Solar Phys (2011) 268: 165–173
DOI 10.1007/s11207-010-9671-8

Solar Research with ALMA

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Received: 30 July 2010 / Accepted: 4 November 2010 / Published online: 24 November 2010

Abstract The *Atacama Large Millimeter/sub-millimeter Array* (ALMA) is a large interferometer that will consist up to 64 high-precision antennas operating in the 31.3 – 950 GHz frequency range. In this frequency range, which is largely unexplored, unique observations with a broad range of scientific objectives (cosmology, cold universe, galaxies, stars and their formation, planets and so on) are expected. Among these tasks there is a unique possibility to observe the Sun and to address several outstanding issues of solar physics. First, the ALMA is briefly described and then the new ESO-ALMA European node (ARC), built at Ondřejov Observatory, is presented. In Europe, this ARC is the only one oriented to solar physics. Consequently, the requirements and limitations for ALMA solar observations, as well as some examples of possible solar-oriented ALMA projects, are shown. A procedure of the preparation and submission of proposals for ALMA observations is mentioned.

Keywords Sun: atmosphere · Radio emission

1. Introduction

The *Atacama Large Millimeter/sub-millimeter Array* (ALMA) (www.almaobservatory.org) is a worldwide project to construct a large interferometer (up to 64 high-precision 12 m and 7 m antennas, operating in the 31.3 – 950 GHz frequency range) in Chajnantor plain of the Chilean Andes at an altitude of 5000 m above sea level (Figure 1). The telescope will be operated from the nearby operational center, located at the elevation of 2900 m. Four main centers are built for the preparation of proposals for observations, data distribution, data analysis and ALMA science and technical supports. Besides the center in Santiago de Chile, there is a main European ESO-ALMA center in Garching, Germany (www.eso.org/sci/facilities/alma/arc/), we have North American ALMA Science Center (NAASC) in Charlottesville, Virginia, USA (science.nrao.edu/alma/index.shtml), and we have the East-Asian ALMA Regional Center in Mitaka, Japan (alma.mtk.nao.ac.jp/EA-ARC/). The European ALMA Regional Center (ARC) is, besides the main center in Garch-

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Figure 1 ALMA antennas at the Chajnantor plain of the Chilean Andes in the District of San Pedro de Atacama, 5000 m above sea level (Courtesy of ESO-ALMA).

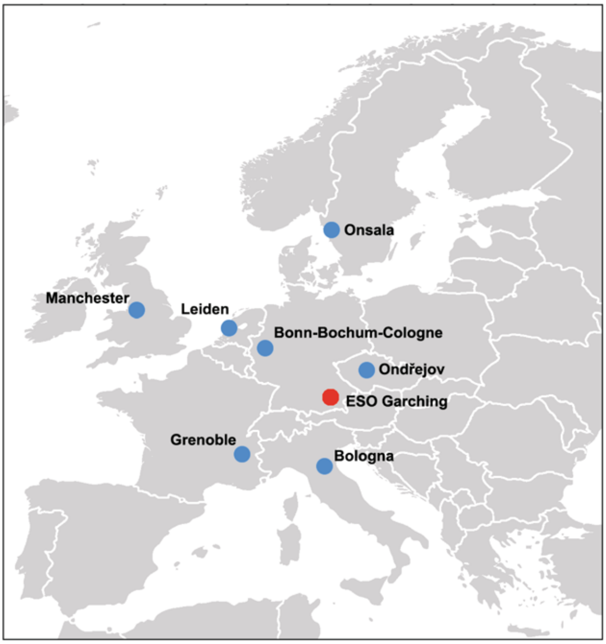

Figure 2 ESO-ALMA nodes in Europe. The red dot marks the main European center in Garching, Germany.

ing, formed by a distributed structure of seven additional nodes (called ARC nodes), which cover various branches of expected ALMA science and which provide better geographical accessibility for ALMA users in Europe (Figure 2).

The science program of ALMA is very broad. It includes molecular clouds in the cold universe, cosmology, the formation of galaxies and clusters of galaxies, formation of stars and planets, astrochemistry, comets and also solar research. Solar physics was included into this ambitious project primarily thanks to A.O. Benz, T. Bastian, S. White, M. Kundu and others. There are several papers introducing ALMA as a future observing instrument for solar research (*e.g.* Bastian, 2002; Loukitcheva, Solanki, and White, 2008).

In this paper, we wish to inform the solar physics community of the present status of the ALMA project, the new ESO-ALMA node at Ondřejov Observatory, which is oriented toward solar physics, and of a unique potential of ALMA for solar physics research.

Table 1 ALMA parameters. λ_{mm} is the wavelength in mm.

Antennas	64
	(25 μm rms, 0.6″ pointing)
Collecting Area	> 7000 m^2
Receivers	10 bands in 31.3 – 950 GHz
	0.3 – 9.6 mm
Field of view	$21'' \times \lambda_{mm}$
Spatial resolution	$0.02'' \times \lambda_{mm} \times$ (10 km/baseline)
Number of baselines	up to 2016

2. ALMA

The construction of ALMA started in 2002 and the project will be completed in 2012. The telescope is located in the Atacama desert in Chile, at the elevation of 5000 m, where superior transmission properties of the atmosphere at mm/sub-mm wavelengths are found. The first call for proposals of observations is expected to be released at the end of 2010 or at the beginning of 2011.

ALMA is a Fourier synthesis telescope. It will consist of up to 64 (12 m and 7 m) antennas (for ALMA parameters, see Table 1). Each pair of antennas measures one Fourier component of the brightness distribution of the radio source. An image of the source is then computed by the inverse Fourier transform of all $N(N-1)/2$ components, where N is the number of antennas in the array, i.e. 2016 in the case of ALMA. The instantaneous field of view of the instrument is given by the antenna size (12 m) and scales linearly with the wavelength (see Table 1). The spatial resolution is determined by the maximum separation of antennas (up to 14 km), and for its wavelength scaling see Table 1. ALMA is also designed to perform very sensitive spectral line observations in the 31.3 – 950 GHz frequency range, which will be divided into ten frequency bands. For more details of ALMA, see www.almaobservatory.org.

Proposals for ALMA observations will be prepared by the ALMA Observing Tool (AOT) software. The procedure of a submission and approval of the ALMA proposals is shown in Figure 3. There will be a two-step procedure, where in the first step the scientific objectives and goals are considered, and if approved by a scientific committee, then, in the second step, detailed technical specifications are checked. On the other hand, observational data will be reduced and analyzed by the Common Astronomy Software Applications (CASA) (casa.nrao.edu). Presently, both of these software packages are in a final testing phase.

3. ESO-ALMA Node (ARC) in Ondřejov

In 2007 the Czech Republic became a new member of the ESO, giving us an opportunity to participate in ESO projects. In November 2008, we have prepared and presented to ESO a proposal to build a new ESO-ALMA node (ARC) in Ondřejov. In December 2009 the ESO-ALMA node at the Astronomical Institute of the Academy of Sciences was formally approved by the ESO Director.

The main purpose of the European ARC nodes is to provide on-line as well as face-to-face support to the ALMA users in matters of proposal preparation, observation planning, and data reduction. The newly formed node in Ondřejov will provide scientific and technical support mainly in the field of solar physics, but also in galactic/extragalactic and relativistic astrophysics, and laboratory measurements and quantum-physics modeling of molecular

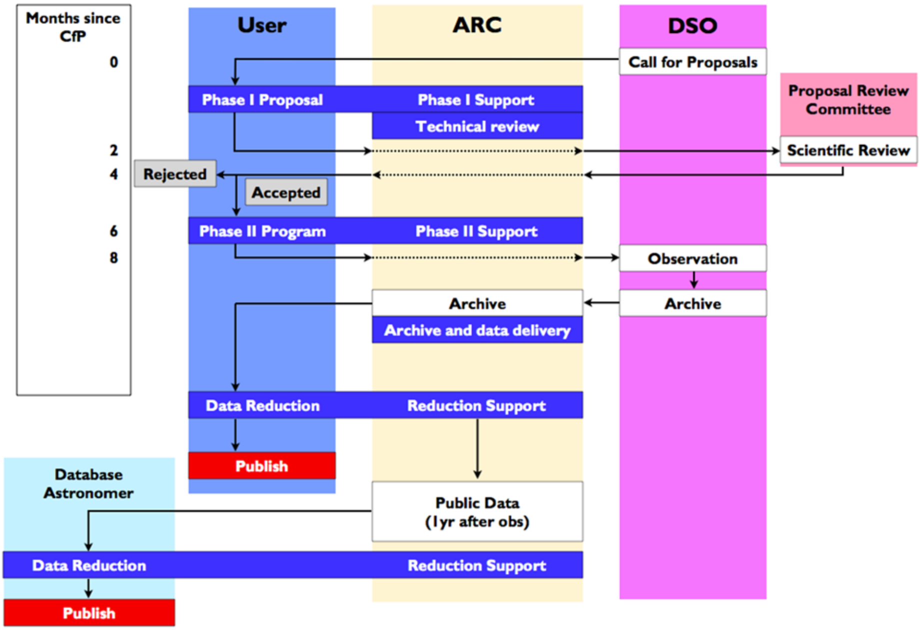

Figure 3 Schema of the submission and approval of proposals for ALMA observations (Courtesy of ESO-ALMA).

spectral lines (in cooperation with the Institute of Chemical Technology in Prague). Since it is a unique node providing support in solar research with ALMA in Europe it is, according to the ARC strategy, open to all European ALMA users requiring assistance with accomplishing their solar-oriented ALMA project.

The formation of the new node in Ondrejov also improved the geographical distribution of the European ARC structure. Thus, for topics which are covered also by other nodes (*e.g.* galactic physics), it represents a natural regional center for the support of users from Central and Eastern Europe.

For details of the new ESO-ALMA node, see http://www.asu.cas.cz/alma. Present activities of the team of this node are:

i) preparation of the infrastructure of the ARC node (computers, data servers, fast internet connections)
ii) participation in official tests of CASA and ALMA Observing Tool software
iii) communication with other European ESO-ALMA nodes through telephone conferences and face-to-face meetings, and
iv) presentation of lectures on ALMA for students

4. ALMA and Solar Research

For the use of ALMA for solar research it is important to know the limitations of ALMA and requirements for solar observations.

- The field of view (FOV) of ALMA is rather small (Table 1). For a detailed study of *e.g.* the "quiet" chromosphere this will not be a problem. However, for the phenomena in which also global effects are important (*e.g.* in solar flares), it would be desirable to increase the FOV; *e.g.* by an observing technique called "on-the-fly" (OTF) (Bastian, 2002).

- Compared with other astrophysical radio sources (*e.g.* molecular clouds, galaxies) the solar radio flux is very strong. On the other hand, detectors of ALMA are very sensitive. Therefore, for solar observations an appropriate attenuation of the signal is necessary.
- To reduce the solar electromagnetic flux reflected to antenna focus, it will be very useful to scatter visible/IR part of the spectrum by the milling of the surface of antennas (Bastian, 2002).
- ALMA can directly measure temperature maps in the chromosphere. For this purpose a precise calibration technique is necessary.
- For transient phenomena such as solar flares, a flexible communication between scientists and observing staff regarding observing targets is necessary. Namely, in proposals for flare observations it would be very difficult to specify observing targets in advance.

In the following, we list a few potential areas in solar physics, which could be advanced through observations with ALMA.

4.1. Study of the Quiet Chromosphere

Studies of the quiet chromosphere using ALMA have been proposed by several authors, *e.g.* by A.O. Benz, T. Bastian, and S.K. Solanki (http://www.eso.org/sci/facilities/alma/science/drsp/22/3_1_1), Bastian (2002) and Loukitcheva, Solanki, and White (2008). The millimeter and sub-millimeter emissions of the quiet Sun originate from the chromosphere and are generated by the thermal free – free processes. The source function is Planckian (as in LTE), but the radio continuum opacity depends on the non-LTE ionization structure of the chromosphere. Because the source function can be well approximated by the Rayleigh – Jeans function, the flux density from the quiet chromosphere at mm/sub-mm wavelengths is linearly related to the kinetic temperature. This enables the study of the temperature structure of the chromosphere directly, contrary to the case of UV radiation, where the intensity is non-linearly coupled to temperature.

In accordance with Loukitcheva, Solanki, and White (2008) we propose to use this 'thermometer' for testing the existing models of the chromosphere (see *e.g.* Fontenla, Avrett, and Loeser, 1993; Carlsson and Stein, 1995). Namely, the chromosphere is the least understood part of the solar atmosphere. There is currently a great deal of debate about its structure. While the classical semi-empirical models (Fontenla, Avrett, and Loeser, 1993) consider a steady temperature rise as a function of height, the new numerical models (Carlsson and Stein, 1995) give the temperature drop outwards, but with shocks generating strong localized heating. We think that the 'thermometer' measurements of ALMA will distinguish between these two kinds of models.

Because the new optical telescope GREGOR (Volkmer *et al.*, 2006) and the Solar Optical Telescope (SOT) onboard *Hinode* satellite (Kosugi *et al.*, 2007) are oriented to similar studies, we propose to make simultaneous observations of the quiet chromosphere combining data from these instruments and ALMA.

4.2. Study of Prominences and Filaments

Early observations of Hα filaments in millimeter wavelength range with low spatial resolution revealed depressions in brightness corresponding to filament locations (Kundu, 1970). More recent observations with better resolution confirm this finding (Bastian, Ewell, and

Zirin, 1993; Harrison *et al.*, 1993). Both prominences observed on the limb, as well as filaments seen against the disk, may exhibit significant opacity at mm/sub-mm wavelengths, as our estimates indicate for typical plasma conditions. Therefore, we expect that these structures will be well resolved by ALMA and thanks to the high spatial resolution we will be able to study the fine structure of the prominence/filament in greater detail. The estimates also indicate that the radiation flux from prominences should significantly exceed ALMA's sensitivity. Similarly to the case of the quiet chromosphere, ALMA can be used as a 'thermometer' and could substantially contribute to the long-lasting debate concerning the kinetic temperature inside the coolest (central) parts of the prominence and the fine-structure threads (Heinzel, Anzer, and Gunár, 2010). Cool plasmas can be detected simultaneously by ALMA and EUV imagers like the Atmospheric Imaging Assembly (AIA) onboard the *Solar Dynamic Observatory* (SDO), where the latter may also reveal connections to hotter surrounding features like prominence cavities or filament channels (see *e.g.* Heinzel *et al.*, 2008).

4.3. Solar Radio Recombination Lines

In accordance with A.O. Benz and C.U. Keller (www.eso.org/sci/facilities/alma/science/drsp/22/3_1_2), and Bastian (2002) we propose to observe the recombination lines of high states of some transition region ions (*e.g.* O IV), which are expected to be observable in the mm/sub-mm wavelength range (Dupree, 1968; Berger and Simon, 1972).

Similarly, it is important to search for high level transitions of H I, especially in solar prominences. Clark, Naylor, and Davis (2000a, 2000b) successfully detected the H I lines for the transitions between levels $n = 20 - 19$ and $n = 22 - 21$ in the 350 μm and 450 μm bands. The measurements of such lines would give us a unique opportunity to measure the magnetic field strength in the regions of the line formation through the Zeeman effect.

4.4. Study of Chromospheric Oscillations and Waves

Detection of solar chromospheric oscillations (especially of three and five minutes) at millimeter wavelengths began with Simon and Shimabukuro (1971) and was later followed by *e.g.* Lindsey and Kaminski (1984) and Lindsey *et al.* (1990). Meanwhile, the interest in all types of oscillations and propagating waves has significantly increased (see *e.g.* Gouttebroze *et al.*, 1999; McIntosh, Fleck, and Tarbell, 2004; Bloomfield *et al.*, 2006), mainly due to their connections to unsolved problems of the chromospheric and coronal heating. We expect that high-resolution observations with ALMA can help to understand how these waves propagate and how they are absorbed in the chromosphere and thus how they contribute to a heating of these layers. These waves can even influence magnetic reconnection due to magnetic field variations in the flare current sheet and can trigger or modulate processes in solar flares, as shown by Sych *et al.* (2009). Thus ALMA observations of chromospheric oscillations and waves, especially in active regions, are highly desirable. Furthermore, in the analysis of ALMA observations it is important to use modern wavelet techniques, which are able to recognize propagating MHD waves on the base of tadpoles in their wavelet spectra (Mészárosová *et al.*, 2009). This type of study has also a strong synergy with the studies in item Section 4.1.

4.5. Study of Microjets in Sunspot Penumbrae

Sunspots represent one of the main targets of observations made by the *Hinode* satellite (Kosugi *et al.*, 2007) and several new findings in this field have recently been reported. Among them there are so-called microjets (Katsukawa *et al.*, 2007; Jurčák and Katsukawa, 2008), which are associated with transient brightenings observed at the boundary of penumbral filaments. They were observed in the Ca II H line, which is formed in the lower chromosphere at temperatures below 10^4 K. Their spatial extent is several thousands of kilometers in length and several hundreds of kilometers in width with a lifetime of about one minute. From a physical point of view the microjets indicate magnetic reconnection processes in very deep layers of the solar atmosphere, where the plasma is not fully ionized. Because processes under such conditions are still not well understood, it would be very important to observe them by ALMA at high spatial resolution.

4.6. Study of Solar Flares

Due to new insights into flare processes, observations of solar flares with ALMA are highly desirable. Five mechanisms have been proposed to explain the flare emission at sub-mm wavelengths: *i*) free-free thermal emission (see *e.g.* Kašparová *et al.*, 2009), *ii*) gyrosynchrotron emission, *iii*) synchrotron emission from relativistic positrons/electrons (Ohki and Hudson, 1975), *iv*) diffusive radiation, and *v*) Cherenkov emission (Fleishman and Kontar, 2010). Because all these mechanisms are directly or indirectly connected with high-energy particles, it is commonly believed that ALMA observations will have a strong potential for the diagnostics of high-energy particles in solar flares. However, to make any such diagnostics, the time resolution of ALMA observations should be in fractions of second.

Predictions of starts and locations of solar flares are very difficult. Furthermore, as indicated by observations of Kaufmann *et al.* (2001, 2009) and Trottet *et al.* (2002), the flare emission at ALMA wavelengths should be generated in small regions at flare-loop footpoints. Therefore, observations of solar flares by ALMA, having a limited time of observations and small field of view, will not be easy. Some help in ALMA flare observations can be found in studies of the so-called quasi-separatrix layers (Démoulin *et al.*, 1996). Namely, using these ideas, Mandrini *et al.* (1997) found that Hα ribbons and hard X-ray sources are located at intersections of the quasi-separatrix layers (given by the magnetic field structure of the active region) with the chromosphere. ALMA flare sources are expected to be located at the same places; therefore, their positions can be predicted by a determination of these intersections using preflare magnetic field measurements.

In order to optimize observations of solar flares, communication between scientists and observers at the operational center regarding the observing target is essential. To facilitate flare observations we shall subscribe to the Max Millennium Message Of The Day (MOTD; http://solar.physics.montana.edu/hypermail/mmmotd/index.html), a daily email service which selects a Target Of Opportunity (TOO) most likely to flare. This service is based on preceding activity and the magnetic configuration of potentially active regions. In doing so we will also increase the likelihood of obtaining support observations from other ground- and space-based instruments. Our strategy shall be to follow the daily TOO when possible, changing observing modes if flares occur.

It is important to mention that at slightly smaller wavelengths around 0.1 mm, similar observations were proposed to be made from space (Vial *et al.*, 2007). Therefore, it would be highly desirable to make simultaneous observations with any such type of instruments. Furthermore, we propose to make simultaneous observations of flares with ALMA and with a new Brazilian dm-array (Sawant *et al.*, 2002), especially because of their close locations.

5. Concluding Remarks

ALMA is a general purpose radio telescope designed to observe various objects in the Universe. Solar science with ALMA is envisaged; however, solar observers will have to compete with other astrophysical communities. But since the observing capabilities of ALMA are so advanced, an involvement of the solar community is highly desirable. To encourage potential observers, the new ESO-ALMA node (ARC) at Ondřejov Observatory is being built under the supervision of ESO. Although we are fully aware of problems which are specific for solar observations (small field of view, strong radio flux, calibration and so on), we hope that the advanced OTF mapping and calibration techniques will overcome these difficulties. ALMA has potential for new insights and new discoveries, especially in the mostly unexplored wavelength range, making it highly desirable for solar research.

Acknowledgements The authors are indebted to Prof. T. Wilson and Dr. P. Andreani from ESO for their great support in building the Ondřejov ALMA node (ARC) and to Prof. J. Palouš for his involvement and help. Prof. G. Mann was also very collaborative during the preparation of our ESO-ALMA proposal. This paper was supported by Grant 300030701 of the Grant Agency of the Academy of Sciences of the Czech Republic, Grant P209/10/1680 of the Grant Agency of the Czech Republic, Research project AV0Z10030501 and the Centre for Theoretical Astrophysics, Prague. The authors thank Ryan Milligan and the Editor for constructive comments, which helped to improve the paper.

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