Ground-based Solar Observations in the Space Instrumentation Era
ASP Conference Series, Vol. 504
Ivan Dorotovič, Catherine E. Fischer, and Manuela Temmer, eds.

Solar Observations with the Atacama Large Millimeter/submillimeter Array (ALMA)

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Abstract. The Atacama Large Millimeter/Submillimeter Array (ALMA) is a joint North American, European, and East Asian project that opens the mm-sub mm wavelength part of the electromagnetic spectrum for general astrophysical exploration, providing high-resolution imaging in frequency bands currently ranging from 84 GHz to 950 GHz (300 microns to 3 mm). It is located in the Atacama desert in northern Chile at an elevation of 5000 m.

Despite being a general purpose instrument, provisions have been made to enable solar observations with ALMA. Radiation emitted at ALMA wavelengths originates mostly from the chromosphere, which plays an important role in the transport of matter and energy, and the in heating the outer layers of the solar atmosphere. Despite decades of research, the solar chromosphere remains a significant challenge: both to observe, owing to the complicated formation mechanisms of currently available diagnostics; and to understand, as a result of the complex nature of the structure and dynamics of the chromosphere. ALMA has the potential to change the scene substantially as it serves as a nearly linear thermometer at high spatial and temporal resolution, enabling us to study the complex interaction of magnetic fields and shock waves and yet-to-be-discovered dynamical processes. Moreover, ALMA will play an important role in the study of energetic emissions associated with solar flares at sub-THz frequencies.

1. ALMA Science

In non-flaring regions, ALMA measures optically thick thermal emission from the lower chromosphere. Since ALMA will observe the Sun at wavelengths dictated by the Rayleigh-Jeans law, the measured brightness temperature directly relates to the physical temperature. This allows ALMA observations to serve as a chromospheric thermometer. When full Stokes parameter observations become available with ALMA (not in cycle 4), measurements of chromospheric magnetic fields should be possible.

In flares, ALMA will observe gyro-synchrotron emission from the non-thermal electrons accelerated by the flare, providing more insight into the particle motions within the lower solar atmosphere.

For details on simulated ALMA observations, see the paper by M. Loukitcheva in these proceedings.

2. ALMA Capabilities

ALMA is an interferometric array comprised of 50×12 m antennas, 12×7 m antennas, and 4×12 m "total power" antennas. It is designed to image celestial sources with a high degree of angular resolution with high sensitivity. Its location allows access to observations in frequency bands with good transmission through the Earth's atmosphere which are divided into individual 10 observing bands.

ALMA's field of view is determined by the antenna diameter D in meters and the observing frequency in GHz as $\Theta_{\rm FOV} \approx 70000''/(D_{\rm m}\nu_{\rm GHz})$ (or $\approx 60''$ for the 12m antennas at 100 GHz). With the exception of the total power and the 7m antennas, the configuration of ALMA's antennas can be changed, yielding varying degrees of angular resolution and surface brightness sensitivity. The angular resolution with which a target can be observed is given by $\Theta_{\rm res} \approx 62''/(L_{\rm km}\nu_{\rm GHz})$, where $L_{\rm km}$ is the maximum spacing between antennas in kilometers for a given antenna configuration. The most compact ALMA configuration has $L_{\rm km} < 1$ and the most extended configuration has $L_{\rm km} = 16$.

3. Solar Development Plan

The ALMA Solar Development Team is an international group, whose activities are funded through NRAO, ESO, and NAOJ. It was formed in 2014 in response to the need for to develop, test, and commission solar observing modes to enable solar observations with ALMA by the wider solar community. In addition, the Team is developing data calibration procedures, software requirements for the Observing Tool, and data reduction software. Here we focus on commissioning efforts, briefly report results of an ALMA solar observing campaign held on 2014 December 9-16, and explore the observing capabilities potentially available in ALMA cycle 4. A follow up test campaign is scheduled for December 2015.

4. Technical Challenges

The Sun is a powerful emitter at mm/sub-mm wavelengths. While the antennas are capable of pointing at the Sun without harm, provisions must be made to allow both quiet and active Sun phenomena to be observed without saturating the ALMA receivers. While a "solar filter" is available to attenuate the signal entering a given receiver, it has several undesirable properties. A more elegant solution was proposed by Yagoubov (2013) whereby the receiver gain can be reduced by de-biasing the SIS mixers, obviating the need for the solar filter in many cases of interest. A major task of the Development Team was to validate observing modes using mixer de-biasing.

5. Proposed Observing Modes

The Team anticipates that limited solar observing capabilities will be offered to the scientific community for the first time in ALMA Cycle 4. Proposals will be due in Spring

2016 and observations will be possible beginning in late 2016. Only two continuum observing bands will be offered initially: bands 3 and 6. Only a single band can be observed at once, though four 2 GHz windows (with 15 MHz spectral resolution) will be available, centered at 93, 95, 105, and 107 GHz in band 3, and 230, 232, 246, and 248 GHz in band 6. These observations will be dual polarization (though full stokes data is not yet available). For cycle 4, the three antenna configurations for solar observations will have baselines as large as 160.7 m, 376.9 m, and 538.9 m, providing a spatial resolution of approximately 3.4″ (1.5″), 1.8″ (0.8″), and 1.2″ (0.5″) at 100 GHz (230 GHz) respectively with a field of view of approximately 1' (30″).

Two observing modes (described below) have been tested in each band, and are expected to be offered for cycle 4 in 2016.

5.1. Single Dish Fast Mapping

Fast mapping (developed by R. Hills, N. Phillips, R. Marsdon, and colleagues) exploits the exquisite precision and repeatability of TP antenna antenna pointing and tracking to map the full disk of the Sun in a matter of minutes using Lissajous or "double-circle" scan patterns. Subregions of the Sun can be mapped even more quickly.

5.2. Synthesis Imaging with ALMA

ALMA can be used to perform high resolution imaging of solar targets in its "de-tuned" or "de- biased" mode. ALMA maps, with an angular resolution of ≈3.2″, represent a linear map of the chromospheric plasma temperature. While these modes may be available for Cycle 4, much more work remains. In order to map larger fields of view, mosaicking or on-the-fly mapping must be implemented. To enable sub-arcsecond imaging, solar modes will need to exploit techniques that are currently available for non-solar observers; namely the use of water vapor radiometers to measure and correct phase variations introduced by the sky.

Acknowledgments. The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. We wish to express our sincere thanks to Tony Remijan and the JAO EOC team for their support during the December observing campaign. We owe particular thanks to A. Hirota and S. Asayama.

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