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CASE STUDY

REVISED Science development study for the Atacama Large Aperture Submillimeter Telescope (AtLAST): Solar and stellar observations

[version 2; peer review: 3 approved]

Sven Wedemeyer[1,2], Miroslav Barta[3], Roman Brajša[4], Yi Chai[3], Joaquim Costa[5], Dale Gary[6], Guillermo Gimenez de Castro[5], Stanislav Gunar[3], Gregory Fleishman[6,7], Antonio Hales[8,9], Hugh Hudson[10,11], Mats Kirkaune[1,2], Atul Mohan[12,13], Galina Motorina[3,14,15], Alberto Pellizzoni[16], Maryam Saberi[1,2], Caius L. Selhorst[6,17], Paulo J. A. Simoes[5,10], Masumi Shimojo[18,19], Ivica Skokić[4], Davor Sudar[4], Fabian Menezes[5], Stephen M. White[20], Mark Booth[21], Pamela Klaassen[21], Claudia Cicone[2], Tony Mroczkowski[22], Martin A. Cordiner[23], Luca Di Mascolo[24-27], Doug Johnstone[28,29], Eelco van Kampen[22], Minju Lee[30,31], Daizhong Liu[32,33], Thomas Maccarone[34], John Orlowski-Scherer[35], Amelie Saintonge[36,37], Matthew Smith[38], Alexander E. Thelen[39]

[1]Rosseland Centre for Solar Physics, University of Oslo, Oslo, Oslo, N-0315, Norway
[2]Institute of Theoretical Astrophysics, University of Oslo, Oslo, Oslo, N-0315, Norway
[3]Astronomical Institute, The Czech Academy of Sciences, Ondrejov, 251 65, Czech Republic
[4]Hvar Observatory, Faculty of Geodesy, University of Zagreb, Zagreb, HR-10000, Croatia
[5]Centro de Rádio Astronomia e Astrofísica Mackenzie, Escola de Engenharia, Universidade Presbiteriana Mackenzie, São Paulo, State of São Paulo, 01302-907, Brazil
[6]Center for Solar-Terrestrial Research, New Jersey Institute of Technology, New Jersey Institute of Technology, Newark, New Jersey, NJ 07102, USA
[7]Institute for Solar Physics, Freiburg, 79104, Germany
[8]National Radio Astronomy Observatory, Charlottesville, Virginia, 22903, USA
[9]Joint ALMA Observatory, Santiago, 763-0355, Chile
[10]SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, G12 8QQ, UK
[11]Space Sciences Laboratory, University of California Berkeley, Berkeley, California, 94720, USA
[12]The Catholic University of America, Washington, District of Columbia, DC 20064, USA
[13]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA
[14]Central Astronomical Observatory at Pulkovo, Russian Academy of Sciences, St. Petersburg, 196140, Russian Federation
[15]Ioffe Institute, Polytekhnicheskaya, St. Petersburg, 194021, Russian Federation
[16]Cagliari Astronomical Observatory, Istituto Nazionale di Astrofisica, Selargius, I–09047, Italy
[17]Núcleo de Astrofísica, Universidade Cidade de São Paulo, São Paulo, State of São Paulo, Brazil
[18]National Astronomical Observatory of Japan, Tokyo, 181-8588, Japan
[19]Graduate University of Advanced Studies (SOKENDAI), Tokyo, 181-8588, Japan
[20]Space Vehicles Directorate, Air Force Research Laboratory, Albuquerque, New Mexico, NM 87117, USA
[21]UK Astronomy Technology Centre, Royal Observatory Edinburgh, Edinburgh, EH9 3HJ, UK
[22]European Southern Observatory, Garching bei Munchen, 85748, Germany
[23]Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, MD 20771, USA
[24]Observatoire de la Cote d'Azur, Universite Cote d'Azur, Nice, Provence-Alpes-Côte d'Azur, CS 34229, 06304, France
[25]

Astronomy Unit, Department of Physics, University of Trieste, Trieste, 34131, Italy
[26]Osservatorio Astronomico di Trieste, Istituto Nazionale di Astrofisica, Trieste, 34131, Italy
[27]Institute for Fundamental Physics of the Universe, Trieste, Italy
[28]NRC Herzberg Astronomy and Astrophysics, Victoria, V9E 2E7, Canada
[29]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, V8P 5C2, Canada
[30]Cosmic Dawn Center, Copenhagen, Denmark
[31]DTU-Space, Technical University of Denmark, Kgs. Lyngby, DK2800, Denmark
[32]Max-Planck-Institut fur extraterrestrische Physik, Garching, D-85748, Germany
[33]Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, 210023, China
[34]Department of Physics & Astronomy, Texas Tech University, Lubbock, Texas, 79409-1051, USA
[35]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, 19104, USA
[36]Department of Physics and Astronomy, University College London, London, England, WC1E 6BT, UK
[37]Max-Planck-Institut fur Radioastronomie, Bonn, D-53121, Germany
[38]School of Physics & Astronomy, Cardiff University, Cardiff, Wales, CF24 3AA, UK
[39]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, CA 91125, USA

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Abstract

Observations at (sub-)millimeter wavelengths offer a complementary perspective on our Sun and other stars, offering significant insights into both the thermal and magnetic composition of their chromospheres.

Despite the fundamental progress in (sub-)millimeter observations of the Sun, some important aspects require diagnostic capabilities that are not offered by existing observatories. In particular, simultaneous observations of the radiation continuum across an extended frequency range would facilitate the mapping of different layers and thus ultimately the 3D structure of the solar atmosphere. Mapping large regions on the Sun or even the whole solar disk at a very high temporal cadence would be crucial for systematically detecting and following the temporal evolution of flares, while synoptic observations, i.e., daily maps, over periods of years would provide an unprecedented view of the solar activity cycle in this wavelength regime.

As our Sun is a fundamental reference for studying the atmospheres of active main sequence stars, observing the Sun and other stars with the same instrument would unlock the enormous diagnostic potential for understanding stellar activity and its impact on exoplanets.

The Atacama Large Aperture Submillimeter Telescope (AtLAST), a single-dish telescope with 50m aperture proposed to be built in the Atacama desert in Chile, would be able to provide these observational capabilities. Equipped with a large number of detector elements for

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1. **Alexander G.M. Pietrow**, Leibniz Institute for Astrophysics Potsdam, Potsdam, Germany
2. **Francesco Pecora**, University of Delaware, Newark, USA
3. **Malcolm Druett**, The University of Sheffield Department of Automatic Control and Systems Engineering, Sheffield, UK

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probing the radiation continuum across a wide frequency range, AtLAST would address a wide range of scientific topics including the thermal structure and heating of the solar chromosphere, flares and prominences, and the solar activity cycle.

In this white paper, the key science cases and their technical requirements for AtLAST are discussed.

Plain language summary

Observations of our Sun and other stars at wavelengths of around one millimeter, i.e. in the range between infrared and radio waves, present a valuable complementary perspective. Despite significant technological advancements, certain critical aspects necessitate diagnostic capabilities not offered by current observatories. The proposed Atacama Large Aperture Submillimeter Telescope (AtLAST), featuring a 50-meter aperture and slated for construction at a high altitude in Chile's Atacama desert, promises to address these observational needs. Equipped with novel detectors that would cover a wide frequency range, AtLAST could unlock a plethora of scientific studies contributing to a better understanding of our host star. Simultaneous observations over a broad frequency range at rapid succession would enable the imaging of different layers of the Sun, thus elucidating the three-dimensional thermal and magnetic structure of the solar atmosphere and providing important clues for many long-standing central questions such as how the outermost layers of the Sun are heated to very high temperatures, the nature of large-scale structures like prominences, and how flares and coronal mass ejections, i.e. enormous eruptions, are produced. The latter is of particular interest to modern society due to the potentially devastating impact on the technological infrastructure we depend on today. Another unique possibility would be to study the Sun's long-term evolution in this wavelength range, which would yield important insights into its activity cycle. Moreover, the Sun serves as a fundamental reference for other stars as, due to its proximity, it is the only star that can be investigated in such detail. The results for the Sun would therefore have direct implications for understanding other stars and their impact on exoplanets. This article outlines the key scientific objectives and technical requirements for solar observations with AtLAST.

Keywords
Sun activity, Sun atmosphere, Sun filaments, prominences, Sun flares, magnetic fields, solar-terrestrial relations, sunspots

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Corresponding author: Sven Wedemeyer (svenwe@astro.uio.no)

Author roles: Wedemeyer S: Conceptualization, Formal Analysis, Project Administration, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Barta M**: Writing – Original Draft Preparation, Writing – Review & Editing; **Brajša R**: Writing – Original Draft Preparation, Writing – Review & Editing; **Chai Y**: Writing – Original Draft Preparation, Writing – Review & Editing; **Costa J**: Writing – Original Draft Preparation, Writing – Review & Editing; **Gary D**: Writing – Original Draft Preparation, Writing – Review & Editing; **Gimenez de Castro G**: Conceptualization, Formal Analysis, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Gunar S**: Conceptualization, Formal Analysis, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Fleishman G**: Conceptualization, Formal Analysis, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Hales A**: Writing – Original Draft Preparation, Writing – Review & Editing; **Hudson H**: Writing – Original Draft Preparation, Writing – Review & Editing; **Kirkaune M**: Conceptualization, Formal Analysis, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Mohan A**: Conceptualization, Formal Analysis, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Motorina G**: Writing – Original Draft Preparation, Writing – Review & Editing; **Pellizzoni A**: Writing – Original Draft Preparation, Writing – Review & Editing; **Saberi M**: Writing – Original Draft Preparation, Writing – Review & Editing; **Selhorst CL**: Writing – Original Draft Preparation, Writing – Review & Editing; **Simoes PJA**: Formal Analysis, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Shimojo M**: Writing – Original Draft Preparation, Writing – Review & Editing; **Skokić I**: Writing – Original Draft Preparation, Writing – Review & Editing; **Sudar D**: Writing – Original Draft Preparation, Writing – Review & Editing; **Menezes F**: Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **White SM**: Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Booth M**: Software; **Klaassen P**: Funding Acquisition; **Cicone C**: Funding Acquisition; **Mroczkowski T**: Funding Acquisition; **Cordiner MA**: Writing – Review & Editing; **Di Mascolo L**: Software, Writing – Review & Editing; **Johnstone D**: Writing – Review & Editing; **van Kampen E**: Formal Analysis, Writing – Review & Editing; **Lee M**: Writing – Review & Editing; **Liu D**: Writing – Review & Editing; **Maccarone T**: Writing – Review & Editing; **Orlowski-Scherer J**: Writing – Review & Editing; **Saintonge A** : Writing – Review & Editing; **Smith M**: Writing – Review & Editing; **Thelen AE**: Writing – Review & Editing

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REVISED **Amendments from Version 1**

The revised version addresses the comments by all three referees and correspondingly includes more than 80 additional references and additional sentences. Most changes aimed at better setting the described solar science cases for AtLAST into context to existing literature. This is particularly the case for studying the thermal structure of the solar atmosphere, solar and stellar flares, Sun-as-a-star techniques, and solar prominences. Also, the revised manuscript emphasises that, at this stage, the basic telescope properties are defined but that any instrument properties remain mostly open. In fact, this manuscript aims to give recommendations for instrumental requirements based on the presented solar science cases in combination with the basic telescope properties. Furthermore, the manuscript has been revised for better readability for a wider audience (who may be more familiar either with wavelengths or frequencies). This also resulted in corresponding changes in Figure 3 and Figure 4. The overall conclusions and recommendations remain unchanged.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

The continuum radiation emitted by the Sun at millimeter wavelengths originates from the chromosphere, the layer of the solar atmosphere located between the photosphere (i.e., the Sun's surface layer) and the corona. The thermal and magnetic structure of the chromosphere is complex and highly dynamic with a plethora of physical processes at work (e.g., De Pontieu *et al.*, 2007a; De Pontieu *et al.*, 2007b; Jess *et al.*, 2009; McIntosh *et al.*, 2011; Testa *et al.*, 2014; Van Doorsselaere *et al.*, 2020; Wedemeyer-Bőhm *et al.*, 2012), many of which induce notable deviations from equilibrium conditions (for example in the ionisation state of hydrogen, Carlsson & Stein, 2002; Hillier *et al.*, 2024). Next to the chromospheric plasma, the continuum at millimeter wavelengths can also probe the cool, dense coronal plasma in filaments and prominences, thus accessing a large range of spatial scales. The largest features like filaments can span substantial fractions of the solar diameter (~30'), followed by Active Regions (often a few arcminutes), and magnetic network cells as the chromospheric imprints of supergranulation cells (20" – 60"). Sunspots (Solanki, 2003), including the penumbra, have diameters of typically 30" but occasionally up to ~ 1', whereas the atmosphere in the Quiet Sun regions exhibits spatial scales of 1-2" and below. It is expected that there is small-scale structure even smaller than ~ 0.1" scales resolved by modern 4m-class optical solar telescopes (Quintero Noda *et al.*, 2022; Rimmele *et al.*, 2020). Likewise, the temporal scales range from about a month for one solar rotation, days for the evolution of sunspots, down to minutes and seconds for small-scale and energetic phenomena.

Consequently, observing the chromosphere and characterising the physical mechanisms that govern this dynamic environment is challenging. So far, there were only a few suitable diagnostic tools available to examine the plasma conditions in the chromosphere such as the spectral lines of singly ionized calcium (Ca II) and magnesium (Mg II) as well as the Hα line. The interpretation of observations in these spectral lines and deriving the physical properties of the plasma in the mapped atmospheric regions is complicated and limited by the complex line formation mechanisms that involve non-local thermodynamic equilibrium effects. The situation is better for the millimeter continuum radiation, which is assumed to be formed mostly under local equilibrium conditions so that the measured brightness temperature should be closely related to the local plasma temperature. Although available telescopes for millimeter wavelengths made notable contributions to solar physics in the past (e.g., Kundu, 1959; Loukitcheva *et al.*, 2014; Trottet *et al.*, 2011, and references therein), they did not have sufficient spatial resolution for resolving the small spatial scales in the solar chromosphere until the Atacama Large Millimeter/submillimeter Array (ALMA) started regular observations of the Sun in 2016 (Bastian, 2002; Karlický *et al.*, 2011; Shimojo *et al.*, 2017b; White *et al.*, 2017). It should also be noted that the chromosphere evolves on timescales well below 1 min, which means that meaningful observations are restricted to very short integration times, essentially leading to snapshot imaging. Techniques like Earth rotation synthesis or combining observations in different array configurations are not viable for solar observations.

The high spatial and temporal resolution and also the prospects for utilising polarisation measurements for measuring magnetic fields in the solar chromosphere make (sub-)millimeter telescopes very powerful tools for investigating the solar chromosphere and thus contributing to the solution of many open questions (see Wedemeyer *et al.*, 2016, and references therein).

It should also be noted that the continuum radiation received at a certain frequency mostly originates from a narrow layer in the solar atmosphere with the mapped height range depending on the used receiver band. Observations of the Sun in different receiver bands thus map different layers in the Sun's atmosphere. Despite already large success of ALMA in advancing solar physics regarding a broad range of topics from the general thermal stratification of the solar atmosphere, large-scale structures like prominences to the energetics of small-scale events like shock waves and spicules (e.g., Alissandrakis *et al.*, 2017; Brajša *et al.*, 2018; Chintzoglou *et al.*, 2021; da Silva *et al.*, 2018; da Silva *et al.*, 2020a; Eklund *et al.*, 2020; Heinzel *et al.*, 2022; Labrosse *et al.*, 2022; Menezes *et al.*, 2022; Molnar *et al.*, 2019; Oliveira e Silva *et al.*, 2022; Rodger *et al.*, 2019; Selhorst *et al.*, 2019; Shimojo *et al.*, 2017a; Skokić *et al.*, 2023; Valle Silva *et al.*, 2021, and many more), there are important science cases that require different observational capabilities. One diagnostic limitation is that observations are limited to one narrow frequency band and therefore to one atmospheric layer at a time, while the solar atmosphere is a prime example of a dynamic, complex, and inherently 3D phenomenon. Therefore, meaningful observations must be carried out strictly simultaneously with as many complementary diagnostics and in as many layers as possible, which is also required to facilitate analysis techniques such as spectroscopic inversions and differential emission measures (e.g., Abe *et al.*, 2022; da Silva Santos *et al.*, 2018; da Silva Santos *et al.*, 2020a; da Silva Santos *et al.*, 2020b;

Hofmann *et al.,* 2022; Loukitcheva & Reardon, 2022; Wedemeyer *et al.,* 2016). This capability could be offered by a large-aperture sub-millimeter facility telescope like the proposed Atacama Large Submillimeter Telescope (AtLAST Klaassen *et al.*, 2020; Mroczkowski *et al.*, 2023; Mroczkowski *et al.*, 2024; Ramasawmy *et al.*, 2022, http://atlast-telescope.org/). Despite an impressive aperture of 50 m, AtLAST would not reach the angular resolution achieved with an interferometric array like ALMA but compensate with other unique features such as a simultaneous wider frequency coverage, thus unlocking complementary science cases. AtLAST would thus have the potential to boost the impact of millimeter observations on solar physics beyond its current state. In this article, key science cases and observing strategies for solar observations with AtLAST are described. At AtLAST's current stage in the development process, the general capabilities of the telescope such as diameter field-of-view, mapping speed etc. have been decided (Mroczkowski *et al.*, 2024), while the technical aspects of the up to 6 foreseen instruments remain open. Please note that the purpose of this article is to set out the technical requirements placed on the telescope, its instruments, and its operations that are necessary to achieve great advances in solar physics (please see Booth *et al.,* 2024 for a summary of all science cases). The discussion of the solar science cases presented here aims at defining the corresponding technical requirements.

2 Key science cases

As detailed in the sections below, AtLAST (Mroczkowski *et al.*, 2024) opens up a new window to science cases that cannot be addressed with existing sub-mm telescopes. In addition, some solar science cases for ALMA (see Bastian *et al.*, 2018; Wedemeyer *et al.*, 2016, and references therein; see also Figure 1 for examples of ALMA single-dish scans of the Sun) and LLAMA (Lépine *et al.*, 2021) like, e.g., atmospheric heating, flares, and prominences, are potential solar use cases for AtLAST, too, thus creating synergies between these observatories. These science cases concern the thermal structure of the solar atmosphere including the thermal structure of prominences and filaments, the related transport of energy and mass, and phenomena related to solar activity. In the following subsections, the key science cases for solar observations with AtLAST are highlighted. Please note that, at this stage, the telescope concept design and requirements are well-defined (Mroczkowski *et al.,* 2024). This includes the technical requirements such as the optical design, receiver cabin layout, primary aperture diameter (50 m), scan speed (up to 3 deg/s), field of view, approximate frequency range (~ 30 – 950 GHz, corresponding to 0.3 – 10 mm), and surface accuracy goals, along with several other key technological concepts such as approaches for metrology, instrument exchange, and energy recovery. However, the first-generation instrumentation priorities have not yet been determined and are under consideration using the solar case presented and other science cases. The resulting instrumental requirements are discussed in Section 3.

2.1 Thermal structure and the atmospheric heating problem

The chromosphere plays an important role in the transport of energy and matter from the vast energy reservoir in the Sun's interior underneath the photosphere to the transition region and corona above. This transport phenomenon and the chromosphere's role in it are essential for understanding the heating of the corona, the origins of the solar wind, and the drivers of solar activity and space weather. The boundaries between the chromosphere and the layers below and above, however, vary

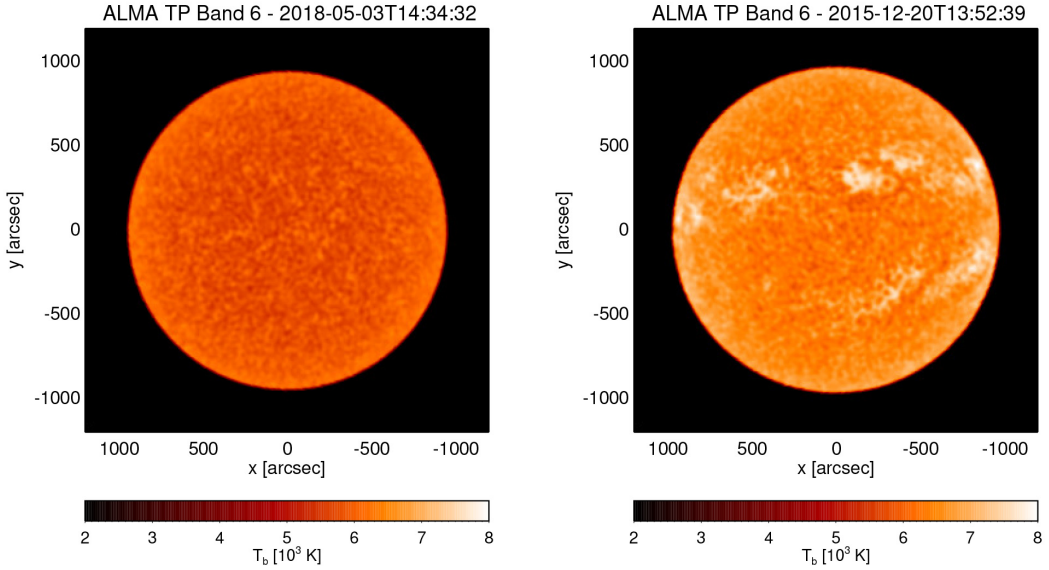

Figure 1. ALMA Total Power (TP) maps in Band 6 (230 GHz) obtained by double-circle scanning at two different times capturing a very quiescent state (left) and a more active state with clearly visible Active Regions including sunspots (right). (ALMA project IDs: 2017.1.00009.S, 2011.0.00020.SV.).

strongly in time and space, making it impossible to define strict height ranges for the layers. Rather, the chromosphere must be understood as an integral part of the solar atmosphere (Wedemeyer-Böhm *et al.*, 2009). The chromosphere can be more suitably characterised based on the notable changes in physical behaviour including deviations from equilibrium conditions and the transition from a thermodynamically to a magnetically dominated domain as expressed by the corresponding change of the ratio of thermal to magnetic pressure, the so-called plasma beta. These changes also give rise to a plethora of physical processes, which are entangled in complicated dynamic ways, rendering the understanding of the workings of our Sun a challenging undertaking (Carlsson *et al.*, 2019).

One of the large open questions in solar physics is the coronal heating problem, which has been known since the late 1930s when observations of spectral lines due to elements in extremely high ionisation stages implied temperatures in excess of a million Kelvin in the corona (Edlén, 1943). As pointed out in the introduction, deriving the plasma properties in the outer solar atmosphere is difficult, which hampered identifying the processes responsible for the transport of the required energy into the corona. As a result, despite significant progress (e.g., Gudiksen & Nordlund, 2005; Klimchuk, 2006; McIntosh & De Pontieu, 2009; Peter *et al.*, 2004, and many more), much of the coronal heating problem remains unsolved today. It should be noted that the Sun is not unique in this sense but rather serves as a reference for other stars that exhibit a corona, too, thus making the solar coronal heating problem relevant for all stars with notable surface convection, i.e. in particular main sequence stars of spectral types G-M.

After decades of research, numerous processes have been identified that are capable of supplying the energy required to account for the high temperatures observed in the Sun. The focus has shifted towards determining which of these processes are most relevant and how exactly they transport and deposit energy. It is likely that a combination of different processes contributes to chromospheric/coronal heating, with their relative importance varying in different solar regions characterized by distinct magnetic field environments and activity levels, i.e. from Active Regions to Quiet Sun regions. Some processes provide continuous heating, while others, such as solar flares, produce a more variable and intermittent heating component due to their transient nature. Typically these phenomena are grouped into processes related to (i) magnetic reconnection/Ohmic heating and (ii) wave heating processes, specifically acoustic and magnetohydro-dynamic (MHD) waves. MHD waves, including Alfvén waves (De Pontieu *et al.*, 2007a; De Pontieu *et al.*, 2014; Jess *et al.*, 2009; van Ballegooijen & Cranmer, 2010), can contribute to plasma heating by perturbing the magnetic field, leading to wave damping and the release of magnetic and kinetic energy, but, in turn, can also be excited by dynamic variations of magnetic field structures. There is a plethora of physical processes and effects that are not only relevant for observations of the Sun but also in a wider plasma physics context, e.g., multi-fluid effects (Krasnoselskikh *et al.*, 2010; Martínez-Sykora *et al.*, 2012), plasma instabilities (e.g., Fontenla *et al.*, 2008), and turbulence (Petrosyan *et al.*, 2010). See the review on ALMA's potential for addressing the chromospheric/coronal heating problem by Wedemeyer *et al.* (2016), which is equally relevant for AtLAST. The resulting heating is evident in phenomena like spicules observed at the solar limb. The multitude of possible heating mechanisms and their potential entanglement has made it challenging to determine which ones are predominant and how their contributions depend on the solar region type. In principle, identifying these mechanisms and understanding their contributions requires quantitative and precise measurements that capture the thermal, magnetic, and kinetic state of chromospheric plasma over time and in three spatial dimensions. AtLAST has the potential to provide such data.

Another important aspect concerns the formation heights of the solar (sub)mm continuum, i.e., the exact layers from where the continuum radiation at a given frequency emerges. ALMA observations and corresponding simulations have led to surprising findings like the imprint of coronal loops in Band 3 (3 mm) observations (see, e.g., Wedemeyer *et al.*, 2020) and a strong variance of the relative formation heights of Band 3 and Band 6 (see, e.g., Chintzoglou *et al.*, 2021; Eklund *et al.*, 2021). See Wedemeyer *et al.* (2022) for a discussion. Strictly simultaneous observations across a wide frequency range — and consequently a broad range of formation heights — could enable AtLAST to better constrain the formation heights and thus allow a more reliable interpretation and reconstruction of the atmospheric 3D structure.

2.2 Solar flares

AtLAST is poised to make significant contributions in addressing numerous unresolved inquiries pertaining to solar flares, a prominent conundrum within contemporary solar physics that continues to be a highly dynamic area of investigation (see, e.g., Wedemeyer *et al.*, 2016 and references therein for more details). Although numerous intricacies remain shrouded in mystery, it is evident that solar flares manifest as a result of the dynamic reconfiguration and interconnection of magnetic fields within the solar atmosphere (see, e.g., Hudson, 2000; Petrie, 2019; Russell *et al.*, 2015; Sun *et al.*, 2012; Wang *et al.*, 1994). Consequently, substantial amounts of energy previously stored within the magnetic field are explosively released during these events, manifesting as both radiation and high-energy particles. This emitted radiation encompasses the entire electromagnetic spectrum, spanning from gamma and X-rays to mm and radio waves.

Solar flares can differ by orders of magnitude in strength, which is typically measured according to the emitted soft X-ray flux. The strongest solar flares ever documented released energy on the order of 10^{32} ergs (Emslie *et al.*, 2005) and are often accompanied by coronal mass ejections (CME) that can impact space weather with notable effects on Earth. The effects manifest themselves from beautiful aurorae to severe disturbances of power grids (like the Quebec blackout in 1989) and satellite infrastructure. As a recent example, we can mention the destruction of the majority of a batch of

Starlink satellites due to solar activity (e.g. Dang *et al.*, 2022). And yet, it cannot be ruled out that even stronger flares exceeding the Carrington event of 1859 could occur with disastrous consequences for our technology-dependent modern society. Such so-called super-flares are observed for other (solar-like) stars (Maehara *et al.*, 2012) (see Section 2.5). While the bolometric radiative energy release of the Carrington event is estimated to be on the order of ~5 × 10^{32} erg (or 2 × 10^{33} erg when adding the kinetic energy of a CME; Cliver & Dietrich, 2013) while TESS observations exhibit stellar flares with radiative energies in excess of 10^{35} erg (Pietras *et al.*, 2022). The study of strong solar flares is thus of utmost importance. An essential observational challenge, which is hampered fully revealing the physical mechanisms behind flares, is connected to the small field of view of many solar telescopes, making it hard to point at the right position at the right time to capture the early stages of a flare. High-cadence observations of the whole solar disk (or at least large regions) with AtLAST (see Section 3.1.1) would thus increase the number of fully observed flares, contributing to unveiling the physical mechanisms behind flares in new ways.

The occurrence rate of a flare is roughly related to the released energy, making the strongest events rare (although varying with the solar cycle) and the much weaker micro- and nano-flares more frequent and ubiquitous. The latter are therefore extremely important as potential contributions to the heating of the corona (see Section 2.1) in a more continuous way across most of the Sun, whereas strong flares are associated with Active Regions.

Despite many decades of research and significant progress, there are still many open questions regarding central aspects of solar and stellar flares on all scales including the particle acceleration mechanisms (e.g. Miller, 1998), quasi-periodic pulsations (e.g. Mohan, 2021; Simões *et al.*, 2015), and the source of the still enigmatic emission at sub-THz frequencies (Fleishman & Kontar, 2010; Kaufmann *et al.*, 1985; Kaufmann *et al.*, 2004; Krucker *et al.*, 2013), i.e. in the frequency range to be covered by AtLAST.

Observations of flare-like brightenings with ALMA, in both interferometric mode (Rodger *et al.*, 2019; Shimojo *et al.*, 2017a) and single-dish (Skokić *et al.*, 2023), have revealed faint and localized sources, likely thermal in origin, and well correlated with the observed emissions in EUV and SXR. Observations of such sub-mm flares might also provide key information about the formation of hot onsets in solar flares revealing the increase of the electron temperature of the chromosphere (see Figure 2) or the presence of non-thermal electrons during flare onsets (da Silva *et al.*, 2023; Hudson *et al.*, 2021).

The mm and sub-mm data can uniquely address several key questions regarding solar flares (Fleishman *et al.*, 2022). For example, in combination with other instruments for higher frequencies (see Section 3.4), the spectral coverage in the mid-IR to sub-mm range can help to unveil the thermal structure of the flaring atmosphere. Radiative-hydrodynamic (RHD) modelling of flares suggest that the emission at wavelengths longer than 50 μm is optically thick, and thus, the observed brightness temperature should directly provide estimates for the electron temperature at the emitting chromospheric layer (Simões *et al.*, 2017). In Figure 2, we provide an example of the temporal evolution of a synthetic flare spectrum from RHD modelling.

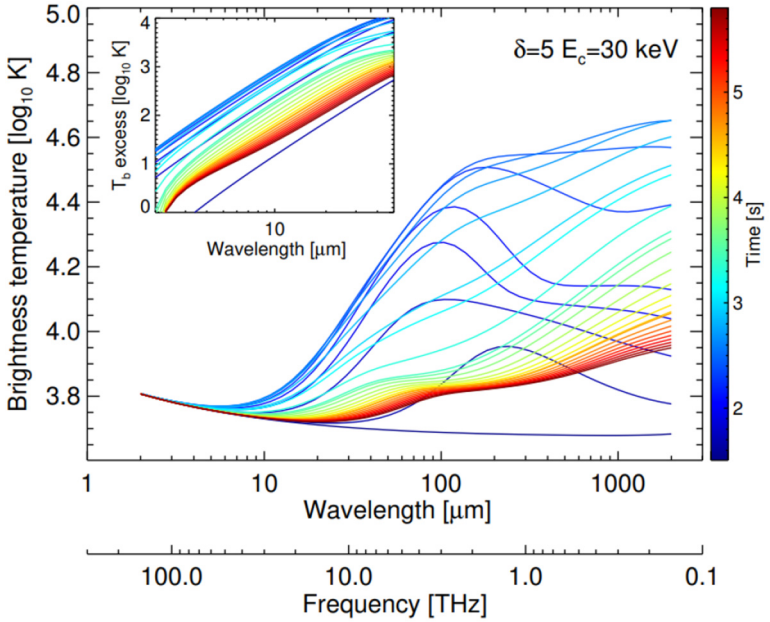

Figure 2. Evolution of a synthetic sub-mm and IR flare T_b spectrum from RHD modelling (from Simões *et al.*, 2017). From these simulations, for $\lambda > 50\mu m$, T_b should provide the electron temperature in the optically thick upper chromosphere (see, e.g., Wedemeyer *et al.*, 2016 and references therein). Please note that the range relevant for AtLAST is for frequencies less than ~1.0 THz.

Addressing these aspects with AtLAST would require high spectral, spatial and temporal resolution and preferably full polarisation (see Section 3), which then would allow for probing the dynamic thermal structure and magnetic structure of the solar atmosphere before, during, and after a flare with potentially ground-breaking insights. While already the thermal free-free radiation produced mostly due by electron-ion free-free absorption and H^- free-free absorption (e.g. Heinzel & Avrett, 2012) contains essential information about the physical mechanisms behind flares, the non-thermal radiation component due to gyrosynchrotron and resonance processes would be essential for constraining the acceleration of charged particles, which is central to understanding flares.

2.3 Solar prominences

Multi-scale observations of solar prominences, i.e. extended structures in the solar atmosphere that stretch upward from the visible surface into the corona (Vial & Engvold, 2015), are another area where AtLAST can make a significant impact. The magnetic field in a prominence supports denser prominence plasma against gravity. The prominence material has a much lower temperature (around 10^4 K) while being surrounded by coronal plasma (around 10^6 K). Here, the prominence magnetic field provides the insulation, which allows the prominence plasma to cool radiatively. Prominences appear as bright when viewed above the solar limb but dark when viewed against the solar disk's brightness (when they are called filaments). Quiescent prominences can extend over a few hundred thousand kilometers, i.e. a significant fraction of the Sun's diameter. These prominences are among the longest-lasting solar phenomena with lifetimes of several days to weeks. In contrast, erupting prominences, as one of the main drivers of space weather, are capable of hurling large amounts of magnetized plasma into interplanetary space at high speeds. The large field of view of AtLAST (45" at 950 GHz to 450" at 100 GHz), combined with its good spatial resolution (1.5" at 950 GHz) and the ability to observe the Sun once a day for extended periods, will offer us opportunities to study the questions of the prominence origin and evolution, together with the drivers that make the prominence magnetic field configurations unstable and erupt.

Moreover, AtLAST will provide simultaneous multi-band coverage, which is a capability that no other facility can provide, at least not in combination with the required angular resolution. AtLAST will therefore enable us to answer also important questions about the thermal properties and energy balance of prominence plasma and to uncover the nature of the prominence plasma transition region spanning from cool cores to the hot corona. Another advantage of observing at millimetre wavelengths lies in their easier interpretation. The spectral lines in the optical and UV used for prominence observations are typically optically thick so that detailed radiative transfer calculations are necessary for their analysis. In contrast, the prominence plasma is mostly optically thin at AtLAST wavelengths, which makes the interpretation much simpler due to the relation between the observed flux and the plasma temperature of the emitting region (see, e.g., Gunár *et al.*, 2016; Gunár *et al.*, 2018; Rodger & Labrosse, 2017). Nevertheless, coordinated observations at millimetre wavelengths by AtLAST and in optical spectral lines (such as Hα) and UV lines (e.g. Mg II h&k) would bring large benefits. This was demonstrated by, for example, da Silva Santos *et al.* (2018) and Hofmann *et al.* (2022). Combined observations of prominences in the Hα line and at millimetre wavelengths (by ALMA) were used to derive the temperature structure of prominence plasma by Labrosse *et al.* (2022) and Heinzel *et al.* (2022). Similar coordinated observations of the solar chromosphere were used by da Silva Santos *et al.* (2020a) and Shimizu *et al.* (2021) and in active regions by da Silva Santos *et al.* (2020b) and Loukitcheva & Reardon (2022).

Joint observations of prominences with AtLAST and ALMA will also be extremely valuable. ALMA interferometry is capable of very high spatial resolution, thus extending the observable domain towards the shortest resolvable scales. On the other hand, the interferometric (Fourier-based) observations are insensitive to the larger-scale structures (larger than the single antenna primary beam). In order to fill the gap around zero in the Fourier space, ALMA uses supplementary single-dish (SD) scanning when observing a multiscale structures, like prominences. However, the ALMA SDs have the same size of 12m and, consequently, there is a little overlap between the domains of scales covered by the high-resolution interferometric data and those obtained from the SD observations. With the much larger dish, AtLAST would provide an excellent bridge connecting both domains and allowing for a proper match of the interferometric and SD data. This is very true in general, but for the limb observations (prominences, spicules) even yet more vital.

2.4 The solar activity cycle

As stated above, millimetre observations have the advantage that the brightness temperatures corresponding to the observed continuum flux are thought to be a close proxy for the chromospheric plasma temperature with the formation height increasing with wavelength. Measuring the polarisation allows for deriving the line-of-sight component of the magnetic field. Daily full-disk maps of the Sun would permit the study of how the temperature (and hence the energy content) evolves in Active Regions, Quiet Sun regions and coronal holes. These data can be compared with other diagnostics (e.g., Egeland *et al.*, 2017), and in particular the evolution of magnetic fields in the solar atmosphere (see, e.g., Livingston *et al.*, 2012 and Tapping & Morgan, 2017 for the relation of magnetic field measurements and the radio flux at a wavelength of 10.7 cm). The solar chromosphere is responsible for most of the UV emission that plays a major role in structuring the Earth's upper atmosphere, and evolution of the millimeter emission will in turn reflect the drivers of solar UV emission. As observations in different frequency bands probe different depths in the solar atmosphere (Vernazza *et al.*, 1981), comparing the evolution in these different layers is important for understanding the transport of energy through the chromosphere. While the solar cycle is already intensively studied at other wavelengths (see Hathaway, 2015 and references therein), repeated sets of such observations obtained over a period of years will reveal how the millimeter emission responds to the solar cycle. A noteworthy demonstration of

the scientific potential is the sequence of observations with the Solar Submillimeter-wave Telescope (SST, Kaufmann *et al.,* 2008) that covers a period longer than one solar cycle (Menezes *et al.*, 2021).

Measuring the solar radius at subterahertz frequencies (submm/mm) allows one to probe the solar atmosphere, since these measurements show the height above the photosphere at which most of the emission at a determined observation frequency is generated (Menezes & Valio, 2017). Changes in the solar radius show it can be modulated with the 11-year activity cycle (mid-term variations) as well as longer periods (long-term variations). The equatorial radius time series was found to be positively correlated to the solar cycle, since the equatorial regions are more affected by the increase of active regions during solar maxima, making the solar atmosphere warmer in these regions; on the other hand, the anticorrelation between polar radius time series and the solar activity proxies could be explained by a possible increase of polar limb brightening during solar minima (Menezes *et al.*, 2021). In the context of the study on the subterahertz solar atmosphere, spicules can affect the measurement of the solar radius and cause the solar limb to appear more diffuse, which can lead to an overestimation of the solar radius. In Menezes *et al.* (2022), the discrepancies between measured limb brightening values and model predictions highlight the need for further studies to improve our understanding of the solar atmosphere. Therefore, it is important to take into account the presence of spicules when measuring the solar radius and limb brightening at different frequencies. Currently, however, there are no full-disk observations of the Sun in the mm range apart from occasional ALMA single-dish Total Power (TP) maps a few times a year.

Please note that the Sun's rotation depends on latitude with a (sidereal) rotation period of down to ~24 days at the equator and up to 35 days at the poles (see, e.g., Balthasar *et al.,* 1986; Schou *et al.*, 1998; Snodgrass, 1983). Any long-lived feature like an Active Region would thus move across the visible disk of the Sun in less than two weeks. However, at the resolution anticipated for AtLAST (see Figure 3), features like Active Regions and sunspots (Solanki, 2003) therein would evolve significantly on a daily timescale. The evolution of Active Regions and the change of the Sun's magnetic nature across a solar cycle would therefore be addressed best via full-disk mapping of the Sun at multiple frequency bands, once per day. Already an initial 1-month campaign covering a full solar rotation would allow for addressing the fundamental unsolved problems mentioned above including the nature of coronal and chromospheric heating problems, whereas much longer sequences are required for addressing the solar activity cycle. Such sequences would also be relevant for producing a larger sample of flare observations, where the individual observations should be time series over an hour or more as daily maps would not capture the temporal evolution of individual flares (see Section 2.2). In addition, these sequences would provide vital complementary input for predictions of the solar activity cycle, which yield important societal impact but, despite much progress, remain challenging (e.g., Balogh *et al.*, 2014; Cameron & Schüssler, 2007; Choudhuri *et al.,* 2007; Dikpati *et al.,* 2006; Hathaway *et al.,* 1999; Pesnell, 2012).

New insights regarding the Sun's activity variations and thus the long-term evolution of our host star could be transferred to other stars as demonstrated by stellar radio/mm observations (e.g., Bastian *et al.*, 2000; Pope *et al.,* 2019; Selhorst *et al.*, 2013; Selhorst *et al.,* 2020). This Sun-as-a-star approach has recently received increasing attention in the context of next-generation exoplanet observations for which it is crucial to separate observable exoplanet signatures from the host star's "background radiation" (see Rackham *et al.*, 2023 and references therein).

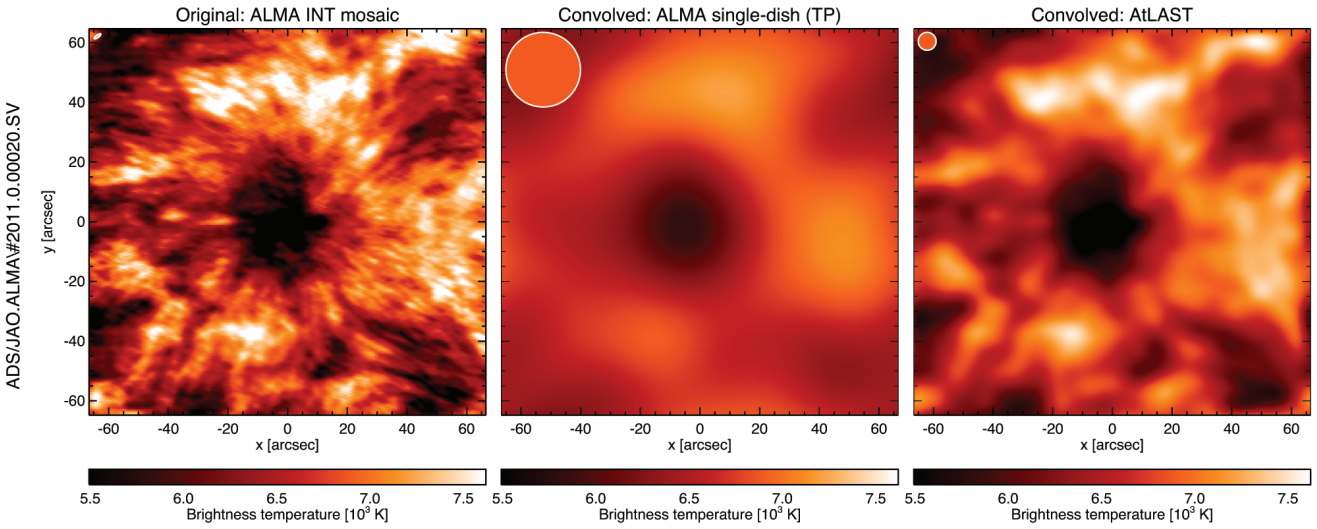

Figure 3. The ALMA sunspot mosaic that was taken during the ALMA SV campaign on December 18, 2015 in Band 6 (230 GHz) at original interferometric resolution (left) and after convolution with a beam corresponding to a single ALMA 12-m (Total Power) antenna (middle) and after convolution with the expected AtLAST beam (right). For reference, the corresponding beam is plotted in the upper left corner of each panel.

2.5 The solar-stellar connection

The Sun, which can be observed spatially resolved, serves as a fundamental reference case for studying the dynamic nature of stellar atmospheres and solar/stellar activity including the occurrence of flares (e.g., Dumusque *et al.*, 2015; Ma *et al.*, 2024; Otsu *et al.*, 2022; Pietrow *et al.*, 2024; Strassmeier *et al.*, 2018; Zhao *et al.*, 2023; see also Section 2.2). In addition to serendipitous detection as a by-product of other observations and surveys, dedicated stellar observations are essential for understanding the structure and activity of stellar atmospheres in general. The sample by Mohan *et al.* (2021) demonstrates the potential of stellar mm observations and, at the same time, illustrates the scarcity of suitable observations. AtLAST could make substantial contributions in this regard, either through targeted observations or also through coincidental (or even archival) detections. In particular, observations of stellar flares in the (sub-)mm range are extremely rare (MacGregor *et al.*, 2018; MacGregor *et al.*, 2020), and yet are crucial for unveiling the physics of these events including particle acceleration and plasma heating and for evaluating the impact of flares on the habitability of exoplanets (see, e.g., Bellotti *et al.*, 2023; Konings *et al.*, 2022; Lammer *et al.*, 2003; Segura *et al.*, 2010, and references therein). At millimeter wavelengths, the flux density of the few detected stellar flares tends to be 10 – 1000 times higher than the quiescent flux. Assuming a typical quiet chromospheric temperature of $\sim 10^4$ K (at 100 GHz) as seen in cool stars (Mohan *et al.*, 2021), the flux density during a flare can vary in the range ~ 0.5 - 50 mJy for a star at a distance of 10 pc. Consequently, stellar flares can be detected even when the stellar disk is spatially unresolved. Observing a broad sample of stellar targets with varying flare intensity distributions therefore complements high-resolution solar flare observations. Translating solar observations into stellar signals, either through dedicated instruments like HARP-N (Cosentino *et al.*, 2012; Dumusque *et al.*, 2015) or POET (Santos, 2023), or by processing, i.e. by employing Sun-as-a-star observational techniques, offers significant scientific potential. Such approaches contribute to the study of stellar atmospheres and can enhance our understanding of the physical mechanisms behind solar and stellar flares (see, e.g., Ma *et al.*, 2024; Otsu *et al.*, 2022; Pietrow *et al.*, 2024).

It is important to emphasise that the flux varies on timescales of a few seconds to minutes. Observing the temporal evolution of a flare, which is essential for exploring the physical mechanisms, thus requires time sequences with accordingly high temporal cadence. Such data sets are typically not generated from a serendipitous detection or as part of a survey but require a dedicated sit-and-stare observation of the same region in the sky. Should the required ultra-high temporal resolution not be achievable with full-disk scans of the Sun (see Section 3), high-cadence flare observations of even a limited FOV could be used to transform the data into a Sun-as-a-star observation using a method like, e.g., the one by Pietrow & Pastor Yabar (2023).

AtLAST would be capable of sit-and-stare observations, providing crucial time-resolved light curves for stellar flares. Given the high sensitivity of AtLAST, stellar flares in cool main sequence stars at distance of up to ~50 pc should be detectable with integration times of a few seconds, thus resolving the relevant timescales. In addition, the anticipated unique capability of observing at multiple frequencies simultaneously, which is typically not provided by other sub-mm instruments and surveys, especially when combined with polarisation capabilities, would enable AtLAST to utilise essential diagnostics such as the variation of the mm spectral index, an indicator of stellar atmospheric activity (Mohan *et al.*, 2022), and strong constraints to the emission mechanism and estimates of the magnetic field strengths in the flaring active regions.

The full potential of flare observations at millimeter wavelengths is only unlocked through coordinated, strictly co-simultaneous observations with other telescopes covering as large a wavelength range across the electromagnetic spectrum as possible. Such coordinated campaigns, which have become common in multi-messenger astronomy and are basically standard procedure for observations of the Sun, demand for PI-driven operations. The scarcity of such coordinated stellar observing campaigns is among the main reasons why there has been only a relatively small number of observations that are indicative of a stellar coronal mass ejection (CME) – an essential component of exo-space weather (Argiroffi *et al.*, 2019; Fuhrmeister & Schmitt, 2004; Guenther & Emerson, 1997; Gunn *et al.*, 1994; Houdebine *et al.*, 1990; Houdebine *et al.*, 1993; Namekata *et al.*, 2022; Veronig *et al.*, 2021; Vida *et al.*, 2016). The success of such campaigns would be greatly enhanced by AtLAST's large FOV and high angular resolution, thus being able to observe multiple stellar targets at the same time while separating the flare source(s) from other components such as close-by active companion stars or disks, making AtLAST ideal for time-resolved coordinated observations of stellar flares. See also the time-domain science cases for AtLAST (Orlowski-Scherer *et al.*, 2024).

3 Observing the Sun with AtLAST

3.1 Diagnostic capabilities and instrumental requirements

There are two major constraints for solar observations at millimeter wavelengths: (i) As the Sun is by far the brightest millimeter source in the sky, sensitivity is not an issue and very short integration times and thus even on-the-fly scanning is possible. (ii) The Sun evolves on short time scales down to seconds and below depending on the scientific target, which requires correspondingly short integration/scan times. Imaging of solar data thus needs to be done as snapshot imaging or over short time windows that should not exceed 1 min for the expected resolution (on the Sun, temporal and spatial scales tend to correlate). As will be detailed in this section, the combination of high angular resolution, high temporal cadence (or at least short integration time), wide frequency coverage, and large dynamic range (i.e., a high ratio between the maximum and minimum measurable brightness temperatures) are crucial for meaningful solar observations with AtLAST (Mroczkowski *et al.*, 2024). In addition, full-Stokes polarimetry would greatly enhance AtLAST diagnostic potential for the Sun.

3.1.1 High angular resolution and spatial mapping. High spatial resolution is of utmost importance for solar observations as much of the relevant dynamics occurs on small spatial scales. Achieving sufficiently high resolution is challenging at millimeter wavelengths, in particular for single-dish telescopes such as AtLAST. While AtLAST's aperture sets a limit, the achievable resolution is still in the relevant range and superior to any previous single-dish observation of the Sun. With an aperture of 50 m, the achievable angular resolution would be 6.5" at a wavelength of 1.3 mm (~230 GHz, ALMA Band 6) and down to just 1.5" at 0.3 mm (~950 GHz, ALMA Band 10) (see Figure 4).

Fast on-the-fly scanning techniques (with a single beam) are used for creating maps of the whole solar disk or limited regions by, e.g, ALMA (White *et al.*, 2017), and could be implemented for AtLAST, too (Kirkaune *et al.* in prep.). The difference to mosaics is that the telescope is not consequently pointing at a set of locations on the Sun, possibly staying at each location for a few seconds as done for ALMA interferometric mosaics, but that telescope keeps observing while moving across the Sun to acquire a time stream that can then be converted into a map. This scanning motion could be accomplished by moving the primary or secondary reflector. Scanning the whole disk with an ALMA TP antenna in a double-circle pattern (Phillips *et al.*, 2015) takes on the order of 10 min. See Figure 1 for examples. The roughly 4 times larger aperture of AtLAST compared to an ALMA 12-m antenna results in an accordingly much smaller (~6 %) beam area. Scanning the whole disk of the Sun would take considerably longer (on the order of $(^{50m}/_{12m})^2 \approx 17$ times, i.e. ~3 hours), which would be sufficient for synoptic studies with just one scan per day but prohibitive for science cases that rely on high temporal cadence. In the latter case, scans would then need to be limited to smaller region, although a compromise between size of the mapped region and overall cadence can be made. In either case, for a time series, the scanning could be continuous.

A multi-pixel detector would significantly enhance the diagnostic possibilities for solar observations with AtLAST. Even for a modest setup with a detector with 1000 pixels in a concentric setup with no overlap, spaced by one beam width, the resulting instantaneously covered region on the Sun (hereafter referred to as the instantaneous field of view, FOV) would cover a region with a radius of about 36 beams. While a single AtLAST beam would be a factor 50/12 smaller than the beam of a 12 m ALMA antenna, using 1000 pixels would effectively make the instantaneous $\text{FOV} = 36 \times \frac{12}{50} = 9$ times larger. As shown in Figure 4, the diameter of the FOV would range from ~ 45" at 950 GHz (ALMA Band 10) to ~ 450" at 100 GHz (ALMA Band 3). Such a FOV would cover a complete sunspot even at the highest frequencies and whole Active Regions at the lower frequencies (see Figure 3). The angular resolution of the final imaging products could be increased by means of a rapid small scan pattern (on scales comparable to the beam

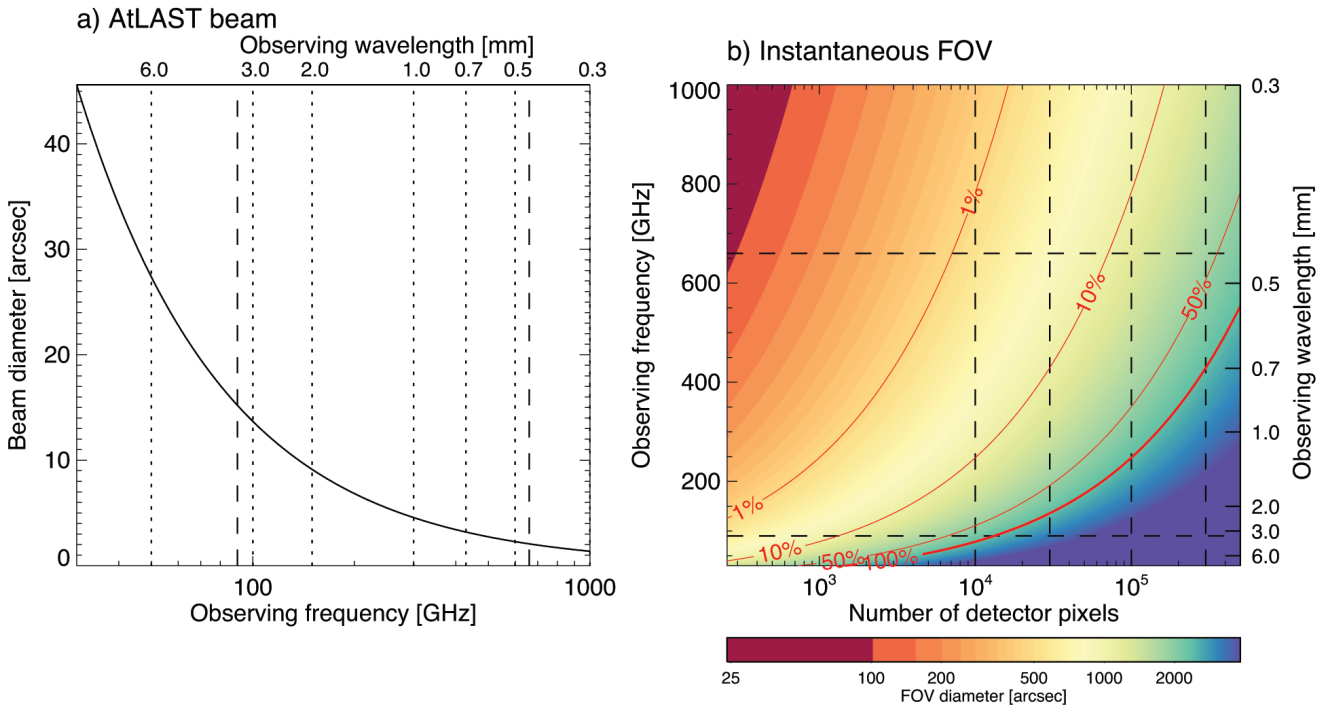

Figure 4. *Left:* AtLAST beam diameter as a function of observing frequency. The vertical dashed lines mark frequencies of 90 GHz and 660 GHz, which we here define as a minimum requirement for the frequency range. *Right:* The resulting diameter of the instantaneous FOV as a function of number of detector pixels and observing frequency (see color legend). The resulting ratio of the FOV area and the whole disk of the Sun is overlaid as red contours. The dashed lines mark selected frequencies and detector numbers for reference. The pixels are assumed to have the size of the corresponding beam and are packed into a circle with no overlap. See Section 3.3 for details.

size and below) that compensates for the above-described pixel spacing. The diameter of the instantaneous FOV would be halved again for a denser pixel setup that allows for Nyquist sampling, which then would not require the mentioned scan pattern. Please see Section 3.3 for a detailed discussion of the detector requirements for solar observations.

Multi-frequency synthesis might offer means to further increase AtLAST angular resolution. However, as the formation height range of the mm continuum (see also Section 2.1) depends on the frequency, only a moderate frequency range should be considered. Depending on the receiver design, multi-frequency synthesis could be an option that could be applied flexibly on AtLAST data sets.

3.1.2 Frequency coverage and spectral setup. An essential aspect to the continuum radiation is that the formation height range from where most of the emission emerges depends on the observing frequency or wavelength. At the highest frequency accessible with ALMA, i.e. 950 GHz (or a wavelength of 0.3 mm), the continuum radiation stems from the upper photosphere and lower chromosphere, whereas the continuum radiation at the shortest frequency of 35 GHz (equivalent to a wavelength just short of 1 cm) originates from the uppermost chromosphere with possible contributions from the transition region. Covering a large frequency range simultaneously or at least rapidly scanning through frequency has thus the potential to map a large height range in the solar atmosphere. In case of scanning through frequency, the scanning speed must be short compared to the dynamical timescales in the solar atmosphere, which are down to seconds and generally well below 1 min (depending also on the achieved spatial resolution).

Observations that cover extended regions on the Sun (or even the whole Sun) across a large frequency range would enable the reconstruction of the three-dimensional thermal structure of the solar chromosphere via tomographic and inversion techniques. Producing a time series at sufficiently high cadence would then enable to assess the temporal variation of the 3D structure — a data product with the potential of truly ground-breaking scientific impact for a very large range of essential topics in solar physics.

The observable frequency range should extend at least from 90 GHz to 660 GHz. Observing at higher frequencies of up to 1 THz would provide higher angular resolution but adequate observing conditions may not occur every day, making these bands unreliable in the context of daily synoptic observations. Even for continuum observations, a high frequency resolution is desirable but already a frequency increment of ~ 100 GHz would allow for excellent scientific results.

While the aforementioned considerations apply to continuum observations, a large number of spectral channels with high spectral resolution and a flexible set-up of the receiver bands would offer additional possibilities. While it has yet to be seen if spectral lines, mostly hydrogen recombination lines and potentially CO, can be detected at millimeter wavelengths, they would have large diagnostic potential for assessing the thermal, kinetic and magnetic state of the chromospheric plasma. It is difficult to answer right now which frequency setup would be necessary to exploit the diagnostic potential of spectral lines but, based on tentative simulations, hydrogen recombination lines might be spread out over one or a few GHz but would require nonetheless a spectral resolution better than 15.6 MHz (as currently offered by ALMA) in order to exploit the full diagnostic potential (e.g., Doppler shifts for line-of-sight velocities).

3.1.3 Sensitivity, integration time, dynamic range. The Sun is by far the brightest millimeter source in the sky with typical brightness temperatures of several thousand Kelvin. Consequently, sensitivity is not a concern and the integration time can be very low, allowing for ultra-high cadence, which is of essence for a range of science cases. The integration time can be much below 1 s depending on possible attenuation strategies (e.g., solar filter or detuning). Important for solar observations, however, is a large dynamic range. ALMA observations in Band 3 and 6 show a wide range of brightness temperatures from as low as 3000 K to above 13 000 K (see, e.g., the data sets in the Solar ALMA Science Archive, Henriques *et al.*, 2022). In general, the mean brightness temperature of the Sun depends on the frequency because the atmospheric height range of the mapped layer depends on frequency and thus on the thermal stratification of the solar atmosphere. In principle, the highest ALMA receiver bands map the transition between the upper photosphere and lower chromosphere (i.e., the classical "temperature minimum" region) with comparatively low temperatures, whereas the lowest ALMA bands (i.e., at higher frequencies) map radiation emerging from the on average much hotter upper chromosphere close to the transition region with its steep jump in temperature. See also Hofmann *et al.* (2022) for a discussion of brightness temperatures obtained with ALMA in comparison to other (less temperature-sensitive) diagnostics and Loukitcheva *et al.* (2019) for an observation of a particularly cool region. In addition to this already wide brightness temperature range, solar flares as a key science case for solar observations with AtLAST (Section 2.2) define the upper end of extreme temperatures that occur on the Sun. Depending on the strength (i.e. overall energy release) of a flare, plasma temperatures exceed 10^6 K or even 10^7 K. A flare thus emits orders of magnitude more radiation than the average (quiescent) Sun as discussed above. It should be noted that the corresponding peak brightness temperature also depends on the observing frequency and the beam size, which is typically too large to resolve the source. From observations of a (very strong) X-class flare with the 1.5m-aperture Solar Submillimeter Telescope (SST, Kaufmann *et al.*, 2008) at 212 GHz an excess brightness temperature of 1.75×10^6 K for an assumed source size of 25", which would remain unresolved (Giménez de Castro *et al.*, 2018). In comparison, AtLAST would have an angular resolution of ~7" at 212 GHz and would thus be able to resolve the source and thus brightness temperatures in excess of 10^6 K. At shorter wavelengths in the sub-mm range, we rely on simulations to estimate the expected brightness of flares (see Figure 2).

Addressing the full range of science cases would thus require to account for a brightness temperature range from typically 3000 K up to 14 000 K for the non-flaring Sun, depending on frequency and resolution, but up to millions of K for flares. Consequently, obtaining a large dynamic range for solar observations and at the same a high sensitivity for non-solar observations is a big challenge for designing of a receiver system that is intended to cover all science cases.

3.1.4 Polarisation. Magnetic fields play an essential role in the Sun's structure, dynamics, and activity. Their impact is clearly visible in Active Regions most notably in the form of sunspots and as large-scale prominences but also the Sun's Quiet Regions harbour magnetic fields in various configurations and strengths. The latter becomes immediately obvious from high-resolution Hα observations (see, e.g., Rouppe van der Voort *et al.*, 2023; Rutten *et al.*, 2008). High-resolution magnetograms obtained from the spectral lines in the photosphere have become a staple in contemporary solar physics relevant to a large range of scientific topics but often also just for context. Reliably measuring the magnetic field in the solar chromosphere above, i.e. the layer that would be observed with AtLAST, is still a current technological challenge, again with much diagnostic potential (see, e.g., Morosin *et al.*, 2022; Pietrow *et al.*, 2020; Vissers *et al.*, 2021). The measured polarization state provides a measure for the longitudinal component of the magnetic field vector in the same layer as the continuum radiation. In the same way, a scan through wavelength (and thus through formation height) 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 with potentially ground-breaking results.

Early observations with ALMA at a frequency of 100 GHz, which were obtained as science verification data in Band 3 (ADS/JAO.ALMA#2011.0.00011.E), indicate that the circular polarization degree is at least 1%. This value is considered a minimum, as the observations were carried out with the 12m-Array only (Shimojo *et al.*, 2024). First regular ALMA observations of the Sun with full polarisation in Band 3 were carried out in 2024 (Cycle 10). Important lessons are expected from these observations, which would have implications for full polarisation observations with AtLAST. In general, circular polarization levels of up to 5% are expected for the Sun at mm wavelengths.

3.2 Observing modes

In order to address the aforementioned key science cases (see Section 2), it would be best to combine 1) long-term synoptic observations with a very low daily load on observing time with 2) campaign-based observations. The synoptic observations could consist of one daily full-disk map or preferably a 10–30 min long time sequence of full-disk maps across a wide predefined frequency range. The resulting long-term data set would be of essential value for studying the solar cycle and all related variations imprinted in the Sun's chromosphere with fundamental implications for stellar activity cycles and their impact on the habitability of exoplanets (White *et al.*, 2023). The campaign-based observations would be more adjusted towards the requirements of individual science cases. The scheduling for observations that require the existence of an Active Region could be planned just a few days ahead as the coordination with other space-borne and ground-based observatories would boost the scientific impact of such AtLAST data. Alternatively, a Target-of-Opportunity (ToO) mode (also possibly confined to a campaign) would ensure observations of flares whenever a suitable Active Region appears.

3.2.1 Solar observing mode 1 – Synoptic full-disk scans. A field-of-view (FOV) that would cover the whole Sun plus a margin around, which is important to include the Sun's outer atmosphere, has a diameter of ~ 2000". Scanning such a region with the comparatively small beam size of AtLAST would require long scan times (see Section 3.1.1). Therefore we expect that multi-pixel detectors will be needed for solar disk mapping as well as other non-solar large FOV studies. The corresponding time needed for scanning the whole FOV would be reduced basically by the number of simultaneously used beams (pixels) and thus the resulting size of the instantaneously covered FOV (see also Section 3.1.1). The required scan time for the whole solar disk would scale accordingly with respect to the single-dish Total Power (TP) scans with ALMA antennas, which take about ~ 10 min. Consequently, a full-disk scan at the lower frequencies could potentially be completed in a few minutes or less, aided by the anticipated high slew speed of 3 deg/s. A smaller number of pixels, e.g. ~ 250 pixels, would directly affect the covered FOV, resulting in correspondingly longer scan times. Please note that very short integration times are sufficient as the Sun is the brightest mm source on the sky, and correspondingly mapping speed is not at all dependent on sensitivity requirements, rather it depends solely on the receiver FOV and antenna slew rates. See Section 3.3 for more considerations regarding multi-pixel detectors.

The short times for completing a scan of the whole solar disk would allow for scheduling a daily solar map, which would have enormous potential for studying the long-term evolution and the solar activity cycle (see Section 2.4).

3.2.2 Solar observing mode 2 – High-resolution time-dependent observations. A selected target, e.g. a sunspot (see Figure 3), would be followed in time for one or several hours (compensating for motion on the sky plus solar rotation) and observed with preferably high cadence (~1s). For comparison, ALMA currently observes the Sun at 1 s cadence, demonstrating the scientific potential of such a high cadence, e.g. for the study of waves (e.g., Eklund *et al.*, 2021; Guevara Gómez *et al.*, 2021; Jafarzadeh *et al.*, 2021; Patsourakos *et al.*, 2020). This mode, which is equivalent to observations at visible wavelengths in a limited field of view, is suitable for a large range of science cases that require a combination of high spatial and temporal resolution.

3.2.3 Solar observing mode 3 – Regional scan sequences. As a compromise between full-disk scans (mode 1) and single-target tracking (mode 2), AtLAST could perform scans of extended regions (or alternatively mosaics, see Section 3.1.1). The size of the covered region on the Sun would depend on the

instantaneous field of view of the multi-pixel detector (see Section 3.3) and the maximum acceptable temporal cadence. Such scans could be repeated continuously for some time, e.g., one hour, providing a good temporal cadence of a large field of view. This mode could be useful for observations of large-scale features such as filaments or entire Active Regions. Such observations would facilitate the detection of flares and filament eruptions and, at the same time, capture their evolution at adequate temporal resolution.

3.3 Instrumentation

The detectors described in this section assume technological progress on a time scale of about 10 years. The specifications are provided by the AtLAST instrument working group (https://www.atlast.uio.no/memo-series/memo-public/instrumentationwgmemo4_29feb2024.pdf). Please note the proposed instruments would have different operation modes and would also be suited for slightly different science cases as the different setups have to make a compromise between instantaneously covered FOV, spectral resolution, frequency range, and possibly temporal cadence due to costs and technological limitations. For instance, an instrument with a too small FOV due to a limited number of pixels would make it more challenging to capture flares, whereas limiting to one frequency band (with spectral channels or not) would only permit observations of the mm continuum originating from a limited height range in the solar atmosphere. In contrast, a multi-chroic setup could facilitate the reconstruction of the atmospheric 3D structure but at the expense of spectral resolution. Consequently, prioritising one of these properties will come at the cost of the others, warranting a detailed study to determine the best instrumental setup in view of the science cases described in Section 2. In Figure 4, the instantaneously covered FOV of multi-pixel detectors with n pixels is illustrated. The pixels are assumed to have the same diameter as the beam diameter d_{beam} at a given observing frequency and are packed with no overlap. Treated as a circle packing problem, the resulting diameter of the FOV is approximated as $d_{\mathrm{fov}} \approx \sqrt{\left(\left(\frac{2}{3}\right)\pi\right)/\sqrt{(3)}}\, d_{\mathrm{beam}}\sqrt{(n)}$.

3.3.1 Multi-chroic continuum camera. A first-generation multi-chroic camera for continuum observations could have 30 000 pixels covering 3 frequencies simultaneously while a second-generation camera could be extended to possibly 300 000 pixels covering 6 frequencies simultaneously. The frequencies would be preferably spread equally over the range from ~ 100 GHz to 700 GHz but adjusted according to the atmospheric transmission at the AtLAST site, e.g., 100, 220, 340, 460, 615, and 700 GHz (see https://almascience.eso.org/about-alma/alma-site). Full polarisation capability would substantially enhance the diagnostic possibilities (see Section 3.1.4).

The details of the detector setup have to be investigated in detail. That includes the spacing between pixels, the total number of pixels, and the resulting instantaneously covered FOV. A fast small circular scanning pattern could be used to fill intermediate pointings. Combining data from circular scans (if possible on a second time scale or at least <10 s) would then allow to produce data with higher angular resolution. Potential scanning strategies are currently being investigated (Kirkaune *et al.* in prep.).

3.3.2 Multi-pixel heterodyne receiver system. A full heterodyne system with 64 spectral pixels (spaxels) and 16 GHz bandwidth seems technologically feasible, whereas, on a 10-years perspective, systems with at least 256 spectral pixels (spaxels) and 30 GHz bandwidth might become possible. Such a detector would allow for exploiting the spectral domain but only with a much smaller number of detector elements as compared to multi-chroic continuum cameras due to the higher cost per pixel (see Section 3.3.1), strongly limiting the instantaneously covered region on the Sun. In combination with spatial scanning strategies, multi-pixel heterodyne receiver system would require compromises between covered field of view and overall temporal cadence, which would need to be adjusted to the needs of individual science cases. These limitations would only make sense if spectral lines are discovered on the Sun which would justify these limitations for accessing the diagnostic potential of spectral lines (see Section 3.1.2).

3.3.3 Integrated Field Unit. While multi-chroic continuum cameras (see Section 3.3.1) and heterodyne receiver systems (see Section 3.3.2) are the extreme cases considered here in terms of field of view versus spectral resolution, Integrated Field Unit could provide a compromise. First-generation units are expected to have a spectral resolving power of $R = \lambda/d\lambda = 500$ with 10 000 detectors (number of spaxels × number of channels) and a frequency range of 70–690 GHz, second generation units could reach $R = 2000$ with 50 000 detectors covering an even wider frequency range. While a resolving power of $R = 2000$ would open diagnostic possibilities for spectral line observations in a narrow frequency range, it would only make sense if spectral lines at mm wavelengths were observable in the Sun. Integrated Field Units would be less efficient than multi-chroic continuum cameras for observing a large frequency range and thus a large height range in the solar atmosphere due to the still limited number of spaxels. With even only 10 frequencies, only 5000 spatial pixels would be available, which is considerably lower than what is expected for multi-chroic cameras. As for multi-pixel heterodyne receiver systems, IFUs would likely only make sense if spectral lines can be observationally exploited. In any case, a realistic evaluation of the scientific potential of IFUs will require a dedicated study.

3.4 Synergies for development and co-observing

Given the complex and dynamic nature of the solar atmosphere, coordinated multi-wavelength multi-instrument observing campaigns are the default modus operandi. This typically involves ground-based and space-borne observatories, which provide complementary data exploiting different continua and spectral lines across the whole spectrum, thus providing large data sets that probe the (ideally complete) thermodynamic and magnetic state of the solar plasma across preferably all atmospheric layers. While such coordinated campaigns are subject to the different time zones of participating instruments,

there are many successful examples including ALMA observations of the Sun, which are typically complemented with space-borne observations with the Solar Dynamics Observatory (SDO) and the Interface Region Imaging Spectrograph (IRIS). See the Solar ALMA Science Archive (SALSA, Henriques *et al.*, 2022) for examples.

Solar observations with AtLAST will be no different. The idea behind the suggested synoptic full-disk observations (see Section 3.2.1) is to provide a reference for complementary observations and to become a cornerstone of future solar observations very much like SDO today.

The development of AtLAST can be fundamental to cover key ranges of the sub-mm spectrum for joint flare observations, along with instruments already in operation, such as the 30 THz cameras at Mackenzie University in São Paulo and at CASLEO, Argentina (Kudaka *et al.*, 2015), the new High Altitude THz Solar photometer at 15 THz (HATS, Giménez de Castro *et al.*, 2020) and future telescopes, such as the Solar Submillimeter Telescope Next Generation (SSTng, Giménez de Castro *et al.*, 2023).

4 Summary of telescope requirements

AtLAST (Mroczkowski *et al.*, 2024) observations of the Sun would produce a large range of valuable contributions to science cases that are difficult if not impossible to address with other existing or planned observatories. The need of high temporal, spatial, and to some extent spectral resolution makes adequate solar observations challenging. At the same time, resolution in one dimension can be sacrificed to boost the resolution in another dimension, e.g., lowering the temporal cadence for increased spatial resolution. Consequently, the best approach combines a multi-pixel detector with fast on-the-fly scanning. Appropriate imaging strategies could be developed during the commissioning phase and through simulations at an earlier stage. Additionally, in case that spectral lines at mm wavelengths are discovered in the Sun, heterodyne receiver systems of IFUs might have important scientific applications but require dedicated studies to realistically assess the feasibility and applicability given the limited possible detector sizes. Since the Sun is a very bright mm source, it could even be possible to split the optical path and feed multiple instruments that are optimised for different, complementary diagnostic purposes. Also, it has yet to be seen which solar science cases require instruments specifically designed for solar observing and which cases could be addressed with general instruments.

To fully unlock AtLAST's potential in this respect, the following instrumental properties are essential:

- **Sufficient instantaneous field-of-view:** A multi-pixel detector is a fundamental requirement as the instantaneously covered region on the sky with a single beam would be insufficient for most solar science cases.
- **Wide frequency coverage:** A wide (quasi-)simultaneous frequency coverage beyond the current setup of ALMA's receiver bands, possibly even covering the whole frequency range from (at least) 90 GHz to 660 GHz, has large scientific potential as it facilitates simultaneous mapping of an extended height range in the solar atmosphere. A multi-chroic camera with a large number of pixels seems to be a promising choice for continuum observations.
- **Full polarisation capabilities** are desirable in order to provide information on chromospheric magnetic fields.
- **High temporal cadence:** While integration times are very short for a bright object like the Sun, spatial (or spectral) scanning in order to cover an adequate spatial (or spectral) region is constrained by the short dynamic timescales. Preferably, the temporal cadence should be less than 1 min but the shorter the better. High detector readout rates are required, especially for fast scanning.
- **Adequate brightness temperature range and accuracy:** As the Sun is the brightest mm source in the sky and can vary in brightness significantly, in particular during flares, a solar filter with well-defined characteristics and large dynamic range for the detector are needed. A brightness temperature accuracy of 100 K or better is important for solar science cases. Consequently, the need for detector cooling will depend on the achievable signal-to-noise ratio.
- **Spectral resolution:** Spectral lines – if successfully detected in the Sun – would enormously increase the diagnostic capabilities. Designing a suitable instrument, possibly based on Integrated Field Units, would require a dedicated study.

Ethics and consent

Ethical approval and consent were not required.

Data availability

This article, which was composed by the Working Group for Solar Science with AtLAST (SoSA) as part of the AtLAST design study, makes use of the following ALMA data: ADS/JAO.ALMA#2011.00020.SV, ADS/JAO.ALMA#2017.1.00009.S.

(https://almascience.eso.org/aq/)

Software availability

The calculations used to derive integration times for this paper were done using the AtLAST sensitivity calculator, a deliverable of Horizon 2020 research project 'Towards AtLAST', and available from this link.

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✔ **Alexander G.M. Pietrow**
Leibniz Institute for Astrophysics Potsdam, Potsdam, Germany

Thank you for the prompt and thorough revision of the article. I believe its readability for non-experts has significantly improved, and the citations are now well integrated. All of my previous concerns have been addressed to my satisfaction. Based on these revisions, I would like to change the status of my review to 'Approved'.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Solar physics, Sun-as-a-star observations, flares, and spectropolarimetric inversions.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 26 December 2024

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✔ **Malcolm Druett**
The University of Sheffield Department of Automatic Control and Systems Engineering, Sheffield, England, UK

Thank you for the invitation to review the revised version of the article. I believe that "Approved" status for this article is warranted based on the updates to the manuscript.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: solar flares, sun: chromosphere, radiative transfer, magnetohydrodynamics, sun as a star

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 12 August 2024

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?

Malcolm Druett
The University of Sheffield Department of Automatic Control and Systems Engineering, Sheffield, England, UK

Review Summary

I was very pleased to read this paper, as I consider the instrument under to discussion to be a very exciting addition to the fleet of instruments we can use to study the Sun and other stars. This paper highlights several promises to advance our understanding of many active research themes using the instrument: coronal heating, the nature of prominences, the production of CMEs and long-term activity cycles. Moreover, this instrument has the potential to add to the joining up of science with millimeter wavelength range co-observations, as well as strengthening our understanding of the links, differences, and gradients in behaviours between our Sun and other stars.

One point I would appreciate the authors addressing is that I was expecting to be first presented with clear, concise summary of the proposed observational parameters before the science use cases in order to be able to understand and evaluate these. The ordering of the sections is such that if you are unfamiliar with the instrument, as many readers may be, you must simply accept the claims about the suitability for each science use case when reading through the paper in order. This concern could be addressed through clear referencing to specific points in later sections, a summary table, or restructuring of the paper.

Also in some of the sections where science use cases are presented, I recommend stronger links to be drawn between the observational capabilities of this instrument and the constraints required to address those science questions. Without these links made explicit to the reader I

believe that the current version of the manuscript has sections that are diluted in informational value, with un-cited, uncorroborated, or decontextualised claims.

The author list boasts an exceptional array of talent that I am certain is capable of addressing these concerns. I recommend edits are made before acceptance.

Introduction

(1) "The thermal and magnetic structure of the chromosphere is complex and highly dynamic with a plethora of physical processes at work, many of which induce notable deviations from equilibrium conditions (for example in the ionisation state of hydrogen). The largest features like filaments can span substantial fractions of the solar diameter (□30')"
This phrasing suggest filaments to be chromospheric plasma rather than cool dense coronal plasma. I recommend the authors to re-phrase this.

(2) "and thus contributing to the solution of many open questions (see Wedemeyer et al., 2016, and references therein)."
This sentence appears to be vague. Perhaps a few examples of key science questions addressed would be instructive to the reader.

(3) The following point is relating to the discussion in this section, I would like to hear the author's feedback on this, but it is not necessarily something that needs to be included in the text unless there are elements that the authors would deem worthwhile enough for inclusion, for example to bolster the strength of claims made within the later sections.

Many of the current authors were also involved in the publications of Chintzoglou et al. 2021 I & II [references 1,2]. Could I ask the authors comment on the findings stated in the summary and conclusions of Chintzoglou et al. 2021 II, regarding the discrepancy between the formation heights of Band 6 found in this study and earlier ones.
Do you believe that discussion of formation height for different solar features have already been resolved clearly to the satisfaction of the community? If not what are the knock-on error bars like for the key science cases based on these uncertainties or disagreements?

(4) "Despite already large success of ALMA in advancing solar physics (e.g. Brajša et al., 2018; Heinzel et al., 2022; Labrosse et al., 2022; Menezes et al., 2022; Oliveira e Silva et al., 2022; Rodger et al., 2019; Selhorst et al., 2019; Shimojo et al., 2017a; Skokić et al., 2023; Valle Silva et al., 2021), there are important science cases that require different observational capabilities"
I recommend that you split these advances into a few themes and at least mention what themes these are that ALMA has advanced. It's the second claim in the introduction of big contributions to advancements in the field with no specific examples yet provided to the reader. Further interesting advances from authors not associated with this work also perhaps warrant consideration in such a list. for example Multiple papers by Da Silva Santos, Chinzoglou, Molnar spring to mind, but there are also others [references 1-8]. I am not requesting an in-depth discussion or an exhaustive list, but some context for the reader who is not familiar with these works.

Key Science Cases

(5) "The chromosphere is an integral part of the solar atmosphere and as such plays an important role in the transport of energy and matter. These are essential for understanding the heating of the corona, the origins of the solar wind, and the drivers of solar activity and space weather. There is a plethora of physical processes involved, which are entangled in complicated dynamic ways, rendering the understanding of the workings of our Sun a challenging undertaking."
(a) citations needed.
(b) "The chromosphere is an integral part of the solar atmosphere and as such plays an important role in the transport of energy and matter."
This sentence currently has low informational value. I suggest either
- simply stating that the chromosphere plays an important role in the transport of energy and matter with some citations
or
- actually explaining what you mean by a little in terms of it being "an integral part" of the solar atmosphere and why. For example, one could argue this in terms of the behaviour changes either side of the plasma beta=1 layer, wave propagation, and non-equilibrium conditions. I am not a fan of characterising something as complicated or shrouded in mystery for the reader to understand that there are unresolved, interesting, and valuable science questions. It would be great if the authors could add some detail to pull back the curtain of mystery and complexity a little.

(6) "As detailed in the sections below, AtLAST (Mroczkowski et al., 2024) opens up a new window to science cases that cannot be addressed with existing sub-mm telescopes. In addition, some solar science cases for ALMA (see Bastian et al., 2018; Wedemeyer et al., 2016, and references therein; see also Figure 1) and LLAMA (Lépine et al., 2021) are potential solar use cases for AtLAST, too, thus creating synergies between these observatories. These science cases concern the thermal structure of the solar atmosphere including the thermal structure of prominences and filaments, the related transport of energy and mass, and phenomena related to solar activity. In the following, the key science cases for AtLAST are highlighted."
(a) I do not see the authors linking Figure 1 to anything stated above. The images show two time points in the solar cycle. To clarify, I am certain that solar cycle data from ALMA has valuable information. However, since none is mentioned or explained here, figure 1 appears to be only a visually satisfying image. Please provide some context in the caption or the text. This could even be a reference to the later point in the paper where this figure is discussed.

(b) Are you saying these listed science cases will be addressed in the following sections? If so, then I request you say that. If not then the statement is too brief to provide any information of value to the reader and I recommend adding citations, context, or both.

2.1 Thermal structure and the atmospheric heating problem

(7) The first part of this section is very nicely stated, although again lacking any citations beyond one early paper relating to the coronal heating problem. Please add citations.

"In principle, identifying these mechanisms and understanding their contributions requires quantitative and precise measurements that capture the thermal, magnetic, and kinetic state of chromospheric plasma over time and in three spatial dimensions. AtLAST has the potential to provide such data."
At this point in the paper, the reader has not been provided with an overview of the capabilities of the instrument, nor have you provided citations with reasoned explanations or estimated of what

observational capabilities could be required to derive these properties at the cadences and spectral/spatial resolutions required. Thus, unless the reader is already previously aware of all these details they have to accept the claim on trust. As stated in the summary I recommend this concern could be adequately addressed with context, references to later sections, or re-structuring of the paper.

2.2 Solar Flares

(8) "AtLAST is poised to make significant contributions in addressing numerous unresolved inquiries pertaining to solar flares, a prominent conundrum within contemporary solar physics that continues to be a highly dynamic area of investigation. Although numerous intricacies remain shrouded in mystery, it is evident that solar flares manifest as a result of the dynamic reconfiguration and interconnection of magnetic fields within the solar atmosphere."
Citations needed here. But I thank the authors of this section for providing sufficient citations elsewhere.

(9) "And yet, it cannot be ruled out that even stronger flares exceeding the Carrington event of 1859 could occur with disastrous consequences for our technology-dependent modern society. Such so-called super-flares are observed for other (solar-like) stars (Maehara et al., 2012) (see Section 2.5). The study of strong solar flares, to which AtLAST can contribute in new ways, is thus of utmost importance."
At this point in the paper without any solid evidence provided of how AtLAST can contribute, we are taking this "utmost importance" on faith. I recommend the authors to talk about the ways in which it can contribute explicitly. For example describing the observational capabilities, cadences, resolutions, atmospheric parameters, and how these relate to the flare science questions identified.

(10) Figure 2:
I assume the close association of mm-continuum radiation with brightness temperature will providing information to answer particular science questions. The relationship in flares is nicely demonstrated by the figure. Please point this out, and mention some of the science cases this will address and explain how the information will help.

(11) "Observations of such sub-mm flares might also provide key information about the formation of hot onsets in solar flares (da Silva et al., 2023; Hudson et al., 2021)."
What sort of key information? Why "might"? Can you analyse whether the information obtained would help address the science questions? I recommend talking a bit about the science questions, the observational requirements and how AtLAST can provide observations that meet those requirements.

(12) "Addressing these aspects with AtLAST would require high spectral, spatial and temporal resolution and preferably full polarisation"
And can/do we have that? The observational capabilities of the instrumentation have not been summarised or discussed. Please address whether you believe this is feasible and justify your position to the reader.

Solar Prominences

(13) "These prominences are among the longest-lasting solar phenomena with lifetimes of several days to weeks. The large field of view of AtLAST, combined with its good spatial resolution and the ability to observe the Sun on daily bases for extended periods, will offer us opportunities to study the questions of the prominence origin, evolution, and eventual instability."
The paragraph below this one makes a nice case for mm studies of prominences.
I recommend that the discussion could be supplemented in several ways:
(a) citations where appropriate.
(b) are there physical processes relating to prominence formation/evolution/instability that occur at scales and cadences you anticipate to be evident at AtLAST's resolution (please also state that resolution), which are not currently accessible via existing solar mm instrumentation?
(c) it may also be worth mentioning the validation and calibration you could perform on estimates of plasma quantities that are otherwise made using inferences from complicated optically thick radiative transfer.

(14) "because the drivers that make the prominence magnetic field configurations unstable and erupt are still not well understood." & "However, it is unclear exactly what sets off these eruptions."
Repetition

Solar Activity Cycle

(15) I recommend that this section could do with a few more citations for the results you discuss - if possible not so dominantly from one of your authors, Menezes. Also please define TP in the text.

(16) "Please note that the Sun’s rotation depends on latitude with a period of down to 24 days at the equator (see, e.g., Schou et al., 1998; Snodgrass, 1983). Any long-lived feature like an Active Region would thus move across the visible disk of the Sun in less than two weeks. However, at the resolution anticipated for AtLAST (see Figure 3), features like Active Regions and the sunspots (Solanki, 2003) therein would evolve significantly on a daily timescale. **This use case** would therefore be addressed best via full-disk mapping of the Sun at multiple frequency bands, once per day."
Please clarify which use case you are referring to - Are you talking about studying the solar cycle in general or some specific observational case within that?

(17) "New insights regarding the Sun’s activity variations and thus the long-term evolution of our host star could be transferred to other stars. This Sun-as-a-star approach has recently received increasing attention in the context of next-generation exoplanet observations for which it is crucial to separate observable exoplanet signatures from the host star’s “background radiation”."
Citations needed.

The Solar Stellar Connection

(18) This section does several things very well that should be highlighted for interpreting my other comments in this review.
(a) cites papers when claims regarding physical processes are made that relate to the science cases.
(b) relates stated capabilities and resolutions/cadences of the instrument directly to the use cases under discussion.

The spectrum of cited authors and findings within the field is rather limited, I suggest a more comprehensive coverage, but other than this the I have no notes on the section.

3 Observing the Sun with AtLAST

(19) The information in this section would have been useful to know earlier, or at least be referenced from the earlier sections. Also given some of the abbreviations are defined in section 3 and used in section 2 I would assume there was already some debate regarding this ordering. Please make section 2 easier to follow for first time readers by linking the claims to information from section 3.

(20) "The Sun evolves on short time scales which prohibits long integration/scan times."
I recommend changing the word "prohibits" to another word, as this doesn't really prohibit long integration times, it just devalues them for resolving transient structures.

(21) "While it has yet to be seen if spectral lines, mostly hydrogen recombination lines and potentially CO, can be detected at millimeter wavelengths, they would have large diagnostic potential for assessing the thermal, kinetic and magnetic state of the chromospheric plasma."
Could you comment on whether there is any ongoing effort to look into the existence of these lines within the proposed spectrum? Do you intend to conduct such a search in the early use cases?

3.1.3 Sensitivity, Integration time, Dynamic range

(22) Regarding the points made in the final paragraph, please could you comment on the outlook for being able to cover the necessary for studying flares? Perhaps some mention of this would be useful in the text too. I do believe there would be very useful information to glean about flare ribbons, condensation and evaporation even from a more limited dynamic range.

3.1.4 Polarisation

(23) "magnetograms obtained from the spectral lines in the photosphere (i.e., the Sun’s surface layer)"
This is the 4th instance of the word photosphere. If you wish to explain what it is, I would recommend doing so at the first instance.

(24) "Reliably measuring the magnetic field in the solar chromosphere above, i.e. the layer that would be observed with AtLAST, is still a current technological challenge, again with much diagnostic potential."
Citations to works from Pietrow, Morosin, and Vissers plus any the authors wish would be useful here [Refences 9-11].

(25) "Early observations with ALMA at a frequency of 100 GHz, which were obtained as science verification data in Band 3 (ADS/JAO.ALMA#2011.0.00011.E),"
I recommend considering if this is the best way to cite this data. Perhaps providing a footnote or a reference to its description elsewhere in the document that says what this is and how to obtain it.

3.2 Observing modes
3.2.1

(26) "with respect to the single-dish Total Power scans with ALMA antennas"
TP is now unabbreviated. I agree with the final statement of this section, that would be a most welcome addition to our field.

3.3 Instrumentation

(27) "the resulting diameter of the FOV is approximated as d fov ≈ ..."
For clarity, I recommend using a format that makes it explicitly clear what is, and what is not, under the large square root. This could also be achieved satisfactorily with parentheses.

3.3.1

(28) "The details of the detector setup have to be investigated in detail. That includes the spacing between pixels, the total number of pixels, and the resulting instantaneously covered FOV. A fast small circular scanning pattern could be used to fill intermediate pointings. Combining data from circular scans (if possible on a second time scale or at least <10 s) would then allow to produce data with higher angular resolution. A detailed study is currently in preparation (Kirkaune et al. in prep.)."
Have the matters been studied in detail, or are being studied in detail (in prep)? If the former, I would recommend an additional citation to a published work referenced in first part of this paragraph.

3.3.2

(29) "Such a detector would allow for exploiting the spectral domain but comes at the price of a much smaller number of detector elements as compared to multi-chroic continuum cameras (see Section 3.3.1),"
Why is this? Simply by re-assignment of those pixels?
and a typo later: overal -> overall

3.3.3

(30) "In any case, a realistic evaluation of the scientific potential of IFUs will require a dedicated study."
Please comment on whether you have plans to perform that study.

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1. Chintzoglou G, De Pontieu B, Martínez-Sykora J, Hansteen V, et al.: ALMA and IRIS Observations of the Solar Chromosphere. I. An On-disk Type II Spicule. *The Astrophysical Journal*. 2021; **906** (2). Publisher Full Text
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3. da Silva Santos J, de la Cruz Rodríguez J, Leenaarts J, Chintzoglou G, et al.: The multi-thermal chromosphere. *Astronomy & Astrophysics*. 2020; **634**. Publisher Full Text

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10. Morosin R, de la Cruz Rodríguez J, Díaz Baso C, Leenaarts J: Spatio-temporal analysis of chromospheric heating in a plage region. *Astronomy & Astrophysics*. 2022; **664**. Publisher Full Text
11. Vissers G, Danilovic S, de la Cruz Rodríguez J, Leenaarts J, et al.: Non-LTE inversions of a confined X2.2 flare. *Astronomy & Astrophysics*. 2021; **645**. Publisher Full Text

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Not applicable

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: solar flares, sun: chromosphere, radiative transfer, magnetohydrodynamics, sun as a star

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 13 Nov 2024

Sven Wedemeyer

We would like to thank the referee for the useful suggestions. We considered all comments, which resulted in an improved manuscript. Please note that the revised version takes into account the comments from all three referees. We added 81 additional references and updated Figs. 3 and 4. In the following, we address all comments in detail.

==========

REFEREE> One point I would appreciate the authors addressing is that I was expecting to be first presented with clear, concise summary of the proposed observational parameters before the science use cases in order to be able to understand and evaluate these. The ordering of the sections is such that if you are unfamiliar with the instrument, as many readers may be, you must simply accept the claims about the suitability for each science use case when reading through the paper in order. This concern could be addressed through clear referencing to specific points in later sections, a summary table, or restructuring of the paper.

ANSWER> We thank the referee for this comment but would like to point out that the purpose of this manuscript is to do the opposite: Summarise key science cases that can be addressed with a large single-dish (sub)mm telescope and then derive instrumental requirements. However, we take this comment seriously and modified the manuscript in this direction.

==========

REFEREE> Also in some of the sections where science use cases are presented, I recommend stronger links to be drawn between the observational capabilities of this instrument and the constraints required to address those science questions. Without these links made explicit to the reader I believe that the current version of the manuscript has sections that are diluted in informational value, with un-cited, uncorroborated, or decontextualised claims.

ANSWER> We would like to refer to our answer to the previous point and will make changes at the appropriate places. We also added two clarifying sentences at the end of the introduction.

==========

(1) "The thermal and magnetic structure of the chromosphere is complex and highly dynamic with a plethora of physical processes at work, many of which induce notable deviations from equilibrium conditions (for example in the ionisation state of hydrogen). The largest features like filaments can span substantial fractions of the solar diameter (≈ 30’)"

This phrasing suggest filaments to be chromospheric plasma rather than cool dense coronal plasma. I recommend the authors to re-phrase this.

ANSWER> We modified this passage accordingly.

==========

(2) "and thus contributing to the solution of many open questions (see Wedemeyer et al., 2016, and references therein)." This sentence appears to be vague. Perhaps a few examples of key science questions addressed would be instructive to the reader.

ANSWER> We modified this passage accordingly.

==========

(3) The following point is relating to the discussion in this section, I would like to hear the author's feedback on this, but it is not necessarily something that needs to be included in

the text unless there are elements that the authors would deem worthwhile enough for inclusion, for example to bolster the strength of claims made within the later sections. Many of the current authors were also involved in the publications of Chintzoglou et al. 2021 I & II [references 1,2]. Could I ask the authors comment on the findings stated in the summary and conclusions of Chintzoglou et al. 2021 II, regarding the discrepancy between the formation heights of Band 6 found in this study and earlier ones.
Do you believe that discussion of formation height for different solar features have already been resolved clearly to the satisfaction of the community? If not what are the knock-on error bars like for the key science cases based on these uncertainties or disagreements?
ANSWER> That is a very good question. One of the surprises from the first ALMA observations was that the formation heights are less clear than what was assumed. This development is expressed in the mentioned Chintzoglou et al. papers. It seems likely that the contribution functions can have multiple components. For instance, the ALMA Band 3 observations by Wedemeyer et al. (2020) show imprints of coronal loops which are clearly located well above the assumed formation height. Forward modelling of mm continuum emission sensitively depends on realistic electron densities, which on the other hand makes the comparison with ALMA observations a critical step in advancing these models and thus our understanding of the solar chromosphere. Strictly simultaneous observations over an extended frequency range, as expected from AtLAST, would be pivotal for better constraining the formation heights and contribution functions, thus enabling more reliable interpretation of the observations. We added a few sentences at the end of Sect. 2.1.
==========
(4) "Despite already large success of ALMA in advancing solar physics (e.g. Brajša et al., 2018; Heinzel et al., 2022; Labrosse et al., 2022; Menezes et al., 2022; Oliveira e Silva et al., 2022; Rodger et al., 2019; Selhorst et al., 2019; Shimojo et al., 2017a; Skokić et al., 2023; Valle Silva et al., 2021), there are important science cases that require different observational capabilities"
I recommend that you split these advances into a few themes and at least mention what themes these are that ALMA has advanced. It's the second claim in the introduction of big contributions to advancements in the field with no specific examples yet provided to the reader. Further interesting advances from authors not associated with this work also perhaps warrant consideration in such a list. for example Multiple papers by Da Silva Santos, Chinzoglou, Molnar spring to mind, but there are also others [references 1-8]. I am not requesting an in-depth discussion or an exhaustive list, but some context for the reader who is not familiar with these works.
ANSWER> The aim was not to provide a review of ALMA results but we nonetheless added a few more references and modified the sentence.
==========
(5 - Key Science Cases) "The chromosphere is an integral part of the solar atmosphere and as such plays an important role in the transport of energy and matter. These are essential for understanding the heating of the corona, the origins of the solar wind, and the drivers of solar activity and space weather. There is a plethora of physical processes involved, which are entangled in complicated dynamic ways, rendering the understanding of the workings of our Sun a challenging undertaking."
(a) citations needed.
(b) "The chromosphere is an integral part of the solar atmosphere and as such plays an important role in the transport of energy and matter."

This sentence currently has low informational value. I suggest either
- simply stating that the chromosphere plays an important role in the transport of energy and matter with some citations
or
- actually explaining what you mean by a little in terms of it being "an integral part" of the solar atmosphere and why. For example, one could argue this in terms of the behaviour changes either side of the plasma beta=1 layer, wave propagation, and non-equilibrium conditions. I am not a fan of characterising something as complicated or shrouded in mystery for the reader to understand that there are unresolved, interesting, and valuable science questions. It would be great if the authors could add some detail to pull back the curtain of mystery and complexity a little.
ANSWER> The sentences contained “low informational value” because they were only meant as an introduction for more detailed information given in that section. Also, this article is not meant to be a review article. However, we took the comment seriously and added extra information to address the challenges more specifically. Moreover, the moved the paragraph to the beginning of Sect. 2.1 as this has now become an introduction to the (thermal) structure of the chromosphere as a science case.
==========
(6) "As detailed in the sections below, AtLAST (Mroczkowski et al., 2024) opens up a new window to science cases that cannot be addressed with existing sub-mm telescopes. In addition, some solar science cases for ALMA (see Bastian et al., 2018; Wedemeyer et al., 2016, and references therein; see also Figure 1) and LLAMA (Lépine et al., 2021) are potential solar use cases for AtLAST, too, thus creating synergies between these observatories. These science cases concern the thermal structure of the solar atmosphere including the thermal structure of prominences and filaments, the related transport of energy and mass, and phenomena related to solar activity. In the following, the key science cases for AtLAST are highlighted."
(a) I do not see the authors linking Figure 1 to anything stated above. The images show two time points in the solar cycle. To clarify, I am certain that solar cycle data from ALMA has valuable information. However, since none is mentioned or explained here, figure 1 appears to be only a visually satisfying image. Please provide some context in the caption or the text. This could even be a reference to the later point in the paper where this figure is discussed.
ANSWER> At this point, the figure is only meant to give a first impression of how the Sun looks like at mm wavelengths. We changed the text to “ALMA (see Bastian et al., 2018; Wedemeyer et al., 2016, and references therein; see also Figure 1 for examples of ALMA single-dish scans of the Sun)”.
==========
(6b) Are you saying these listed science cases will be addressed in the following sections? If so, then I request you say that. If not then the statement is too brief to provide any information of value to the reader and I recommend adding citations, context, or both.
ANSWER> We do not understand the problem. The last sentence reads “In the following, the key science cases for AtLAST are highlighted.” and thus clearly indicates that detailed information is given in the following sections. We added the word “subsections” to make this more obvious.
==========
(7a - Sect. 2.1) The first part of this section is very nicely stated, although again lacking any citations beyond one early paper relating to the coronal heating problem. Please add

citations.
ANSWER> We added more recent references.
==========
(7b) "In principle, identifying these mechanisms and understanding their contributions requires quantitative and precise measurements that capture the thermal, magnetic, and kinetic state of chromospheric plasma over time and in three spatial dimensions. AtLAST has the potential to provide such data."
At this point in the paper, the reader has not been provided with an overview of the capabilities of the instrument, nor have you provided citations with reasoned explanations or estimated of what observational capabilities could be required to derive these properties at the cadences and spectral/spatial resolutions required. Thus, unless the reader is already previously aware of all these details they have to accept the claim on trust. As stated in the summary I recommend this concern could be adequately addressed with context, references to later sections, or re-structuring of the paper.
ANSWER> This is clearly a misunderstanding that is understandable as the referee likely received the manuscript without the necessary context. This manuscript, together several others covering other astronomical topics, is a result of the first design phase. At this point, the telescope properties are defined but no instruments have been designed. The purpose of this article is to outline what AtLAST - based on the telescope specs - could do and how a corresponding instrument should be designed to make full of use of that. We see that a reader may indeed not understand this approach. We made therefore changes to clarify this point at the end of the introduction (Sect. 1).
==========
(8 - Sect. 2.2 Solar Flares) "AtLAST is poised to make significant contributions in addressing numerous unresolved inquiries pertaining to solar flares, a prominent conundrum within contemporary solar physics that continues to be a highly dynamic area of investigation. Although numerous intricacies remain shrouded in mystery, it is evident that solar flares manifest as a result of the dynamic reconfiguration and interconnection of magnetic fields within the solar atmosphere."
Citations needed here. But I thank the authors of this section for providing sufficient citations elsewhere.
ANSWER> We added a few more references.
==========
(9) "And yet, it cannot be ruled out that even stronger flares exceeding the Carrington event of 1859 could occur with disastrous consequences for our technology-dependent modern society. Such so-called super-flares are observed for other (solar-like) stars (Maehara et al., 2012) (see Section 2.5). The study of strong solar flares, to which AtLAST can contribute in new ways, is thus of utmost importance."
At this point in the paper without any solid evidence provided of how AtLAST can contribute, we are taking this "utmost importance" on faith. I recommend the authors to talk about the ways in which it can contribute explicitly. For example describing the observational capabilities, cadences, resolutions, atmospheric parameters, and how these relate to the flare science questions identified.
ANSWER> The “utmost importance" referred to studying flares and not flare observations with AtLAST. We rephrased and extended this part and now point at AtLAST capability to observe the whole disk of the Sun at high cadence, which increases the chance to capture the early stages of flares more systematically. This feat will indeed provide essential new

data.
==========
(10 - Figure 2)
I assume the close association of mm-continuum radiation with brightness temperature will providing information to answer particular science questions. The relationship in flares is nicely demonstrated by the figure. Please point this out, and mention some of the science cases this will address and explain how the information will help.
ANSWER> The close relation between continuum flux and brightness temperature is mentioned already in the introduction as it is a fundamental reason for observing at mm wavelengths. The scientific implications are discussed in Sect. 2. For instance, this aspect is particularly important for Sect. 2.1. We revised Sect. 2 correspondingly.
==========
(11) "Observations of such sub-mm flares might also provide key information about the formation of hot onsets in solar flares (da Silva et al., 2023; Hudson et al., 2021)."
What sort of key information? Why "might"? Can you analyse whether the information obtained would help address the science questions? I recommend talking a bit about the science questions, the observational requirements and how AtLAST can provide observations that meet those requirements.
ANSWER> We updated this sentence but refrain from expanding this point too much as the article is not intended to become a complete review of all solar science at mm wavelengths.
==========
(12) "Addressing these aspects with AtLAST would require high spectral, spatial and temporal resolution and preferably full polarisation"
And can/do we have that? The observational capabilities of the instrumentation have not been summarised or discussed. Please address whether you believe this is feasible and justify your position to the reader.
ANSWER> As stated above, the intention of this manuscript is opposite. As written in that section, it would be important to probe the magnetic structure of the chromosphere, which would require polarisation capabilities. This requirement, which is met by the telescope, must then also be met by an instrument, which has not been designed yet. This manuscript provides a first impression of the instrumental requirements for making AtLAST able to address key solar science cases.
==========
(13 - Solar Prominences) "These prominences are among the longest-lasting solar phenomena with lifetimes of several days to weeks. The large field of view of AtLAST, combined with its good spatial resolution and the ability to observe the Sun on daily bases for extended periods, will offer us opportunities to study the questions of the prominence origin, evolution, and eventual instability."
The paragraph below this one makes a nice case for mm studies of prominences.
I recommend that the discussion could be supplemented in several ways:
(a) citations where appropriate.
(b) are there physical processes relating to prominence formation/evolution/instability that occur at scales and cadences you anticipate to be evident at AtLAST's resolution (please also state that resolution), which are not currently accessible via existing solar mm instrumentation?
(c) it may also be worth mentioning the validation and calibration you could perform on estimates of plasma quantities that are otherwise made using inferences from complicated

optically thick radiative transfer.
ANSWER> We edited the section accordingly.
==========
(14) "because the drivers that make the prominence magnetic field configurations unstable and erupt are still not well understood." & "However, it is unclear exactly what sets off these eruptions." Repetition
ANSWER> In connection with replying to other referee comments, we edited this section and resolved the issue.
==========
(15 - Solar Activity Cycle) I recommend that this section could do with a few more citations for the results you discuss - if possible not so dominantly from one of your authors, Menezes. Also please define TP in the text.
ANSWER> We appreciate the comment but would like to point out that there are not many studies monitoring the solar cycle at mm/radio wavelengths that could be cited here, which is exactly why AtLAST could contribute significantly to this science case. However, we added a several related references to this section.
==========
(16) "Please note that the Sun's rotation depends on latitude with a period of down to 24 days at the equator (see, e.g., Schou et al., 1998; Snodgrass, 1983). Any long-lived feature like an Active Region would thus move across the visible disk of the Sun in less than two weeks. However, at the resolution anticipated for AtLAST (see Figure 3), features like Active Regions and the sunspots (Solanki, 2003) therein would evolve significantly on a daily timescale. This use case would therefore be addressed best via full-disk mapping of the Sun at multiple frequency bands, once per day."
Please clarify which use case you are referring to - Are you talking about studying the solar cycle in general or some specific observational case within that?
ANSWER> We clarified this point in the corresponding sentence.
==========
(17) "New insights regarding the Sun's activity variations and thus the long-term evolution of our host star could be transferred to other stars. This Sun-as-a-star approach has recently received increasing attention in the context of next-generation exoplanet observations for which it is crucial to separate observable exoplanet signatures from the host star's "background radiation"."
Citations needed.
ANSWER> We added some citations.
==========
(18 - The Solar Stellar Connection) This section does several things very well that should be highlighted for interpreting my other comments in this review.
(a) cites papers when claims regarding physical processes are made that relate to the science cases. (b) relates stated capabilities and resolutions/cadences of the instrument directly to the use cases under discussion.
The spectrum of cited authors and findings within the field is rather limited, I suggest a more comprehensive coverage, but other than this the I have no notes on the section.
ANSWER> Thanks for this positive comment. We added more references, in particular regarding exo-space-weather.
==========
(19 - Sect. 3) The information in this section would have been useful to know earlier, or at

least be referenced from the earlier sections. Also given some of the abbreviations are defined in section 3 and used in section 2 I would assume there was already some debate regarding this ordering. Please make section 2 easier to follow for first time readers by linking the claims to information from section 3.
ANSWER> We follow the suggestion and added cross-references to Sect. 3 at appropriate places.
==========
(20) "The Sun evolves on short time scales which prohibits long integration/scan times."
I recommend changing the word "prohibits" to another word, as this doesn't really prohibit long integration times, it just devalues them for resolving transient structures.
ANSWER> We replaced “prohibits" with "requires correspondingly short".
==========
(21) "While it has yet to be seen if spectral lines, mostly hydrogen recombination lines and potentially CO, can be detected at millimeter wavelengths, they would have large diagnostic potential for assessing the thermal, kinetic and magnetic state of the chromospheric plasma."
Could you comment on whether there is any ongoing effort to look into the existence of these lines within the proposed spectrum? Do you intend to conduct such a search in the early use cases?
ANSWER> That question is hard to answer at the current stage. It would ultimately depend on the instruments that would be built for AtLAST because the detection and then the use as diagnostics of these spectral lines would require sufficient spectral resolution. However, at this point it is unclear what these requirements are exactly and if/how an adequate instrument would be built. These questions should and will be address in the next development phase of AtLAST.
==========
(22 - Sect. 3.1.3) Regarding the points made in the final paragraph, please could you comment on the outlook for being able to cover the necessary for studying flares? Perhaps some mention of this would be useful in the text too. I do believe there would be very useful information to glean about flare ribbons, condensation and evaporation even from a more limited dynamic range. ANSWER> Such information would certainly be useful but depends on the properties of the available instruments which are not defined at all at this stage. We believe that the paragraph adequately outlines the requirements and resulting challenge and that any more specific discussion of selected aspects of flares in this paragraph would be too speculative. Rather, these points are material for a more detailed paper in connection with an instrumental design study.
==========
(23 - Sect. 3.1.4) "magnetograms obtained from the spectral lines in the photosphere (i.e., the Sun’s surface layer)"
This is the 4th instance of the word photosphere. If you wish to explain what it is, I would recommend doing so at the first instance.
ANSWER> At first use, we write now “photosphere (i.e., the Sun’s surface layer)”.
==========
(24) "Reliably measuring the magnetic field in the solar chromosphere above, i.e. the layer that would be observed with AtLAST, is still a current technological challenge, again with much diagnostic potential."
Citations to works from Pietrow, Morosin, and Vissers plus any the authors wish would be

useful here [Refences 9-11].
ANSWER> That is a good suggestion. We added the references.
==========
(25) "Early observations with ALMA at a frequency of 100 GHz, which were obtained as science verification data in Band 3 (ADS/JAO.ALMA#2011.0.00011.E),"
I recommend considering if this is the best way to cite this data. Perhaps providing a footnote or a reference to its description elsewhere in the document that says what this is and how to obtain it.
ANSWER> We do not agree and keep the ALMA project ID where it is. ALMA policy demands that all IDs of employed data are clearly specified.
==========
(26 - Sect. 3.2.1) "with respect to the single-dish Total Power scans with ALMA antennas"
ANSWER> TP is now unabbreviated. I agree with the final statement of this section, that would be a most welcome addition to our field.
==========
(27- Sect. 3.3 Instrumentation) "the resulting diameter of the FOV is approximated as d fov ≈ ..."
For clarity, I recommend using a format that makes it explicitly clear what is, and what is not, under the large square root. This could also be achieved satisfactorily with parentheses.
ANSWER> Done.
==========
(28 - Sect. 3.3.1) "The details of the detector setup have to be investigated in detail. That includes the spacing between pixels, the total number of pixels, and the resulting instantaneously covered FOV. A fast small circular scanning pattern could be used to fill intermediate pointings. Combining data from circular scans (if possible on a second time scale or at least <10 s) would then allow to produce data with higher angular resolution. A detailed study is currently in preparation (Kirkaune et al. in prep.)."
Have the matters been studied in detail, or are being studied in detail (in prep)? If the former, I would recommend an additional citation to a published work referenced in first part of this paragraph.
ANSWER> We write now “Potential scanning strategies are currently being investigated (Kirkaune et al. in prep.).”
==========
(29 - Sect. 3.3.2) "Such a detector would allow for exploiting the spectral domain but comes at the price of a much smaller number of detector elements as compared to multi-chroic continuum cameras (see Section 3.3.1)," Why is this? Simply by re-assignment of those pixels? and a typo later: overal -> overall
ANSWER> We write now “...only with a much smaller number of detector elements as compared to multi-chroic continuum cameras due to the higher cost per pixel...”
==========
(30 - Sect. 3.3.3) "In any case, a realistic evaluation of the scientific potential of IFUs will require a dedicated study." Please comment on whether you have plans to perform that study.
ANSWER> This is simply a statement with no indication who will do it when. One of the next steps (in a few years) will be the initial design phase of potential instruments for AtLAST. It is too early to say anything more specific right now.

Competing Interests: No competing interests were disclosed.

Reviewer Report 08 August 2024

https://doi.org/10.21956/openreseurope.18862.r42516

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Francesco Pecora
University of Delaware, Newark, Delaware, USA

Wedemeyer et al. presented a white paper on the technical properties of the AtLAST observatory that are needed to advance the current and planned generations of observatories. They also discuss a series of science questions that could be addressed with AtLAST including the atmospheric heating problem and the investigation of solar flares.

Below are some comments that would hopefully improve its clarity.

1. Abstract. Typo, “simultaneously” should be “simultaneous”.
2. Abstract. In the last two paragraphs, if I understand correctly, it is suggested that AtLAST could observe other stars. However, in the science cases, this opportunity is not addressed. Why?
3. Section 2. If authors think it is appropriate, they could describe the potential synergy with the upcoming PUNCH mission (DeForest et al. 2022 10.1109/AERO53065.2022.9843340). For instance, it could be interesting to have AtLAST detailed observations at the sun’s surface and match them with unprecedented observations of CMEs.
4. Section 2.1 end of first paragraph. It is probably advisable to define “late-type stars”.
5. Section 2.1. The phenomena candidate for heating processes may include turbulence. Providing some references could be appropriate too, e.g. Cranmer (2002 [Ref - 2]) (https://doi.org/10.1023/A:1020840004535) for a review.
6. Section 2.2 end of second paragraph (“And yet…”). It is potentially interesting to add a point of discussion based on Gosling (1993 [Ref - 3]) (https://doi.org/10.1029/93JA01896)
7. Section 2.4 third paragraph (“Please note…”), the authors could mention the rotation period close to the poles as well.
8. Section 3.1, point (ii) is slightly unclear. Did the authors intend that to observe fast phenomena, high temporal resolution is needed? On the same paragraph, what do the authors mean with “large dynamic range”?
9. Section 3.1.1. “With an aperture…” the authors point to Fig.4 that has units of GHz. For ease of the reader, would it be possible to either express relevant quantities in GHz in this paragraph or add another axis that makes direct contact with the units of this paragraph?
10. Sec. 3.1.1 second paragraph. “Scanning…longer”. Can it be quantified how long?
11. Fig. 4 caption. Why are the frequencies of 90GHz and 660GHz relevant? In the text it seems

that 100GHz and 950GHz are mentioned.

12. Sec. 3.1.1 last paragraph. Define formation height range.
13. Sec. 3.1.4 last paragraph. When is Cycle 10?
14. Sec. 3.2 “10 min long...”. How much of the sun’s surface would this cover?
15. Same paragraph, define ToO.
16. The three methods described in Sec.s 3.2.1-3.2.3 are interesting. Is it possible to explicitly state what would be the spatial resolution, full FOV and temporal cadence for each one of them?

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1. DeForest C, Killough R, Gibson S, Henry A, et al.: Polarimeter to UNify the Corona and Heliosphere (PUNCH): Science, Status, and Path to Flight. *2022 IEEE Aerospace Conference (AERO)*. 2022. 1-11 Reference Source
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3. Gosling J: The solar flare myth. *Journal of Geophysical Research: Space Physics*. 1993; **98** (A11): 18937-18949 Publisher Full Text

Is the background of the case’s history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Not applicable

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Turbulence

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 13 Nov 2024

Sven Wedemeyer

We would like to thank the referee for the useful suggestions. We considered all comments, which resulted in an improved manuscript. Please note that the revised version takes into account the comments from all three referees. We added 81 additional references and updated Figs. 3 and 4. In the following, we address all comments in detail.

==========

1. Abstract. Typo, “simultaneously” should be “simultaneous”. ANSWER> ok.

==========

2. Abstract. In the last two paragraphs, if I understand correctly, it is suggested that AtLAST could observe other stars. However, in the science cases, this opportunity is not addressed. Why? ANSWER> That is mostly due to the initial topics covered in the first AtLAST design study (which resulted in several manuscripts like this one). Those topics did not include stellar observations. Given the synergies between solar and stellar physics, we wanted to at least point at this connection. The manuscript therefore (already in its submitted form) contains a section on the solar-stellar connection (Sect. 2.5).

==========

3. Section 2. If authors think it is appropriate, they could describe the potential synergy with the upcoming PUNCH mission (DeForest et al. 2022 10.1109/AERO53065.2022.9843340). For instance, it could be interesting to have AtLAST detailed observations at the sun’s surface and match them with unprecedented observations of CMEs. ANSWER> As far as we can see, the PUNCH mission will be launched in about 4 months with nominal mission duration of 2 years. This mission will thus complete in 2026 (plus any extension) and thus well before AtLAST would commence operations. It seem therefore strange to mention PUNCH in connection with AtLAST.

==========

4. Section 2.1 end of first paragraph. It is probably advisable to define “late-type stars”. ANSWER> We write now instead "for all stars with notable surface convection, i.e. in particular main sequence stars of spectral types G-M."

==========

5. Section 2.1. The phenomena candidate for heating processes may include turbulence. Providing some references could be appropriate too, e.g. Cranmer (2002 [Ref - 2]) (https://doi.org/10.1023/A:1020840004535) for a review. ANSWER> While it is certainly correct that turbulence should be mentioned in this context, the same is true for a large range of other processes and effects. We do not intend to give a complete review on this topic but expanded this part with two sentences and several references.

==========

6. Section 2.2 end of second paragraph (“And yet...”). It is potentially interesting to add a point of discussion based on Gosling (1993 [Ref - 3]) (https://doi.org/10.1029/93JA01896) ANSWER> We disagree with the referee. The claim put forward by Gosling in 1993 was controverse from the beginning and been disproven countless times with increasing support from new and more detailed observations. Hugh Hudson (among the authors of this article) summarised it as follows in the paper by Hudson et al. (1993): “In a recent paper Gosling (1993) claims that solar flares are relatively unimportant for understanding the terrestrial consequences of solar activity, and argues that coronal mass ejections (CMEs) produce the most powerful terrestrial disturbances. This opinion conflicts with observation, as it is well known that CMEs and flares are closely associated, and we disagree with Gosling's insistence on a simplistic cause-and-effect description of the interrelated phenomena of a solar flare. In this brief response we present new Yohkoh data and review

older results that demonstrate the close relationships among CMEs, flares, filament eruptions, and other forms of energy release such as particle acceleration." The progress in our understanding of the origins and impact of space weather since 1993 is substantial, providing solid and convincing arguments against the (simplistic) claim by Gosling.
==========
7. Section 2.4 third paragraph ("Please note..."), the authors could mention the rotation period close to the poles as well. ANSWER> Done.
==========
8. Section 3.1, point (ii) is slightly unclear. Did the authors intend that to observe fast phenomena, high temporal resolution is needed? On the same paragraph, what do the authors mean with "large dynamic range"? ANSWER> Sorry but we do not understand why this point is not clear. As stated, the "Sun evolves on short time scales which requires correspondingly short integration/scan times". Consequently, any observation of small details requires fast imaging. Regarding the dynamic range, we added in parentheses "(i.e., a high ratio between the maximum and minimum measurable brightness temperatures)".
==========
9. Section 3.1.1. "With an aperture..." the authors point to Fig.4 that has units of GHz. For ease of the reader, would it be possible to either express relevant quantities in GHz in this paragraph or add another axis that makes direct contact with the units of this paragraph? ANSWER> Fair point. We now mention both wavelengths and frequencies.
==========
10. Sec. 3.1.1 second paragraph. "Scanning...longer". Can it be quantified how long? ANSWER> It is difficult to give a definite answer but simply based on the telescope diameters we now write "longer (on the order of $(50m/12m)2 \approx 17$ times, i.e. ~3 hours)"
==========
11. Fig. 4 caption. Why are the frequencies of 90GHz and 660GHz relevant? In the text it seems that 100GHz and 950GHz are mentioned. ANSWER> We added the following to the caption: "which we here define as a minimum requirement for the frequency range." While we happily would use an instrument with a frequency range up to 950 GHz, the high frequency come with an accordingly small beam, thus making scanning the full disk at reasonable cadence challenging while the observing conditions are typically much more demanding for the highest frequencies. It thus not clear if the additional technical challenges are worth the resulting data for the highest frequencies - except for some lucky cases which of course could be scientifically interesting for individual targets but not so much for long series of daily maps. See Sect. 3.1.2.
==========
12. Sec. 3.1.1 last paragraph. Define formation height range.
ANSWER> We refer now to Sect. 2.1 in which the formation height aspect is now introduced.
==========
13. Sec. 3.1.4 last paragraph. When is Cycle 10?
ANSWER> Done.
==========
14. Sec. 3.2 "10 min long...". How much of the sun's surface would this cover?
ANSWER> Also full-disk maps. Now clarified in the manuscript.
==========
15. Same paragraph, define ToO.
ANSWER> Done.

==========
16. The three methods described in Sec.s 3.2.1-3.2.3 are interesting. Is it possible to explicitly state what would be the spatial resolution, full FOV and temporal cadence for each one of them? ANSWER> Sorry but no such details can be given at this points. These numbers will depend on the instrumental design which itself may well depend on technological aspects that are currently under development and therefore hard to pin down. This manuscript attempts to give a first (qualitative) impression of solar observations with AtLAST and why it is worthwhile to invest more effort into developing a suitable instrument.

Competing Interests: No competing interests were disclosed.

Reviewer Report 05 August 2024

https://doi.org/10.21956/openreseurope.18862.r42510

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?

Alexander G.M. Pietrow
Leibniz Institute for Astrophysics Potsdam, Potsdam, Germany

This manuscript discusses the construction and utilization of the 50-meter single-dish Atacama Large Aperture Submillimeter Telescope (AtLAST). The primary goal is to provide a comprehensive sub-mm diagnostic tool for studying the Sun's chromosphere, and that of other stars. This telescope will help fill the resolution gap around zero in Fourier space, and its large size will allow for overlap between the ALMA resolution space in a way that the existing 12-meter single dishes cannot. This is a timely and valuable project that will help further explore solar and stellar spectra beyond the infrared.
However, several aspects of the current version of the paper are unclear. Therefore, I suggest making modifications to address these issues before the paper is accepted for indexing. Additionally, some minor points could be improved in the revised manuscript. I have both comment types below in order of appearance. All comment locations are based on the PDF of the first version of the manuscript.

1. **Page 5, second column, second paragraph, first half**; This paragraph gives a good overview of solar physics done in sub-mm wavelengths, but does not emphasize the importance of these bands in combination with other wavelength bands. Especially for spectroscopic inversions and differential emission measures. (e.g. [Ref 1-6]) Could the authors mention these aspects and cite relevant literature?
2. **Page 5, second column, second paragraph, second half**; I believe that this is the location where AtLASTs capabilities (proposed wavelength bands, cadences, resolution, etc.) should be summarised for the reader. This currently happens in multiple locations across the manuscript and an overview would be very helpful. Table1 from [Ref - 7] is a good example.
3. **Page 6, second column, last paragraph**; This paragraph should be more quantitative with

examples and citations.

4. **Page 7, first column, second paragraph**; The Carrington event has an energy of the same order of magnitude as the 1e32 erg described in the same paragraph (~5e31 erg, e.g. [Ref - 8]) How much stronger (in orders of magnitude) are solar flares expected to be? [Ref - 9] puts the limit at ~1e36 for flares in general.
5. **Page 7, second column, second paragraph**; I believe that the word associated should be correlated instead.
6. **Page 7, figure 2**; Please mark the AtLAST bands on the figure, or mention them in the caption.
7. **Page 8, section 2.3**; Perhaps a link could be made with prominence models and how measurements in the sub-mm would provide valuable constraints for such models (e.g. [Ref 10-12]).
8. **Page 9, first column, first paragraph**; The acronym TP has not been defined.
9. **Page 9, first column, second paragraph**; It is not fully clear if this paragraph suggests a high-cadence observing mode, or daily full disk images. I believe that it is the latter, but in that case, solar flares should be removed from this list as the odds of capturing them are very low for daily maps. Unless the authors mean that tracking the evolution of active regions will shed light on flare physics, in which case this should be clarified. Additionally, the Solanki reference should be moved to the first mention of sunspots and perhaps [Ref - 13] could be added where it is pointed out that active regions move at different velocities than the quiet Sun.
10. **Page 9, second column, second paragraph**; I believe that a bigger summary should be given concerning sun-as-a-star observations in other wavelengths and how AtLAST would add to these programs. Some suggested citations on instruments, and Sun-as-a-star work done with these instruments concerning Sun-as-a-star flares can be found in [Ref 14-19]. A short discussion of how resolved vs unresolved flare studies [Ref 17-19] help with understanding flare observations would fit here. Additionally, if a flare is caught at a high cadence with a limited FOV, would it be feasible to turn this into a sun-as-a-star observation using a method similar to e.g. [Ref - 20]?
11. **Page 9, figure 3**; Please add an additional panel that shows the resolution with an ALMA SD dish. This would give a good comparison between existing and proposed instrumentation.
12. **Page 10, first column one, third paragraph**; "...still no confident detection of a stellar coronal mass ejection..." This is a very strong statement that would need to discuss proposed detections and explain why they are not confident. I suggest saying that only a relatively low number of CMEs has been detected so far, and cite [Ref 21-29].
13. **Page 10, first column one, fourth paragraph**; "...very short integration times and..." Could you give an order of magnitude value here?
14. **Page 10, second column one, second paragraph**; The last part of this paragraph should be moved to the front (See point 2).
15. **Page 10, second column one, second paragraph**; "On-the-fly scanning" How is this different from taking a mosaic? If it is not, perhaps it could be mentioned that this is similar or equivalent to taking a mosaic. In section 3.2.3 (pp13) they are equated to mosaics.
16. **Page 11, figure 4**; Please add a wavelength axis to panels a and b, as was done in Fig. 2. Additionally, should the vertical solid line in panel b also be dashed?
17. **Page 12, first column, second paragraph**; The cited source does not discuss cold temperatures below ~4500 K, perhaps the authors could add a small discussion on these lower temperatures and their implications, given that they are below that of the temperature minimum. Citation 4 (last part of section 4.1) offers a good summary and an

explanation of why other chromospheric proxies are not sensitive to these temperatures.

18. **Page 12, first column, second paragraph**; "...the 1.5m-aperture Solar Submillimeter Telescope (SST).." This telescope has already been introduced in the first paragraph of section 2.4, although without the citation.
19. **Page 12, first column, second paragraph**; Perhaps a figure could be added of the FAL-C model (temperature vs height) and the approximate heights at which the telescope different bands are sensitive be marked.
20. **Page 13, first column, first paragraph**; ToO -> undefined acronym
21. **Page 13, first column, second paragraph**; "..would require long scan times." Please give an order of magnitude estimate. The latter part of this paragraph does explain it somewhat, but I suggest this is edited to be more clear.
22. **Page 13, first column, third paragraph**; "..high cadence." -> please give an estimate.
23. **Page 13, second column, second paragraph**; "...slightly different science cases..." Please specify.
24. **Page 13, second column, second paragraph**; equation on the last line. Please give in larger mode for readability and give a numerical approximation of the constant.
25. **Throughout**; The manuscript has a preference for frequency over wavelength when discussing bands, however, it gives both at some locations in the text. I suggest that this is homogenized and that the wavelength is also given to improve readability for those outside of radio astronomy.

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Is the background of the case's history and progression described in sufficient detail?

Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Not applicable

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Solar physics, Sun-as-a-star observations, flares, and spectropolarimetric inversions.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 13 Nov 2024

Sven Wedemeyer

We would like to thank the referee for the useful suggestions. We considered all comments, which resulted in an improved manuscript. Please note that the revised version takes into account the comments from all three referees. We added 81 additional references and updated Figs. 3 and 4. In the following, we address all comments in detail.
==========
1. Page 5, second column, second paragraph, first half; This paragraph gives a good overview of solar physics done in sub-mm wavelengths, but does not emphasize the importance of these bands in combination with other wavelength bands. Especially for spectroscopic inversions and differential emission measures. (e.g. [Ref 1-6]) Could the authors mention these aspects and cite relevant literature?
ANSWER> We edited the section accordingly.
==========
2. Page 5, second column, second paragraph, second half; I believe that this is the location where AtLASTs capabilities (proposed wavelength bands, cadences, resolution, etc.) should be summarised for the reader. This currently happens in multiple locations across the manuscript and an overview would be very helpful. Table1 from [Ref - 7] is a good example. **ANSWER>** This is clearly a misunderstanding that is understandable as the referee likely received the manuscript without the necessary context. This manuscript, together several others covering other astronomical topics, is a result of the first design

phase. At this point, the telescope properties are defined but no instruments have been designed. The purpose of this article is to outline what AtLAST - based on the telescope specs - could do and how a corresponding instrument should be designed to make full of use of that. We see that a reader may indeed not understand this approach. We made therefore changes to clarify this point at the end of the introduction (Sect. 1). A table as suggested (Ref -7) is not possible at this stage, simply because that information does not exist.

==========

3. Page 6, second column, last paragraph; This paragraph should be more quantitative with examples and citations.

ANSWER> While we appreciate the suggestion, we would like to emphasise that this article is not meant to be a complete review article. We considered all comments of all three referees already to an extent that expanded the manuscript over its intended scope. As mentioned earlier in the article, a more complete review over solar mm science cases is provided by, e.g., Wedemeyer et al. 2016. We mentioned that now at the beginning of Sect. 2.2. ==========

4. Page 7, first column, second paragraph; The Carrington event has an energy of the same order of magnitude as the 1e32 erg described in the same paragraph (~5e31 erg, e.g. [Ref - 8]) How much stronger (in orders of magnitude) are solar flares expected to be? [Ref - 9] puts the limit at ~1e36 for flares in general.

ANSWER> Thanks for this interesting addition. We added a corresponding sentence (but state the values provided by the given references).

==========

5. Page 7, second column, second paragraph; I believe that the word associated should be correlated instead.

ANSWER> Changed.

==========

6. Page 7, figure 2; Please mark the AtLAST bands on the figure, or mention them in the caption.

ANSWER> Figure 2 is on page 5 in the submitted double-column version. Assuming that is the figure in question, we added a sentence to the caption.

==========

7. Page 8, section 2.3; Perhaps a link could be made with prominence models and how measurements in the sub-mm would provide valuable constraints for such models (e.g. [Ref 10-12]).

ANSWER> We completely agree with the referee that the links between the prominence models and the sub-mm observations are important and interesting to describe. However, we would rather avoid an inclusion of a few superficial ideas about how the new observations will impact this rich field of solar physics. There are many sub-fields of the prominence modelling, for example the radiative transfer modelling, magnetic field simulations and extrapolations, 2.5D and 3D MHD models, and the latest complex models bringing many of these ingredients together. We could hardly do justice to the entire field in a few sentences, but we cannot review the state-of-the-art of the field in this paper either. However, we updated the section (also in response to the other referees' comments).

==========

8. Page 9, first column, first paragraph; The acronym TP has not been defined.

ANSWER> Done.

==========
9. Page 9, first column, second paragraph; It is not fully clear if this paragraph suggests a high-cadence observing mode, or daily full disk images. I believe that it is the latter, but in that case, solar flares should be removed from this list as the odds of capturing them are very low for daily maps. Unless the authors mean that tracking the evolution of active regions will shed light on flare physics, in which case this should be clarified.
Additionally, the Solanki reference should be moved to the first mention of sunspots and perhaps [Ref - 13] could be added where it is pointed out that active regions move at different velocities than the quiet Sun.
ANSWER> Fair point. We added another sentence to clarify this and added the references as suggested.
==========
10. Page 9, second column, second paragraph; I believe that a bigger summary should be given concerning sun-as-a-star observations in other wavelengths and how AtLAST would add to these programs. Some suggested citations on instruments, and Sun-as-a-star work done with these instruments concerning Sun-as-a-star flares can be found in [Ref 14-19]. A short discussion of how resolved vs unresolved flare studies [Ref 17-19] help with understanding flare observations would fit here. Additionally, if a flare is caught at a high cadence with a limited FOV, would it be feasible to turn this into a sun-as-a-star observation using a method similar to e.g. [Ref - 20]?
ANSWER> We would not like to add a detailed discussion of resolved vs unresolved flare studies as the manuscript is not intended to be a comprehensive review. We have nevertheless extended the section accordingly and added the suggested references.
==========
11. Page 9, figure 3; Please add an additional panel that shows the resolution with an ALMA SD dish. This would give a good comparison between existing and proposed instrumentation. **ANSWER>** We updated the figure accordingly.
==========
12. Page 10, first column one, third paragraph; "...still no confident detection of a stellar coronal mass ejection..." This is a very strong statement that would need to discuss proposed detections and explain why they are not confident. I suggest saying that only a relatively low number of CMEs has been detected so far, and cite [Ref 21-29].
ANSWER> We have toned down the statement and added all suggested references.
==========
13. Page 10, first column one, fourth paragraph; "...very short integration times and..." Could you give an order of magnitude value here?
ANSWER> Done.
==========
14. Page 10, second column one, second paragraph; The last part of this paragraph should be moved to the front (See point 2).
ANSWER> See our answer to point 2. Instead we moved the paragraph addressing the chromosphere at the beginning of Sect. 2 into Sect. 2.1 and added two sentences with the basic telescope properties and refer to Sect. 3 for the definition of instrumental requirements. It is important to note that defining these requirements based on the basic telescope properties and the possible science cases is the main purpose of this manuscript, which can then serve as basis for future instrument design studies.
==========

15. Page 10, second column one, second paragraph; “On-the-fly scanning” How is this different from taking a mosaic? If it is not, perhaps it could be mentioned that this is similar or equivalent to taking a mosaic. In section 3.2.3 (pp13) they are equated to mosaics.
ANSWER> This is a misunderstanding. On-the-fly scanning is not the same as mosaics. We clarified this in Sect. 3.2.3. and added another sentence in Sect. 3.1.1. to explain the difference.
==========
16. Page 11, figure 4; Please add a wavelength axis to panels a and b, as was done in Fig. 2. Additionally, should the vertical solid line in panel b also be dashed?
ANSWER> We updated the figure accordingly.
==========
17. Page 12, first column, second paragraph; The cited source does not discuss cold temperatures below ~4500 K, perhaps the authors could add a small discussion on these lower temperatures and their implications, given that they are below that of the temperature minimum. Citation 4 (last part of section 4.1) offers a good summary and an explanation of why other chromospheric proxies are not sensitive to these temperatures.
ANSWER> While we appreciate the suggestion, the purpose of this section is to motivate the need for a high dynamic range. A discussion of low temperatures and the related trouble of applying a correct offset for interferometric observations with ALMA would divert too much from this purpose. We nonetheless expanded the text somewhat and added more references.
==========
18. Page 12, first column, second paragraph; “...the 1.5m-aperture Solar Submillimeter Telescope (SST)..” This telescope has already been introduced in the first paragraph of section 2.4, although without the citation.
ANSWER> Fixed.
==========
19. Page 12, first column, second paragraph; Perhaps a figure could be added of the FAL-C model (temperature vs height) and the approximate heights at which the telescope different bands are sensitive be marked.
ANSWER> We would rather not want to use the FAL-C model as a reference. As we now describe in more detail in Sect. 2.1, i) the chromosphere is highly dynamic and that is not well represented by an average stratification as in the FAL-C model and ii) the exact formation heights of the mm continuum are currently an open question, which would make any such information uncertain. Instead, the manuscript makes it clear that AtLAST (like ALMA) would observe the chromosphere without going into too much detail.
==========
20. Page 13, first column, first paragraph; ToO -> undefined acronym
ANSWER> Fixed..
==========
21. Page 13, first column, second paragraph; “..would require long scan times.” Please give an order of magnitude estimate. The latter part of this paragraph does explain it somewhat, but I suggest this is edited to be more clear.
ANSWER> We refer now to the updated Sect. 3.1.1 where the longer scan times are now discussed
==========
22. Page 13, first column, third paragraph; “..high cadence.” -> please give an estimate.

ANSWER> Done. We also added why this is desirable as demonstrated by ALMA.
==========
23. Page 13, second column, second paragraph; "...slightly different science cases..." Please specify.
ANSWER> We expanded this part.
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24. Page 13, second column, second paragraph; equation on the last line. Please give in larger mode for readability and give a numerical approximation of the constant.
ANSWER> We assume that this comment addresses the equation for the FOV. Please note that the typesetting was done by ORE based on our Latex (Overleaf) generated version. We hope that the editors can take up this suggestion when typesetting the final version.
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25. Throughout; The manuscript has a preference for frequency over wavelength when discussing bands, however, it gives both at some locations in the text. I suggest that this is homogenized and that the wavelength is also given to improve readability for those outside of radio astronomy.
ANSWER> While it is more common to use frequency and while the conversion is relatively easy, we added both at several places to make the text easier to understand for a broader range of readers.

Competing Interests: No competing interests were disclosed.