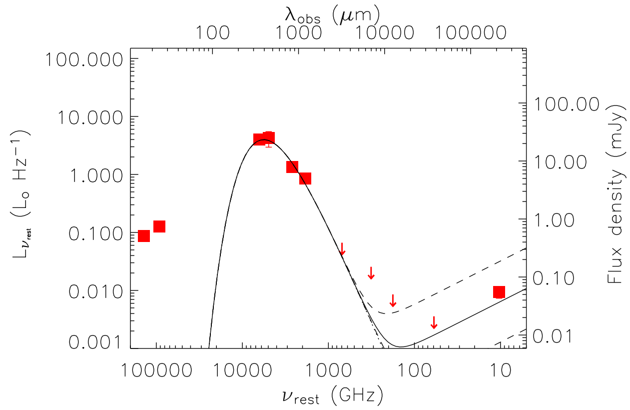

Figure 8. The radio through IR SED for the highest redshift QSO, 1148+5251 at $z = 6.4$ *(Beelen et al. 2004). The curve shows the expected SED for a star forming galaxy.*

emission, from the most distant QSO 1148+5251 at $z = 6.4$ (Bertoldi et al. 2003a,b; Walter et al. 2003; Carill et al. 2004), implies very early enrichment of heavy elements and dust in galaxies, presumably via star formation, within 0.8 Gyr of the big bang (Figure 7). The presence of a massive starburst in the host galaxy of 1148+5251 is supported by the observed radio-FIR SED (Figure 8), which follows the radio-FIR correlation for star forming galaxies, with an implied star formation rate of order 10^3 $M_\odot$ year^{-1} (Beelen et al. 2004). Likewise, high resolution imaging of the CO emission shows that the gas extends over ≈ 1", with two peaks separated by 0.3", suggesting a merging galaxy system (Figure 9). HST imaging shows that the optical QSO is associate with the southern CO peak (White et al. 2004). And from the gas dynamics, Walter et al. (2004) conclude that the supermassive black hole forms prior to the formation of the stellar bulge in the earliest AGN host galaxies.

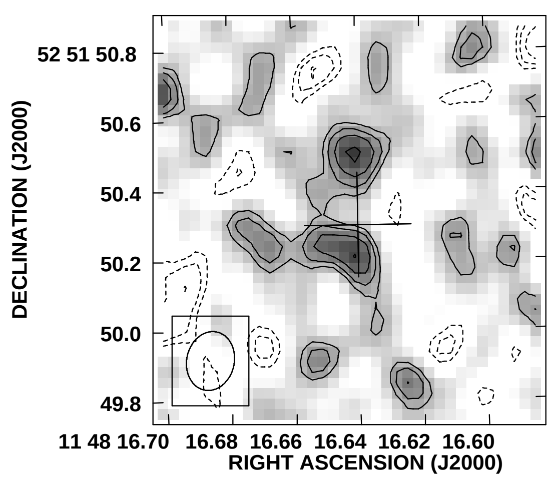

Figure 9. A high resolution (0.15") VLA image of the CO 3-2 emission from the highest redshift QSO, 1148+5251 at $z = 6.4$ *(Walter et al. 2004). HST imaging of the optical QSO shows that it is associated with the southern CO component (White et al. 2004).*

These studies of 1148+5251 demonstrate the power of mm line and continuum studies of the earliest galaxies and AGN. Unfortunately, the observations of 1148+5251 stretch current instrumentation to the extreme limit, such that only rare and pathologic objects are detectable, ie. hyperluminous IR galaxies with $L_{FIR} > 10^{13}$ $L_\odot$. The two orders of magnitude increase in sensitivity afforded by ALMA will enable study of the molecular gas and dust in the first 'normal' galaxies within the EoR. Such studies will reveal the physics and chemistry of molecular gas reservoirs required for star formation, and provide a unique probe of gas dynamics and dynamical masses of the first galaxies. In parallel, radio continuum studies with nJy sensitivity in the frequency range 1 to 10 GHz with the EVLA and, eventually, the SKA, will present a dust-unbiased view of star formation in these systems.

As a concrete example of the types of objects that might be studied, consider the galaxies being discovered in Lyα surveys at $z \sim 6$. The typical UV luminosity is a few$\times 10^{10}$ $L_\odot$. Making the standard factor five dust correction for typical high redshift star forming galaxies (ie. Ly-break galaxies) implies an FIR luminosity $\sim 10^{11}$ $L_\odot$. The predicted thermal emission from warm dust at 250 GHz is 25 μJy, which can be detected at 4σ with ALMA in one transit (6hrs). We expect one or two of these objects in every ALMA FoV.

Lastly, an important aspect of the molecular line observations of galaxies within the EoR is that they give the most accurate redshifts (by far) for the host galaxies. Typical high ionization broad metal emission lines from QSOs are notoriously uncertain in terms of the host galaxy redshifts, with offsets typically on the order of 10^3 km s^{-1} (Richards et al. 2002), while Ly α emission lines are affected severely by absorption. Accurate host galaxy redshifts are crucial in the calculation of the size of cosmic Stromgren spheres around objects within the EoR, since these sizes are derived from the redshift difference between the host galaxy and the on-set of GP absorption (Wyithe & Loeb 2004). The sizes of these ionized regions have been used to constrain the IGM neutral fraction (Wyithe et al. 2005), setting a lower limit to the neutral fraction of 0.1 at $z \sim 6.4$, two orders of magnitude more stringent than the lower limit set by the GP effect.

6. MILLIMETER VLBI OBSERVATIONS OF THE GALACTIC CENTER

A final program we consider is (sub)mm VLBI observations of the supermassive black hole at the Galactic center, including (phase array) ALMA as the most sensitive element in the array. Other possible elements include the LMT, CARMA, JCMT (or CSO or SMA), the HHT, PdBI, and the IRAM 30m. These observations will allow for imaging at $\sim 10\mu$as resolution, well matched to the scale of the expected general relativistic shadow of the SMBH in Sgr A* (Falcke et al. 2000).

Figure 10 shows the expected signature of the black hole on the non-thermal brightness distribution at (sub)mm wavelengths. These observations will provide the ultimate evidence for the existence of a SMBH at the Galactic center, provide a fundamental test of strong field GR, and are the most direct method for separating a Kerr (ie. spinning) from a Schwarzschild black hole. At a minimum, the sensitivity per baseline is adequate to perform model fitting on relatively short timescales (minutes), while the VLBI array itself has enough antennas to provide both closure amplitude and phases, and hence should be adequate for hybrid imaging of the GR shadow of Sgr A*. The existence of reasonable mm-VLBI calibrators (eg NRAO 530) in the vicinity of Sgr A* will allow for phase-referenced fringe fitting, although the source itself is strong enough, and the UV coverage dense enough, to allow for hybrid mapping as well.

The source Sgr A* has been detected at 220 GHz on the PdBI – Pico Veleta baseline (resolution = 300 uas) with a flux density of 2.0 Jy, and an upper limit to the size of order 100 uas (Krichbaum et al. 1998). The proposed observations will have more than an order of magnitude better resolution, more than two orders of magnitude better sensitivity, and, again, enough antennas to perform proper imaging of the general relativistic shadow of Sgr A*.

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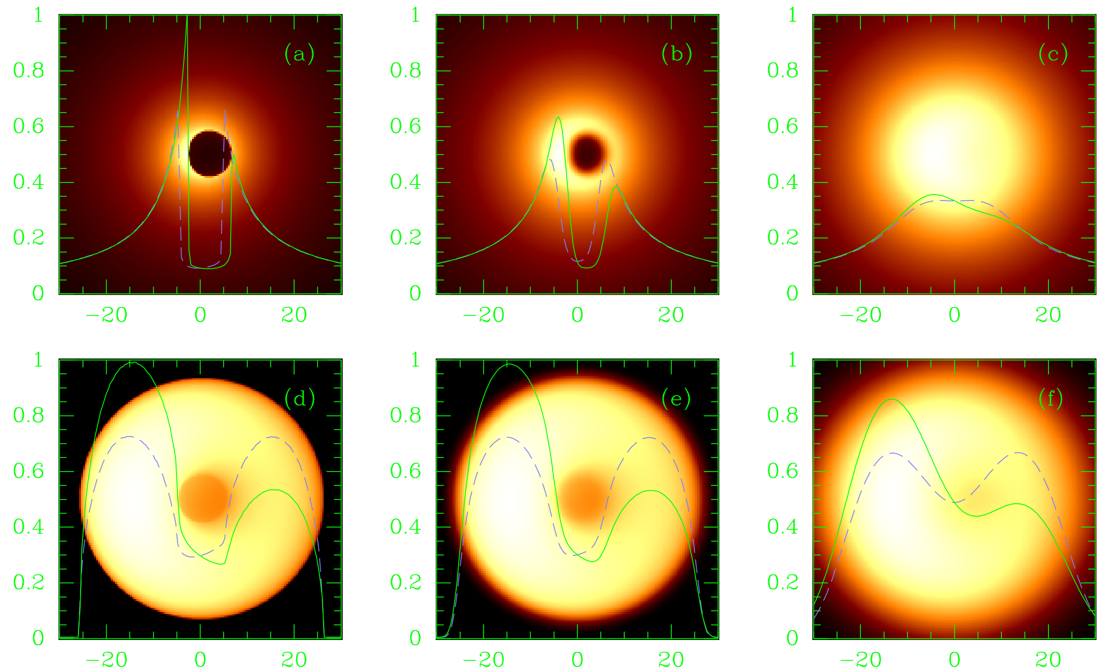

Figure 10. Simulations of the expected general relativistic shadow of the Galactic center supermassive black hole as seen in (sub)mm VLBI images at 10's μas resolution (Falcke et al. 2000). The predicted signature depends strongly on whether the hole is rotating (upper frames) or not (lower frame), ie. Kerr or Schwarzschild, since rotation affects the radius of the last stable orbit. The left frames are the model. The center frames are for observations at 0.6mm, including scattering, and the right frames are at 1.3mm. The tick marks along the X axis are in μas.

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