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The Future of mm/submm Interferometry: The ALMA Project

Stéphane Guilloteau

ALMA European Project Scientist
Institut de Radio Astronomie Millimétrique, 300 rue de la piscine
F-38406 Saint-Martin-D'Hères, France
and
European Southern Observatory, Karl Schwarzschild Str-2, Garching, Germany

Abstract. ALMA, the Atacama Large Millimeter / Sub-millimeter Array will be the first instrument allowing very high angular resolution (down to 0.01″) with sufficient sensitivity to image thermal emission from dust and molecules in proto-planetary disks at wavelengths where these disks are optically thin. Its unsurpassed characteristics will make it a premier instrument to study the formation of binary and multiple systems. I present here the projected characteristics of ALMA, in particular the expected sensitivities and frequency coverage, and illustrates some possible applications relevant to the study of binary star formation.

1. Introduction

The example of the GG Tau binary system (Guilloteau & Dutrey, this proceeding) illustrates the power of mm interferometry for the study of young binary and multiple systems. Although the stars themselves remain undetected at mm wavelengths, mm observations provide the only direct measurement of the stellar masses. This particular match of the mm domain to the study of young stellar system result from three properties. First, the circumstellar material is essentially dark and rather cold (from a few K to a few 100 K, except in the innermost regions). Second, by an appropriate coincidence, most of the abundant lighter molecules have their lower rotational lines in the mm window. Third, the interstellar dust, though only present with tiny densities, becomes easily optically thick even in the near-IR. Hence, young stars are often hidden in visible lights by their surrounding envelopes, but at mm wavelengths, the opacity becomes low enough to be able to see throughout (except perhaps in the innermost regions). A large mm / sub-mm interferometer like ALMA, which will provide unsurpassed sensitivity and angular resolution is particularly suited to the studies of these environments.

2. The ALMA Project

The ALMA project is designed to overcome the limitations of the current mm arrays, both in angular resolution and collecting power. Unfortunately, in an interferometer, an improvement in angular resolution by a factor F requires an improvement in sensitivity by a factor F^2. ALMA is intended to provide a factor 10 better angular resolution than current arrays, hence will require a 100 times better sensitivity. At these wavelengths, receivers approach the quantum limit, and the atmosphere dominates the noise. Thus, such a gain in sensitivity can only come from the detection bandwidth (for continuum, but not for spectral lines where it is limited by the Doppler width) and the collecting area. The ALMA project is the result of studies for several original projects:
- the US-MMA with a collecting area of 2000 m^2 (40 8-m antennas), emphasis on wide field imaging, and sub-mm capabilities
- the European LSA, with a collecting area of 10000 m^2 (60 15-m antennas), emphasis on high angular resolution, in the mm domain only
- the Japanese LMSA, with a collecting area of 4000 m^2 (50 10-m antennas), emphasis on sub-mm frequencies.

These preliminary studies have led to a US-European consortium which is currently studying an ALMA project consisting of:
- 64 antennas of 12 meter diameter, providing 7000 m^2 (7 times larger than the IRAM-PdB)
- 20 μm surface accuracy for the antennas to provide high efficiency at the shortest wavelengths (near 350 μm).
- 0.6$''$ pointing accuracy, to allow high quality imaging at all frequencies
- A receiver concept allowing observations at frequencies between 30 GHz and 900 GHz. 4 receiver bands, covering the 3 mm 1.3 mm, 0.8 mm and 0.5 mm atmospheric windows are foreseen in the initial complement of receivers
- A system design allowing full polarization measurements.
- Array configurations ranging from a dense, compact array of $\simeq$ 160 m diameter to an extended configuration of more than 12 km diameter. Combined with the observing frequencies, this provides angular resolution from 12$''$ to 0.006$''$.
- Wide field imaging capabilities, by the inclusion of mosaicing techniques and total power measurements.
- High detection bandwidth (16 GHz instantaneous).

Serious discussions are proceeding with Japan, which may join as an equal partner, leading to an enhanced project. This project, currently under definition may comprise in addition an array of smaller antennas to improve the wide field imaging capability, a more powerful correlator system, and more receiver bands.

Compared to current instruments, ALMA will represent a major step forward. It will be 50 to 100 times more sensitive than the IRAM-PdB for continuum observations (15 to 25 times more sensitive for spectral lines). In the sub-mm domain, ALMA will be 40 to 100 times more sensitive than the SMA. ALMA will be the first **imaging** array at mm and sub-mm wavelengths: rather than having to rely on Earth rotation for aperture synthesis, its 2048 baseline will provide snapshot images of high quality. ALMA will provide routinely angular resolutions of order 0.1$''$, and allow to reach 0.01$''$. Finally, thanks to the combination of instantaneous imaging capability and high sensitivity, ALMA will allow complete surveys to be carried out.

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In order for ALMA to stand for its promises, a number of challenges have to be overcome.

International Collaboration With the VLT, the Keck observatory, Gemini, and the LBT, the optical community has access to a large number of competing facilities. On the contrary, there will be a single ALMA. The United States (NRAO), Canada, and a consortium or organisations from many European countries (ESO member states, the UK, Spain) have joined the ALMA project. Japan is participating to the studies and expected to join ALMA in some relatively near future.

An outstanding site Since atmosphere is the main contribution to noise, it is primordial to select the best possible site to minimize its impact. The anticipated site is Llano de Chajnantor in the high Atacama desert in Chile, is located at 5000 m altitude. Construction and operation at such an elevation are clear concerns.

Low Cost but High Quality Antennas Antennas will certainly be the largest industrial contribution to the project. The performance specifications are quite tight, but the cost must be kept to a minimum: the projected production cost is less than 3 M$ per antenna. To match these contradictory requirements, the ALMA project has ordered from industry two prototypes, from two manufacturers. This minimizes the technological risk, but also allow a better price control by maintaining some competition.

Large series of (excellent) receivers ALMA will be able to accomodate 10 different frequency bands, each in dual-polarisation. The total number of receivers far exceeds the receiver production of the whole world in the last 10 years. Yet, each ALMA receiver should be better than the best existing prototype today.

High frequency capabilities Although fringes have been obtained up to 450 GHz with the CSO-JCMT interferometer, no imaging has yet been performed at such frequencies. The signal between telescopes will need to be transported using optical fibers, with re-connection each time an antenna is moved, preserving the phase information.

"Blind" Adaptive Optics Even on the excellent site, the atmospheric seeing at mm and sub-mm wavelengths is of order 0.2 to $0.6''$. Obtaining the ultimate angular resolution will thus require some analogous to adaptive optics. Unfortunately, no bright source is ever available in the antenna field of view to perform such a referencing. Correction of the pathlength variations due to the atmosphere will be done in a completely blind mode, which is possible because the pathlength fluctuations are dominated by fluctuations of the water vapor content. Since water also dominates the sky emissivity variations, monitoring the sky brightness, preferably within a spectral line of water (e.g. near 183 GHz), allows to predict pathlengths fluctuations.

Huge data rate ALMA will have a large number of baselines and spectral channels. The minimum dump time is setup by Earth rotation, and is only of a few seconds. Hence the typical data rate for ALMA is of order 100 GBytes/hour, and can be even larger for specific experiments such as on-the-fly mosaicing.

An "All Purpose" instrument ALMA will cover very different areas of Astronomy. Hence, it must be designed to be easy to use for any astronomer. The design goal is to provide an instrument delivering high quality images just as easily as a simple camera. While the simple applications (mm frequencies,

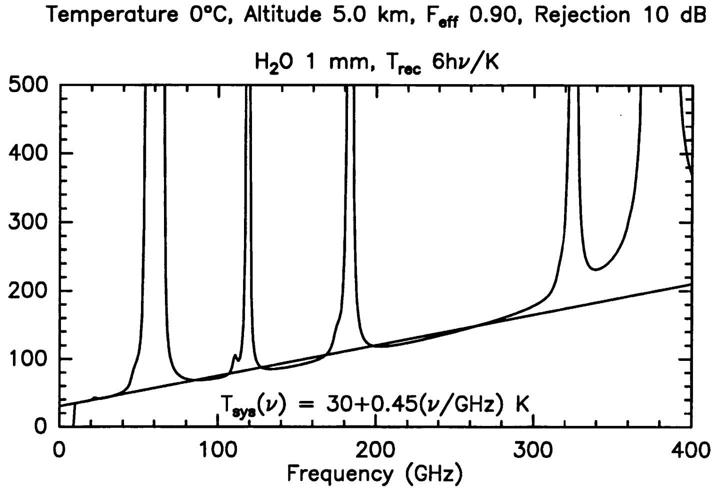

Figure 1. Typical system temperatures for ALMA in the millimeter range.

narrow field of view) can already be automatically treated by current softwares, the more complex images (high frequencies, mosaics) will require advances in image processing. The simplicity of the user interface will also be an important issue.

3. ALMA and Multiple Stellar System Formation

The expected system temperature as function of observing frequency are given in Figure 1 and 2, with reasonable assumptions about the receiver performances (not too optimistic, but not too conservative either) and atmospheric conditions. The expected sensitivity in flux density can be derived using the classic interferometer noise formula

$$\Delta S_\nu = \frac{\mathcal{J}}{\eta} \frac{T_{\rm sys}}{\sqrt{n(n-1)\Delta\nu}} \tag{1}$$

where $\Delta\nu$ is the observing bandwidth, t the integration time, n the number of antennas, and $\mathcal{J}$ is the antenna gain (Jy per Kelvin) given by

$$\mathcal{J} = \frac{2k}{\eta_a A} \approx 33 \mathrm{Jy/K} \tag{2}$$

η_a being the aperture efficiency and A the area of one antenna. In Eq.1, η is an efficiency factor including atmospheric decorrelation, quantization efficiency, instrumental phase noise, etc... The **brightness sensitivity** can be derived from the flux density and synthesized beam width θ by

$$\Delta S = \frac{2k\pi\theta^2}{\lambda^2} \Delta S \tag{3}$$

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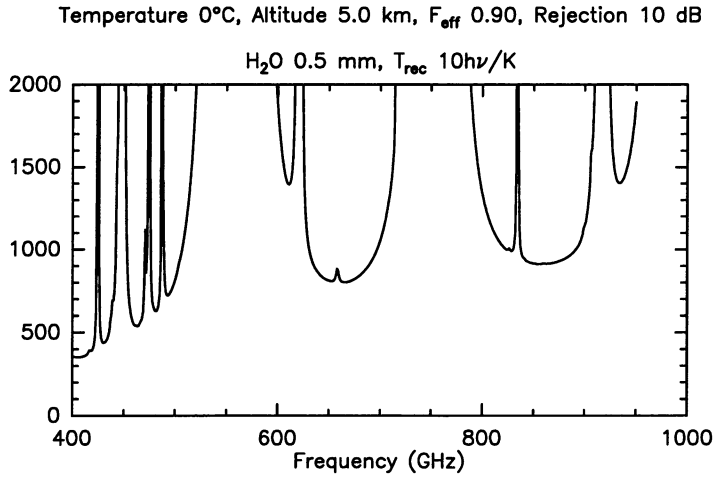

Figure 2. System temperatures for ALMA in the sub-millimeter range, for a precipitable water vapor content of 0.5 mm. Such conditions are expected about 20 % of the time.

Plugging into Eq.1 the numbers from Fig.1 and 2 gives sensitivity of 10μJy in 1 hour at 230 GHz, corresponding to 0.23 mK in brightness for 1″ resolution, and 0.5 K for the highest possible resolution (0.025″). At 900 GHz, the sensitivity in 6 hours is $\simeq$ 40μJy, or 1.2 K at 0.007″. These numbers have to be compared to the typical surface brightness for dust emission, 0.1 to 10-100 K, as in Fig.3.. Figure 3. presents the sensitivity in line and continuum compared to the expected brightness for a "representative" circumstellar disk at a distance of 150 pc. ALMA will be able to compare molecular emission to dust emission from 30 AU up to the outer edge of the disk (500 AU). In continuum, ALMA will also be sensitive to the presence of dust in the inner regions, down to 0.25 AU. A useful way of expressing the sensitivity is in terms of surface density of material. Using the typical dust emissivity for such environment, $K_\nu = 0.1(\nu/1000\mathrm{GHz})$ cm^2/g (including the mass of gas), and appropriate temperature range, e.g. 30 to 300 K, ALMA could detect surface densities of order 0.15 g/cm^2 at its higher resolution, well below the values required for giant planet formation (a few g/cm^2).

With such characteristics, ALMA will undoubtedly make a major contribution to the study of close binary systems and proto-binaries. A few examples are given below.

Binary Separation Range While current instruments have revealed circumbinary disks around binaries of 0.3 - 0.8″ separation, ALMA will be able to explore a much wider domain of binary separation, from 0.01 to 3-10″, at the smaller end because of its increased angular resolution, and at the larger end because of its high surface brightness sensitivity.

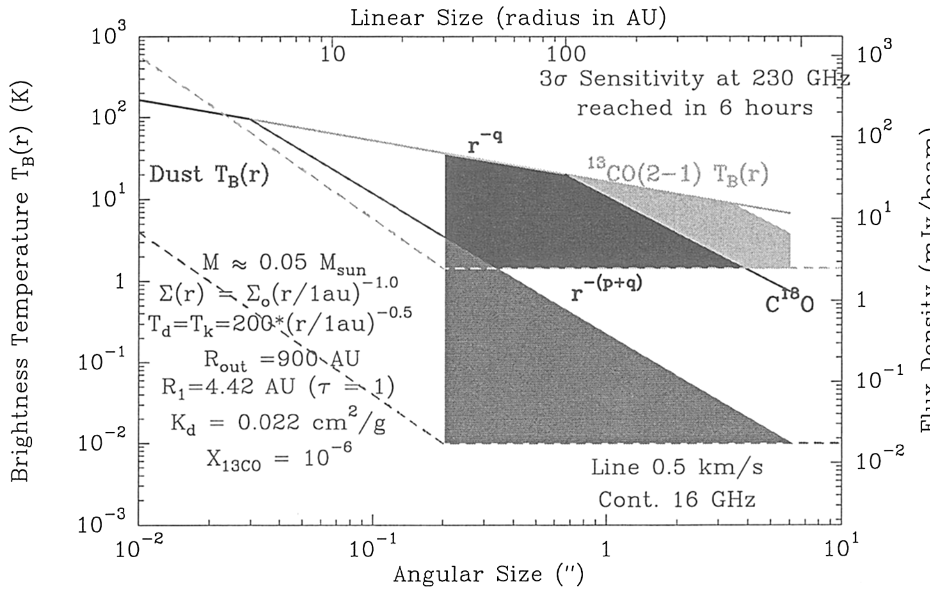

Figure 3. Brightness distribution of dust emission at 1.3mm (dark grey), ^{13}CO J=2-1 (grey) and C^{18}O J=2-1 (black) lines in a circumstellar disk. The sensitivity curves at 3σ for the continuum (dashed line in dark grey) and the lines (dashed line in grey) are given for ALMA and an angular resolution of 0.2″. The angular size (″) is scaled to the Taurus distance (150 pc) with radius in AU. The interferometer is only sensitive to disk emission above the sensitivity curves. Filled areas correspond to the regions of the disk where the emissions are detectable and resolved. See also Dutrey 2000 (in "Science with ALMA", A.Wootten ed.)

Proto Binary Statistics Since 60 to 90 % of all stars form in binary systems, this is a key in the star and planet formation process. Because it could reach regions 10 times further than current instruments, with sensitivities allowing to detect less than 0.01 $M_\odot$ of material, ALMA will be able to provide statistics on the (proto)-binary fraction in star formation regions with very different properties. Comparing, in a statistically meaningful sense, this binary fraction in very different regions, either regions of isolated star formation like Taurus, or dense clusters like Orion, will be a major clue in the understanding of the star formation process

Binary Masses Another useful number is the sensitivity for spectral line observations. For a velocity resolution of 0.15 km.s^{-1}, the expected brightness sensitivity is 3 K in 6 hours of integration at 0.1″ resolution near 230 GHz. Since the kinetic temperature in proto-planetary disks is 30-100 K or more, ALMA will be able to provide resolved images of even optically thin lines. This should allow to measure the rotation pattern in **individual** circumstellar disks around binary stars with > 0.4″ separation, like e.g. UY Aur, providing direct stellar mass estimates. Total system masses could be derived from the kinematics of the circumbinary disk.

Warps, Gaps and other tidal effects As illustrated by the case of GG Tau, mm arrays can provide clear images of tidal gaps in multiple systems. Disk warping can be detected through accurate inclination measurements, which are possible because of the kinematic information. ALMA will even allow to detect gaps created by proto-planets. Fig.4 gives a simple simulation of how ALMA would see the inner part of a circumstellar disk in which a tidal gap has been cleared by a (proto)-planet. The gap width is 1 AU, its radius 30 AU, and the gap-disk contrast 90 %. The source is assumed to be located at 150 pc. Fig.4 show that, although the angular resolution is only 4 AU, the gap is visible at 230 GHz. No noise has been added to the simulation. The expected noise level is 0.01 mJy/beam, or 0.5 K, well below the measured gap intensity, which is a few K. At higher frequencies, e.g. 690 GHz, the increased angular resolution allows to see the gap more clearly, and the expected noise level, around 1.2 K, still much smaller than expected difference between the gap and the surrounding disk. Note that this simulation is intentionally very primitive: it includes a single configuration of ALMA, so that the "large" scale structures (structures larger than $0.2''$) are not properly recovered. Inclusion of data from the more compact arrays (the 3 km ring) would avoid the resulting artifacts. Despite this simplification, the gap is nevertheless well detected.

Binary Mass Ratio & Separation Although direct mass measurements may only be possible for a small fraction of the systems, the structure of the tidal gaps indirectly reflects the binary mass ratio and separation. Since gaps would be relatively easy to detect, ALMA could provide evidence for low mass companions which would remain undetectable through direct IR/optical imaging because of the insufficient image contrast.

Streamers In a system like GG Tau, ALMA could easily detect the dusty streamers which are likely to feed the inner disks from the circumbinary disks, not only through dust emission, but also detecting molecules in such streamers. This would allow accurate determination of the mass flow rate.

4. ALMA Development and Calendar

ALMA is currently in a design and development phase until end of 2001. Funding for the construction is expected to start in 2002. The prototype antennas should be delivered to the Very Large Array site for testing at the end of 2001. A detailed costing of the project has been made, resulting in a total cost of $\sim$ 550 M$, including contingency. For such a total cost, ALMA will be equipped to cover 4 receiver bands, covering 85-115 GHz, 210-275 GHz, 275-370 GHz, and 600-720 GHz, but the dewar will be build to accomodate 10 receivers. If Japan joins as a major partner, more ambitious goals would be set to ALMA. This "enhanced" ALMA project would certainly cover most frequency bands from 30 to 900 GHz, but also perhaps be complemented by a "compact" array

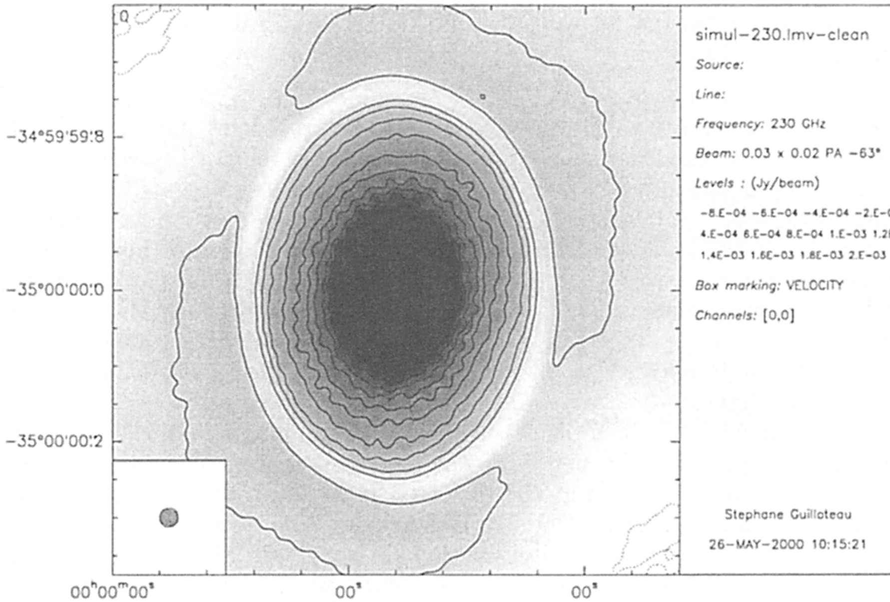

Figure 4. Simulation of a gap in a proto-planetary disk observed with ALMA at 230 GHz. Contour spacing is 0.2 mJy/beam or 10 K, about 20 times larger than the expected noise level.

to enhance its wide field imaging capability. First antennas are expected to be delivered on the site in 2005. Construction will then proceed at a rate of 8 to 12 antennas per year, depending mostly on financing aspects. With this scenario, ALMA first science operation would start near 2006, and progressively reach its full completion near 2010.

References

References on ALMA can be found in the proceedings of "Science with ALMA", edited by A.Wootten, ASP Conference series, 2000. The project description and up-to-date information are available on the WEB
at the ESO Web site, http://eso.org/projects/alma or
at the NRAO Web site, http://www.alma.nrao.edu.
The ALMA Science Case, prepared for the European proposal to ESO, can be found at http://iram.fr/ guillote/.

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