Revealing the Sun’s Alfvénic waves

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**Summary**

Alfvénic waves are thought to be a key mechanism for energy transfer in the Sun’s atmosphere, providing the energy to meet the radiative losses of the dense chromosphere and hotter, tenuous corona, along with the demands required to accelerate the solar wind. In recent years there has been clear evidence for the presence of low-frequency (f<10 mHz) Alfvénic waves through the chromosphere and corona, and they are ever-present throughout the solar cycle. Many models exist which provide support for the critical role of Alfvénic waves. However, there are details of the waves journey from photosphere to corona to solar wind that remain unverified and key parameters which remain unconstrained. The Alfvénic waves also offer the chance to explore the difficult to measure coronal magnetic field. Fortunately, new and future instrumentation (e.g., the Coronal Solar Magnetism Observatory - COSMO) will provide exciting opportunities to discover key aspects of the waves’ propagation and dissipation and permit regular estimates of the magnetic field. We encourage the community to focus on developing these aspects in the coming years.

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*Figure 1 A depiction of some of the broader questions surrounding the journey of Alfvenic waves in the lower solar atmosphere. The background is an image of the low corona observed with SDO, highlighting the fine-scale density structuring present throughout. The lower insets show the unresolved energy flux of Alfvénic waves from CoMP and examples of displacement time-series corresponding to resolved Alfvénic waves measured from the image-plane in SDO data.*

**Introduction** The coronae of many low mass, late-type main sequence stars are known to be heated to temperatures in excess of a million degrees (Testa et al. 2015). The high temperature of the coronae leads to the emission of radiation at X-ray and EUV wavelengths, which can influence the evolution and habitability of orbiting exoplanets through effects such as atmospheric erosion ([Linsky 2019](https://ui.adsabs.harvard.edu/link_gateway/2019LNP...955.....L/doi:10.1007/978-3-030-11452-7)). The level of X-ray emission appears linked to the amount of unsigned magnetic flux and the rotation rate of the star (stellar EUV emission is difficult to observe) and is well correlated with chromospheric activity. Many of these solar-like stars are also thought to possess a hot, magnetised stellar wind, which leads to mass loss and angular momentum loss (spin-down) of the stars. Energy deposition in the chromosphere is also thought to play a pivotal role in mass loss ([Shoda et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020ApJ...896..123S/doi:10.3847/1538-4357/ab94bf)).

Hence understanding the mechanisms behind the deposition of energy in the chromospheric and coronal plasma (and the wind) is critical, due the impact on many aspects of the evolution of low mass stars and their planetary systems. However, even 80 years after the identification of hot solar corona ([Edlen 1943](https://ui.adsabs.harvard.edu/abs/1943ZA.....22...30E/abstract)) and 60 years after the discovery of the solar wind, we are still grappling with the physical processes that convert magnetic energy to power the stellar atmospheric dynamics.

One of the suggested candidate mechanisms is the dissipation of Alfvénic waves, which are highly incompressible magnetohydrodynamic waves whose main restoring force is magnetic tension. Significant progress has been made in the last decade from a theoretical standpoint, with state-of-the-art numerical models having confirmed the importance of Alfvénic waves in energy transfer, showing their potential to heat the chromospheric & coronal plasma and accelerate the stellar wind ([Van Doorsselaere et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020SSRv..216..140V/doi:10.1007/s11214-020-00770-y), [Banerjee et al. 2021](https://ui.adsabs.harvard.edu/link_gateway/2021SSRv..217...76B/doi:10.1007/s11214-021-00849-0)). Typically, these models rely on some form of turbulence (e.g., incompressible MHD turbulence, turbulence due to instabilities) as a mechanism to cascade wave energy from the driving to dissipation scales. These turbulence-driven atmospheric models are now routinely being utilised for predicting the solar wind ([van der Holst et al. 2019](https://ui.adsabs.harvard.edu/link_gateway/2019ApJ...872L..18V/doi:10.3847/2041-8213/ab04a5), [Réville et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020ApJS..246...24R/doi:10.3847/1538-4365/ab4fef)), simulating the environment around planet-hosting stars ([Alvarado-Gómez et al. 2016](https://doi.org/10.1051/0004-6361/201628988)), and studying the long-term evolution of sun-like stars ([Shoda et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020ApJ...896..123S/doi:10.3847/1538-4357/ab94bf)). While producing promising results (e.g., reproduction of large-scale plasma parameters in the solar wind), these models typically contain several critical but unconstrained or weakly constrained (i.e., through reproducing ambiguous diagnostics, e.g., non-thermal line widths) parameters, which ultimately control the details of the energy transport and deposition by the waves. **To advance our knowledge across a broad range of topics in solar and stellar physics, it is necessary to observe details of the waves journey through the stars’ atmospheres and deliver observational constraints on the properties of Alfvénic waves.**

Furthermore, the coronal magnetic field plays a crucial role in energy transport and dissipation, linked directly to chromospheric and coronal emission. It is also a key driver of atmospheric dynamics, responsible for solar eruptions. Hence precise knowledge of coronal magnetism and its storage and release of energy is vital in many areas of solar and stellar physics. Currently, our community does not have the access to routinely measured coronal magnetic fields. This arises from a lack of suitable observations, incomplete understanding of the atomic processes involved in chromospheric and coronal emission, and limited inversion method capabilities. The only routine tools available to probe coronal magnetic field structures are magnetic field extrapolations that are computed from photospheric magnetic field measurements. These have been proven over time to be unreliable, as most implied assumptions are not accurate for coronal or chromospheric conditions ([Hardi et. al, 2015](https://doi.org/10.1051/0004-6361/201527057)). Several methods have been proposed to address this but of particular interest is the use of Alfvénic wave propagation to successfully infer magnetic fields through coronal seismology. The Alfvénic waves propagation depends upon the local magnetic and plasma conditions, hence measurement of certain properties, e.g., the propagation speeds, permits inversions to estimate the magnetic field ([Yang et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020Sci...369..694Y/doi:10.1126/science.abb4462)). **A focus in the next decade should be the exploration of the usefulness of magnetic field inversion from coronal seismology and its combination with complementary diagnostic techniques.**

**Current situation** In the previous decade we saw the first tentative steps in observationally probing Alfvénic wave propagation through the Sun’s atmosphere. The Coronal Multi-Channel Polarimeter (CoMP) provided regular ground-based observations of the off-limb corona in the Fe XIII 1074 nm emission line (spatial sampling ~4”, cadence 30s), and analysis of Doppler velocities revealed that low-frequency (0.1-10 mHz) Alfvénic (surface Alfvén/kink) modes were readily seen over the entire corona and throughout the solar cycle ([Tomczyk et al 2007](https://www.science.org/doi/abs/10.1126/science.1143304); [Morton et al. 2019](https://www.nature.com/articles/s41550-018-0668-9)). In addition, the full-disk, high-resolution data from NASAs Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) demonstrated that the velocity signals had a counterpart in imaging data, revealed as the transverse displacement of the fine-scale structuring that comprises the inhomogeneous coronal plasma ([McIntosh et al. 2011](https://www.nature.com/articles/nature10235); [Thurgood et al. 2014](https://iopscience.iop.org/article/10.1088/2041-8205/790/1/L2)). Despite having the facilities to observe the Alfvénic waves, volumes of high-quality data, and the impetus provided by promising modelling results, the number of observational studies on the propagating Alfvénic waves have been limited. The reasons for this lack of attention are unclear, with much more interest devoted to the large-amplitude, harmonic standing modes in active regions. Part of the issue may lie with the challenge provided in measuring the propagating waves (although it has been demonstrated to be feasible), with the displacement amplitudes bordering the resolution limit of SDO/AIA and the wave packets appearing stochastically. For those observational studies that have taken place, the majority have often focused on rudimentary properties such as amplitudes and periods in a particular region of the Sun’s atmosphere.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Facility** | **Spectral ranges/lines (nm)** | **Stokes** | **Resolution** | | **Field of view** | **Launch/first light + citation** |
| **Spatial**  **(“)** | **Temporal (s)** |
| DKIST (Cryo-NIRSP) | 1000 - 5000 | IQUV | 0.12 | >1 | 5’x5’ | Commissioning  [Fehlmann et al. 2016](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9908/99084D/Cryogenic-near-infrared-spectropolarimeter-for-the-Daniel-K-Inouye-Solar/10.1117/12.2232218.full) |
| UCoMP | 500-1100 | IQUV | 3 | 30 | 1.03-2 R☉ | Commissioning  [Landi et al. 2016](https://doi.org/10.1002/2016JA022598) |
| SOLAR-C EUVST | 17-21.5, 46-122 | I✢ | 0.4 | 1 |  | >2026  [Shimizu et al. 2019](https://doi.org/10.1117/12.2528240) |
| MUSE | 10.8, 17.1, 28.4 | I✢ | 0.4 | 0.5-30 |  | 2026 or 2028 [De Pontieu et al. 2022](https://ui.adsabs.harvard.edu/link_gateway/2022ApJ...926...52D/doi:10.3847/1538-4357/ac4222) |
| PROBA3 (ASPIICS) | 535–565, 530, 587 | I\* | 2.8 | <10 | 1.1-3 R☉ | 2023  [Shestov et al 2021](https://doi.org/10.1051/0004-6361/202140467) |
| COSMO | 380-1500 | IQUV | 2 | ~30 | 1.03-2 R☉ | Later this decade Tomczyk et al. 2022 |

✢ Spectroscopic; \* Imaging

However, the upcoming data from a range of facilities offers a rich opportunity to probe the wave physics in greater detail, opening up new spatial and temporal scales (details in above table). The facilities are a mix of ground- and space-based, offering either highly focused views on portions of the Sun’s atmosphere (DKIST, SOLAR-C EUVST, MUSE) or much broader vantages of the lower to middle corona through coronagraphs (uCoMP, PROBA3, COSMO). The expected characteristics of each facility are given in the table above. They have the potential to provide highly complementary views of Alfvénic wave behaviour through the upper chromosphere and low to middle corona; and all offer an opportunity for examining new scales or under-observed regions of the corona.

In the following we review some of the unknown details surrounding wave propagation through the atmosphere and what we have learnt from the currently available data. We also indicate where these new facilities may be able to progress our understanding.

***How do Alfvénic waves contribute to chromospheric/coronal heating?***

Answering this broad question requires increasing our knowledge on many other aspects of the waves’ journey through the solar atmosphere. A fundamental unknown is *which mechanisms are responsible for generating Alfvénic waves?* and can provide a meaningful energy flux. The long-standing paradigm is that the waves are generated by the interaction of the photospheric convection with the network magnetic fields and propagate upwards. This is believed to excite waves with temporal (<10 mins) and spatial (1000 km) scales comparable to the granulation ([Cranmer & Van Ballegoojien 2005](https://iopscience.iop.org/article/10.1086/426507)). However, observations from the CoMP instrument show that the coronal velocity (energy) power spectrum (Figure 1) extends to lower frequencies than expected from the photospheric granulation, with the suggestion that low frequency Alfvénic waves may originate from magnetic reconnection ([Cranmer 2018](https://iopscience.iop.org/article/10.3847/1538-4357/aac953)). The observed coronal power spectrum also shows a clear, broad enhancement around 4 mHz, which is not expected from photospheric driving. The location of the enhancement is nearly co-incident with the envelope of the *p*-mode power spectrum, and its presence has been suggested to arise from a double mode conversion process of acoustic to Alfvén modes ([Khomenko & Cally 2012](https://iopscience.iop.org/article/10.1088/0004-637X/746/1/68), [Cally 2017](https://academic.oup.com/mnras/article/466/1/413/2666400)). More recent numerical models have suggested that Alfvenic waves can also be generated in the chromosphere via the Hall effect ([González-Morales et al. 2020](https://www.aanda.org/articles/aa/full_html/2020/10/aa37938-20/aa37938-20.html)). The rate at which all these mechanisms are effective at contributing to the coronal Alfvénic wave flux depends upon the local plasma and magnetic field conditions, and raises the question, *what is the relative energy flux through different magnetic regions?* The CoMP data has revealed that there appears to be some variation in the shape of the power spectrum between different regions ([Morton et al. 2016](https://iopscience.iop.org/article/10.3847/0004-637X/828/2/89), [2019](https://www.nature.com/articles/s41550-018-0668-9)), but the studies were rather coarse due to instruments spatial resolution (4.6”) and a requirement for integrating spectra over many neighbouring spatial locations, i.e., magnetic configurations. The low spatial resolution relative to the fundamental cross-sectional scales of the coronal structures (0.3”- 3.2” [Brooks et al. 2013](https://iopscience.iop.org/article/10.1088/2041-8205/772/2/L19), [Antolin et al., 2015](https://iopscience.iop.org/article/10.1088/0004-637X/806/1/81)), has likely also hidden a variety of Alfvénic modes from view. It is expected that a plethora of torsional/rotational Alfvénic modes are present in a highly structured plasma environment such as the corona ([De Pontieu et al. 2014](http://adsabs.harvard.edu/abs/2014Sci...346D.315D)). Photospheric observations reveal a wealth of potential drivers in the form of vortices ([Bonet et al. 2008](https://iopscience.iop.org/article/10.1086/593329)). While there have been a handful of individual examples of torsional motions at the coronal heights ([Okamoto et al. 2016](http://adsabs.harvard.edu/abs/2016ApJ...831..126O), [Kohutova et al. 2020](https://ui.adsabs.harvard.edu/abs/2020A&A...633L...6K)), the evidence for their existence throughout the corona is lacking. They are expected to be equally ubiquitous as the kink mode and transport a comparable energy flux. Hence, the question remains, *are torsional/rotational modes abundant in the corona and what is their contribution to the Alfvénic wave energy budget?*

The importance of the chromosphere for controlling the flow of mass and energy through the solar atmosphere had been widely recognised for nearly two decades. Yet we still do not have a clear answer to *how does the chromosphere regulate the transfer of Alfvénic wave energy?* There are several known factors that could play a significant role in reflecting, converting, or dissipating wave energy before it reaches the corona. The reflection occurs due to the increase in Alfvén speed throughout the lower solar atmosphere and is strongest at the top of chromosphere as it transitions to the corona ([Cranmer & Van Ballegoojien 2005](https://iopscience.iop.org/article/10.1086/426507)). The current estimates for wave reflection are typically derived assuming that the transition region has a near discontinuity in density. However, the chromosphere at the network boundaries is known to be extremely dynamic being composed of spicules, jets of chromospheric material continually launched upwards into the corona. This potentially could lead to smoother Alfvén speed profiles between the chromosphere and corona and reduce the wave reflection. Initial indications suggest this may be the case, with an estimate of smoother density profiles in coronal holes from Alfvénic wave observations ([Weberg et al 2020](https://iopscience.iop.org/article/10.3847/1538-4357/ab7c59)), and a measurement of Alfvénic wave reflection along spicules appearing lower than traditional expectations ([Okamoto & De Pontieu 2011](https://ui.adsabs.harvard.edu/abs/2011ApJ...736L..24O/abstract)).

Perhaps a more important factor is the weakly ionised nature of the chromosphere, which has received significant theoretical attention in recent years ([Ballester et al. 2018](https://ui.adsabs.harvard.edu/link_gateway/2018SSRv..214...58B/doi:10.1007/s11214-018-0485-6)). The weak ionisation leads to enhanced diffusivity through the collisions of the ions and neutrals, leading to strong dissipation of high frequency (>10 mHz) Alfvénic waves ([Vranjes et al. 2008](https://www.aanda.org/articles/aa/abs/2008/05/aa8274-07/aa8274-07.html), [Soler et al. 2019](https://ui.adsabs.harvard.edu/link_gateway/2019ApJ...871....3S/doi:10.3847/1538-4357/aaf64c)). This extra diffusion would ultimately impact the power spectrum of waves that enter the corona and potentially control the time/length-scales associated with wave-based heating. Previous observations from CoMP were unable to access the necessary frequency range to examine the shape of the coronal spectra at the higher frequencies, limited by instrumental factors and sensitivity.

For those waves that pass the gauntlet of the chromosphere and enter the corona, they must somehow deposit their energy in the corona. The ohmic diffusivity in the corona is tiny and waves are required to somehow transfer their energy to small spatial scales for wave dissipation to become efficient. In homogenous plasmas, phase mixing is too weak to achieve this and Alfvenic turbulence is seemingly the only answer. Although the direct evidence for wave turbulence does not exist – leaving the question as *to whether Alfvénic wave turbulence developed in the chromosphere/lower corona*? – indications from solar wind data suggest that higher-cadence observations may be required to resolve the frequency regime containing the inertial range. Fortunately, the corona is highly inhomogeneous perpendicular to the magnetic field, with ample evidence for over-dense structures throughout the corona. The density inhomogeneity across the field leads to resonant mode conversion ([Terradas et al. 2010](https://ui.adsabs.harvard.edu/link_gateway/2010A&A...524A..23T/doi:10.1051/0004-6361/201014845)), induces instabilities ([Terradas et al 2008](https://ui.adsabs.harvard.edu/link_gateway/2008ApJ...687L.115T/doi:10.1086/593203)), enhances rates of phase mixing ([Soler et al. 2019](https://iopscience.iop.org/article/10.3847/1538-4357/aaf64c)), and permits a uni-turbulence ([Magyar et al. 2017](https://ui.adsabs.harvard.edu/link_gateway/2017NatSR...714820M/doi:10.1038/s41598-017-13660-1)). However, the rates at which these phenomena take place are governed by the relative over-density of the coronal structure to the local ambient environment (as well as the thickness of the boundary layers), with larger over-densities leading to greater impacts. Evidence for the role of such processes is perhaps best found indirectly in the observed rapid damping of standing kink modes in dense active region loops. The contribution of these processes in the quiet Sun and coronal holes is less clear. Recent evidence from studies with CoMP reveal the propagating kink modes are only weakly damped in the quiet Sun ([Tiwari et al. 2021](https://iopscience.iop.org/article/10.3847/1538-4357/ac10c4)), while measurements of coronal holes show that the waves show nearly no damping below 1.2 Rsun ([Morton et al. 2015](https://www.nature.com/articles/ncomms8813)). Taken with the fact that the fine-scale structure of the quiet Sun and coronal holes shows less emission over the background in EUV lines, when compared with Active Regions, indicates that the density contrast might be small ([Morton et al. 2021](https://iopscience.iop.org/article/10.3847/1538-4357/ac324d)), and the above-mentioned effects are weak. Hence there is still very much an open question as to *what are the rates of energy deposition by Alfvénic waves in the chromosphere/corona?*

Over the next decade, the cohort of instruments expected to be available will provide several improvements, opening a new discovery space in wave observations. The vastly improved spatial resolutions of the DKIST, EUVST and MUSE will permit focused views on individual magnetic structures and offer the ability to observe small-scale dynamics (e.g., other wave modes, instabilities). The instrumentation also delivers improved cadences (dependent upon observing modes), which is key for examining the high frequency Alfvénic waves. EUVST and MUSE offer the opportunity for long observational runs not afforded to ground-based facilities. This would enable greater frequency resolution, allowing improved constraints on the shape of the power spectra across the frequency range and insights into the different wave driving mechanisms. Further, co-temporal, co-spatial observations that cover a broad range of temperatures are possible with MUSE (0.1MK to 12MK), EUVST (20kK to 15MK), and COSMO (10kK to 5MK), enabling studies of wave energy propagation across the transition region. These focused measurements would be supported by the synoptic measurements from UCoMP (and later COSMO), providing a broader picture of Alfvénic waves throughout the lower off-limb corona. COSMO offers a unique opportunity to further obtain diagnostics for estimates of electron density, temperature, and magnetic field (through waves and polarimetry); permitting significant constraints to be placed on wave-based plasma heating.

**What is the role of Alfvénic waves in the heating/acceleration of the solar wind?**

It is widely appreciated that the properties of solar wind are highly dependent upon where the energy is deposited in the corona ([Leer & Holzer 1980](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JA085iA09p04681)). Hence, the contribution of Alfvénic waves to mass loss/heating/acceleration depends on how the wave energy is dissipated.Recent numerical models have shown the Alfvénic waves can deposit their energy below the sonic point through the parametric decay instability (PDI), generating large amplitude compressible MHD slow waves which are subject to shock formation ([Suzuki & Inutsuka 2005](https://iopscience.iop.org/article/10.1086/497536), [Mastumoto & Suzuki 2014](https://academic.oup.com/mnras/article/440/2/971/1023567)). Above the sonic region, incompressible mechanisms such as MHD turbulence, phase mixing, etc. are likely in action. However, the growth of the PDI depends upon wave frequency and its contribution to energy dissipation is also dependent upon the correlation length scales associated with wave driving ([Shoda et al. 2018 a](https://iopscience.iop.org/article/10.3847/1538-4357/aaa3e1),[b](https://iopscience.iop.org/article/10.3847/1538-4357/aac218)). The heating rate associated with turbulence is also considered to be strongly dependent upon the correlation length scale ([Verdini et al. 2010](https://iopscience.iop.org/article/10.1088/2041-8205/708/2/L116), [Shoda et al. 2018](http://adsabs.harvard.edu/abs/2018ApJ...853..190S)). Current observational results have little to say on these aspects, and the outstanding questions are *how do Alfvénic waves evolve between the solar corona and the solar wind?* *And do they wave vary across the solar cycle?* Observational results from CoMP have been restricted to the low corona (<1.3 Rsun) and show that Alfvénic waves are largely undamped in coronal holes and amplitude of Doppler velocity fluctuations follow the expected WKB evolution with height ([Morton et al. 2015](https://www.nature.com/articles/ncomms8813)). Although, observations of non-thermal emission line widths have potentially hinted of wave damping around 1.3 Rsun ([Hahn & Savin 2013](https://iopscience.iop.org/article/10.1088/0004-637X/776/2/78), [Gupta 2017](https://ui.adsabs.harvard.edu/abs/2017ApJ...836....4G), [Hara 2019](https://ui.adsabs.harvard.edu/abs/2019ApJ...887..122H)). These results are somewhat puzzling and potentially controversial. No mechanism has been put forward to explain such a rapid and abrupt damping. More recent studies suggest that instrumental scattered light could influence the results ([Zhu et al 2021](https://iopscience.iop.org/article/10.3847/1538-4357/abf1e3)), the waves could be out of energy equipartition ([Cranmer 2018](https://iopscience.iop.org/article/10.3847/1538-4357/aac953)), or that ion populations may be in non-equilibrium ([Gilly & Cranmer 2020](https://iopscience.iop.org/article/10.3847/1538-4357/abb1ad)). A picture containing text, device, gauge, control panel

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*Figure 2 A view of the off-limb corona from CoMP. The image reveals the fine-scale magnetised structures at the base of large-scale features that extend into the heliosphere.*

Further, an important factor that is missed from most Alfvén wave driven wind models is the presence of inhomogeneity perpendicular to the magnetic field. As already mentioned, this could have significant implications for such models, permitting alternative mechanisms for wave dissipation ([Magyar et al. 2017](https://www.nature.com/articles/s41598-017-13660-1), [Pagano & De Moortel 2019](https://ui.adsabs.harvard.edu/abs/2019A&A...623A..37P)). Recent results suggest it can also influence the evolution of correlation length scales ([Magyar & van Doorselaere 2022](https://doi.org/10.48550/arXiv.2208.09059)) The fine-scale density structuring is seen across images of the low corona (with scales <1 Mm, e.g., Figures 1 and 2) but has also been reported to be present up to heights of 5-14 Rsun with scales of at least 20 Mm ([DeForest et al. 2018](http://ui.adsabs.harvard.edu/abs/2018ApJ...862...18D/abstract)). Hence the fine-scale density structuring is expected to be present throughout the middle corona up to the Alfven critical surface (zone). The obvious question is then *What is the impact of inhomogeneities perpendicular to the magnetic field on Alfvénic waves as they propagate into the heliosphere?* At present, there are no observational results that can guide an answer. CoMP enables one to probe the dynamics at the base of the large-scale structures, e.g., the streamers, as seen in Figure 2. However, probing the evolution of waves through the middle corona is likely to be critical, as this is a region where many physical processes occur that ultimately determine the outflow into the heliosphere ([West et al 2022](https://arxiv.org/abs/2208.04485)).

Over the coming decade we envision beginning to probe Alfvénic wave propagation in the upper regions of the low corona (<1.5 Rsun) with spectroscopic observations from UCoMP, marginally extending the observable regions of the corona given by its predecessor. There is a chance this view could overlap with the sonic region, offering unique insights into wave dissipation below this critical area. Further progress will likely be dependent upon COSMO becoming operational, pushing the observational space into the middle corona and entering a region where undiscovered but potentially key physics occurs (summarised above). The improved sensitivity and spatial resolution (over UCoMP) will enable measurements of flows and plasma parameters in the young solar wind ([Morton et al. 2015](https://www.nature.com/articles/ncomms8813)). There is also the potential for imaging observations to play a role in discovery, with PROBA3 offering high resolution coronagraphic data from space. From expected radial expansion rates of coronal structures and wave amplification due to the decreasing plasma density, there is a possibility that Alfvénic motions could be measurable using image-plane techniques.

**Is it feasible to exploit Alfvénic waves via magneto-seismology to provide routine and meaningful characterisation of the plasma and magnetic field conditions in the corona?**

As new instrumentation and facilities like DKIST (Cryo-NRISP, DL-NIRSP), UCoMP, COSMO, etc. move into operational phases, there will be the capability to measure novel full Stokes IQUV polarimetry of the corona. This will enable the community to directly probe the coronal magnetic field, without relying on the limitations that hinder extrapolations. The coronal lines commonly selected for this are forbidden magnetic dipole lines formed in the saturated Hanle regime. This leads to degeneracies in the inversions that can be improved with additional information (e.g., the CLEDB full polarimetric inversion [Judge at al. 2021](https://iopscience.iop.org/article/10.3847/1538-4357/abebd8), [Paraschiv & Judge, 2022](https://link.springer.com/article/10.1007/s11207-022-01996-5)). Recently, it was successfully demonstrated that measurements of Alfvénic wave propagation from CoMP Doppler oscillations could be used to infer plane-of-sky magnetic fields strengths and orientation in the solar corona ([Yang et al. 2020](https://ui.adsabs.harvard.edu/link_gateway/2020Sci...369..694Y/doi:10.1126/science.abb4462)). The Alfvénic wave tracking approach is mostly sensitive to POS magnetic fields, while spectro-polarimetric inversions like CLEDB are primarily sensitive to the LOS component. This opens up the possibility for utilizing Alfvén wave observations, that when coupled to a spectro-polarimetric inversion, will contain enough information to infer a full vector field without the need of formally including the Stokes V component that is challenging to measure in the corona, even for the next gen instrumentation (Paraschiv, 2022, in prep.). Although such an approach needs to be validated, it shows untapped potential of Alfvénic waves and coronal seismology, which can be extremely important in answering the crucial science questions surrounding the nature of the coronal magnetic field.

Over the next few years, UCoMP (in combination with coronal line synthesis) can be used to explore this exciting avenue. The improved spatial resolution and larger field of view (over CoMP) will enable finer estimates of the coronal magnetic field over a wider range of heights. It is envisioned that new methodology for analysing propagating Alfvénic waves will be required to maximise the results and improve uncertainties. However, it will only be with the arrival of COSMO that there will be an opportunity to jointly measure both the wave properties and Stokes vectors in unison; delivering robust and regular global coronal magnetic field measurements that are vital for many science questions across solar physics.

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