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Exploring the Sun with ALMA

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The Atacama Large Millimeter/submillimeter Array (ALMA) Observatory opens a new window onto the Universe. The ability to perform continuum imaging and spectroscopy of astrophysical phenomena at millimetre and submillimetre wavelengths with unprecedented sensitivity opens up new avenues for the study of cosmology and the evolution of galaxies, the formation of stars and planets, and astrochemistry. ALMA also allows fundamentally new observations to be made of objects much closer to home, including the Sun. The Sun has long served as a touchstone for our understanding of astrophysical processes, from the nature of stellar interiors, to magnetic dynamos, non-radiative heating, stellar mass loss, and energetic phenomena such as solar flares. ALMA offers new insights into all of these processes.

ALMA solar science

Radiation from the Sun at millimetre and submillimetre wavelengths largely originates from the chromosphere, the relatively thin interface between the radiation-dominated photosphere and the magnetically dominated corona. The chromosphere is highly dynamic in nature as magnetohydrodynamic (MHD) waves propagate up from the photosphere below and form shocks that dissipate their energy (for example, Wedemeyer, 2016).

The chromosphere remains an outstanding problem in solar physics and, by extension, stellar physics. The central question is: why does the Sun's atmosphere increase in temperature above the visible photosphere as one proceeds up through the chromosphere and into the corona? What are the heating mechanisms? How is energy transported? What is the role of the magnetic field? ALMA is needed to help establish the thermodynamic structure of the chromosphere and to gain an understanding of how mechanical and radiative energy are transferred through that atmospheric layer.

Much of what is currently known about the chromosphere has relied on spectroscopic observations at optical and ultraviolet wavelengths using both ground- and space-based instrumentation. While a lot of progress has been made, the interpretation of such observations is complex because optical and ultraviolet lines in the chromosphere form under conditions of non-local thermodynamic equilibrium. In contrast, emission from the Sun's chromosphere at millimetre and submillimetre wavelengths is more straightforward to interpret as the emission forms under conditions of local thermodynamic equilibrium and the source function is Planckian. Moreover, the Rayleigh-Jeans approximation is valid ($h\nu/kT \ll 1$) and so the observed intensity at a given frequency is linearly proportional to the temperature of the (optically thick) emitting material. By tuning across the full suite of ALMA's frequency bands it is possible to probe the entire depth of the chromosphere.

Wedemeyer et al. (2016) comprehensively discuss the potential of ALMA in this context. In brief, observations of thermal emission from material at chromospheric temperatures will be a mainstay of ALMA's solar physics programme. Multi-band, high-resolution, time-resolved observations of the chromosphere at millimetre and submillimetre wavelengths with ALMA will play a key role in constraining models of chromospheric and coronal heating.

In addition, ALMA will be important for addressing puzzles associated with solar filaments and prominences that form along magnetic neutral lines. Although they are at chromospheric temperatures, they occur at coronal heights and are therefore immersed in much hotter plasma. Quiescent prominences can remain stable for days or even weeks but may then become unstable and erupt. ALMA offers new insights into the thermal structure and dynamics of prominences, their formation, and their eventual loss of equilibrium.

ALMA observations of non-thermal emission will also be of crucial importance. Although observations of small flares or small eruptive events may be observed using the existing modes described below, observations of solar flares are not yet feasible with ALMA in general. Unlike quiescent solar emission, solar flares produce intense non-thermal radiation as a result of energetic electrons interacting with the local magnetic field. ALMA will be sensitive to emission from the most energetic of these electrons. An important discovery by Kaufmann et al. (2004) is that some flares produce a spectral component at millimetre/submillimetre wavelengths with an inverted spectrum — the so-called "sub-terahertz" component, which is distinct from the non-thermal gyrosynchrotron component. Krucker et al. (2013) discuss it at length, yet the origin of the sub-terahertz flare component remains unknown. ALMA will play a central role in understanding its origin.

Each of these broad science themes additionally informs the burgeoning field of "Space Weather", which is aimed at understanding the drivers of disturbances in the solar corona and wind and their effects on Earth and the near-Earth environment.

Enabling solar observing with ALMA

Building on preliminary work performed in East Asia, Europe, and by the Joint ALMA Observatory, the Solar Development Team was formed in late 2013, supported by the National Science Foundation, ESO and East Asia. Its aims were to enable solar observations with ALMA. The work is supported by an extensive science simulations effort — the Solar Simulations for the Atacama Large Millimetre Observatory Network (Wedemeyer et al., 2015). For example, Heinzel et al. (2015) simulated high-resolution observations of fine structures in solar prominences at millimetre wavelengths. Extensive testing and validation were carried out in 2014 and 2015, leading to the acceptance of solar observing with ALMA in Cycle 4 (see below).

Support for solar science was part of the ALMA science programme from its inception, yet considerable work was needed in practice to implement solar observing modes — work that is still ongoing. Provisions were made to ensure that ALMA antennas could safely point at the Sun without damaging the extremely precise telescope hardware; in particular, the surface panels were chemically roughened in order to scatter optical and infrared radiation and reduce the radiative heating of the sub-reflector and other elements to safe levels. However, there are additional factors to consider when observing the Sun. While ALMA's sensitive receivers are not damaged by pointing at the Sun, they saturate when such an intense signal is introduced into the system, resulting in a strongly non-linear performance.

There are two approaches to mitigating the problem: attenuate the signal introduced into the receiver, or increase the "headroom" of the receiver to ensure that its response remains linear by reducing the receiver gain. Both approaches are possible with ALMA. The first approach was implemented through the use of a solar filter on the ALMA Calibration Device. The solar filter attenuates the incident signal by a frequency-dependent amount that allows solar observations in a given frequency band. However, solar filters have a number of undesirable properties for mapping the quiet (i.e., non-flaring) Sun: they greatly reduce the sensitivity with which calibrator sources can be observed; they cause frequency-dependent complex gain changes; and they introduce significant wavefront errors into the illumination pattern of the antenna, which result in distortions to the antenna beam shape and increased side lobes. Therefore, while solar filters will be needed for observations of stronger solar flares, the second approach was developed for quiet Sun programmes.

Yagoubov (2013) pointed out that the ALMA superconductor-insulator-superconductor (SIS) mixers could be de-tuned or de-biased to reduce the mixer gain and effectively increase the level at which receivers saturate, thereby allowing solar observing without the use of the solar filters. This idea is illustrated in Figure 1, which shows the SIS current gain (left axis) and conversion gain (right axis) plotted against the voltage bias for ALMA Band 3. The normal voltage bias tuning is on the first photon step where the gain conversion is a maximum. However, the mixer still operates at other voltage bias settings. These produce lower conversion gain but, since the dynamic range scales roughly inversely with gain, these settings can handle larger signal levels before saturating. This operational mode is referred to as the mixer de-biased (MD) mode. Observing both the source and calibrators in a specific MD mode obviates the need to explicitly measure the change in system gain introduced by the mode.

Another consideration, however — regardless of whether the solar filter or the MD mode is used — is that the input power changes significantly as the antennas move from the (solar) source to a calibrator and back. Signal levels must remain within nominal limits along the path to the analogue-to-digital converters and the correlator. Stepped attenuators

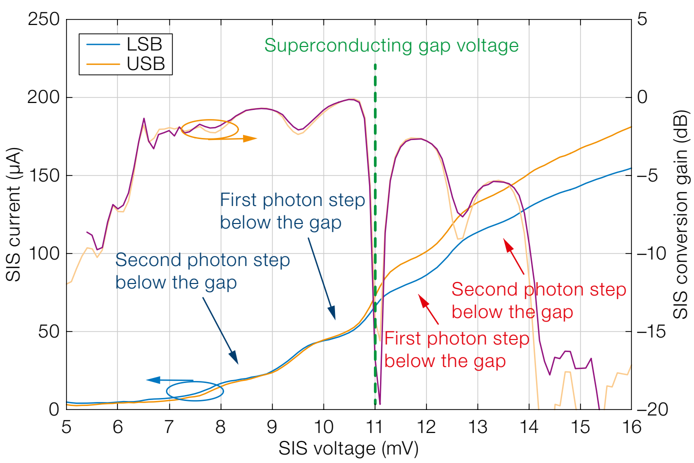

Figure 1. Plot of SIS current and conversion gain as a function of voltage setting for ALMA Band 3 at a local oscillator frequency of 100 GHz. The arrowed ellipses indicate the relevant ordinate: left for the SIS current and right for the conversion gain. See Shimojo et al. (2017a) for additional details.

are used for this purpose. A concern was whether the variable attenuators themselves would introduce unacceptable (differential) phase variation between the source and calibrator settings, thereby corrupting phase calibration referenced against suitable sidereal calibrators. A second concern was whether there are differences between the spectral window bandpass response between source and calibrator scans as a result of attenuator settings. It is a testament to the system design that neither concern proved to be a significant issue. Extensive testing in 2014 showed that the different attenuator settings used to observe calibrator sources and the Sun do not introduce significant phase errors or distort the frequency bandpass. MD observing modes were therefore adopted as the basis for observations of the quiet Sun.

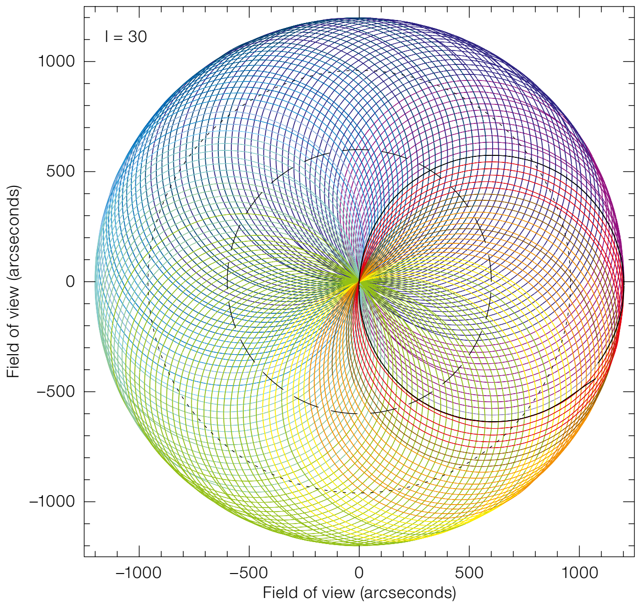

Figure 2. Example of the double-circle pattern used to perform single-dish fast-scan total power maps of the solar disc, with a map spacing of 30 arcseconds. The dotted line indicates the solar limb (radius 960 arcseconds). The rainbow colour variation indicates the progress of the pointing pattern with time and the dashed line indicates the track of the centroids of the individual minor circles in the pattern. See White et al. (2017) for additional details.

Two additional challenges are posed by solar observations. First, the complex brightness distribution of the Sun contributes significant power on angular scales ranging from sub-arcsecond scales to the diameter of the solar disc, the details of which vary on short timescales (tens of seconds). Good instantaneous sampling of the aperture plane is needed to recover measurements over the full range of angular scales. The 7-metre antennas in the fixed Atacama Compact Array were therefore included as well as those in the 12-metre array so as to sample a broader range of angular scales. All antennas were processed through the baseline correlator. In order to recover the Sun's brightness distribution on the largest angular scales, all interferometric observations were supplemented by full-disc fast-scan total power maps (Phillips et al., 2015) in the relevant frequency bands (Figures 2 and 3). These can be combined with the interferometric data via "feathering" to produce photometrically accurate maps of the Sun's brightness distribution.

Second, water vapour radiometers (WVRs) are used on each ALMA antenna to measure variations in the electrical path length introduced by the overlying atmosphere. These measurements are particularly important on long interferometric baselines for correcting differential phase variations. Unfortunately, the WVRs saturate when ALMA's antennas are pointed at the Sun and WVR measurements are therefore unavailable for solar observations. As a consequence, observations of the Sun with long-baseline antenna configurations cannot currently be supported.

The extensive solar development efforts required to bring solar observing modes to the solar community are documented in two papers. Shimojo et al. (2017a) discuss the steps necessary to implement

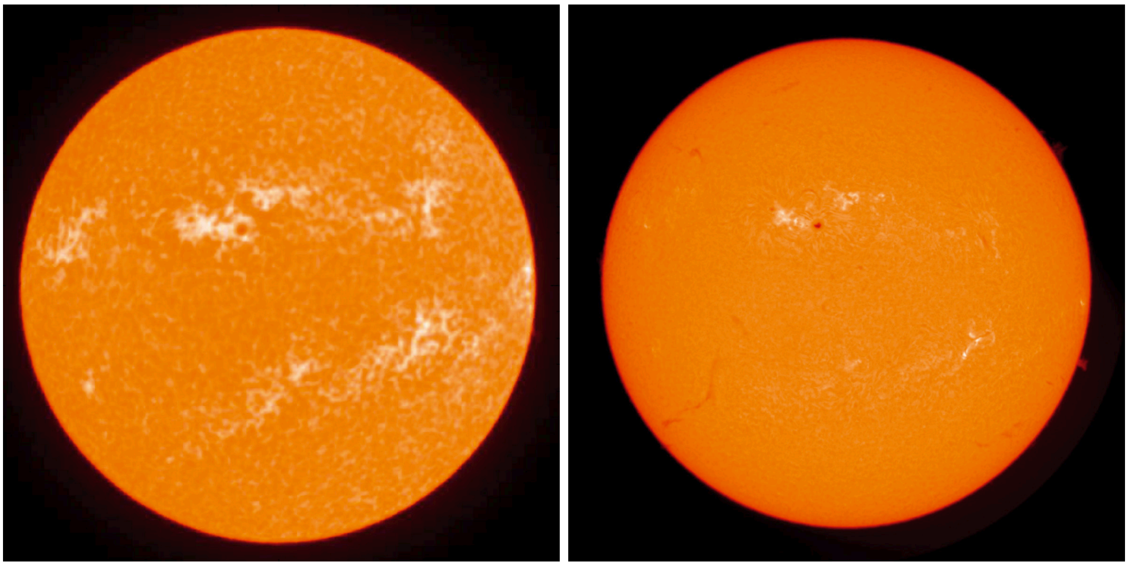
Figure 3. Left: Example of a full-disc fast-scan total power map in Band 9 (0.45 mm) on 18 December 2015 using a scan pattern similar to that shown in Figure 1. Right: The corresponding image in Hα.

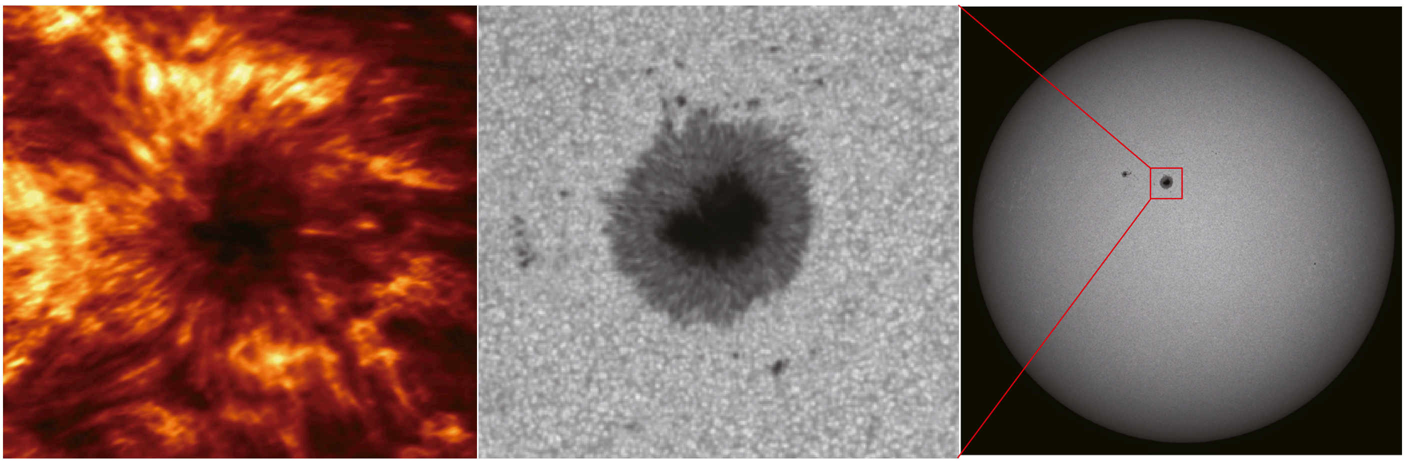

Figure 4. Right: A white-light continuum image of the Sun obtained by the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory showing a sunspot imaged by ALMA. Centre: A detail of the same. Left: Map of the sunspot in Band 6 (1.25 mm). The map was formed by a mosaic of 149 individual antenna pointings. The data were acquired as part of science verification on 18 December 2015. See Shimojo et al. (2017) for additional details.

interferometric imaging of the Sun, and White et al. (2017) describe fast-scan total power mapping of the Sun. Examples of maps obtained by ALMA during science verification are shown in Figures 3 and 4.

ALMA Cycle 4

Solar observing was first made available to the community in Cycle 4 with the call for proposals in March 2016. Cycle 4 solar programmes were restricted to continuum observations in two frequency bands, Band 3 (3 mm) and Band 6 (1.25 mm) using MD mode observing. Since WVR measurements are not possible, solar observing programmes were further restricted to the use of the three most compact 12-metre antenna configurations (C40-1, C40-2, and C40-3). Using C40-3, the maximum possible angular resolutions for Bands 3 and 6 were approximately 1.5 arcseconds and 0.63 arcseconds, respectively.

Nearly 50 solar proposals were received in Cycle 4 and roughly a third of these were approved and allocated observing time at priority A or B. The solar physics community is inherently multi-wavelength in practice. A wide variety of ground- and space-based assets are available that add tremendous scientific value to ALMA observations. For Cycle 4, these include the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al., 2014), which is led by NASA and operates at ultraviolet wavelengths, and the Hinode mission, which is led by the Japan Aerospace Exploration Agency (JAXA) in cooperation with NASA, the UK Science and Technology Facilities Council (STFC), ESO, and the Norwegian Space Centre (Kosugi et al., 2007), and which operates at optical, extreme ultraviolet (EUV), and soft X-ray wavelengths. Numerous ground-based optical telescopes also participated.

Emission from the Sun can change dramatically on short timescales. Even so-called "quiet" Sun emission from non-flaring active regions may evolve significantly over the course of a day. Meeting the science goals of a particular programme may therefore pose operational and scheduling challenges. The need to respond quickly to changing targeting requests is of paramount importance. In order to image a specific target on the Sun, ALMA must correctly track the Sun's physical ephemeris, offsets relative to the physical ephemeris, and its rotation. ALMA can accommodate observations of ephemeris objects such as the Sun through user-provided files that specify the exact target coordinates as a function of time. A convenient tool, the ALMA solar ephemeris generator — based on the Jet Propulsion Laboratory (JPL) HORIZONS web interface[1,2] — was developed by Ivica Skokić to generate files like these quickly. A solar observer can now specify the target offset relative to the centre of the Sun, and use a model to correct for the Sun's differential rotation.

An observing strategy that mitigates, in part, some of the complexity associated with scheduling solar programmes is to execute them during an "observing campaign". That is, in coordination with relevant missions and telescopes, a fixed window of time is designated in one or more antenna configurations during which the bulk of the ALMA solar observing is discharged. This worked well for Cycle 4 observing programmes from an operational standpoint, although the communication strategy between the ALMA Principal Investigator, the ALMA duty astronomer and ALMA operations needs further refinement.

Early science

ALMA science verification data were released to the community in January 2017[3,4]. These data[4] validated solar observing modes released to the community for Cycle 4 observing and have served as the basis for a number of recent scientific papers. Several studies made full use of the interferometric and fast-scan total power data and others made use of the superb fast-scan total power maps of the full disc of the Sun alone:

– Shimojo et al. (2017b) studied the eruption of a plasmoid in a solar active region jointly at 3 mm, in the EUV (Solar Dynamics Observatory) and in soft X-rays (Hinode), demonstrating the utility of both the time-resolved, snapshot imaging capabilities of ALMA and the use of multi-wavelength observations to constrain the properties of the plasmoid.

- Bastian et al. (2017) compared ALMA 1.25-mm observations of an active region with the corresponding observations of the Mg II ultraviolet emission made by IRIS. The ALMA data comprised a 149-point mosaic of a solar active region that was feathered with the corresponding fast-scan total power map. Although believed to form at similar heights in the chromosphere, there are distinct differences between the millimetre brightness temperature and the ultraviolet radiation temperature, which are attributed to regional dependencies of the formation height and/or an increased degree of coupling between the ultraviolet source function and the local gas temperature in hotter and denser areas of the active region.

- Iwai et al. (2017) discovered a significant 3-mm brightness enhancement in the centre of a sunspot umbra that is coincident with enhancements in the 1330 Å and 1400 Å ultraviolet continuum images observed by IRIS. The enhancement may be intrinsic to sunspot umbrae at chromospheric heights, or alternatively could be the millimetre counterpart to a polar plume.

- Loukitcheva et al. (2017a) made detailed comparisons of ALMA observations of a sunspot at 1.25 and 3 mm with models of sunspot umbrae and penumbrae, finding that none of the extant models gives a satisfactory fit to the dual-band high-resolution ALMA observations. Observations between 1.25 and 3 mm (Bands 4 and 5) are needed, as well as additional multiband observations of many more sunspots.

- Allisandrakis et al. (2017) exploited fast-scan total power maps at both 1.25 and 3 mm to assess the brightness variation of the quiet Sun from the centre to the limb, inverting the transfer equation to infer the dependence of plasma temperature on optical depth.

- Brajša et al. (2018) also used fast-scan total power maps to characterise the Sun's millimetre radiation in comparison with the chromospheric and coronal emission seen at optical and EUV wavelengths, finding a high degree of correlation, even including millimetre counterparts to coronal X-ray bright points.

These early results already anticipate the richness and diversity of the solar observations to come under regular observing. With the support of additional frequency bands and new capabilities, the breadth of solar science that can be addressed by ALMA will be fully realised. We conclude with a brief discussion of future capabilities for solar observing.

Future capabilities

To date, ALMA has barely scratched the surface of the scientific potential of millimetre and submillimetre observations of the Sun. In addition to analysing and publishing the wealth of results from Cycle 4 observations in Bands 3 and 6, much work remains to enable observations in additional frequency bands and to deploy new observing modes. These, in turn, will allow the full power of ALMA to be brought to bear on the fundamental science questions outlined above.

Additional frequency bands
The frequency range sampled by ALMA offers a powerful probe of the solar chromosphere. At present, observations in Band 3 and Band 6 are supported. The intention of the Solar Development Team is to provide support for observations in Band 7 (0.85 mm) and Band 9 (0.45 mm) in Cycle 7 to allow deeper layers of the chromosphere to be observed. Evaluation of Bands 7 and 9 for solar observing is currently under way. In future years, observations in frequency bands filling the gaps between Bands 3, 6, 7, and 9 will be enabled.

Polarimetry
A key capability of ALMA for all scientific communities is to fully support the quantitative characterisation of the polarisation properties of the observed millimetre/submillimetre radiation, usually in the form of the Stokes polarisation parameters. Of fundamental importance to understanding a range of physical processes is the measurement of chromospheric magnetic fields. Ultimately, measurements of Stokes V (circular polarisation) to a precision of 0.1 % are needed to fully exploit polarimetric observations of the Sun. Details of how solar polarimetric observations will be exploited and the requirements for ALMA are discussed by Loukitcheva et al. (2017b).

Imaging spectroscopy
Support for spectral-line-mode observing is required to detect and exploit observations of radio recombination lines (RRLs) and, possibly, other atomic and molecular transitions in the solar atmosphere. Clark et al. (2000a, b) reported line widths of order 500 MHz for the hydrogen RRLs H21α and H19α, suggesting that relatively low-resolution "time division mode" observations with ALMA may be sufficient for early exploitation of RRLs.

Solar flares
The strategy employed for observing the quiet Sun in Bands 3 and 6 using the MD receiver modes will not be feasible for solar flares, which can produce intense radiation that far exceeds the ubiquitous thermal background of the solar chromosphere. For solar flare observations solar filters must be used. The East Asia team has previously demonstrated the use of solar filters for flare observations but detailed calibration procedures have yet to be fully defined.

Science subarrays
The spectrum of continuum radiation from the Sun is a key observable. Given the dynamic nature of solar emissions at millimetre and submillimetre wavelengths, observations are needed in as many frequency bands as possible on a timescale commensurate with the phenomenon of interest. In practice, this is a challenge. It may be possible to timeshare between two or more frequency bands on timescales of tens of seconds for some programmes, but others (for example, observations of solar flares) will require strictly simultaneous observations in two or more frequency bands. This will require dividing the array into two or more subarrays that are each capable of observing the Sun independently.

Fast regional mapping
Solar-mode observing currently includes support of full disc total power mapping

as an adjunct to the interferometric observations. The total power maps have scientific value in their own right and, for certain applications, may be preferable to interferometic observations. The ALMA Solar Development Team has demonstrated that fast-scan mapping could be performed on sub-regions of the Sun at a relatively high cadence (tens of seconds). Continuous fast-scan mapping of regions on scales of just a few arcminutes using two or more total power antennas to provide multi-band imaging would be a valuable mode to observe certain aspects of solar flares and eruptive phenomena.

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Links

[1] The ALMA solar ephemeris generator: http://celestialscenes.com/alma/coords/CoordTool.html
[2] JPL Horizons web interface: https://ssd.jpl.nasa.gov/horizons.cgi
[3] ALMA solar observations: http://www.almaobservatory.org/en/announcement/alma-starts-observing-the-sun/
[4] ALMA science verification data: https://almascience.nrao.edu/alma-data/science-verification

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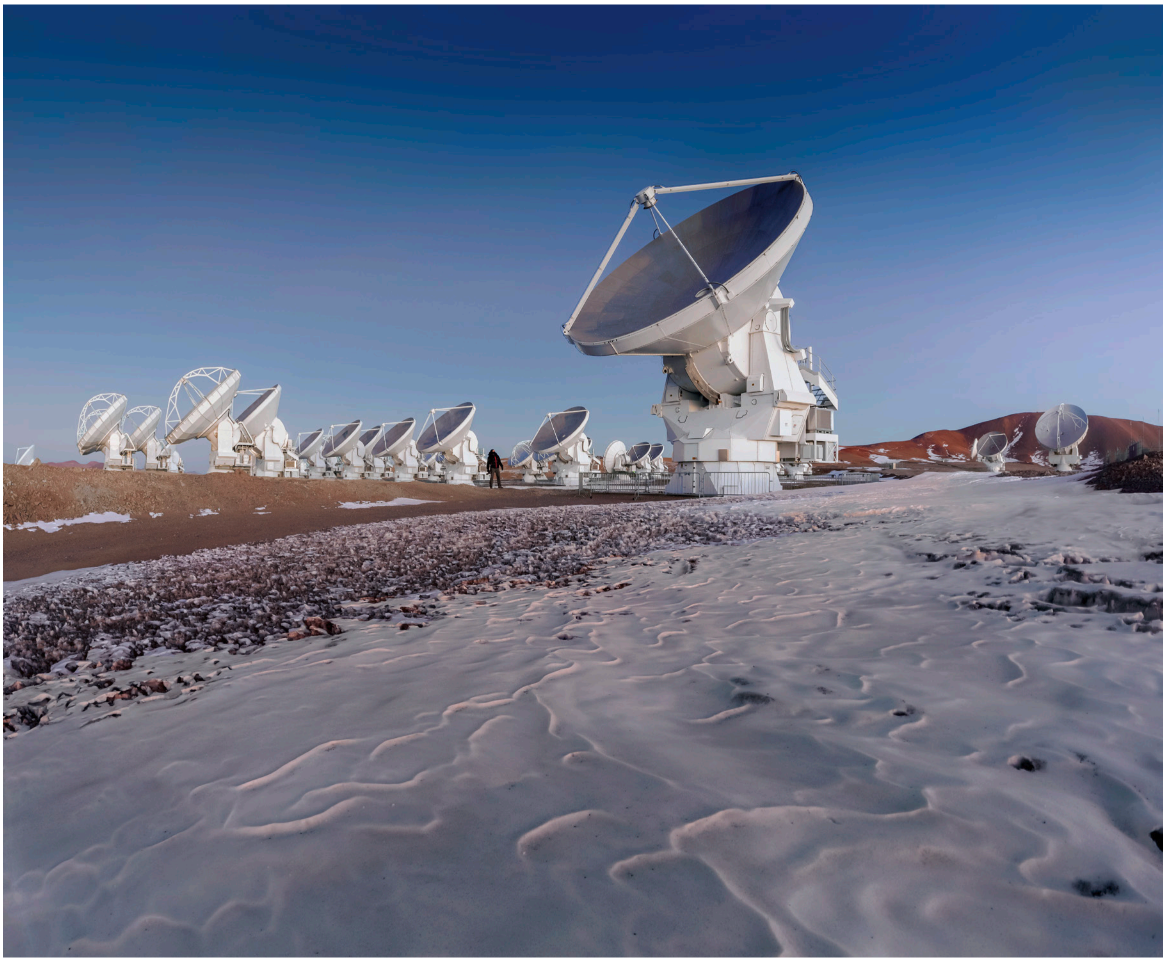

ALMA in 2017, just after a particularly harsh winter.