A Revised Graduated Cylindrical Shell Model and its Application to a Prominence Eruption Postprint

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Abstract

In this paper, the well-known graduated cylindrical shell (GCS) model is slightly revised by introducing longitudinal and latitudinal deflections of prominences originating from active regions (ARs). Subsequently, it is applied to the three-dimensional (3D) reconstruction of an eruptive prominence in AR 13110, which produced an M1.7 class flare and a fast coronal mass ejection (CME) on 2022 September 23. It is revealed that the prominence undergoes acceleration from 246 to 708 km s−1. Meanwhile, the prominence experiences southward deflection by 15° ± 1° without longitudinal deflection, suggesting that the prominence erupts non-radially. Southward deflections of the prominence and associated CME are consistent, validating the results of fitting using the revised GCS model. Besides, the true speed of the CME is calculated to be 1637 ± 15 km s−1, which is 2.3 times higher than that of prominence. This is indicative of continuing acceleration of the prominence during which flare magnetic reconnection reaches maximum beneath the erupting prominence. Hence, the reconstruction using the revised GCS model could successfully track a prominence in its early phase of evolution, including acceleration and deflection.

Full Text

Preamble

A Revised Graduated Cylindrical Shell Model and its Application to a Prominence Eruption

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Abstract

In this paper, the well-known graduated cylindrical shell (GCS) model is slightly revised by introducing longitudinal and latitudinal deflections of prominences originating from active regions (ARs). Subsequently, it is applied to the three-dimensional (3D) reconstruction of an eruptive prominence in AR 13110, which produced an M1.7 class flare and a fast coronal mass ejection (CME) on 2022 September 23. It is revealed that the prominence undergoes acceleration from 246 to 708 km s^{-1}. Meanwhile, the prominence experiences southward deflection by $15° \pm 1°$ without longitudinal deflection, suggesting that the prominence erupts non-radially. Southward deflections of the prominence and associated CME are consistent, validating the results of fitting using the revised GCS model. Besides, the true speed of the CME is calculated to be 1637 ± 15 km s^{-1}, which is 2.3 times higher than that of the prominence, implying continuing acceleration of the prominence between 17:57 UT and 18:23 UT.

Main Text

It is obvious that the two legs of the prominence are much brighter than its top. In panel (c1), the prominence presents a clear helical structure, implying that the magnetic fields supporting the prominence are most probably a flux rope. The bottom panels of Figure 6 [Figure 6: see original paper] show the same images, which are superposed with projections of the reconstructed flux rope (atrovirens, magenta, and blue dots) using the revised GCS model. The 3D reconstruction is performed by repeatedly adjusting the free parameters described in Section 2, while the source region location (f = −84°, = 15°) is fixed. The best-fit model is subjectively judged when projections of the flux rope nicely match the prominence in EUV images. From Figures 6(a2)–(c2), it is revealed that the fitting of the prominence using the revised GCS model is satisfactory. The derived parameters are: h = 150(cid:1), $\alpha = 45°$, = 0.087 (δ = 5°), $f_1 = 0°$, $_1 = 16°$, and $\gamma = 20°$. The height of the leading edge is hLE = 396 6, the edge-on width of the flux rope is $\omega\mathrm{EO} = 2\delta = 10°$, and the face-on angular width is $\omega\mathrm{FO} = 2(\alpha + \delta) = 100°$. The flux rope axis deviates from the local vertical direction by 16°.

The Ne VII line is formed at 0.5 MK in the upper transition region (Tian 2017). Meanwhile, the EUVI (Wuelser et al. 2004) on board STA detected the prominence in 195 and 304 Å from another perspective (Figure 1 Figure 1: see original paper). In Figure 6, the top panels show the prominence simultaneously observed by AIA 304 Å (base-difference image), SWAP 174 Å (base-difference image), and EUVI 304 Å (original image) passbands around 17:55:40 UT. Due to the low cadence (10 minutes) of the EUVI 304 Å passband, this is the only time when the prominence is entirely visible in all instruments. Owing to the smaller FOV of AIA compared to SWAP, the leading edge reaches a heliocentric distance (hHC) of 1.4 Re. Although there is only one time of simultaneous observations of the prominence from multiple perspectives, 3D reconstruction could still be conducted using observations from telescopes along the Sun-Earth connection (Thernisien et al. 2006).

In Figure 7 [Figure 7: see original paper], the top panels show the prominence observed by AIA 304 Å and SWAP 174 Å around 17:57:27 UT. The prominence was fully visible in the SWAP 174 Å image at 17:57:25 UT, but was only partly visible in the AIA 304 Å image at 17:57:29 UT. The bottom panels show the same images overlaid with projections of reconstructed flux ropes (atrovirens and magenta dots). Consistency between the shapes of the prominence and flux ropes indicates that the fittings are still gratifying. The derived parameters are drawn in Figures 3(c)–(d).

Before 17:54:00 UT, the prominence rose gradually and was entirely recorded in the AIA 304 Å and SUTRI 465 Å passbands. Figure 8 [Figure 8: see original paper] shows 304 Å images (a1–a5) and 465 Å images (b1–b5) with the reconstructed flux ropes overlaid with projections (atrovirens and blue dots) during 17:49–17:53 UT. The prominence looks like an ear and the two legs are much clearer than the top. The reconstructed flux ropes coincide with the prominence much better at the legs than at the top due to its irregular and asymmetric shape. The derived parameters are drawn in Figures 3(c)–(d).

Linear fittings of hLE are separately performed during 17:49:17–17:52:17 UT and 17:53:30–17:57:30 UT, giving rise to true speeds of 246 and 708 km s^{-1} for the erupting prominence. Accordingly, the prominence was undergoing acceleration during its eruption (17:49–17:57 UT). In Figure 3 Figure 3: see original paper, the time variation of hHC is plotted with blue circles, which has the same trend as hLE. The value of γ increases from 0° to 30°, which is probably indicative of counterclockwise rotation of the prominence axis during eruption (Fan & Gibson 2003; Zhou et al. 2020). The edge-on width ωEO remains constant at 10°. The face-on width ωFO decreases from 162° to a minimum of 100° around 17:53:45 UT and increases to 104° around 17:57:25 UT. The inclination angle $_1$ increases slightly from 14° to 16°, suggesting a southward deflection of the prominence. The values of f_1 remain 0°, meaning that there is no longitudinal deflection.

In Table 2 , the CPA of the CME is 85°–88°, indicating a southward deflection of the CME by 11°–14°. In this regard, deflections of the prominence and related CME are accordant, which justifies the results of fitting using the revised GCS model. Furthermore, the true speeds (V_3D) of the CME are estimated to be 1653 and 1622 km s^{-1} using the apparent speeds in the FOVs of LASCO/C2 and STA/COR2, which are very close to each other. It is noted that the speed of the CME (1637 ± 15 km s^{-1}) is 2.3 times higher than that of the prominence, implying continuing acceleration of the prominence between 17:57 UT and 18:23 UT.

4. Summary and Discussion

In this paper, the GCS model is slightly revised by introducing longitudinal and latitudinal deflections of prominences originating from ARs. Subsequently, it is applied to the 3D reconstruction of an eruptive prominence in AR 13110, which produced an M1.7 class flare and a fast CME on 2022 September 23. It is found that the prominence undergoes acceleration from 246 to 708 km s^{-1}. Meanwhile, the prominence experiences southward deflection by 14°–16° without longitudinal deflection, suggesting that the prominence erupts non-radially. Southward deflections of the prominence and associated CME are consistent, validating the results of fitting using the revised GCS model. Besides, the true speed of the CME is calculated to be 1637 ± 15 km s^{-1}, which is 2.3 times higher than that of the prominence. This is indicative of continuing acceleration of the prominence during which flare magnetic reconnection reaches maximum beneath the erupting prominence. Hence, the reconstruction using the revised GCS model could successfully track a prominence in its early phase of evolution until 1.5 Re including acceleration and deflection.

Morphological reconstructions of prominences/filaments are abundant using stereoscopic observations in UV, EUV, and Hα passbands from two or three viewpoints. The triangulation method has been widely used to perform reconstructions of both quiescent and AR prominences (Li et al. 2011; Bi et al. 2013; Guo et al. 2019). However, this method utilizes simultaneous images from two perspectives. In the current study, there is only one moment (17:55:45 UT) of observations from SDO/AIA and STA/EUVI when the triangulation method is usable (Figure 6). On the contrary, the revised GCS model is at work even if there are observations from a single perspective (Figures 7, 8), although more perspectives impose better constraints and have lower uncertainties. This is particularly advantageous to the reconstruction of hot channels since routine observations in hot emission lines (such as 94, 131 Å) with STEREO and SolO/EUI are still unavailable. Calculations of the thermal energies of hot channels using this model will be the topic of our next paper.

Of course, there are limitations of the revised GCS model. First, the model is applicable to AR prominences whose footpoints are close to each other, instead of quiescent prominences with much larger sizes and extensions. Second, the model is applicable to coherent, loop-like prominences, rather than those presenting irregular and ragged shapes.

Lastly, 3D reconstructions of prominences are severely constrained by the FOVs of solar telescopes working at UV, EUV, and Hα wavelengths, which is in contrast to the reconstructions of CMEs observed by coronagraphs with much larger FOVs. In Figure 3(b), the heliocentric distance of the flux rope leading edge reaches 1.5 Re at 17:57:25 UT, which is still blocked by the occulting disk of LASCO/C2.

With the advent of the peak year of the 25th solar cycle, large-scale solar eruptions are booming, which have a sustained impact on the near-Earth space environment. Precise reconstructions of the shape and direction of eruptive prominences and the related CMEs will undoubtedly improve our ability to forecast space weather. In the future, more case studies and statistical analysis are worthwhile using stereoscopic observations from spaceborne and ground-based telescopes, such as SDO/AIA, STEREO/EUVI, SolO/EUI, SWAP, SUTRI, the Chinese Hα Solar Explorer (CHASE; Li et al. 2022a), and the New Vacuum Solar Telescope (NVST; Liu et al. 2014).

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