

## Postprint: On-Orbit Radiometric Calibration of WST and SDI

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### Abstract

The Lyman-alpha Solar Telescope ( $L\alpha$  Solar Telescope, LST) is one of the payloads on the Advanced Space-based Solar Observatory (ASO-S, Chinese name “Kuafu-1”) satellite, which includes three scientific instruments: the White-light Solar Telescope (WST), the Solar Disk Imager (SDI), and the Solar Corona Imager (SCI). WST operates in the  $(360\pm 2)\text{nm}$  (*nearwhite - light*) band, SDI operates in the  $(121.6\pm 4.5)\text{nm}$  (ultraviolet Lyman-alpha) band, and both have a field of view of  $1.2 R_{\odot}$  ( $R_{\odot}$  is the solar radius, with the entire field of view equivalent to  $38.4^{\circ}$ ). Through the imaging data from WST and SDI, one can explore the triggering and response of solar eruptive activities in the lower atmosphere (photosphere, chromosphere, and transition region), such as studying the triggering mechanisms of solar flares, the physical properties of white-light flares, and the morphological evolution and kinematics of eruptive filaments/prominences, as well as deriving physical parameters of the solar atmosphere. To obtain physical parameters of different features in the solar atmosphere observed by WST and SDI, such as flare energy, prominence temperature and density, etc., it is necessary to convert their observed Digital Number (DN) values into physical units (e.g.,  $\text{erg}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$ ), a process known as radiometric calibration. Radiometric calibration is one of the essential steps in the scientific data production process for WST and SDI. Currently, the on-orbit radiometric calibration of both WST and SDI uses the Sun as a reference source, with the former utilizing solar spectral data published by the American Society for Testing and Materials (ASTM) in 2020, and the latter using observations from the Extreme Ultraviolet Sensors (EUVS) onboard the Geostationary Operational Environmental Satellite R (GOES-R). The on-orbit radiometric calibration coefficients and their uncertainties for WST and SDI during normal observation periods from August 2023 to February 2024 are presented. An empirical formula is obtained by fitting the daily average values of the WST on-orbit radiometric calibration coefficients. Using the radiometrically calibrated data, it is possible to calculate

the energy radiated by solar flares in the white-light and Lyman-alpha bands and to obtain prominence density, etc., which facilitates the achievement of the scientific objectives of WST and SDI.

## Full Text

## Preamble

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## In-Flight Radiometric Calibrations of WST and SDI

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## Abstract

The Lyman-alpha Solar Telescope (LST) is one of the payloads onboard the Advanced Space-based Solar Observatory (ASO-S, also known as “Kuafu-1”) satellite, comprising three scientific instruments: the White-light Solar Telescope (WST), the Solar Disk Imager (SDI), and the Solar Corona Imager (SCI). Both WST and SDI have a field of view of 1.2 (where is the solar radius, with the full field equivalent to 38.4°) and operate in the  $(360 \pm 2) \text{ nm}$  (nearwhite – light) and  $(121.6 \pm 4.5) \text{ nm}$  (ultraviolet Lyman – alpha) bands, respectively. Imaging data from WST and SDI enable exploration of the triggering and response of solar light flares, and the morphological evolution and kinematics of erupting filaments/prominences, as well as derivation of the solar constant ( $\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ ) through a process known as radiometric calibration. Radiometric calibration is an essential step in the scientific data production pipeline for WST and SDI. Currently, both WST and SDI in-flight radiometric calibrations use the Sun as a reference source, with the former employing solar spectral data released by the American Society for Testing and Materials (ASTM) in 2020 and the latter using observations from the Extreme Ultraviolet Sensors (EUVS) onboard the Geostationary Operational Environmental Satellite R (GOES-R). This paper presents the in-flight radiometric calibration coefficients and their uncertainties for WST and SDI during the normal observation period from August 2023 to February 2024. An empirical formula is derived by fitting the daily averages of the WST in-flight radiometric calibration coefficients. Using the radiometrically calibrated data, we can calculate the energy radiated by solar flares in both white-light and Lyman-alpha bands and determine prominence density, thereby facilitating the achievement of WST and SDI scientific objectives.

**Keywords:** Sun: flares, Sun: prominences, techniques: radiometric calibration, instrumentation: WST, instrumentation: SDI

## 1 Introduction

The Sun is the nearest star to Earth. While providing energy for our planet, violent activities in its atmosphere—such as solar flares and coronal mass ejections, the primary drivers of space weather—can have catastrophic impacts on terrestrial life [1-2]. The energy of solar eruptive activities originates primarily from the solar magnetic field [3-4]. Therefore, studies of solar magnetic fields, flares, and coronal mass ejections not only deepen our understanding of the energy sources, triggering mechanisms, and dissipation processes of solar eruptive activities but also provide crucial theoretical support for space weather forecasting [5].

China's first comprehensive solar exploration satellite, the Advanced Space-based Solar Observatory (ASO-S, Chinese name “Kuafu-1”), was successfully launched on October 9, 2022 [6-9]. The primary scientific objectives of ASO-S are to investigate the origin, evolution, and causal relationships among solar magnetic fields, flares, and coronal mass ejections (collectively termed “one magnetic field, two eruptions”) [8-9].

The Lyman-alpha Solar Telescope (LST) is one of three payloads onboard ASO-S, consisting of three scientific instruments: the White-light Solar Telescope (WST), the Solar Disk Imager (SDI), and the Solar Corona Imager (SCI) [10-12]. WST and SDI both have a field of view of  $1.2^\circ$  ( $38.4'$ ), with observation bands of  $(360 \pm 2) \text{ nm}$  (nearwhite - light) and  $(121.6 \pm 4.5) \text{ nm}$  (ultraviolet Lyman - alpha), respectively. SCI has a field of view of  $35.2' - 80.0'$  and two observation bands:  $(122.6 \pm 3) \text{ nm}$  (ultraviolet Lyman - alpha) and  $(700 \pm 32) \text{ nm}$  (white-light). LST is designed to continuously image the solar disk and inner corona up to 2.5 simultaneously in the ultraviolet Lyman-alpha and white-light bands, aiming to track solar eruptive phenomena from the disk center to the inner corona, explore relationships among eruptive prominences, flares, and coronal mass ejections, investigate the dynamic processes and evolution of solar eruptions, diagnose the solar wind, and derive physical parameters of the solar atmosphere [10].

Raw data from solar telescopes are recorded as digital numbers (DN) and must undergo calibration (e.g., dark-field and flat-field corrections) before scientific analysis. To obtain physical parameters of the solar atmosphere such as density and energy, further radiometric calibration is required. Radiometric calibration comprises two types: ground-based (also called laboratory) calibration and in-flight calibration. For in-flight calibration, astronomically stable celestial bodies with known irradiance within the instrument's field of view serve as standard reference sources, including stars, the Sun, and solar system objects (e.g., planets and comets). Many space-based solar telescopes have employed stars as reference sources for in-flight radiometric calibration, such as the Ultraviolet

Coronagraph Spectrometer (UVCS) [13] and Large Angle Spectroscopic Coronagraph (LASCO) [14] onboard the Solar and Heliospheric Observatory (SOHO), and the Metis coronagraph onboard Solar Orbiter (SO) [15]. When using stars as reference sources, selection criteria typically include: (1) bright stars (apparent magnitude  $< 8$ ); (2) appropriate spectral types; (3) stable brightness and long-term observability; and (4) visibility to the telescope. For example, SO/Metis in-flight radiometric calibration primarily uses B-type stars. During calibration observations in June 2020 and March 2021, Metis observed dozens of calibratable stars, ultimately determining in-flight radiometric calibration coefficients and uncertainties that were found to be consistent with ground-based measurements. The Sun serves as a reference source primarily because its brightness remains stable in specific bands (e.g., white-light or near white-light), and numerous solar spectral data are available for radiometric calibration [16].

This paper focuses on the in-flight radiometric calibration of LST/WST and LST/SDI, both using the Sun as a reference source with the aid of solar reference or observational data. The paper is organized as follows: Section 2 describes the specific in-flight radiometric calibration methods for WST and SDI; Section 3 presents the detailed calibration processes and provides the in-flight radiometric calibration coefficients, uncertainties, empirical formulas, and instrument performance degradation; Section 4 summarizes and discusses the results.

## 2 In-Flight Radiometric Calibration Methods

Ideally, WST and SDI could use suitable stars as standard reference sources. Unfortunately, neither instrument has captured any stars during actual calibration observations. Given that solar irradiance in WST's 360 nm band is extremely stable with available reference spectral data, and that solar observations in a band similar to SDI's Lyman-alpha band exist internationally (already radiometrically calibrated), the current in-flight radiometric calibrations for WST and SDI primarily use the Sun itself as the reference source, assisted by reference spectral data and solar observational data, respectively.

### 2.1 WST In-Flight Radiometric Calibration Method

We use the solar reference spectral data released by the American Society for Testing and Materials (ASTM) in 2020 (ASTM G173-03)<sup>1</sup> to perform in-flight radiometric calibration for WST. provides the extraterrestrial solar spectral irradiance from 358 nm to 362 nm at 0.5 nm intervals. Integrating this band yields a total solar irradiance of  $3.7349 \text{ W} \cdot \text{m}^{-2}$  at the WST (360 $\pm$ 2) nm band ( $1 \text{ W} \cdot \text{m}^{-2} \cdot \{2\} = 10^3 \text{ erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ ). Substituting this into the equation yields the WST in-flight radiometric calibration coefficient  $C_{WST}$  (in units of  $\text{erg} \cdot \text{cm}^{-2} \cdot \text{DN}^{-1}$ ), where  $R_{WST}$  is the full-disk integrated count rate observed by WST (in  $\text{DN} \cdot \text{s}^{-1}$ ).

## 2.2 SDI In-Flight Radiometric Calibration Method

We use data from the Extreme Ultraviolet Sensors (EUVS) onboard the Geostationary Operational Environmental Satellite R (GOES-R) (already radiometrically calibrated) to perform in-flight radiometric calibration for SDI. One of GOES-R/EUVS' s working bands is ultraviolet Lyman-alpha (118-127 nm), which is very close to SDI' s working band (117.1-126.1 nm). Notably, in both bands, the Lyman-alpha line (121.6 nm) dominates the contribution, while other lines or continuum contributions are minimal [17]. Daily Level 2 data from EUVS can be conveniently obtained from the GOES-R website<sup>2</sup>. [Figure 1: see original paper] shows the full-disk integrated flux in the Lyman-alpha band observed by EUVS in January 2023, with panel (a) presenting the complete observational data and panel (b) showing the results after removing geocoronal absorption effects. The SDI in-flight radiometric calibration coefficient  $C_{SDI}$  (in  $\text{erg} \cdot \text{cm}^{-2} \cdot \text{DN}^{-1}$ ) is obtained through the relation  $C_{SDI} = F_{Ly\alpha}/R_{SDI}$ , where  $R_{SDI}$  is the full-disk integrated count rate observed by SDI (in  $\text{DN} \cdot \text{s}^{-1}$ ). It should be noted that GOES-R/EUVS enters Earth' s atmosphere at fixed times daily; since ultraviolet photons are easily absorbed by Earth' s atmosphere, EUVS observed flux values are significantly lower than normal during these periods (as shown in the small box in the upper right corner of Figure 1: see original paper). Therefore, data from these periods must be removed (as shown in Figure 1: see original paper) before being used for SDI in-flight radiometric calibration.

## 3 In-Flight Radiometric Calibration

Both WST and SDI in-flight radiometric calibrations use Level 1 data, i.e., images that have undergone dark-field and flat-field corrections. Before formal radiometric calibration, preprocessing of WST and SDI Level 1 data is required, such as removing outliers, followed by radiometric calibration using reference solar irradiance at 360 nm or the Lyman-alpha band. The radiometrically calibrated WST and SDI data are defined as Level 2 data and can subsequently be used for calculating various physical parameters.

### 3.1 WST In-Flight Radiometric Calibration

[Figure 2: see original paper] shows a Level 1 image observed by WST, with intensity units in DN. Since WST in-flight radiometric calibration uses full-disk integrated counts, we need to fit the solar disk (shown as a white circle). Given the large number of images observed daily by WST, fitting the solar disk for each image would be computationally expensive. Verification shows that background pixels outside the solar disk account for only about 0.1% of the total image brightness. Therefore, we instead use the sum of counts from the entire image for WST in-flight radiometric calibration, which greatly improves computational efficiency while having negligible impact on the calibration results. Additionally, due to image anomalies (e.g., bad blocks), WST data contain

some excessively large or small outliers, which can be excluded by calculating the variance of all data. It should be noted that WST has two attenuators with different transmittances, corresponding to different radiometric calibration coefficients. Since WST primarily uses attenuator 1 for in-flight observations, this paper focuses on radiometric calibration of data from WST attenuator 1.

Due to unstable observations during the in-orbit testing period (November 2022 to April 2023) and satellite eclipse season (May to July 2023), we only select data from the normal observation period (after August 2023) for radiometric calibration. Specifically, the WST in-flight radiometric calibration dataset covers August 2023 to February 2024. [Figure 3: see original paper] presents the WST in-flight radiometric calibration results. Panel (a) shows the full-disk integrated counts observed by WST (with outliers removed) and the exposure time as functions of time. Panel (b) shows the ratio of these two quantities (black curve), i.e., the full-disk integrated count rate over time. From August 2023 to late December 2023, the full-disk integrated counts (and count rate) observed by WST exhibit an increasing trend, followed by a gradual decrease through February 2024. This variation is actually related to changes in the Sun-Earth distance, which can be corrected by multiplying by a scaling factor equal to the square of the ratio of the current Sun-Earth distance to the average Sun-Earth distance. The corrected full-disk count rate curve is shown as the cyan line in Figure 3: see original paper, revealing that the corrected count rate decreases over time, reflecting gradual degradation of WST instrument performance. Figure 3: see original paper shows the WST in-flight radiometric calibration coefficient over time after accounting for Sun-Earth distance variation, demonstrating an overall increasing trend that also indicates WST instrument performance degradation.

Uncertainty is a crucial metric for evaluating WST in-flight radiometric calibration errors. [Figure 4: see original paper] illustrates the temporal evolution of WST in-flight radiometric calibration uncertainty. First, the daily variation is obtained from the standard deviation of daily average WST in-flight radiometric calibration coefficients (shown as error bars in [Figure 4: see original paper]), yielding an overall uncertainty of 0.12% (denoted as  $\epsilon_1$ ) for this period. Second, since the calibration uses data after dark-field and flat-field corrections, the precision of these corrections must be considered. WST flat-field calibration uses the Kuhn-Lin-Loranz (KLL) method [18-19] with an uncertainty of 0.42% ( $\epsilon_2$ ); WST dark-fields are simulated, and their uncertainty cannot currently be quantified. Finally, the total WST in-flight radiometric calibration uncertainty  $\epsilon$  is given by:

$$\epsilon = \sqrt{\sum_{i=1}^n \epsilon_i^2} \quad (1)$$

where  $n$  is the number of uncertainty components and  $\epsilon_i$  represents each uncertainty value. Using this formula, the total WST uncertainty during August 2023 to February 2024 is at least 0.44%. Furthermore, if the variation rate of monthly

average WST in-flight radiometric calibration coefficients (pink dots in [Figure 4: see original paper]) is taken as the instrument performance degradation rate, WST performance degraded by approximately 1.02% during this period.

Fitting the daily averages of WST in-flight radiometric calibration coefficients from August 2023 to February 2024 yields an empirical formula that greatly facilitates WST scientific data production. Given that the calibration coefficients increase approximately linearly with time during this period, we adopt a linear function for fitting. [Figure 5: see original paper] shows the fitting result (green line), yielding the empirical formula  $f(t) = 2.565 \times 10^{-13}t - 3.414 \times 10^{-9}$ , where  $t$  is time in seconds (with the starting point at 12:00:00 UTC on January 1, 2000) and  $f(t)$  is the in-flight radiometric calibration coefficient. Using either the daily average coefficients or this empirical formula, WST observed images can be radiometrically calibrated. [Figure 6: see original paper] shows the calibrated result, converting image DN values to irradiance.

### 3.2 SDI In-Flight Radiometric Calibration

The Level 1 images used for SDI in-flight radiometric calibration are shown in [Figure 7: see original paper], with intensity units in DN. In the ultraviolet Lyman-alpha band, cosmic rays and occasional bad pixels or blocks in SDI images cause some anomalies in SDI full-disk integrated counts, which are removed before radiometric calibration.

The SDI in-flight radiometric calibration dataset covers the same period as WST, from August 2023 to February 2024. [Figure 8: see original paper] presents the SDI in-flight radiometric calibration results. Panel (a) shows SDI full-disk integrated counts (with outliers removed) and exposure time versus time. Panel (b) shows their ratio (blue curve), i.e., the full-disk integrated count rate over time. During this period, SDI full-disk integrated counts (and count rate) show an overall decreasing trend with some periodic variations of approximately 25 days. Notably, these periodic variations are consistent with the Lyman-alpha flux variations observed by GOES-R/EUVS (purple curve in Figure 8: see original paper). The SDI in-flight radiometric calibration coefficients obtained using EUVS Lyman-alpha flux are shown in Figure 8: see original paper, exhibiting an overall increasing trend (primarily due to instrument performance degradation) with a superimposed  $\sim 25$ -day periodic variation. Possible causes for this periodic variation include: (1) solar transition region radiation (represented by Lyman-alpha) varies with solar rotation and activity with a  $\sim 25$ -day period [20]; (2) incomplete matching between SDI and EUVS working bands and instrument response functions; and (3) differences in SDI and EUVS orbits. The latter two factors cannot completely remove the aforementioned periodic variation.

[Figure 9: see original paper] shows the temporal evolution of SDI in-flight radiometric calibration uncertainty, calculated similarly to WST. First, the standard deviation of daily average SDI radiometric calibration coefficients (daily fluctuations, shown as error bars in [Figure 9: see original paper]) yields an overall

standard deviation of 0.59% ( $\epsilon_1$ ) for August 2023 to February 2024. Second, SDI flat-field and dark-field calibration errors must be considered, with SDI flat-field calibration error at 2.32% [18–19] ( $\epsilon_2$ ); SDI dark-field is not a true dark-field, making its error difficult to assess. Third, the GOES-R/EUVS radiometric calibration uncertainty of 10% [16] ( $\epsilon_3$ ) must be included. Using Equation (1), the SDI in-flight radiometric calibration uncertainty during this period is at least 10.28%.

With the SDI in-flight radiometric calibration coefficients, SDI Level 1 images can be calibrated to Level 2. [Figure 10: see original paper] shows the calibrated solar image from [Figure 7: see original paper], converting DN values to irradiance. Additionally, long-term variation in the calibration coefficients allows estimation of SDI instrument performance degradation. Similar to WST, we use monthly averages of SDI in-flight radiometric calibration coefficients (pink dots in [Figure 9: see original paper]) to estimate the degradation rate. The monthly averages show a linear increasing trend with a variation rate of approximately 6.71%, indicating SDI performance degraded by about 6.71% during this period. It should be noted that SDI's degradation rate has stabilized during this time-frame; in fact, SDI performance degraded by over 30% in the first few months after launch.

## 4 Summary and Discussion

This paper describes the in-flight radiometric calibration processes and results for ASO-S/LST/WST and ASO-S/LST/SDI. Radiometric calibration is a necessary step in the scientific data production pipeline for WST and SDI; only after radiometric calibration can WST and SDI data be used to calculate various physical quantities (e.g., temperature, density, and energy).

Both WST and SDI in-flight radiometric calibrations use the Sun as the reference source. Solar reference irradiance in the WST ( $360 \pm 2$ )  $\text{nm}$  band is obtained from ASTM spectral data, while the  $\alpha$  band reference irradiance is obtained from GOES-R/EUVS observations. The ratio of reference irradiance to flight radiometric calibration coefficients. Currently, daily average calibration coefficients are saved in separate files. Using our provided radiometric calibration software, users can complete the calibration process. Based on radiometrically calibrated data, scientific users have already derived physical parameters such as white-light flare energy and coronal Lyman-alpha radiation intensity [21–22].

The key results are: (1) Both WST and SDI in-flight radiometric calibrations use the Sun as the reference source, with datasets covering August 2023 to February 2024. Both instruments' calibration coefficients increase slowly with time, indicating gradual instrument performance degradation. SDI calibration coefficients also exhibit  $\sim 25$ -day periodic fluctuations. (2) During August 2023 to February 2024, the in-flight radiometric calibration uncertainties for WST and SDI are approximately 0.44% and 10.28%, respectively, with instrument performance degradation rates of 1.02% and 6.71%, respectively—indicating more pronounced degradation in SDI. (3) The empirical formula for WST in-flight ra-

diometric calibration coefficients is  $f(t) = 2.565 \times 10^{-13}t - 3.414 \times 10^{-9}$ , where  $t$  is time in seconds starting from 12:00:00 UTC on January 1, 2000. This empirical formula is applicable at least for the period from August 2023 to February 2024.

For WST in-flight radiometric calibration, the currently used reference irradiance is constant (i.e., time-independent). In reality, due to solar activity (e.g., flares, plages), solar irradiance at 360 nm also exhibits an ~11-year variation cycle (though relatively small), particularly within the 11-year solar activity cycle. As Solar Cycle 25 approaches its peak (expected in 2025), this long-term variation can be measured with increasing precision. Future calibrations will gradually account for this effect and correct the calibration coefficients accordingly.

Solar activity (particularly flares) significantly affects solar radiation flux in the Lyman-alpha band. During periods of frequent solar activity, SDI in-flight radiometric calibration errors increase accordingly. It should be noted that GOES-R/EUVS radiometric calibration errors during flares can be as high as 25% [23], which would significantly increase SDI in-flight radiometric calibration uncertainty (from the current 10.28% to over 25%). This is why we currently use daily average calibration coefficients rather than instantaneous values for radiometric calibration. During solar activity maximum, dozens of large flares (e.g., M-class and above) may occur daily, necessitating further consideration of flare activity effects on SDI in-flight radiometric calibration in the future.

In-flight radiometric calibration must be performed throughout the satellite's entire lifetime. Over the coming years, WST and SDI in-flight radiometric calibrations will require continuous tracking and monitoring. On one hand, calibration results should be updated as appropriate (e.g., the WST radiometric calibration coefficient empirical formula); on the other hand, instrument performance degradation must be monitored. When instrument degradation reaches a certain level, self-cleaning procedures or adjustments to regular exposure times may be required.

Currently, both WST and SDI in-flight radiometric calibrations use the Sun itself as the reference source. While not ideal, this is the most practical operational approach available. In subsequent calibration observations, if WST and/or SDI capture relatively bright stars, planets, or even comets, we will attempt radiometric calibration using these reference sources and cross-validate the results with the current solar-based approach.

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## References

1. Gopalswamy N. *GSL*, 2016, 3: 8
2. Shibata K, Tanuma S. *EP&S*, 2001, 53: 473
3. Chen P F. *LRSP*, 2011, 8: 1
4. Alex S, Mukherjee S, Lakhina G S. *JASTP*, 2006, 68: 947
5. Gan W Q, Zhu C, Deng Y Y, et al. *RAA*, 2019, 19: 156
6. 甘为群, 诸成, 陈斌, 等. *天文学报*, 2022, 63: 60
7. Gan W Q, Zhu C, Chen B, et al. *ChA&A*, 2023, 47: 441
8. Gan W Q, Zhu C, Deng Y Y, et al. *SoPh*, 2023, 298: 68
9. Li H, Chen B, Feng L, et al. *RAA*, 2019, 19: 158
10. Chen B, Li H, Song K F, et al. *RAA*, 2019, 19: 159
11. Feng L, Li H, Chen B, et al. *RAA*, 2019, 19: 162
12. Pauluhn A, Huber M C E, von Steiger R. *ISSIR*, 2002, 182: 281
13. Llebaria A, Lamy P, Danjard J F. *Icarus*, 2006, 182: 281
14. De Leo Y, Burtovoi A, Teriaca L, et al. *A&A*, 2023, 676: A45
15. Gueymard Christian A. *SoEn*, 2004, 76: 423
16. Machol J, Snow M, Woodraska D, et al. *E&SS*, 2019, 6: 46
17. 李敬伟, 黎辉, 封莉, 等. *天文学报*, 2020, 61: 39
18. Li J W, Li H, Li Y, et al. *RAA*, 2021, 21: 121
19. Zhang X J, Deng L H, Fei Y, et al. *ApJ*, 2023, 951: L3
20. Jing Z C, Li Y, Feng L, et al. *SoPh*, 2024, 299: 11
21. Li S T, Feng L, Ying B L, et al. *ApJ*, 2024, 969: L16
22. Thiemann E M B, Eparvier F G, Woodraska D, et al. *JSWSC*, 2019, 9A: 43

23. Howard R A. GMS, 2006, 165: 7

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