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Science with ALMA

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Abstract. In this contribution I briefly describe the ALMA project and its current status and timeline. ALMA has been designed and is being built to allow to achieve transformational science in the coming decades. The combination of ALMA, the fully mature VLT/VLTI and later the E-ELT will be a unique asset offered by ESO to the european astronomical community, and an opportunity that Italy should capitalize on.

1. Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA) has been designed and is being built to become the leading ground based observatory at millimeter and submillimeter wavelengths in the foreseable future. Following the successful millimeter interferometry experiments in the 1980s, using limited number of antennas mostly located at a relatively low altitude, projects were independently proposed in Europe, North America and Japan to built new (sub)millimeter observatories capable of overcoming the limitations of low altitude, limited collective area and frequency coverage, and poor image fidelity. These plans were later merged to become the ALMA project.

The highest level science requirements for ALMA are:

1. The ability to detect spectral line emission from CO or C II spectral line emission from 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 (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), permitting the determination of their physical and chemical properties and magnetic field structures and the detection of tidal gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0.1 arcsec. Here the term precise image 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 degrees.

The ability to achieve these goals translates in an instrument design with a large collecting area ($\sim 7000\ \mathrm{m}^2$), a wide frequency coverage in the millimeter and sub-millimeter wavelength range, a large number of antennas for efficient and reliable aperture synthesis, a superb

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Fig. 1. Panoramic views of the Chajnantor plateau, the ALMA Operations Site, approximately looking to the north (top panel) and to the south (bottom panel). The altitude of the plateau is 5000 m, and it is located close to the city of San Pedro de Atacama in northern Chile. The semi-active Lascar volcano (just over 5900 m peak) is visible at the left side of the top panel.

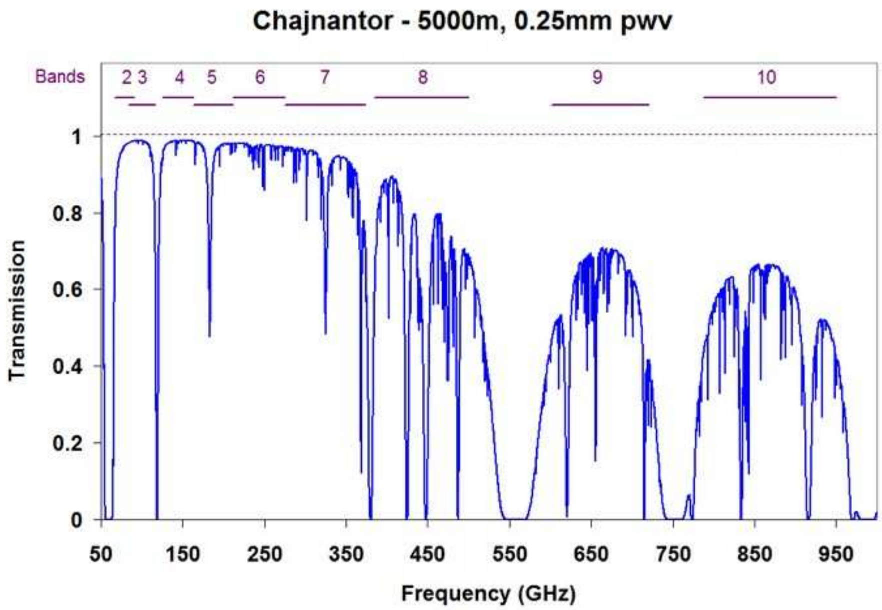

Fig. 2. Bottom panel: atmospheric transparency at the Chajnantor site in good (but not exceptional) conditions. Top panel: frequency coverage of the ALMA frequency bands.

angular resolution, and a site with favorable atmospheric conditions.

ALMA will initially consist of 54 twelve meter and 12 seven meter diameter antennas located on the Chajnantor altiplano at an altitude of 5000 m in northern Chile (see Fig. 1). The plateau offers a relatively constant altitude site for arranging the ALMA antennas in several different configurations. In the most compact configuration the longest available baseline will be of only ∼150 m, in the most extended it will be up to ∼15 km. To fully exploit the excellent conditions on the site for submillimeter observations, ten receiver bands covering all the atmospheric transparency windows from 30 GHz to 1 THz are planned (see Fig. 2). The six highest priority bands (3, 4, 6, 7, 8 and 9) will be available from the start of full science operations at the end of 2012, a decision based on the review of an ongoing R&D program is pending on band 10, and a limited number of band 5 receivers will also be available as part of an EC-FP6 funded program. The remaining frequency bands will be added to the array in a subsequent phase.

2. Transformational Science with ALMA

The combination of the excellent site, antenna and receiver quality imply that ALMA will routinely achieve sub-mJy sensitivity in the continuum in all fully available bands. The large bandwidth (8GHz) and flexible correlator will allow a wide range of spectral line applications.

With these characteristics ALMA will be one of the most versatile observatory in the world with applications ranging from observations of the Sun and Solar System objects, of stars and the interstellar medium in our Galaxy and beyond, to a probe of the formation and evolution of galaxies. The ALMA Design Reference Science Plan (Hogerheijde 2006) is a collection of almost 150 science programs that could be executed with ALMA during the first few years of full operations and it is used as a reference to ensure that the observatory will meet its scientific objectives.

The scientific programs of the worldwide astronomical community were recently reviewed and discussed at an international conference "Science with the Atacama Large Millimeter Array: A New Era for Astrophysics" (2008, Ap&SS, 313). The conference book contains a comprehensive description of many science programs that will be made possible with ALMA, here I just show two examples closely related to the ALMA top science goals and presented at the conference by Carilli et al. (2008) and Wolf (2008).

In Fig. 3 the potential of ALMA to detect molecular and atomic gas at high redshift is shown (Carilli et al. 2008). The increase in frequency coverage and sensitivity of ALMA will allow to detect and study the molecular gas at high redshift in a similar fashion as it is done today in the local universe. The [CII]$\lambda 158\mu$m line, which is expected to be the main coolant of the warm neutral ISM in galaxies, will be redshifted into the ALMA band and will be a powerful probe of the star formation rate of high redshift galaxies. For galaxies with star formation rates above ∼10 $M_\odot$/yr, this line is expected to be detectable in a few hrs with the baseline ALMA system in the redshift ranges z∼1 to 8 and beyond z∼10. When the full complement of Band 5 receivers will be installed, the line will also be detectable in the redshift range 8-10, assuming that the conditions in these galaxies is similar to what we can extrapolate from observations in the local Universe. Indeed, recent APEX and IRAM-30m observations of the [CII] line in high redshift galaxies produced very encouraging results and suggesting that the ratio between the [C II] line and far infrared luminosity in primordial galaxies may even be higher than expected (Maiolino et al. 2009). Molecular line emission from the cold ISM is expected to be fainter than for [C II] but, in a reasonable integration time, it will also be possible to study the molecular content of high redshift galaxies. As an illustration, Fig. 3 shows a simulated 24 hrs integration time ALMA spectrum for a rich molecular environment at redshift ∼6.4 (Carilli et al. 2008).

Simulated ALMA observations of a planet-forming protoplanetary disk around nearby solar mass stars are shown in Fig. 4 (Wolf 2008). The ALMA simulated observation at the highest frequency and with the longest available baselines show the effect of the protoplanet on the circumstellar disk structure and the material accreting onto the protoplanet. The simulations are for face-on disks around the nearest young stellar objects (50 and 100 pc for r

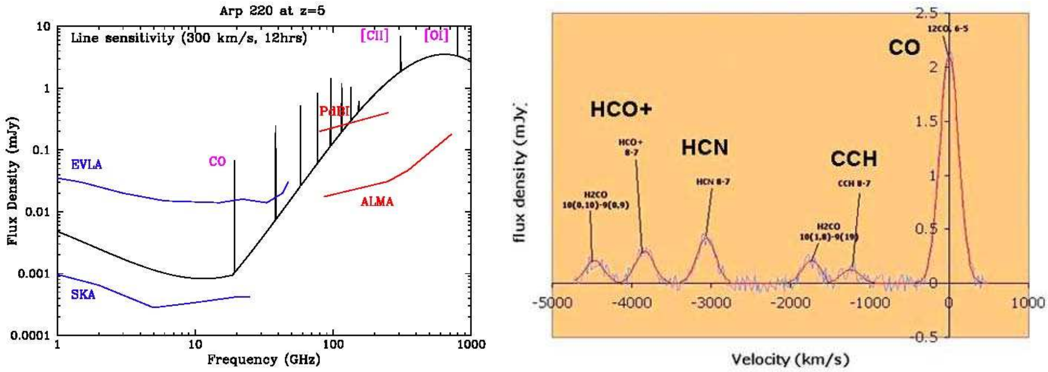

Fig. 3. Left panel: frequency coverage and spectral sensitivity of ALMA compared with the spectral energy distribution and spectrum of the ultraluminous galaxy Arp220 redshifted to z=5 and with the most sensitive current millimeter array (PdBI) and the next generation of centimeter wave telescopes. Right panel: simulated ALMA spectrum of the molecular gas in J1148+5251 at z=6.42 for an integration time of 24 hrs (adapted from Carilli et al. 2008).

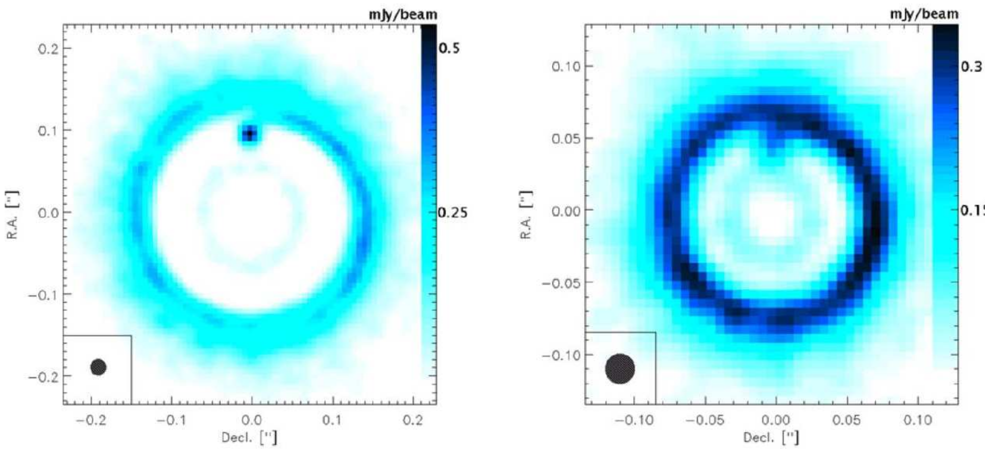

Fig. 4. Simulated ALMA observations of a planet-forming protoplanetary disks. The simulations are for a 1 M_J protoplanet at 5 AU from a 0.5 $M_\odot$ star at 50 pc (left) and 100 pc (right) from the Sun. The observing frequency is 900 GHz using the most extended ALMA configuration (adapted from Wolf 2008).

the two figures). The simulations assume long Earth rotation synthesis observations (∼ 8 hrs) and excellent weather conditions and calibration performances.

3. ALMA in the context

Full science operations with ALMA are foreseen for 2012, the initial years of ALMA full operations will thus coincide with the VLT 2^{nd} and 3^{rd} generation instruments and with the second generation VLTI instruments. In Fig. 5, adapted from Kurz et al. (2002), we show the ALMA parameter space, in terms of frequency coverage and spatial resolution, compared with other facilities in the coming decade.

In terms of spatial resolution, ALMA is an excellent match to the complement of op-

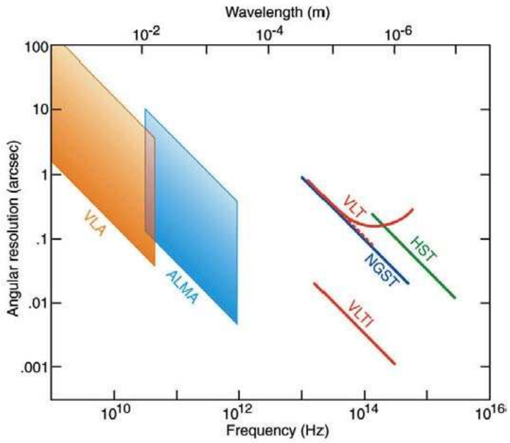

Fig. 5. Frequency-Angular resolution parameter space of ALMA compared with some current and future leading observatories (Kurz et al. 2002).

tical and infrared capabilities offered by the Paranal observatory. the third top level science requirement (Sec. 1) was designed to ensure that ALMA will deliver at millimeter wavelengths data of comparable quality to those achieved with large groundbased optical telescopes – equipped with Adaptive Optics systems – and space observatories – HST and JWST.

The wavelength coverage of ALMA is an excellent complement to the optical and infrared for a wide number of science cases. Just to give a couple of examples, in the extragalactic and high-z context, ALMA will allow to probe the interstellar medium of galaxies while optical/infrared studies are mostly sensitive to the stellar component; in the case of circumstellar disks, ALMA will be sensitive to the bulk of the material throughout the disk, while optical and near infrared studies are a key probe of the disk atmosphere and the interaction between the inner disk and the star. A growing number of studies in various fields of astrophysics are showing the importance of combining observations at different wavelengths. The combination of ALMA and the VLT/VLTI, which will be later joined by the E-ELT, will be an exceptional asset for European astronomers. To maximize the scientific return from these facilities, several of the ESO member countries are investing heavily in the support of groups and scientific projects using (sub-)millimeter facilities and even countries not traditionally strong in this field are creating new groups hiring experts from abroad. The Italian astronomical community has historical weaknesses in these scientific areas, mostly because of the lack of direct access to competitive facilities in the past, to ensure a competitive use of ALMA specific actions should probably be considered by INAF and the universities.

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