Solar and Stellar Multi-scale Activity
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A Complementary View of Solar and Stellar Activity at Millimeter Wavelengths

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Abstract. Observations at (sub-)millimeter wavelengths provide a valuable complementary perspective on the Sun and other stars, particularly regarding the thermal and magnetic structure, as well as the dynamics of their chromospheres and the resulting activity. While significant progress has been made in (sub-)millimeter solar observations, certain critical aspects still require diagnostic capabilities beyond those available with current observatories. In particular, simultaneous observations of the radiation continuum across an extended frequency range would enable the mapping of different atmospheric layers and, ultimately, the three-dimensional structure of the solar atmosphere. Capturing large regions of the Sun–or even the entire solar disk–with high temporal cadence would be essential for systematically identifying and tracking the temporal evolution of solar flares. Synoptic observations at higher angular resolution, such as daily maps spanning multiple years, would offer an unprecedented perspective on the solar activity cycle in this wavelength regime. Given that the Sun serves as a fundamental reference for investigating the atmospheres of active main sequence stars, utilizing the same instrument to observe both the Sun and other stars would unlock significant diagnostic potential for studying stellar activity and its implications for exoplanet habitability. The proposed Atacama Large Aperture Submillimeter Telescope (AtLAST), when equipped with a large array of detector elements to probe the radiation continuum across a broad frequency range, would be well-suited to deliver these essential observational capabilities. We present an overview of key science cases for AtLAST and considerations for the design of an instrument in comparison to potential upgrades of the Atacama Large Millimeter/submillimeter Array (ALMA), highlighting future scientific opportunities for studying solar and stellar activity.

Keywords. The Sun, stellar atmospheres, chromosphere, stellar activity, millimeter radiation, telescopes, instrumentation

1. Introduction

The solar atmosphere is stratified but dynamically coupled, exhibiting highly dynamic and intermittent behaviour (Wedemeyer et al. 2009, and references therein). It is structured across a broad range of spatial and temporal scales and hosts a multitude of processes, many of which are subject to non-equilibrium effects, such as hydrogen ionisation (Carlsson & Stein 2002), and non-local thermodynamic equilibrium (non-LTE) conditions (de la Cruz Rodríguez et al. 2010). To understand these complex phenomena, comprehensive data sets are essential. At the same time, the dynamic and intermittent nature of the solar chromosphere makes observations challenging. The formation of many spectral lines and continua is complex, introducing persistent uncertainties in

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the derivation of fundamental plasma properties, such as temperature. Moreover, the enormous range of spatial and temporal scales is difficult to capture in full. Inevitably, instruments must compromise between spatial, temporal, and spectral resolution and coverage. Consequently, as the Sun – unlike most other astronomical objects – evolves on short timescales, the acquisition of images must be sufficiently fast. The dynamic nature of the Sun thus poses particular difficulties when using general-purpose instruments. In the following, we are exploring the prospects of the continuum radiation at millimeter wavelengths for measuring the thermal and magnetic structure of the solar atmosphere (see also the review by Wedemeyer et al. 2016). Millimeter observations also offer considerable potential for studying the atmospheres of other stars, even though main-sequence stars will remain unresolved for now. As the Sun serves as a crucial benchmark for such studies, using the same instrument to observe both the Sun and other stars would provide powerful diagnostics of stellar activity and its consequences for exoplanet habitability.

2. The potential of millimeter-wavelength diagnostics

In the solar atmosphere, the opacity at millimeter wavelengths mainly arises from free-free absorption involving electrons with protons, neutral hydrogen, and H^- ions (see, e.g., White et al. 2006; Wedemeyer et al. 2016, and references therein). The atmospheric height at which the continuum radiation emerges increases with wavelength, enabling the probing of different layers of the solar atmosphere, or more specifically, the chromosphere. The continuum intensity then provides a linear measure of the local electron temperature of the probed layer, offering a straightforward diagnostic of thermal conditions in the solar atmosphere. Measurements of polarisation allow for the determination of the line-of-sight component of the magnetic field strength (Bogod & Gelfreikh 1980; Grebinskij et al. 2000). By combining observations at multiple wavelengths, it is, in principle, possible to apply tomographic analyzes to derive the three-dimensional thermal, magnetic, and kinetic structure of the solar chromosphere. However, the layers probed at a given wavelength are highly corrugated and dynamic, complicating their interpretation (see Fig. 1). There are even signs that the continuum radiation may not always originate from a well-defined height range, but that, owing to the complex atmospheric structure, multiple layers may sometimes contribute (Wedemeyer et al. 2020). At the same time, the rapid temporal evolution of chromospheric features necessitates high-cadence observations to capture the relevant dynamics accurately. Tomographic reconstruction of the 3D time-dependent atmospheric structure would therefore require simultaneous multi-wavelength observations, combined with sophisticated data inversion techniques (da Silva Santos et al. 2020a).

3. The Atacama Large Millimeter/submillimeter Array (ALMA)

The Atacama Large Millimeter/submillimeter Array (ALMA), consisting of 66 antennas located in the Atacama Desert in Chile, has enabled regular interferometric imaging of the Sun since 2016 (Bastian 2002; Karlický et al. 2011; Shimojo et al. 2017a; White et al. 2017). ALMA provides measurements of the continuum intensity in frequency Bands 3 to 5 and Band 7, covering the range from 90 to 350 GHz, corresponding to wavelengths between approximately 0.9 and 3.3 mm. These observations can be performed at a cadence of 1 second, allowing high-temporal-resolution studies of solar dynamics. In addition, regular polarisation measurements in Band 3 have been available since 2024, offering diagnostics of the line-of-sight magnetic field component (Shimojo et al. 2024).

Despite its capabilities, ALMA faces certain diagnostic limitations. Snapshot imaging at a cadence of 1 second is challenging due to the limited number of interferometric baselines available at any given time. Furthermore, observations are restricted to a single

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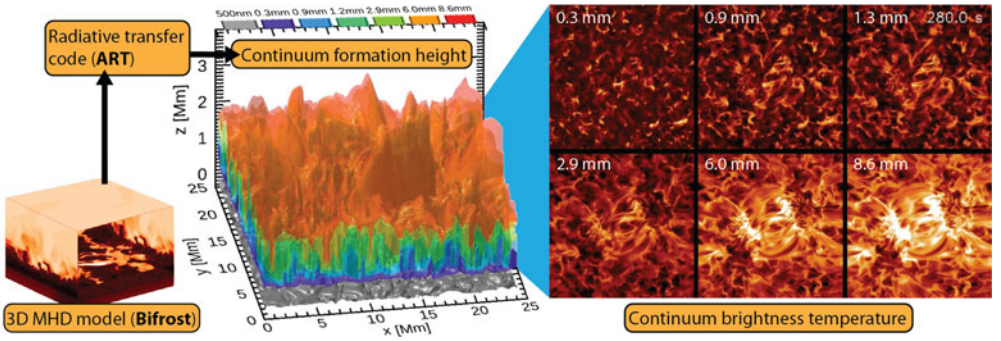


Figure 1. Synthesised brightness temperatures and formation heights derived from a 3D solar atmosphere model calculated with the Bifrost (Gudiksen et al. 2011; Carlsson et al. 2016) and ART (de la Cruz Rodríguez et al. 2021) codes, demonstrating the tomographic capabilities of high-cadence multi-wavelength observations. The surfaces of optical depth unity (middle) and the corresponding brightness temperature (or intensity) maps (right) are shown for various wavelengths.

receiver band at a time, which precludes simultaneous multi-height observations and thus makes tomographic analysis infeasible. The available field of view is also limited, which constrains the spatial extent of the observed solar regions. Nonetheless, ALMA observations, owing to their high cadence and high angular resolution (for this wavelength range), have produced the first promising results (e.g., Shimojo et al. 2017b; Yokoyama et al. 2018; Brajša et al. 2018; Jafarzadeh et al. 2019; Rodger et al. 2019; Selhorst et al. 2019; Wedemeyer et al. 2020; da Silva Santos et al. 2020b; Eklund et al. 2020; Nindos et al. 2020; Patsourakos et al. 2020; Brajša et al. 2021; Chintzoglou et al. 2021; Guevara Gómez et al. 2021; Jafarzadeh et al. 2021; Nindos et al. 2021). Science-ready data products are available via the Solar ALMA Science Archive (SALSA†), as described by Henriques et al. (2022). Nevertheless, it is fair to say that ALMA's scientific potential for studying the Sun is far from being fully exploited, mostly because of the difficulties in acquiring sufficient observing time and the complications in imaging and post-processing for such a dynamic target.

4. Future observatories

While we here focus on the complementarity of AtLAST (Sect. 4.1) and ALMA (Sect. 4.2), there are several other facilities that are worth mentioning, for instance, the Frequency Agile Solar Radiotelescope (FASR Gary et al. 2023), recommended in the U.S. solar and space physics decadal survey, and the Solaris project for continuous solar monitoring and space weather applications (Pellizzoni et al. 2024).

4.1. *AtLAST*

The Atacama Large Aperture Submillimeter Telescope (AtLAST) is a planned 50-metre single-dish antenna to be located at high altitude ($\sim$5100 metres), preferably near the ALMA site in the Atacama Desert in Chile. The project is being developed by an international consortium of approximately 150 participants, coordinated by the University of Oslo. The conceptual design of the telescope was completed in 2024 (Mroczkowski et al. 2025), and the second EU-funded development phase is currently ongoing (2025–2028). Construction of AtLAST, however, still requires dedicated funding.

† http://sdc.uio.no/salsa/

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Despite its large aperture, AtLAST will offer an angular resolution of approximately 1.5" at 950 GHz and around 15" at 100 GHz, which is lower than the angular resolution achievable with ALMA across baselines of a few 100 m. Consequently, AtLAST will address different science cases than ALMA. AtLAST's would offer unique capabilities due to the use of innovative technologies for a renewable energy system, active optics based on closed-loop metrology, and a wide field of view with a diameter of up to 2 degrees, and – most importantly – next-generation instrumentation. While the instruments are yet to be designed, the telescope could be equipped with a multi-chroic camera or focal plane arrays. A first-generation camera is expected to consist of approximately 50,000 detector elements† ("pixels"), while the second generation may reach up to 300,000 pixels. Such a detector array could enable simultaneous continuum observations at 4–8 frequency bands, covering a spectral range from approximately 90 to 700 GHz (or possibly up to 1 THz). According to the study by Kirkaune et al. (2025) using the maria telescope simulator (van Marrewijk et al. 2024), the first generation of such an instrument could achieve multi-frequency scans of the entire solar disk within less than a minute, while the second generation could potentially reduce this cadence to just a few seconds. Such an instrument would enable high-cadence, full-disk, multi-band diagnostics of the solar atmosphere. The anticipated data, when processed with advanced data inversion techniques (da Silva Santos et al. 2020a), could provide three-dimensional tomography of the thermal and magnetic structure of the solar atmosphere. Such capability is particularly valuable for capturing dynamic solar events such as flares in their early phases and across their full spatial extent – a feat that is hard to accomplish with a small field of view as presently available for ALMA.

4.2. *ALMA2040*

The ALMA2040 initiative aims to realise a transformative upgrade of the Atacama Large Millimeter/submillimeter Array (ALMA) to meet the demands of next-generation astrophysical observations. This initiative is being developed in response to ESO's Expanding Horizons call, with a proposal submission deadline in 2027.

The proposed upgrades would bring significant diagnostic improvements in terms of sensitivity and frequency coverage, which are directly relevant for stellar observations but also for observations of the Sun. Increasing the number of antennae would provide a much higher number of interferometric baselines, thereby enabling superior image fidelity for solar observations. The proposed capability for simultaneous multi-band observations could make solar tomography possible, allowing for the reconstruction of the three-dimensional thermal and magnetic structure of the solar atmosphere. In addition, the upgrades are expected to deliver enhanced angular resolution, which are essential for resolving fine-scale structures in the solar atmosphere. Focal Plane Arrays (FPAs) are another option for increasing ALMA's scientific potential for studying the Sun. The resulting multiple beams would increase ALMA's instantaneous field of view substantially, making it possible to observe a whole Active Region at high cadence without the need to revert to mosaicking with a correspondingly much lower cadence. This option would be crucial for capturing flares and studying their temporal evolution in the millimeter wavelength range.

5. Solar Science Cases at Millimeter Wavelengths

Observations of the Sun at millimeter wavelengths contribute significantly to our understanding of both, the solar structure and solar activity. One of the key open questions in solar physics is the *coronal heating problem*: How is the solar corona heated to

† As of 2025, cameras with 64 × 64 pixels are commercially available.

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temperatures exceeding one million Kelvin? This fundamental issue, known for almost a century (Grotrian 1934; Edlén 1945), remains unresolved and is central to investigations of the solar atmosphere.

Solar activity represents another major science case. Energetic events, such as solar flares, are triggered by magnetic reconnection and can release vast amounts of energy. Coronal mass ejections (CMEs) involve the ejection of plasma clouds into interplanetary space and are key drivers of space weather phenomena. Other aspects of solar activity include the solar wind and the operation of the solar dynamo, which governs the generation and temporal evolution of the Sun's magnetic field over the solar activity cycle. These processes have direct implications for Earth, where space weather can impact technological systems and necessitate accurate forecasting (Pomoell & Poedts 2018).

The high-cadence observations of the full solar disk planned for AtLAST would enable continuous monitoring of solar activity. During an observing run, all flares above the instrument's sensitivity threshold will be detected, ensuring a comprehensive record of eruptive events.

6. Stellar Science Cases – The solar-stellar connection

The Sun serves as the ultimate reference star for stellar astrophysics. Its proximity enables detailed, spatially resolved observations that are not feasible for other stars, offering an in-depth understanding of fundamental processes. By studying the Sun as a star, one can calibrate and interpret unresolved stellar observations, particularly concerning the thermal and magnetic structure of stellar atmospheres. These insights are essential for studying stellar atmospheres and activity across different stellar types. The potential of millimeter observations for investigating the thermal structure of stellar atmospheres has been explored by the EMISSA project, resulting in an initial catalogue of 12 main sequence stars, including the Sun. The employed ALMA observations are complemented by data from other telescopes covering a broad wavelength range. In particular, the presence of a temperature excess at millimeter wavelengths, analogous to what is observed in the solar chromosphere, provides a quantitative means to evaluate atmospheric heating as a function of spectral type. This excess can be quantified in the form of a novel stellar activity indicator ($\alpha_{\rm mm}$). For further details, see Mohan et al. (2021, 2022). Future observations from AtLAST and an upgraded ALMA would allow to extend the sample substantially thanks to much increased sensitivity.

Moreover, observations at millimeter wavelengths can contribute to the detection and characterisation of exoplanets, particularly through the analysis of stellar activity that may influence observational signals. Understanding such activity is also crucial for assessing exo-space weather, which can affect the habitability of exoplanets by influencing their atmospheres and potential for hosting life. The combination of solar and stellar flare observations – with AtLAST, an upgraded ALMA, or both – will offer a unique basis for comparative studies and a deeper understanding of magnetic energy release in stellar atmospheres. The resulting flare models would have important implications for evaluating the evolution of exoplanet atmospheres and their habitability (Segura et al. 2010; Mamonova et al. 2025).

7. Conclusions and Outlook

Radiation at millimeter wavelengths offers powerful and complementary diagnostic capabilities for studying solar and stellar atmospheres. It provides a direct measure of the thermal structure, with spectral indices offering further constraints on temperature gradients, while polarisation measurements enable the inference of magnetic field strengths.

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Looking ahead, several promising observatories are being planned for beyond the 2030–2040 timeframe, although they have yet to be fully funded. Among them, AtLAST – a 50-metre single-dish telescope – is designed to provide fast, multi-frequency scanning with a large field of view, making it particularly well suited for full-disk solar observations and high-cadence 3D tomography. In parallel, the ALMA2040 initiative proposes major upgrades to the Atacama Large Millimeter/submillimeter Array, aimed at enhancing imaging capabilities for solar observations and increasing sensitivity for stellar studies. It is important to emphasise that the solar and stellar science case for ALMA (Wedemeyer et al. 2016) and for AtLAST (Wedemeyer et al. 2024) are largely complementary due to differences in properties such as the field-of-view. Together, these developments will significantly advance the use of millimeter continuum and polarisation diagnostics in understanding chromospheric heating, magnetic activity, and dynamic processes in the Sun and other stars.

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