Study on Real-time Monitoring Method for Dust-scattered Stray Light in the Spectral Imaging CoronaGraph of the Chinese Meridian Project Phase II (Postprint)

Authors: Da-Yang Liu, Xiao-Yu Yu, Hong-Xin Zhang, Zheng-Hua Huang, Li-Dong Xia, Ming-Zhe Sun, Xian-Liang Mao, Bo-Yu Sun, Ning Tang, Hui Fu, Wei-Xin Liu, Chao Zhang and Jian-Ping Han

Date: 2025-02-25T00:00:00+00:00

Abstract

The dust-scattered stray light in an inner-occulted coronagraph mainly arises from dust particles on the surfaces of the objective lens. Due to the random accumulation of dust on the lens surfaces, it is challenging to monitor this type of stray light and no application can be used for its real-time monitor in the past. In this study, we provide a system and method to overcome this issue, and these have been applied to the Spectral Imaging CoronaGraph (SICG) of the Chinese Meridian Project. The method is based on the relation between the sizes of dust particles and its stray light level at the imaging plane established in the laboratory and the relation between the real size of dust particles and the occupancies on the imaging plane. To monitor the stray light levels accounted for by dusts, one needs only an image of the objective lens that can be provided by the auxiliary imaging system that specially comes with SICG. Our tests show that the errors of the method are less or about 2%, giving a strong confidence in its accuracy. It provides a handy tool to monitor the dust level of the objective lens of SICG and has significantly improved the efficiency of the pipeline of stray light control.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:015010 (9pp), 2025 January

https://doi.org/10.1088/1674-4527/ad981c
CSTR: 32081.14.RAA.ad981c

Measurements of the Solar Coronal Magnetic Field Based on Coronal Seismology with Propagating Alfvénic Waves: Forward Modeling

Yuhang Gao[1],[2], Hui Tian[1], Tom Van Doorsselaere[2], Zihao Yang[1],[3], Mingzhe Guo[2], , and Konstantinos Karampelas[2]

[1] School of Earth and Space Sciences, Peking University, Beijing 100871, China; huitian@pku.edu.cn
[2] Centre for Mathematical Plasma Astrophysics, Department of Mathematics, KU Leuven, Celestijnenlaan 200B bus 2400, B-3001 Leuven, Belgium
[3] High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307, USA
Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai 264209, China

Received 2024 October 23; revised 2024 November 12; accepted 2024 November 13; published 2025 January 2

Abstract

Recent observations have demonstrated the capability of mapping the solar coronal magnetic field using coronal seismology based on ubiquitous propagating Alfvénic/kink waves through imaging spectroscopy. We established a magnetohydrodynamic model of a gravitationally stratified open magnetic flux tube, exciting kink waves that propagate upward along the tube. Forward modeling was performed to synthesize the Fe XIII 1074.7 and 1079.8 nm spectral line profiles, which were then used to determine the wave phase speed, plasma density, and magnetic field using seismological methods. A comparison between the seismologically inferred results and the corresponding input values verifies the reliability of the seismology method. In addition, we identified several factors that could lead to errors during magnetic field measurements. Our results may serve as a valuable reference for current and future coronal magnetic field measurements based on observations of propagating kink waves.

Key words: Sun: corona – Sun: magnetic fields – magnetohydrodynamics (MHD)

1. Introduction

The magnetic field plays a crucial role in various physical processes in the solar and stellar coronae. The dissipation of magnetic energy is believed to drive solar eruptive events (e.g., flares and coronal mass ejections) and cause heating of the corona. While the magnetic field in the lower solar atmosphere can be reliably measured through spectro-polarimetric observations, direct measurements of the coronal magnetic field have remained challenging for decades. Several methods have been proposed and attempted, including spectro-polarimetry of coronal infrared lines [35, 34, 50], coronal radio observations [8, 12, 52], and magnetic-field-induced transitions of extreme ultraviolet emission lines [32, 33, 29, 7, 6]. However, these approaches all face limitations and none of them can be used for routine measurements of the global coronal magnetic field.

Another technique for measuring the coronal magnetic field is coronal seismology, which combines magnetohydrodynamic (MHD) wave theory with observed wave parameters (e.g., period, amplitude, propagation speed, damping time) to diagnose various physical properties, particularly the magnetic field. Different wave phenomena in the corona have been used for coronal seismology, including standing kink waves in coronal loops [45, 1, 61, 55, 15, 14, 69, 31, 70], propagating slow magneto-acoustic waves [25], sausage waves [4, 22, 30], propagating kink waves in streamers [5, 21], and torsional oscillations in solar surges [26]. However, these studies provided only one-dimensional magnetic field distributions or single values in specific coronal structures, such as oscillating loops or streamers.

To create global two-dimensional (2D) magnetic field maps, we need to utilize ubiquitous and continuous wave phenomena. The pervasive propagating disturbances in Dopplergrams [58, 57, 37, 43, 44] observed by the Coronal Multi-channel Polarimeter (CoMP; [59]) are ideal for this purpose. These propagating disturbances are interpreted as kink or Alfvénic waves [62], and their propagation speeds are naturally linked to the local magnetic field. Based on these CoMP observations, [67, 66] successfully measured the global distribution of the coronal magnetic field for the first time. Following these successful attempts, routine (continuous) measurement of the global coronal magnetic field based on similar observations from the Upgraded CoMP (UCoMP; [28]) has been recently achieved, enabling the construction of coronal synoptic magnetograms (Carrington maps) [65].

The CoMP and UCoMP instruments can conduct spectroscopic observations of the Fe XIII lines at 1074.7 and 1079.8 nm in the coronal region above the solar limb. From the Dopplergrams of Fe XIII 1074.7 nm, propagating kink waves can be identified throughout the corona. The propagation or phase speed c_k of these waves (also named the kink speed) can be obtained by constructing a time-distance (TD) map of Doppler velocity, while the coronal density can be inferred from the observed Fe XIII 1079.8 nm/1074.7 nm intensity ratio.

For kink waves, we have

$$c_k = \sqrt{\frac{2B_i^2}{\mu_0(\rho_i + \rho_e)}}$$

where μ_0 is the magnetic permeability, and B and ρ are the magnetic field and mass density, respectively. The subscripts i and e refer to parameters inside and outside the magnetic flux tubes (the waveguides), respectively. Since CoMP and UCoMP likely cannot resolve individual flux tubes, we can only work with an average density $\langle\rho\rangle$. Furthermore, in the low-β coronal environment, the internal and external magnetic fields are often assumed to be approximately equal (see e.g., [57, 43, 70]). This leads to the simplified expression for the kink speed

$$c_k = \frac{B}{\sqrt{\mu_0\langle\rho\rangle}}$$

which is widely used in estimations of coronal magnetic fields [38, 66, 67, 65].

Given the potential of these measurements to provide routine coronal magnetograms on a daily basis, which could play a crucial role in future solar physics research, it is essential to thoroughly assess the reliability and robustness of the methodology used in [66, 67] and [65]. [39] performed three-dimensional (3D) MHD simulations of propagating kink waves under various conditions and conducted forward modeling to evaluate the reliability of this method in deriving the magnetic field strength. Their findings indicated that the magnetic field strengths inferred through seismology closely match the input values, typically with an error less than \$ \$20%. However, there is a limitation in their simulation: they utilized a non-stratified setup that excluded the effects of gravity, resulting in uniform initial density and propagation speed in the vertical direction.

The gravitational stratification can play a significant role as it causes the Alfvén speed and kink speed c_k to vary with height. This variation can affect the wave tracking method, which typically relies on a linear fit of velocity signals (e.g., see Figure 6 [Figure 6: see original paper] in [57]). Therefore, it is important to assess how the gravitational stratification affects the seismological results and estimate the possible error range.

We conducted 3D MHD simulations of propagating kink waves in stratified coronal open flux tubes. Following [39], we employed forward modeling to compare the seismologically derived results with the actual values of physical parameters from our simulation. This paper is organized as follows: Section 2 describes our simulation setup and methodology, Section 3 presents the simulation and forward-modeling results along with detailed comparisons between seismology results and input values, and Section 4 provides a discussion and summary of our findings.

2. Method

The model used in this study is a gravitationally stratified, open magnetic flux tube with a radius of 1 Mm, similar to that in [16] (hereafter referred to as Paper I). The main difference is that the initial magnetic field in this study is set at around 4 G, instead of 10 G, to better match the seismologically inferred results in [67]. As in Paper I, the magnetic field is oriented in the z direction and remains nearly uniform across the simulation domain, with only small spatial gradients to maintain total pressure balance. As a result, the Alfvén and kink speeds increase with height as the density decreases due to stratification. A relaxation process of 2400 s was conducted to achieve a quasi-magnetohydrostatic state, as illustrated in Figure 1 [Figure 1: see original paper]. The figure demonstrates that the post-relaxation magnetic field has some spatial variation but mostly within 0.7 G.

The kink wave driver is also similar to that in Paper I, with a velocity amplitude of 8 km s^{-1} and a period of 300 s. The primary velocity perturbation is along the x direction.

We ran the 3D MHD simulation in Cartesian coordinates with the PLUTO code [41]. The simulation domain spanned $[-4, 4]$ Mm $\times$ $[-4, 4]$ Mm $\times$ $[0, 150]$ Mm, with a uniform grid of $128 \times 128 \times 1024$ cells, providing spatial resolutions of 62.5 km in the horizontal (x and y) directions and 146.5 km in the vertical (z) direction. We chose a second-order parabolic spatial scheme and a Roe Riemann solver. The boundary conditions were set to be outflow, except for the lower boundary, where the kink wave driver was introduced by adjusting v_x and v_y, while other parameters were fixed. As in Paper I, the upper 50 Mm ($z > 100$ Mm) was set as a velocity absorption region (VAR) to minimize numerical reflections from the upper boundary (see also [20, 13, 47]). For the subsequent analysis, we only considered the region below $z = 100$ Mm, which can provide physical results.

Once the kink wave driver was applied, the propagating waves were rapidly excited, with their properties thoroughly analyzed in Paper I. Here, we focus on assessing the reliability of the seismology method described in Section 1 using the simulation outputs. To do so, we performed forward calculations to synthesize spectroscopic observables of CoMP and UCoMP, namely, the Fe XIII 1074.7 and 1079.8 nm spectral line profiles. Specifically, we used synthesized observation of the 1074.7 nm line to perform wave tracking and determine the propagation speed, while synthesized observation of the 1079.8 nm line was only employed for density diagnostics using the intensity ratio method [66, 67].

We applied the FoMo code [60] to synthesize the spectral profiles at all pixels in the yz plane. The photo-excitation (see [68, 66]) was not considered for simplification, as its effects on the spectral lines are not significant in the lower corona. The line of sight (LOS) was chosen as the x axis. In this way, we can reconstruct 2D maps (in the yz plane) of intensity and Doppler velocity by fitting a single Gaussian to each spectral profile. The resulting maps consist of 128 pixels in the y direction from -4 Mm to 4 Mm, and 500 pixels in the z direction from 0 Mm to 100 Mm. Since the primary velocity perturbation is along the x direction (or in the LOS plane), the Doppler velocity maps capture the wave propagation signals, while the intensity maps do not show any transverse displacement.

3. Results

3.1. Before Degrading

We first generated TD maps of the Doppler velocity along the z direction, which can be produced at each y position. In Figure 2 Figure 2: see original paper, the TD map along the flux tube's axis (i.e., $y = 0$) is presented, clearly illustrating the propagation of Doppler velocity disturbances. The increasing slope reflects the growing propagation speed with height. However, after 400 s, unusual patterns appear due to wave reflections. Despite efforts to suppress numerical reflections from the upper boundary at $z = 150$ Mm using a VAR (see Section 2), it is still difficult to eliminate all reflections. Some reflections may come from the layer at $z = 100$ Mm, which is the lower boundary of the VAR, while others could be attributed to the vertical inhomogeneities of density and phase speed. As noted in previous studies, even smooth phase speed gradients can cause partial wave reflection [63, 23, 46, 3]. In fact, real CoMP observations of coronal kink waves often reveal both upward and downward propagating components [57, 43]. However, when calculating the propagation speed, these reflected waves can introduce significant errors. To reduce this, we applied the Fourier filtering method to separate the upward and downward propagating wave components (see e.g., [57, 54, 36, 56, 67]). Figure 2(B) depicts the TD map for the upward-propagating component, which is used to determine the phase speed.

By applying the wave-tracking method to all pixels (for more details, see e.g., [67]), we obtained a 2D phase speed distribution, as shown in Figure 3(A). For most pixels, the phase speed falls in the range of 200–800 km s^{-1} (see also Figure 4(B)), with a general trend of increasing with altitude, though some fluctuations are present (see relevant discussions in Section 4).

Next, we derived the density by calculating the intensity ratio of the synthesized 1074.7 and 1079.8 nm intensity maps. The theoretical relationship between intensity ratio and density can be obtained from the CHIANTI database [10]. The obtained density values are compared with the input values, as shown in Figure 4(A). The input density corresponds to the emissivity-weighted density along the LOS [65]:

$$\rho_{\text{los}} = \frac{\int \rho\epsilon \, dx}{\int \epsilon \, dx}$$

where ϵ is the Fe XIII 1074.7 nm line emissivity at the corresponding pixel, calculated using the IDL routine `emiss_calc.pro` from the CHIANTI software package.

The comparison indicates that the density derived from the intensity ratio is reliable for most pixels, though about 20% of pixels show an overestimation (\$ \$15%). However, this overestimation would not lead to large errors in the seismologically inferred magnetic field, as only the square root of density is needed during the calculation.

With the derived phase speed and density, we calculated the magnetic field B_{seis}. Here we chose to treat the phase speed as the local Alfvén speed (i.e., $c_k = B_{\text{seis}}/\sqrt{\mu_0 \rho_{\text{FeXIII}}}$), rather than employ Equation (1). Because in our magnetic field configuration, Equation (1) can only provide the phase speed as a function of z; however, here with a high spatial resolution, we are also interested in the horizontal distribution of phase speed and magnetic field. We note that such a choice may lead to some errors, especially within the flux tube region, which will be further discussed in Section 4. In Figure 4(B), we compared the Alfvén speed in the model and the wave propagation speed obtained from wave tracking. Despite some noticeable discrepancies, the overall correspondence between the two is reasonably good.

The calculated magnetic field is shown in Figure 3(B), and its relative error (compared to the input value, B_{los}, which was calculated in the same manner as ρ_{los}) is presented in Figure 3(C). The contours that correspond to the values of $±$30% indicate that the relative error is less than 30% for most pixels. Figure 4(C) and (D) display histograms of B_{seis} and its relative error, respectively. Statistically, there is a slight overestimation of the magnetic field by $ $5% (with a standard deviation of 17%). Given that the 5% bias is quite small, the results support the reliability of the coronal seismology technique. Further discussion on the error distributions in Figure 3(C) and the cause of the overestimation can be found in Section 4.

3.2. After Degrading

We then degraded the spatial and temporal resolutions to match those of CoMP observations, with a pixel size of approximately 3.3 Mm and a cadence of 36 s. We focused on the central pixels (from $y = -1.65$ Mm to $y = 1.65$ Mm), which fully encompass the flux tube (diameter $ $2 Mm). At this resolution, finer structures at the tube boundary are unresolved, similar to the case in observational studies [66, 67].

We can now track the physical parameters along the tube axis. Figure 5 shows the phase speed, density, and magnetic field as a function of height z. In panel (A), the phase speed derived using the wave tracking method (c_{seis}) is compared to the characteristic speeds in the model (input values). The c_{seis} closely matches the input kink speed ($c_{k,\text{input}}$), which lies between the internal and external Alfvén speeds.

Panel (B) shows the density derived from the Fe XIII intensity ratio (ρ_{FeXIII}), which also falls between the internal density (ρ_i) and external density (ρ_e) in the model. The ρ_{FeXIII} is slightly higher than the emissivity-weighted density along the LOS (ρ_{los}), similar to the pre-degradation results shown in Figure 4(A). When calculating the magnetic field with Equation (2), the density value should ideally be the average $\langle \rho \rangle = (\rho_i + \rho_e)/2$, because Equation (2) is derived from Equation (1) when assuming $B_i = B_e$. However, in practice, ρ_{FeXIII} is used, which is slightly lower than $\langle \rho \rangle$. This means that using ρ_{FeXIII} as a representative of $\langle\rho\rangle$ can lead to a slight underestimation. The density underestimation is about 12%–20% based on Figure 5(B), and the resulting error in $B_{\rm seis}$ would be minimal (less than 5%) since the density is taken under the square root.

In fact, the deviation of $\rho_{\rm FeXIII}$ from $\langle\rho\rangle$ can vary with the filling factor, which represents the fraction of the pixel occupied by the flux tube. Given the current pixel size (3.3 Mm), LOS integration length (8 Mm), and flux tube radius (1 Mm), the filling factor is approximately 12%. If the filling factor is lower, the $\rho_{\rm FeXIII}$ will be closer to ρ_e, increasing the density underestimation. The maximum underestimation depends on the density contrast $\zeta = \rho_i/\rho_e$, with the deviation factor given by $\rho_{\rm FeXIII}/\langle\rho\rangle = (1+\zeta)/(2\zeta)$. In our simulation, ζ was initially set to be 3, but after relaxation, it decreased to around 2 (see Figure 1(D)). Such a value is comparable with previous observational estimates [55, 64, 42].

We tested the case with a reduced filling factor (5%), where a density contrast of 2 led to an underestimation of \$ \$30%. Therefore, parameters like the filling factor and density contrast can be crucial when assessing the accuracy of coronal magnetic field measurements.

Figure 5(C) presents the magnetic field inferred from coronal seismology ($B_{\rm seis}$), compared to the internal (B_i), external (B_e), and emissivity-weighted ($B_{\rm los}$) magnetic fields. The $B_{\rm seis}$ ranges from 3.9 to 5.1 G, with errors below 15%, indicating that the technique of coronal seismology can be used for reliable measurements of coronal magnetic field strengths.

4. Discussion and Conclusion

In this study, we tested the accuracy of previously developed seismological techniques based on observations of propagating kink waves for deriving coronal magnetic fields. The results indicate that seismology-based measurements of the magnetic field are accurate and reliable to a large extent.

In the high-resolution case, we obtained a 2D distribution of the magnetic field ($B_{\rm seis}$) and its relative error. For most regions, the relative error is less than 30%, as shown in Figure 3(C). Statistically, the average magnetic field derived from coronal seismology is about 5% larger than the input value. Although this case has a much higher resolution than the CoMP and UCoMP observations, the pixel size (62.5 km in the z direction and 200 km in the y direction) and cadence (12 s) can be comparable to those of the Cryogenic Near-Infrared Spectro-Polarimeter (Cryo-NIRSP; [11]) and the Diffraction-Limited Near-Infrared Spectropolarimeter (DL-NIRSP; [24]) of the Daniel K. Inouye Solar Telescope (DKIST; [48]). These instruments offer high-resolution coronal spectroscopic observations with the Fe XIII lines [49], and recently [50] successfully obtained a coronal LOS magnetogram with Cryo-NIRSP observation based on the Zeeman effect. With rapid repeated raster scans, it is possible that DKIST could also detect propagating transverse waves via Doppler velocity measurements, enabling seismological diagnostics of the plane-of-sky (POS) coronal magnetic field. In this way, DKIST observations can also provide maps of the POS magnetic field, but with much higher spatial resolution compared to CoMP and UCoMP. Our results, particularly Figure 3, can serve as a reference for such diagnostics. Combined with Stokes-V measurements, DKIST may then be able to achieve measurements of the full magnetic field vector.

Nevertheless, we note that some errors appear in the seismologically inferred magnetic field. First, large errors appear near the upper and lower boundaries (around $z = 0$ and $z = 100$ Mm). This is due to the Fourier filtering method used to subtract downward propagating wave components. As shown in Figure 2(B), the upward propagating components of the Doppler velocity show some artificial velocity amplification near the upper and lower boundaries, especially after 250 s. This could affect the phase speed determination through wave tracking, leading to errors in B_{seis} near the z boundaries. Thus, in observations, it may be useful to exclude boundary signals before calculating phase speeds. Another contributing factor comes from the wave-tracking process itself. When calculating the phase speed, a certain number of data points along the propagating direction is required. Near the lower and upper boundaries, fewer data points will be available to perform cross-correlation, leading to larger uncertainties in the calculated phase speed and consequently in the inferred magnetic field.

Second, overestimations were observed inside or along the lateral boundaries of the flux tube. This is likely because we treat the phase velocity as the Alfvén speed, which applies well to regions away from the flux tube or cases with spatial averaging (see [67] and Section 3.2). However, in this case, we modeled kink waves, and the flux tube can be well resolved. Thus, at the flux tube region, particularly the tube boundary, it would be more appropriate to apply Equation (1) since the waves have dominant kink wave characteristics [18]. Calculating the magnetic field with $c_k = B_{\mathrm{seis}}/\sqrt{\mu_0 \rho_{\mathrm{FeXIII}}}$ leads to overestimation at high-density regions, explaining the positive errors within the flux tube in Figure 3(C). In future DKIST observations, we would suggest first applying Equation (2) to diagnose the magnetic field outside the flux tube (B_e), then calculating the magnetic field inside the flux tube (B_i) with Equation (1).

In addition, there are some other confusing patterns in Figure 3(B) and (C). For instance, B_{seis} and the relative error manifest fluctuations along the z direction. These might be related to longitudinal oscillations excited by kink waves due to some nonlinear effects [17, 9, 53]. Further investigations are needed to understand these patterns.

When we degraded the spatial and temporal resolutions to approximately match those of CoMP, we found that distributions of phase speed, density, and B_{seis} along z all show remarkable similarities to the input values (Figure 5). Again, we can notice a deviation near the upper and lower boundaries, particularly the lower one. However, within the height range of 20–80 Mm, the magnetic field error is generally less than 10%.

Additionally, the CoMP instrument has recently been upgraded to UCoMP, which has a slightly higher spatial resolution and a larger field of view. Our main conclusions should also apply to the case with UCoMP observations [65]. We also tested the case when degrading to UCoMP's pixel size ($ $2.2 Mm), and the results are largely similar to those shown in Figure 5, with a slightly smaller error.

Another factor that may impact the phase speed and magnetic field measurements is the magnitude of the input magnetic field and phase speed. A stronger magnetic field and higher phase speed result in steeper slopes in the TD maps of Doppler velocity, which can reduce the accuracy of the wave-tracking method, particularly when the spatial and temporal resolutions are degraded. We ran a separate simulation with a background magnetic field of $ 10*G*, *whichgivesphasespeedsof*1–2*Mms*^{-1}.*Wefoundasystematicunderestimationofthemagneticfieldbyapproximately*30R_ $ is 1–4 G [34, 19, 27, 67, 70], which is more comparable with the case discussed in Section 3.

In conclusion, the seismology technique based on propagating kink waves can provide reliable coronal magnetic field measurements according to our forward modeling. We note that this study only focuses on open coronal structures, including plumes in coronal holes and fan loops at the boundaries of active regions [43, 2]. Specifically, in our simulation, the magnetic flux tube is perpendicular to the solar surface, with both gravity and magnetic field aligned along the tube axis. However, propagating kink waves can be detected not only in these structures but also in closed-field regions [58, 66, 67]. Our magnetic configuration can roughly describe one leg of a large-scale closed coronal loop, where the curvature can be neglected. For smaller loops where curvature cannot be ignored, our model is no longer applicable due to differences in gravitational stratification. Nevertheless, for such loops, phase speed along the axis often shows minimal variation [40, 54, 70], and this is thus similar to the case in [39], where a model without any vertical gradient in phase speed was used. Therefore, this study complements previous research by highlighting the importance of phase speed variation along the flux tube in coronal seismology.

Finally, we would like to mention that our model has some limitations. The vertical gradient of the magnetic field and the magnetic expansion are not included. Additionally, we did not consider the effect of internal flows along the flux tube, which are frequently reported and can affect the apparent wave propagation speed [51, 43]. Moreover, in real observations, there are often multiple flux tubes overlapping along the LOS, introducing further complexities that may affect wave-tracking accuracy and magnetic field measurements. In Figure 6 of [65], comparisons between seismological results and global coronal MHD models revealed some discrepancies, particularly at higher latitudes where open field lines may dominate. Future work that incorporates more realistic models could offer a more sophisticated evaluation of magnetic field measurements through coronal seismology and help clarify the discrepancies in [65].

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC, grant No. 12425301), the Strategic Priority Research Program of the Chinese Academy of Sciences (grant No. XDB0560000), and the National Key R&D Program of China No. 2022YFF0503800. M.G. acknowledges support from the National Natural Science Foundation of China (NSFC, grant No. 12203030). T.V.D. was supported by the C1 grant TRACEspace of Internal Funds KU Leuven and a Senior Research Project (G088021N) of the FWO Vlaanderen. Furthermore, TVD received financial support from the Flemish Government under the long-term structural Methusalem funding program, project SOUL: Stellar evolution in full glory, grant METH/24/012 at KU Leuven.

The research that led to these results was subsidized by the Belgian Federal Science Policy Office through the contract B2/223/P1/CLOSE-UP. It is also part of the DynaSun project and has thus received funding under the Horizon Europe program of the European Union under grant agreement (No. 101131534). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, and therefore the European Union cannot be held responsible for them. K.K. acknowledges support by an FWO (Fonds voor Wetenschappelijk Onderzoek—Vlaanderen) postdoctoral fellowship (1273221N).

References

References

[1] Aschwanden, M. J., De Pontieu, B., Schrijver, C. J., & Title, A. M. 2002, SoPh, 206, 99

[2] Banerjee, D., Krishna Prasad, S., Pant, V., et al. 2021, SSRv, 217, 76

[3] Bose, S., TenBarge, J. M., Carter, T., et al. 2024, ApJ, 971, 72

[4] Chen, S.-X., Li, B., Xiong, M., Yu, H., & Guo, M.-Z. 2015, ApJ, 812, 22

[5] Chen, Y., Feng, S. W., Li, B., et al. 2011, ApJ, 728, 147

[6] Chen, Y., Li, W., Tian, H., et al. 2023, RAA, 23, 022001

[7] Chen, Y., Li, W., Tian, H., et al. 2021, ApJ, 920, 116

[8] Chen, B., Shen, C., Gary, D. E., et al. 2020, NatAs, 4, 1140

[9] Del Zanna, L., Velli, M., & Londrillo, P. 2001, A&A, 367, 705

[10] Dere, K. P., Del Zanna, G., Young, P. R., & Landi, E. 2023, ApJS, 268, 52

[11] Fehlmann, A., Kuhn, J. R., Schad, T. A., et al. 2023, SoPh, 298, 5

[12] Fleishman, G. D., Gary, D. E., Chen, B., et al. 2020, Sci, 367, 278

[13] Gao, Y., Guo, M., Van Doorsselaere, T., Tian, H., & Skirvin, S. J. 2023, ApJ, 955, 73

[14] Gao, Y., Hou, Z., Van Doorsselaere, T., & Guo, M. 2024a, A&A, 681, L4

[15] Gao, Y., Tian, H., Van Doorsselaere, T., & Chen, Y. 2022, ApJ, 930, 55

[16] Gao, Y., Van Doorsselaere, T., Tian, H., Guo, M., & Karampelas, K. 2024b, A&A, 689, A195

[17] Goldstein, M. L. 1978, ApJ, 219, 700

[18] Goossens, M., Terradas, J., Andries, J., Arregui, I., & Ballester, J. L. 2009, A&A, 503, 213

[19] Gopalswamy, N., Nitta, N., Akiyama, S., Mäkelä, P., & Yashiro, S. 2012, ApJ, 744, 72

[20] Guo, M., Duckenfield, T., Van Doorsselaere, T., et al. 2023, ApJL, 949, L1

[21] Guo, M., Li, B., Van Doorsselaere, T., & Shi, M. 2022, MNRAS, 515, 4055

[22] Guo, M.-Z., Chen, S.-X., Li, B., Xia, L.-D., & Yu, H. 2016, SoPh, 291, 877

[23] Hahn, M., D'Huys, E., & Savin, D. W. 2018, ApJ, 860, 34

[24] Jaeggli, S. A., Lin, H., Onaka, P., et al. 2022, SoPh, 297, 137

[25] Jess, D. B., Reznikova, V. E., Ryans, R. S. I., et al. 2016, NatPh, 12, 179

[26] Kohutova, P., Verwichte, E., & Froment, C. 2020, A&A, 633, L6

[27] Kumari, A., Ramesh, R., Kathiravan, C., Wang, T. J., & Gopalswamy, N. 2019, ApJ, 881, 24

[28] Landi, E., Habbal, S. R., & Tomczyk, S. 2016, JGRA, 121, 8237

[29] Landi, E., Hutton, R., Brage, T., & Li, W. 2020, ApJ, 904, 87

[30] Li, B., Antolin, P., Guo, M. Z., et al. 2020, SSRv, 216, 136

[31] Li, D., & Long, D. M. 2023, ApJ, 944, 8

[32] Li, W., Grumer, J., Yang, Y., et al. 2015, ApJ, 807, 69

[33] Li, W., Yang, Y., Tu, B., et al. 2016, ApJ, 826, 219

[34] Lin, H., Kuhn, J. R., & Coulter, R. 2004, ApJL, 613, L177

[35] Lin, H., Penn, M. J., & Tomczyk, S. 2000, ApJL, 541, L83

[36] Liu, J., McIntosh, S. W., De Moortel, I., Threlfall, J., & Bethge, C. 2014, ApJ, 797, 7

[37] Liu, J., McIntosh, S. W., De Moortel, I., & Wang, Y. 2015, ApJ, 806, 273

[38] Long, D. M., Valori, G., Pérez-Suárez, D., Morton, R. J., & Vásquez, A. M. 2017, A&A, 603, A101

[39] Magyar, N., & Van Doorsselaere, T. 2018, ApJ, 856, 144

[40] McIntosh, S. W., de Pontieu, B., Carlsson, M., et al. 2011, Natur, 475, 477

[41] Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228

[42] Morton, R. J., Tiwari, A. K., Van Doorsselaere, T., & McLaughlin, J. A. 2021, ApJ, 923, 225

[43] Morton, R. J., Tomczyk, S., & Pinto, R. 2015, NatCo, 6, 7813

[44] Morton, R. J., Weberg, M. J., & McLaughlin, J. A. 2019, NatAs, 3, 223

[45] Nakariakov, V. M., & Ofman, L. 2001, A&A, 372, L53

[46] Pascoe, D. J., De Moortel, I., Pagano, P., & Howson, T. A. 2022, MNRAS, 516, 2181

[47] Pelouze, G., Van Doorsselaere, T., Karampelas, K., Riedl, J. M., & Duckenfield, T. 2023, A&A, 672, A105

[48] Rimmele, T. R., Warner, M., Keil, S. L., et al. 2020, SoPh, 295, 172

[49] Schad, T. A., Kuhn, J. R., Fehlmann, A., et al. 2023, ApJ, 943, 59

[50] Schad, T. A., Petrie, G. J., Kuhn, J. R., et al. 2024, SciA, 10, eadq1604

[51] Soler, R., Terradas, J., & Goossens, M. 2011, ApJ, 734, 80

[52] Tan, B. 2022, RAA, 22, 072001

[53] Terradas, J., & Ofman, L. 2004, ApJ, 610, 523

[54] Threlfall, J., De Moortel, I., McIntosh, S. W., & Bethge, C. 2013, A&A, 556, A124

[55] Tian, H., McIntosh, S. W., Wang, T., et al. 2012, ApJ, 759, 144

[56] Tiwari, A. K., Morton, R. J., Régnier, S., & McLaughlin, J. A. 2019, ApJ, 876, 106

[57] Tomczyk, S., & McIntosh, S. W. 2009, ApJ, 697, 1384

[58] Tomczyk, S., McIntosh, S. W., Keil, S. L., et al. 2007, Sci, 317, 1192

[59] Tomczyk, S., Card, G. L., Darnell, T., et al. 2008, SoPh, 247, 411

[60] Van Doorsselaere, T., Antolin, P., Yuan, D., Reznikova, V., & Magyar, N. 2016, FrASS, 3, 4

[61] Van Doorsselaere, T., Nakariakov, V. M., & Verwichte, E. 2007, A&A, 473, 959

[62] Van Doorsselaere, T., Nakariakov, V. M., & Verwichte, E. 2008, ApJL, 676, L73

[63] Verdini, A., & Velli, M. 2007, ApJ, 662, 669

[64] Verwichte, E., Van Doorsselaere, T., White, R. S., & Antolin, P. 2013, A&A, 552, A138

[65] Yang, Z., Tian, H., Tomczyk, S., et al. 2024, Sci, 386, 76

[66] Yang, Z., Tian, H., Tomczyk, S., et al. 2020a, ScChE, 63, 2357

[67] Yang, Z., Bethge, C., Tian, H., et al. 2020b, Sci, 369, 694

[68] Young, P. R., Del Zanna, G., Landi, E., et al. 2003, ApJS, 144, 135

[69] Zhang, Q. M., Chen, J. L., Li, S. T., Lu, L., & Li, D. 2022, SoPh, 297, 18

[70] Zhong, S., Nakariakov, V. M., Miao, Y., Fu, L., & Yuan, D. 2023, NatSR, 13, 1169

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.