New Eyes on the Sun — Solar Science with ALMA

Sven Wedemeyer[1]

[1] University of Oslo, Norway

In Cycle 4, which starts in October 2016, the Atacama Large Millimeter/submillimeter Array (ALMA) will be open for regular observations of the Sun for the first time. ALMA's impressive capabilities have the potential to revolutionise our understanding of our host star, with far-reaching implications for our knowledge about stars in general. The radiation emitted at ALMA wavelengths originates mostly from the chromosphere — a complex and dynamic layer between the photosphere and the corona that is prominent during solar eclipses. Despite decades of intensive research, the chromosphere is still elusive due to its complex nature and the resulting challenges to its observation. ALMA will change the scene substantially by opening up a new window on the Sun, promising answers to long-standing questions.

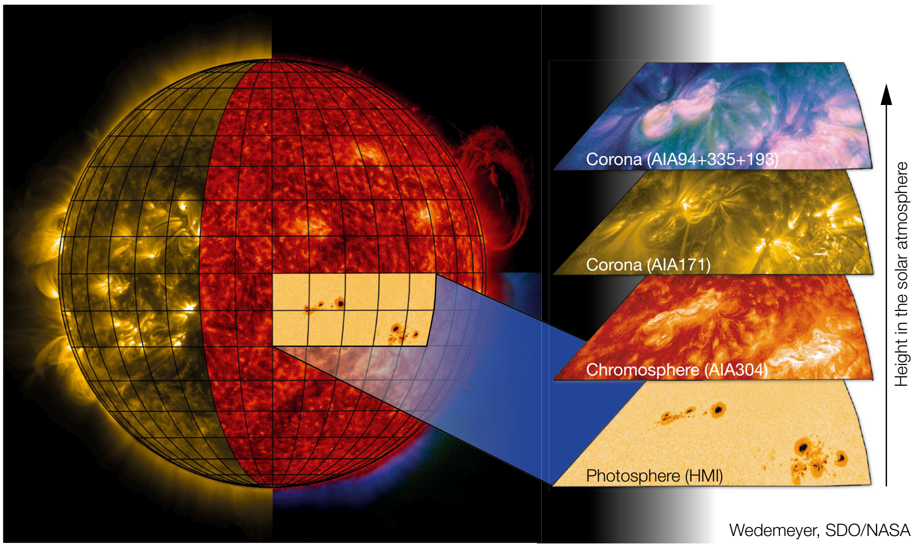

Figure 1. The Sun as seen with NASA's space-borne Solar Dynamics Observatory (SDO) on 20 December 2014, exhibiting a prominence on the top right limb of the solar disc. The images on the right side show close-ups of an active region observed in different filters, which essentially map plasma within different temperature ranges and thus at different height ranges in the solar atmosphere. The lowest panel shows the photosphere, whereas the top two images map the corona at temperatures of more than 6×10^5 K and at millions of Kelvin, respectively. ALMA will observe mostly the intermediate layer, the chromosphere, which is displayed in red.

The Sun — A dynamic multi-scale object

The impressive progress in ground-based and space-borne solar observations, together with numerical modelling, has led to a dramatic change in our picture of the Sun. We know now that the solar atmosphere, i.e., the layers above the visible surface, cannot be described as a static stack of isolated layers. Rather, it has to be understood as a compound of intermittent, highly dynamic domains, which are intricately coupled to one another. These domains are structured on a large range of spatial scales and exhibit a multitude of physical processes, making the Sun a highly exciting plasma physics laboratory.

High-resolution images and movies from modern solar observatories impressively demonstrate the Sun's complexity, which is aesthetic and challenging at the same time (see Figure 1). While most of the Sun is covered by quiet (or quiescent) regions, a few active regions are prominently apparent. They are characterised by strong magnetic field concentrations, visible in the form of sunspots, and produce flares, i.e., violent eruptions during which high-energy particles and intense radiation at all wavelengths are emitted. It is fascinating to realise that the Sun, a reliable source of energy sustaining life on Earth, is at the same time the source of the most violent and hazardous phenomena in the Solar System.

Observing the elusive solar chromosphere

The different radiation continua and spectral lines across the whole spectrum originate from different domains or layers within the solar atmosphere and probe different, complementary plasma properties. Consequently, simultaneous multi-wavelength observations, as obtained during coordinated campaigns with space-borne and ground-based instruments, are a standard in modern solar physics.

Unfortunately, only a few suitable diagnostic techniques for probing plasma conditions in the chromosphere are available. Amongst the most important, currently used, diagnostics are the spectral lines of singly ionised calcium (Ca II) and magnesium (Mg II), and Hα. Examples of observations of the chromosphere in the Ca II spectral line at 854 nm are shown in Figure 2 for different types of region on the Sun, all of them exhibiting a complicated structure shaped by the interaction of magnetic fields and dynamic processes.

The real problem, however, lies in the interpretation of these observations because these spectral lines have complicated formation mechanisms, which include non-equilibrium effects that are a direct result of the intricate nature of the chromosphere. This layer marks the transition between very different domains in the atmosphere of the Sun. Many simplifying assumptions that can be made for the photosphere no longer hold for the rarer chromosphere. There, the matter is optically thick for some wavelength ranges, but mostly transparent for others. The ionisation degree of hydrogen, the major ingredient of the Sun's plasma, is clearly out of equilibrium due to hot, propagating shock waves ionising the gas, but recombination does not occur instantaneously. Consequently, the observed intensities of chromospheric diagnostics usually depend on a large number of factors, which are non-local and involve the previous evolution of the plasma. Deriving the true plasma properties from an observable is therefore a complicated task with limited accuracy.

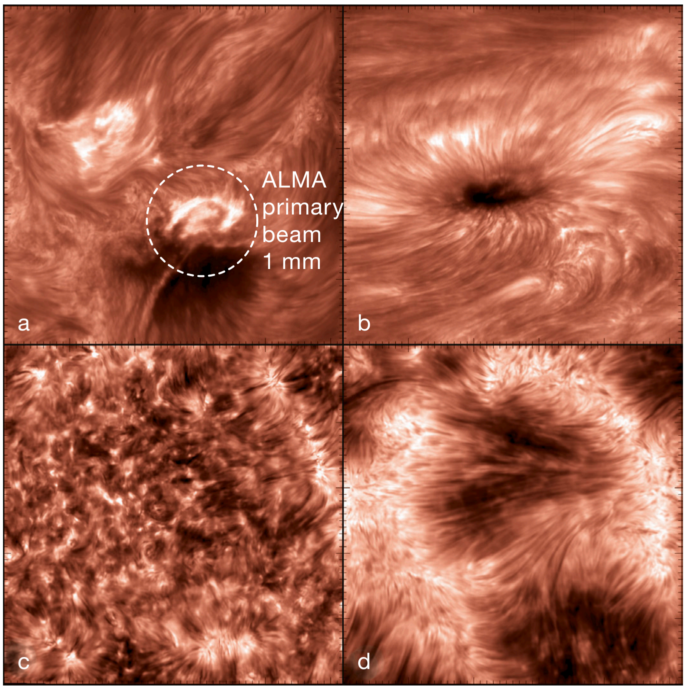

Figure 2. Chromospheric images taken in the core of the Ca II infrared triplet line at a wavelength of 854.2 nm, one of the currently most used chromospheric diagnostics. The observations were carried out with the Swedish 1-metre Solar Telescope. The field of view is about 1 × 1 arcminute (~ 1/30 of the solar diameter). (a) An active region with an ongoing medium-class flare (inside the circle). (b) The chromosphere above a sunspot close to the limb. (c) A quiet region inside a coronal hole close to the disc centre. (d) A decaying active region with a pronounced magnetic network cell close to the disc centre. Courtesy of L. Rouppe van der Voort (see also Wedemeyer et al., 2015).

The combination of the complicated, dynamic and intermittent nature of the chromosphere, with its non-linear relations between observables and plasma properties and the small number of useful diagnostics, have hampered progress in our understanding of this enigmatic layer. On the other hand, this challenge has driven the development of instrumentation and theory. Currently, ground-based observations with the Swedish 1-metre Solar Telescope (SST), aided by adaptive optics and advanced image reconstruction methods, achieve a spatial resolution of ~ 0.1 arcseconds, which corresponds to about 70 kilometres on the Sun. The next generation of solar telescopes with mirror diameters of the order of 1.5 metres currently, and 4 metres in the near future, will continue pushing towards smaller scales, which seems inevitably required in order to explain many observed solar phenomenon not yet understood.

ALMA and a new view of the Sun

The solar radiation continuum at millimetre wavelengths, as will be observed with ALMA, may provide answers to many open questions because it serves as a nearly linear thermometer for the plasma in a narrow layer of the solar chromosphere. In other words, the radiation at millimetre wavelengths gives direct access to fundamental properties such as the gas temperature, which are otherwise not easy to obtain. This unique capability comes, unfortunately, at a price, namely the comparatively long wavelength and the resulting low resolution for a given telescope size compared to optical telescopes. Resolving the relevant spatial scales on the Sun would require enormous single telescope apertures. The technical answer to this problem lies in the construction of large interferometric arrays composed of many telescopes, mimicking a large aperture and facilitating reliable imaging of an extended source like the Sun. Despite many noteworthy efforts in the past, only ALMA can now achieve imaging with an effective spatial resolution, which is, at the shortest wavelengths, close to what is currently achieved at visible wavelengths and thus is sufficient for investigating the small-scale structure of the solar chromosphere.

High-resolution imaging is only one of several key capabilities that make ALMA so interesting for solar observing. In addition, the high achievable temporal and spectral resolution and the ability to measure polarisation are crucial. Since the chromosphere changes on short dynamic timescales, long integration times result in smearing out the pattern, most notably on the smallest scales, which tend to evolve fastest. The first ALMA observations in Cycle 4 will already be able to allow for a time resolution of only 2 seconds, which enables the study of the complex interaction of magnetic fields and shock waves and yet-to-be-discovered dynamical processes — features that otherwise would not be observable. At the same time, the necessary high time resolution makes observing the Sun different from many other astronomical objects. Exploiting the Earth's rotation for improving the Fourier *u*–*v* plane coverage is not an option and thus other solutions are required for adequate imaging of solar features.

The continuum radiation received at a given wavelength originates from a narrow layer in the solar atmosphere with the height depending on the selected wavelength (see Figure 3). At the shortest wavelengths accessible with ALMA, i.e. 0.3 millimetres, the radiation stems from the upper photosphere and lower chromosphere, whereas the uppermost chromosphere is mapped at ALMA's longest wavelength (just short of 1 centimetre). Rapid scanning through wavelength, which might be achieved via rapid receiver band switching in the future, thus implies scanning through height in the solar atmosphere. Such observation sequences could be developed into tomographic techniques for measuring the three-dimensional thermal structure of the solar chromosphere — a true novelty with a significant scientific impact. The polarisation, which ALMA can measure, provides a measure of the longitudinal component of the magnetic field vector at the same time and in the same layer as the continuum radiation. In the same way, a scan through wavelength can be used to reconstruct the three-dimensional magnetic field structure in the solar chromosphere. Measuring the magnetic field in this layer is in itself a hot topic and has been tried many times.

Furthermore, the many spectral channels and the flexible set-up of the ALMA receiver bands opens up a number of new possibilities. Radio recombination and molecular lines at millimetre wavelengths

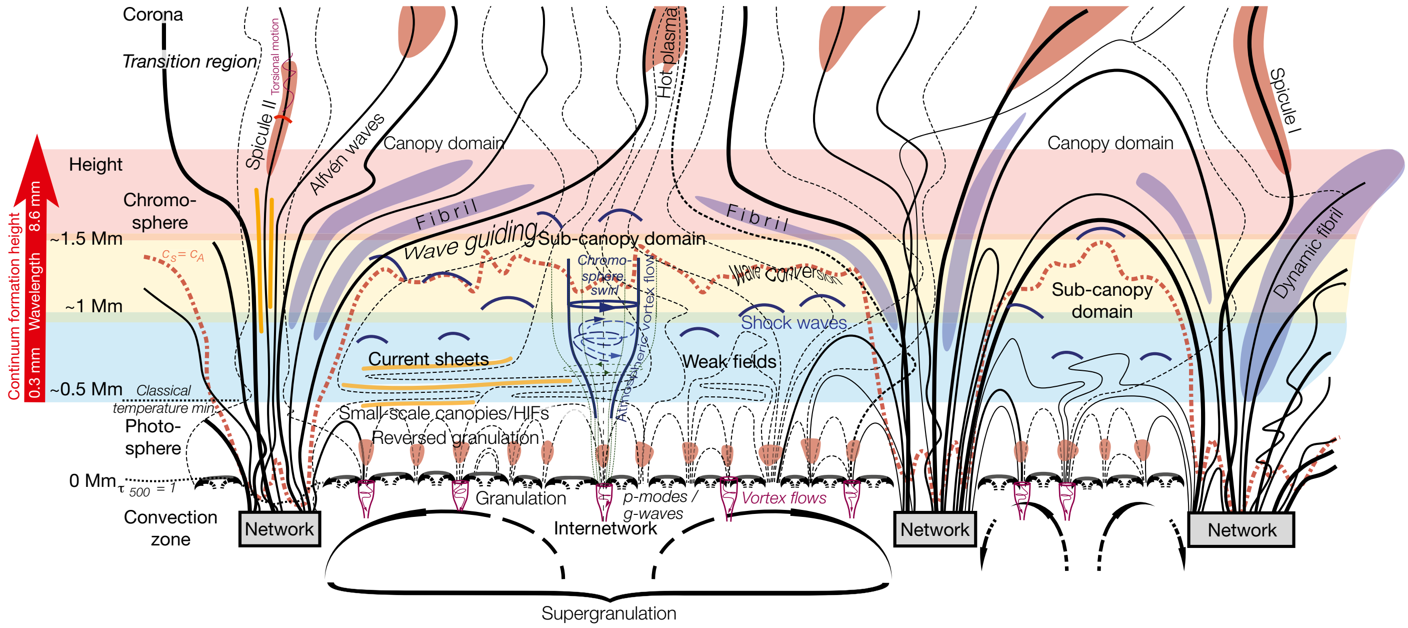

Figure 3. Schematic structure of the atmospheric layers in Quiet Sun regions, i.e. outside the strongest magnetic field concentrations, exhibiting a multitude of different phenomena. The black solid and dotted lines represent magnetic field lines. The arrow to the left and coloured bars illustrate the height range mapped by ALMA. Aspect ratio is not to scale. From Wedemeyer et al. (2015).

are expected to have a large diagnostic potential, providing complementary information about the thermal, kinetic and magnetic state of the chromospheric plasma and possibly adjacent layers. These unprecedented capabilities promise important new findings for a large range of topics and progress in fundamental questions in contemporary solar physics, although the details need to be investigated first.

Central questions in solar physics

The chromosphere plays an important role in the transport of energy and matter throughout the solar atmosphere and influences a number of currently poorly understood phenomena. Given ALMA's unique capabilities, there is little doubt that ALMA will advance our knowledge of the chromosphere in all its different flavours ranging from quiet solar regions to flares. In particular, substantial progress can be expected regarding central questions in contemporary solar physics, which we describe below.

Atmospheric heating

Since the late 1930s, it has been known that the gas temperature in the outer layers of the Sun rises, counter-intuitively, from a temperature minimum of around 4000 K at only a few hundred kilometres above the visible surface to values in excess of a million degrees Kelvin in the corona (Edlén, 1943; see Figure 5). The obvious conclusion is that the outer layers of the Sun are heated, but more than 70 years later it is still not clear exactly how. The same applies to the outer layers of other stars, too, making coronal and chromospheric heating a central and long-standing problem in modern astrophysics.

After many decades of research, a large number of processes are known, which could potentially provide the amount of energy required to explain the high temperatures deduced from observations. The question has therefore shifted to which processes exactly are the most relevant. It seems plausible to assume that a mix of different processes is responsible and that their heating contributions vary for the different types of region on the Sun, each of which have different magnetic field environments and thus different activity levels. Some processes provide continuous heating, producing a basal contribution, while others (e.g., flares, see below) have by nature a more transient effect and cause more variable and intermittent heating.

Next to magnetic reconnection processes and Ohmic heating, wave heating processes emerge as the most likely heating candidates outside flaring regions (see, e.g., De Pontieu et al., 2007). The waves can be primarily distinguished between acoustic and magnetohydrodynamic (MHD) waves, where the latter are subdivided into different wave modes, including for example Alfvén waves. MHD waves can in general contribute directly or indirectly to heating the atmospheric plasma, i.e., through perturbation of the magnetic field resulting in damping of the waves and the associated release of magnetic and kinetic energy. The consequences of this heating are, for instance, observed in the form of the ubiquitous spicules at the solar limb.

A large number of observations and theoretical models suggest further potential candidates for relevant heating mechanisms, for example magneto-acoustic shocks, gravity waves, (magneto-acoustic) high frequency waves, transverse kink waves, multi-fluid effects and plasma instabilities, to name just a few. The large number of possible heating mechanisms has made it difficult to determine which of them actually dominate and how their heating contributions depend on the type of region on the Sun. Knowledge of their characteristic properties, e.g., their spectral signatures, would in principle allow the different mechanisms to be identified,

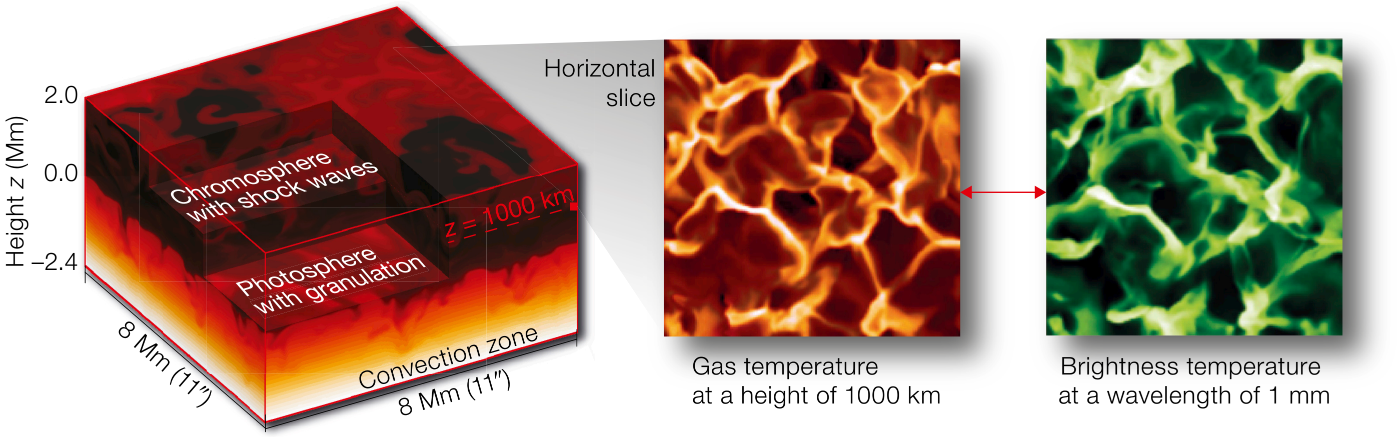

Figure 4. Illustration of a 3D numerical model of a small region in the solar atmosphere (left). The gas temperature in a horizontal cross-section in the chromosphere at a height of 1000 km (centre) corresponds closely to the brightness temperature at a wavelength of 1 mm (right) as derived from a detailed radiative transfer calculation involving the whole model atmosphere. The close match between patterns demonstrates that ALMA can serve as a linear thermometer for the chromospheric plasma.

the disentangling of their contributions and could reveal the sources and sinks of heating in the chromosphere through which all energy has to pass on its way into the corona. This crucial task, however, ultimately requires quantitative and precise measurements, which can produce datasets that completely and unambiguously describe the thermal, magnetic and kinetic state of the chromospheric plasma in a way that is time-dependent and in three spatial dimensions. ALMA has the potential to deliver just such impressive datasets, making it a potential game-changer that would take an essential step towards answering the chromospheric/coronal heating problem.

The answer to the heating problem would have direct implications for the nature of stellar atmospheres and their activity in general. Observations of the activity as a function of stellar type, e.g., by using the observed flux density in the Ca II H + K spectral lines as a chromospheric activity indicator, reveal a lower limit, known as basal flux (Schrijver, 1987). The exact source of this basal flux, however, is still debated. It is most likely the combined product of heating due to acoustic waves and processes connected to the atmospheric magnetic field. In this respect, the Sun may serve as a Rosetta Stone for deciphering the various contributions from the different phenomena to stellar activity, and ALMA would be the tool of choice.

Solar flares

ALMA will also be able to make substantial contributions to answering many open questions concerning solar flares, which can be considered as one of the major problems in contemporary solar physics and thus a very active field of research. While many details are as yet unknown, it is clear that solar flares are produced by the violent reconfiguration and reconnection of the magnetic field in the solar atmosphere. As a result, large amounts of energy, which were stored in the magnetic field prior to an event, are released explosively in the form of radiation and high-energy particles, which are accelerated to very high speeds. The emitted radiation covers the whole electromagnetic spectrum from gamma-rays and X-rays to radio waves. The strongest solar flares observed occur in active regions with strong magnetic fields and release energy on the order of a few 10^{32} ergs, equivalent to a few billion megatons of TNT (Emslie et al., 2005).

Not all flares are equally strong, but they span a large range of strengths. The much weaker micro- and nano-flares occur on small spatial scales and may contribute to the heating of the corona in a more subtle and continuous way. In contrast, the strongest flares are sometimes accompanied by coronal mass ejections (CME) and can lead to the ejection of solar plasma into interplanetary space. Such space weather events can have notable effects on Earth, ranging from beautiful aurorae to disruptions of

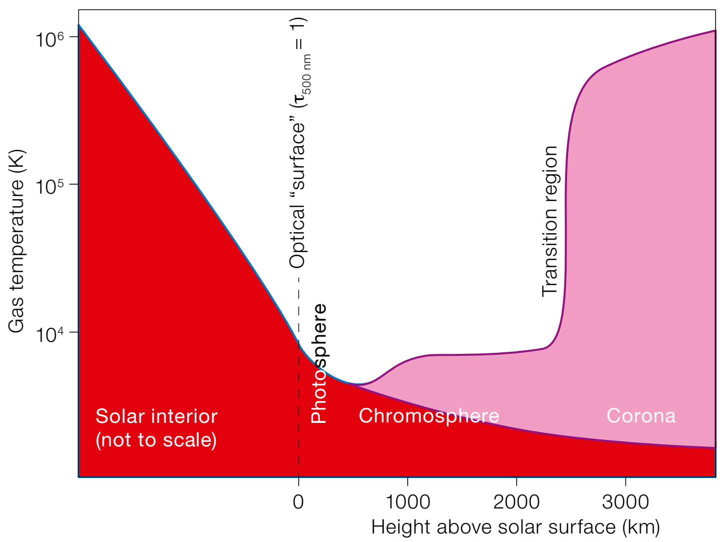

Figure 5. Schematic average gas temperature of the Sun as function of height. The lower curve illustrates how the temperature in the upper layers would decline without heating, whereas the upper curve is the actual average profile implied by observations.

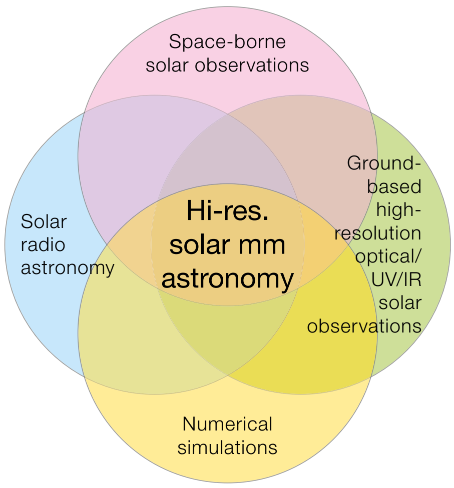

Figure 6. Shaping a new research field: high-resolution solar millimetre astronomy.

power grids (like the Quebec blackout in 1989) and the satellite infrastructure on which our modern society so sensitively depends.

The strong flares observed so far may not mark the upper end of the scale. The possible occurrence of super-flares is discussed (Maehara et al., 2012), which may release more energy than the infamous Carrington event of 1859. This powerful geomagnetic storm was the result of a CME hitting the Earth's magnetosphere associated with a strong solar flare, resulting in aurorae unusually far from the poles, visible in Hawaii, Cuba, Liberia and Queensland, but also responsible for the failure of telegraph systems. A CME of similar strength occurred in 2012 but luckily missed the Earth. Such super-energetic events are certainly rare, but they would have truly devastating consequences for modern society and must therefore be studied. Super-flares have been observed on other stars and red dwarf stars even exhibit mega-flares, which can be more than a thousand times stronger than their strongest (known) solar analogues and thus exceed the bolometric luminosity of the whole star in minutes (Hawley & Pettersen, 1991).

Open questions about solar and stellar flares on all scales concern, for example, the particle acceleration mechanisms and the source of the still-enigmatic emission component, which is observed at sub-THz frequencies. ALMA's high spectral, spatial and temporal resolution for observations in the sub-THz range, together with the ability to probe the thermal structure and magnetic fields in flaring regions, promise ground-breaking discoveries in this respect. Already the thermal free-free radiation, which is mostly due to electron-ion free-free absorption and H^- free-free absorption, provides much needed information. In addition, however, ALMA can also detect the non-thermal radiation component produced by gyro-synchrotron and gyroresonance processes, which become important in the vicinity of strong magnetic fields and can thus provide important clues about the acceleration of charged particles during flares. Another intrinsic feature of flares, which can be exploited by ALMA, are quasi-periodic pulsations, which constrain the physical mechanisms behind the accumulation and release of magnetic energy and the acceleration of particles.

Solar prominences

ALMA is an ideal tool for probing the cool plasma in the solar atmosphere and will therefore be able to contribute to answering many still-open questions about solar prominences. Solar prominences are extended structures in the solar atmosphere that reach up from the visible surface into the corona (Vial & Engvold, 2015). Prominences appear bright when seen above the solar limb (Figure 1, top right) and as (dark) filaments when seen against the bright solar disc. The gas contained in a prominence is much cooler (some 10^4 K) and denser than the surrounding 10^6 K coronal plasma and is supported by magnetic fields against gravity.

Quiescent prominences exhibit large-scale structures that can measure a few 100 000 kilometres, thus stretching over a significant portion of the Sun. These prominences can remain stable for many days or weeks, making them one of the longest-lived solar phenomena. Their fine structures, on the other hand, change on timescales of a few minutes. In contrast, active prominences live for a much shorter time, exhibit large-scale motions and can erupt within hours. Erupting prominences can propel substantial amounts of magnetised plasma at high speeds into interplanetary space and are thus one of the primary sources of space weather. It is not clear what exactly triggers such eruptions. Among the processes, which may contribute and could be studied with ALMA, are (giant) solar tornadoes, which form at some of the legs of prominences. The rotation of the magnetic prominence legs builds up twist in the magnetic field of the overlying prominence, which may eventually cause a destabilisation of the whole structure.

Other important questions, which could be addressed with ALMA, concern: the thermal structure of prominence bodies with their spatial fine-structure, which is composed of fine sub-arcsecond threads; and the transition to the ambient coronal medium, with resulting implications for the energy balance of prominences. Equally, it is not yet settled what the elementary magnetic field structures are or how they connect to the field at the solar surface. In this respect, ALMA observations at high spatial and temporal resolutions will help to track the changes of the prominence plasma and the magnetic field, giving clues on how solar prominences form, how they evolve and eventually diminish or erupt.

The advantage of using ALMA lies again in the easier interpretation of the observations. The spectral lines in the optical and ultraviolet currently used for prominence observations are optically thick, so that detailed radiative transfer calculations are necessary for their analysis. In contrast, the prominence plasma is optically thin at ALMA wavelengths, which makes the interpretation much simpler and straightforward. In addition, observations of waves and oscillations in prominences provide essential information and constraints on the magnetic field structure. Prominences have already been seen with ALMA during test observations and will certainly be an exciting target both for high-resolution studies of their dynamic fine-structure and for mosaics capturing their large-scale structure.

Preparing the future

As in many other fields of astrophysics, numerical simulations have become an essential tool in solar physics. They help to simulate what ALMA might observe

(Figure 4). Such artificial observations of the Sun allow for the development and optimisation of observing strategies, which are quite different for the dynamic Sun than for most other ALMA targets. For this purpose, and in connection with solar ALMA development studies, an international network was initiated in 2014, which aims at defining and preparing key solar science with ALMA through simulation studies: SSALMON[1] (Solar Simulations for the Atacama Large Millimeter Observatory Network). The network has currently (as of early 2016) 77 members from 18 countries around the world. Furthermore, the SolarALMA project, funded by the European Research Council from 2016 to 2021 and hosted at the University of Oslo, aims at addressing the heating problem through a synthesis of ALMA observations and numerical simulations.

In essence, these developments illustrate that a new research field is emerging, which could be named high-resolution solar millimetre astronomy (schematically shown in Figure 6). This new field brings together solar radio astronomy, which was previously limited to lower spatial resolution, and ground-based and space-borne high-resolution observations at other wavelength ranges, combined with state-of-the-art numerical modelling. This is a truly golden era for studies of the solar chromosphere with many exciting scientific results expected for the coming years.

Acknowledgements

Future solar observing with ALMA is made possible due to the dedicated work of many colleagues as part of Commissioning and Science Verification/Extension of Capabilities (CSV/EOC) activities carried out by the solar development teams of the North American, European and East Asian ALMA Regional Centres (ARCs) and the Joint Astronomical Observatory (JAO), and as part of recent SSALMON publications. Special thanks in connection with this article go to H. Hudson and N. Labrosse.

References

De Pontieu, B. et al. 2007, Science, 318, 1574
Edlén, B. 1943, Zeitschrift für Astrophysik, 22, 30
Emslie, A. G. et al. 2005, Journal of Geophysical Research (Space Physics), 110, A9, 11103
Hawley, S. L. & Pettersen, B. R. 1991, ApJ, 378, 725
Maehara, H. et al. 2012, Nature, 485, 478
Schrijver, C. J. 1987, A&A, 172, 111
Vial, J.-C. & Engvold, O. 2015, A&SS Library, Vol. 415, (Switzerland: Springer International Publishing)
Wedemeyer, S. et al. 2015, SSRv, Online First

Links

[1] SSALMON: http://ssalmon.uio.no

ESO/C. Malin

A meteor burning up in the Earth's atmosphere was captured on camera during a time-lapse exposure of the Atacama Large Millimeter/submilimeter Array (ALMA) at Chajnantor.