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Memorie della

The ALMA project

R. Cesaroni

Osservatorio Astrofisico di Arcetri, INAF, largo Fermi 5, 50125 Firenze, Italy
e-mail: `cesa@arcetri.astro.it`

Abstract. The need for a large interferometer operating at (sub)millimeter wavelengths has lead to the Atacama Large Millimeter Array project. A brief review of the characteristics of the instrument is given and a few applications to a selected sample of astronomical problems are illustrated.

Key words. Interferometers – High angular resolution

1. Introduction

The technological developments obtained in recent years have made possible the construction of telescopes that can access frequency ranges well beyond those traditionally used for radioastronomical observations. Instruments of this type, operating at $\lambda < 1$ cm, are single dish telescopes such as e.g. the IRAM 30-m antenna on Pico Veleta, the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO) in Hawaii, and the Heinrich Hertz Telescope on Mount Graham. In order to achieve better angular resolution, interferometers have also been constructed, among which the IRAM array on Plateau de Bure and that operated by the Owens Valley Radio Observatory (OVRO). The problem is that, unlike single dish telescopes, the interferometers mentioned above can observe only at millimpeter wavelengths: as a consequence, present day observations cannot achieve large frequency coverage (down to $\lambda < 1$ mm) and good angular resolution at the same time. The sole interferometer planned to work at shorter wavelengths is the Submillimeter Array (SMA), which has just seen the first light on Mauna Kea. The Atacama Large Millimeter Array (ALMA) project is conceived to overcome all of these problems as it will be a large sensitive interferometer operating at millimeter and submillimeter wavelengths.

2. Importance of the (sub)millimeter regime

In Sect. 6 we shall discuss possible applications of ALMA to a selection of astronomical problems, which themselves justify the effort to perform observations in a technologically challenging regime such as the millimeter and sub-millimeter ranges. However, it is worth stressing a few simple reasons which demonstrate the importance of (sub)millimeter astronomy.

The large majority of the rotational and vibrational transitions of molecules happen to fall at $\lambda < 1$ cm: as more than 1000 lines

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Send offprint requests to: R. Cesaroni
Correspondence to: cesa@arcetri.astro.it

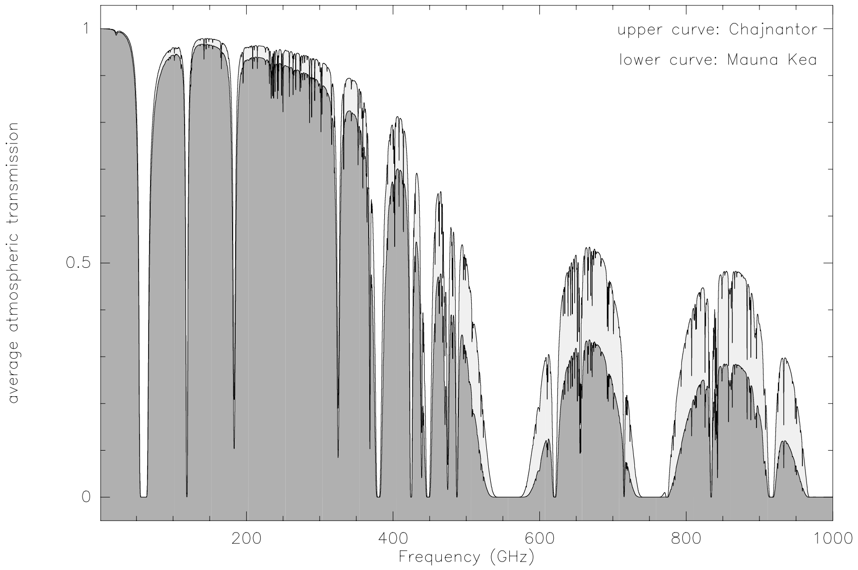

Fig. 1. Typical atmospheric transmissions at ALMA site and Mauna Kea.

have been observed to date, it is easy to realise how rich can be the information obtainable from the study of these frequency range. In particular, simultaneous observations of many different lines of the same molecular species will allow assessing the physical parameters of the emitting gas. As for the continuum emission, one has to keep in mind that most objects in the universe are "cold": from planets to the microwave background, all have emission peaking at millimeter or sub-millimeter wavelengths. It is also important to point out that the intensity of the thermal continuum from dust in molecular clouds increases roughly like $I_\nu \propto \nu^3$ approximately for $\lambda < 100\,\mu$m: this favours observations at short wavelengths. Finally, it is worth mentioning that the peak of the continuum emission of starburst galaxies is shifted towards the submillimeter range for $z > 1$: this effect fully compensates the weakening of the emission due to red-shift of the radiation, thus making the sub-millimeter regime an excellent tool to study this type of objects.

3. Need for an interferometer

The instrumental angular resolution, θ, is related to the observing wavelength and the antenna diameter, D, by the well known relation $\theta \simeq 1.2\,\lambda/D$. This implies that for $100~\mu\mathrm{m} < \lambda < 1$ cm large values of D are necessary to achieve sub-arcsecond resolutions such as those needed in many astronomical problems. For example, in order to resolve objects such as high red-shift galaxies or circumstellar disks at millimeter wavelengths, $\theta \simeq 0\farcs1$ is required, which in turn implies $D \simeq 10$ km. Obviously, diameters that large can be attained only with interferometric techniques.

On the other hand, high angular resolution sets strong constraints on the sensitivity, as the 1σ RMS noise of an interferometer is related to the maximum baseline D through the expression

$$\Delta T_{\rm B} \propto \frac{T_{\rm sys} D^2}{N\, A \sqrt{t\, \delta\nu}} \qquad (1)$$

where $T_{\rm B}$ indicates the brightness temperature measured by the instrument, $T_{\rm sys}$ the system temperature, N the number of the antennas, A the area of each antenna, t the integration time, and $\delta\nu$ the bandwidth. Clearly, the larger the baseline, the higher will be the noise. Therefore, in order to increase the angular resolution without reducing the sensitivity, large collecting areas $N\,A$ are necessary. This can be achieved either with a large number of small antennas or with a small number of large antennas. As we shall see in the next section, for ALMA the latter solution has been chosen for a variety of reasons which would be too lengthy to discuss here.

It must also be noted that another shortcoming of interferometers is that they cannot image objects larger than a maximum size which is inversely proportional to the minimum separation between the antennas: the latter, of course, cannot be less than the antenna diameter. This may be a serious problem especially at the highest frequencies, because such a maximum size can be as small as a few arcsec. A possible solution is represented by hybrid mapping, using a single dish or an additional interferometer with smaller dishes (and hence shorter minimum baselines).

4. The instrument

The ALMA project is the result of a collaboration between Europe, U.S.A., and Japan. Although the details of the instrument have still to be fixed, an approximate description can be already given (see the official web site of ALMA for more information: **http://www.hq.eso.org/projects/alma/**). ALMA will be an interferometer made out of 64 dishes with 12 m diameter, resulting in a total collecting area of 7000 m^2. Italy is contributing as a member of ESO, which leads the European consortium taking care of the project. The estimated cost will be huge (∼800 million dollars) but the exact amount – and hence the potentialities of the instrument – will depend on the effective participation of Japan which has still to fund the project.

The antennae will be equipped with 11 receivers allowing for a frequency coverage from 30 to 900 GHz and will be arranged in at least 5 different configurations with 2016 baselines each: this makes possible to adapt the instrument to the resolution and sensitivity required, depending on the astronomical problem of interest. The largest baseline length will be ∼14 km corresponding to a maximum angular resolution of $\sim 0\farcs004$ at 900 GHz. The site chosen for the interferometer is Llano de Chajnantor, at 5000 m altitude in northern Chile. The operative centre will be in San Pedro de Atacama, located at 1 hour drive from the site, at 2500 m altitude. This site is estimated to be better than Mauna Kea in Hawaii, where the JCMT and CSO are located (see Fig. 1). This is especially important at frequencies above 400 GHz where the atmospheric transmission depends critically on water vapour. Another advantage of the site is that being at a latitude of –23° it will make possible to cover the southern hemisphere which is still poorly known at (sub)millimeter wavelengths. On the other hand is is clear that given the altitude of the site, the instrument will have to resist extreme weather conditions, with occasionally strong winds and temperatures ranging from –20 to +20 C. For this reason special care has been taken of the antennas: three prototypes are currently built by EIE for Europe, Vertex for USA, and Mitsubishi for Japan. The requirements are that such antennae should be able to operate with winds up to 10 m s^{-1} and attain a relative pointing accuracy of $0\farcs6$: the latter is necessary at the highest frequencies where the half power beam width of the single antenna is as small as $7''$.

A non negligible aspect of the ALMA project will be the problems related to

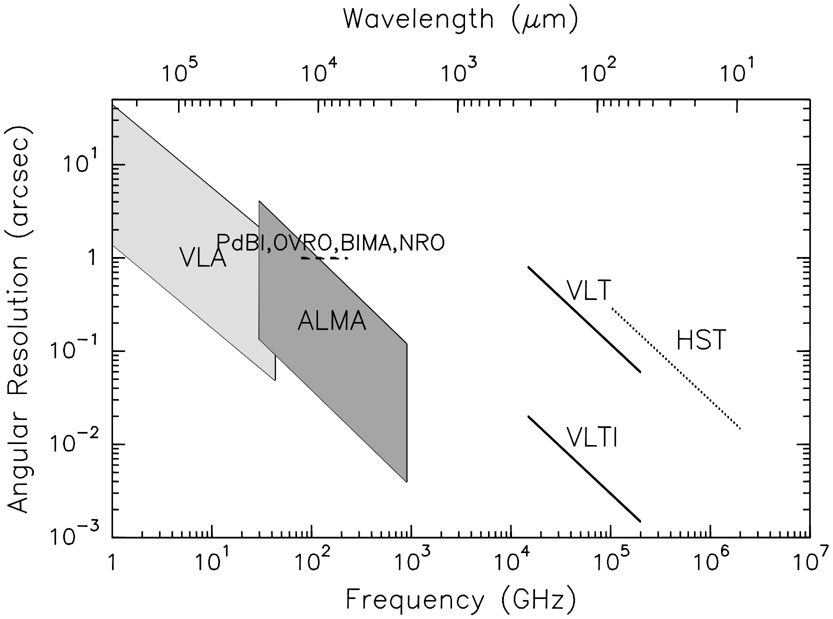

Fig. 2. Comparison between ALMA angular resolution and those of other currently operating telescopes.

proposal preparation, data acquisition, and data calibration and reduction. Given the complexity of the instrument, a simulator is strictly required to help the proposer in testing the feasibility of the observations and planning the best observational strategy to achieve the proposed goals. Also, in order to optimise the use of the observing time a highly specialised software will be developed: this should be flexible enough to adjust the observing schedule in real time, taking into account a large set of parameters such as the project priority, the weather conditions, the source visibility, etc.. Finally, a pipeline should guarantee a first-order automatic calibration and reduction of the data. The purpose of all these facilities is to make ALMA easily accessible even for users with no experience in radio astronomy.

5. Comparison with other instruments

The most relevant characteristics of any telescope are its angular resolution and sensitivity. It seems hence convenient to compare the resolution and sensitivity achievable by ALMA with those of other already available instruments. This is done in Fig. 2 for the angular resolution: clearly, ALMA will represent the extension of the Very Large Array to wavelengths below 1 cm; on the other hand, it will be complementary to telescopes operating in the IR or optical regimes with comparable resolution.

As already pointed out in Sect. 3, angular resolution is useless without a suitable sensitivity. The best way to appreciate the improvement represented by ALMA over similar instruments currently operating in the same frequency domain, is to make a comparison between ALMA and

Table 1. Ratios between some parameters of ALMA and PdBI

	T_{sys}	$N\,A$	$\delta\nu$	D
ALMA/ PdBI	1/3	7	1 (line) 20 (cont.)	1–30

the Plateau de Bure interferometer (PdBI), which is the best millimeter interferometer available to date. According to Eq. (1), the ratio between the sensitivity of ALMA and that of PdBI depends on the corresponding ratios of the parameters in the right hand side of the expression: these are given in Table 1. On this basis, it is easy to evaluate for example the relative "speed", namely the ratio between the integration times required by the two instruments to reach the same noise level. Such a ratio, $t_{\text{PdBI}}/t_{\text{ALMA}}$, can be estimated from Table 1 and the expression of t obtained from Eq. (1):

$$t \propto \frac{T_{\text{sys}}^2 D^4}{A^2 \delta\nu} \tag{2}$$

We conclude that *for the same angular resolution (i.e. D)* we find $t_{\text{PdBI}}/t_{\text{ALMA}} \simeq 500$ for line and 10000 for continuum observations. In practice, this means that ALMA will be able to produce images of the same quality as obtained now with PdBI in a time two or three orders of magnitude smaller, thus making possible, for instance, big unbiased surveys of selected regions of the sky.

Unfortunately, for the high angular resolution configurations the D^4 term in Eq. (2) overwhelms the other factors, so that longer integration times will be necessary and only the strongest sources will be detectable. In order to give an idea of how this will limit the observations, one can compute the maximum distance, d, at which a source resolved with PdBI will be properly mapped by ALMA with the same noise level, integration time, and *linear* resolution. The latter requirement implies the use of a maximum baseline $D \propto d$, so that Eq. (2) becomes

$$d \propto \frac{A^{0.5}\,\delta\nu^{0.25}}{T_{\text{sys}}^{0.5}} \tag{3}$$

which indicates that, with respect to PdBI, ALMA will image a given object up to a distance 5 (for line) and 10 (for continuum) times larger. This corresponds to increasing the number of detectable objects respectively by two and three orders of magnitude – assuming they are uniformly distributed in space.

6. Scientific goals

A large number of scientific problems may be attacked with ALMA. In the following we shall briefly illustrate a few applications to diverse fields.

6.1. Solar system

A Kuiper belt object with a 200 km diameter at a distance of 40 AU, can be easily detected as a point source by ALMA: at 230 GHz its flux would be $\sim$50 μJy, which corresponds to a 10σ detection in 1 hour.

Another application might be the study of the surface of Pluto and Charon. Their maximum separation is $0\farcs5$ and their diameters are $0\farcs14$ and $0\farcs08$ respectively. At 400 GHz the ALMA half power beam width should be $\sim 0\farcs02$, enough to resolve both bodies (see Fig. 3), and the sensitivity in 1 hour integration is $\sim$1 K, to be compared with the 39 K brightness temperature of the Pluto-Charon pair as measured with the 30-m IRAM telescope.

6.2. Extra-solar planets

Planets orbiting around nearby stars could be imaged *directly* with ALMA. For example, the Sun-Jupiter pair at the distance of α-Cen (1.34 pc) would have a separation of $3\farcs9$ and the flux at 345 GHz would be 19 mJy and 6 μJy, respectively. The integration time required (a few days) is long

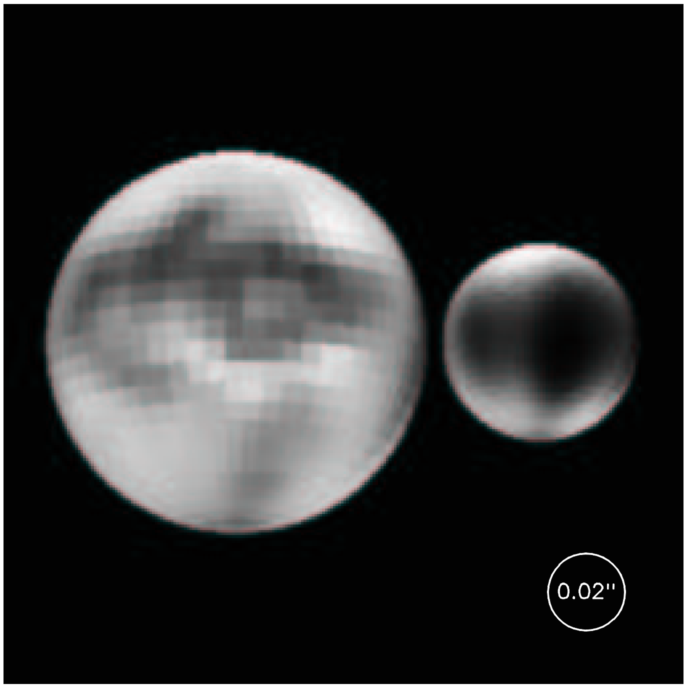

Fig. 3. Albedo distributions of Pluto and Charon obtained from mutual occultations of the two bodies with a maximum entropy method (courtesy Marc W. Buie, Lowell Observatory). The circle in the bottom right indicates to the resolution attainable with ALMA at 400 GHz.

but certainly worthwhile. Here, the problem is the high dynamic range (∼3000) required to image a faint object close to a brilliant one: the solution is represented by self-calibration which takes profit of the strong pointlike emission of the star to correct any phase error and hence reach the dynamic range needed. It has been estimated that extrasolar planets could be detected up to a maximum distance of 5 pc.

Although direct detection of the planets is expected to be challenging, it should be much easier to reveal the gaps caused by the planets in their parental disks. Numerical simulation indicate that the angular resolution attainable with ALMA will allow sampling the innermost regions (down to few AU) of the closest sources thus making possible the detection of such gaps.

6.3. Circumstellar disks

To date only few examples of circumstellar disks around young stellar objects are known and only in the case of GG Tau (Guilloteau et al. 1999) has a detailed map of the geometrical and kinematical structure on a 100 AU scale been obtained. With current interferometers, the study of these objects is limited within ∼200 pc, which in practice precludes the possibility of revealing disks around high-mass stars, given the rarity of these compared to low-mass stars: note that the nearest region of *massive* star formation, the Orion cloud, lies at 500 pc. A rough estimate of the maximum distance at which ALMA will be able to map circumstellar disks can be obtained using the discussion in Sect. 5: this should be up to ∼10 times larger than that reachable with PdBI, namely 2 kpc for disks around low-mass stars and 20 kpc for those around high-mass stars, which are expected to be an order of magnitude larger (see e.g. Cesaroni et al. 1999) and hence easier to resolve.

6.4. Circumstellar envelopes

The study of mass loss in the last stages of stellar evolution has been spectacularly demonstrated by images obtained in various molecular tracers of the onion-shell structure in IRC+10216 (Guélin et al. 1996). The spectral capabilities of ALMA combined with the high angular resolution and sensitivity will make it possible to push the investigation of the shell down to few AU from the star in many molecular transitions *simultaneously*. This will allow the study of the chemical composition of the envelope at different radii. Proper motion measurements of the shell might even be feasible: for a star at 300 pc, an expansion velocity of 15 km s^{-1} corresponds to an increase in radius of $0.''01$ in a year time: a comparison between images taken at an interval of a few years could hence furnish an estimate of the angular expansion rate: the combination of this with the radial velocity will give the distance to the source and a full 3-D description of the shell.

6.5. Extragalactic studies

CO emission has been recently detected in several high-redshift objects, such as the famous cloverleaf quasar Kneib et al. (1998) at z=2.56 and the quasar BR1202-07 (Omont et al. 1996) at z=4.69. Observations of CO at high redshifts have advantages with respect to HI, because, for example, a CO(3–2) line (rest frequency 346 GHz) redshifted to 100 GHz is $\sim 3\ 10^7$ times stronger than an HI line redshifted to 400 MHz; note also that at the latter frequency much man-made radio interference is present. Galaxies at much larger z will be detectable with ALMA: a rough estimate indicates that a galaxy like ARP220 could be visible up to z=8 in the C II 158 μm line and up to z=20 in the continuum. As for the latter, it is worth pointing out that for objects at high z the continuum peak due to warm dust emission falls just in the submillimeter range thus making ALMA the ideal instrument to study protogalaxies at $z \geq 5$.

7. Conclusions

ALMA will represent a crucial step for astronomy at 7 mm $\geq \lambda \geq$ 300 μm in the near future. Not only it will be *several* orders of magnitude more powerful than the best millimeter interferometers currently available, but it will be able to observe the *sub*-millimeter domain of the spectrum at high angular resolution, as never done before. The interest for this instrument will not be confined to the radioastronomical community, as virtually all fields of astronomical research may find applications suitable to ALMA. In this context it is also important to consider the synergy between ALMA and new generation telescopes such as the Very Large Telescope Interferometer (VLTI) or the New Generation Space Telescope (NGST), which will yield orders-of-magnitude improvements in our knowledge of important topics ranging from the formation of stars to that of galaxies. It is hence crucial that the Italian astronomical community gets involved in this project as much as possible, as it will represent an important key to the future of astronomical research.

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