Tethered Prominence-CME Systems Captured during the 2012 November 13 and 2013 November 3 Total Solar Eclipses

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Abstract

We report on white light observations of high latitude tethered prominences acquired during the total solar eclipses of 2012 November 13 and 2013 November 3, at solar maximum, with a field of view spanning several solar radii. Distinguished by their pinkish hue, characteristic of emission from neutral hydrogen and helium, the four tethered prominences were akin to twisted flux ropes, stretching out to the limit of the field of view, while remaining anchored at the Sun. Cotemporal observations in the extreme ultraviolet from the Solar Dynamics Observatory (SDO/AIA) clearly showed that the pinkish emission from the cool (≈10³ – 10⁵ K) filamentary prominences was cospatial with the 30.4 nm He II emission, and was directly linked to filamentary structures emitting at coronal temperatures ≥10⁸ K in 17.1 and 19.3 nm. The tethered prominences evolved from typical tornado types. Each one formed the core of different types of coronal mass ejections (CMEs), as inferred from coordinated LASCO C2, C3, and STEREO A and B coronagraph observations. Two of them evolved into a series of faint, unstructured puffs. One was a normal CME. The most striking one was a “light-bulb” type CME, whose three-dimensional structure was confirmed from all four coronagraphs. These first uninterrupted detections of prominence-CME systems anchored at the Sun, and stretching out to at least the edge of the field of view of LASCO C3, provide the first observational confirmation for the source of counter-streaming electron fluxes measured in interplanetary CMEs, or ICMEs.

Key words: Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences – Sun: magnetic fields

Supporting material: animations

1. Introduction

Prominences are the most complex magnetic structures that protrude into the solar corona. Their pinkish hue in broadband white light eclipse images is due to a combination of emission from neutral hydrogen and helium, with the strongest emission being from Hα. Thus, they consist primarily of neutrals and low ionized elements, 100 times cooler and 100 times denser than the surrounding hot (>10⁶ K) corona (e.g., Tandberg-Hanssen 1995). The eruption of prominences and their consequent triggering of coronal mass ejections (CMEs) is now amply documented from coordinated observations close to the Sun, either in Hα or the extreme ultraviolet (EUV), and from coronagraphs (e.g., Munro et al. 1979; Gopalswamy et al. 1996; Gopalswamy & Hanaoka 1998; Gilbert et al. 2000; Gopalswamy et al. 2003; Jing et al. 2004). Evidence for the prominence-CME link is further supported by the complexity of magnetic structures common to both, such as the direction of the twist and rotation of the magnetic field embedded within them. Such observations have led to the interchangeable use of the term “magnetic flux rope” for both (see, e.g., Gibson & Fan 2006).

In some models (e.g., Amari et al. 2010), the link between prominences and CMEs is intrinsically driven by flux cancellation around a magnetic neutral line, the rise of a twisted flux rope and magnetic reconnection in the overlying arcade, resulting in the formation of a current sheet. Such models can often lead to tethered prominences, i.e., twisted magnetic flux ropes that stretch outwards without totally detaching from their anchor at the Sun (e.g., Gosling et al. 1995; Gibson & Fan 2008). One of the indications of the existence of tethered systems is the discovery, several decades ago, of counter-streaming electron fluxes in CMEs in interplanetary space (or ICMEs) in almost 50% of the measurements, i.e., fluxes of electrons moving in opposite directions (Gosling et al. 1987, 2001; Crooker et al. 2004). These bi-directional electron streams can only be accounted for if the field lines forming the CME envelope are still anchored to the Sun at both ends.

At present, there are no single observations that can capture the prominence-CME link in an unambiguous manner, except for total solar eclipse observations, because they span an uninterrupted field of view starting from the solar surface and extending out to several solar radii. This areal span is essential for identifying the dynamic connectivity between prominences and CMEs, their sustained connectivity to the Sun as they expand outwards, and the thermodynamic (temperature and composition) connection between the two. Multi-wavelength eclipse observations have shown that prominences are enshrouded by the hottest material in the corona (Habbal et al. 2010). Recently, spectroscopic observations made during the 2015 total solar eclipse by Ding & Habbal (2017) showed that filamentary sections from eruptive prominences maintained their distinct composition of neutral and low ionized states of Fe and Mg, as they were entrained within the over 2 × 10⁶ K filamentary structures of a CME front. While the dynamics of prominences and CMEs are so closely intertwined, there is no theory or model, at present, that can explain how their plasma properties can remain so clearly distinct.
Although eclipse observations have frequently captured the imprint of the passage of CMEs through the corona, as they disrupt its large-scale structures for several hours (e.g., Habbal et al. 2011; Alzate et al. 2017), very rarely have they captured a CME in eclipse images (see Hanaoka et al. 2014). One of the first such records was illustrated in a hand-drawn image made by G. Tempel during the 1860 July 18 eclipse that traversed Spain. In Tempel’s remarkable image, an unusual helical structure was drawn very close to the Sun. At the time, it was considered an oddity, and some were skeptical about the reliability of Tempel’s account. With the discovery of CMEs from space-based coronagraphs in the early 1970s (Tousey 1973; Gosling et al. 1974; MacQueen et al. 1980), it became plausible that Tempel had actually captured one. However, to date, there have been no reports of spatially uninterrupted detections of tethered prominence-CME systems starting from the Sun, and expanding into interplanetary space.

In this Letter, we present remarkable white light eclipse observations, taken on 2012 November 13 and 2013 November 3, which serendipitously captured four tethered prominence-CME systems. The tethered prominences formed the cores of different types of CMEs, as was further established through cotemporal ancillary data from the Solar Dynamics Observatory (SDO)/AIA, LASCO C2 and C3, and STEREO COR2 A and COR2 B, which remained anchored to the Sun. Despite their paucity, these observations demonstrate that total solar eclipses provide, at present, the only observational opportunity to capture an uninterrupted spatial coverage of tethered prominence-CME systems spanning several solar radii, which also establish the likely coronal source of counter-streaming electrons associated with ICMEs.

2. Eclipse Observations and Image Processing Tools

The total solar eclipse white light images of 2012 and 2013, shown in Figures 1(a) and 2(a), were acquired by C. Emmanouilidis. Totality started at 20:37:39 UT on 2012 November 13 at his observing site in Northern Australia. The camera used was a modified Canon 5D Mark I (CMOS sensor), which extended the sensitivity in the red wavelength range, including Hα. C. Emmanouilidis modified the camera and removed both the low-pass glass filters in front of the sensor to provide the maximum possible resolution in the raw data. The camera was coupled with a Takahashi TSA102 refracting telescope with a 102 mm f/8 aperture and a Takahashi TOA-35 coma corrector. The corona was imaged with a sequence of exposure times ranging from 1/1000 to 8 s, over the 115 s duration of totality.

The 2013 November 3 eclipse was observed from Gabon, starting at 13:52:40 UT, using the same sequence of exposure times as in 2012, over its 62 s duration. The optics consisted of a Takahashi FSQ-106 astrograph refracting telescope with a 106 mm f/5 aperture matched with a Nikon D7100 (which at the time was the only DSLR on the market without any low-pass filter in front of its CMOS sensor). A second wider field Takahashi FS-60C refracting telescope with a 60 mm f/6 aperture and a dedicated coma corrector was used with a Canon 350D DSLR camera, also modified to provide extended sensitivity in the red. The inset in Figure 2 was taken with the refracting telescope, which serendipitously captured a “light-bulb” type CME in its entirety, with its bright core and bubble encapsulating the tethered prominence seen in the smaller field of view.

In both expeditions, a redesigned German equatorial mount provided both a sturdy platform for the instruments but also a quick installation feature that made relocation possible, especially in Australia, because of the fast changing weather patterns. The data were recorded with preprogrammed Python scripts, and the cameras were fully controlled by a laptop computer.

The eclipse images were processed using the method developed by Druckmüller (2009, 2013) in which a sequence of 10 or more images with different exposure times were aligned using a modified phase correlation technique (a technique that does not require reference points). The Adaptive Circular High-pass Filter (ACHF; Druckmüller et al. 2006) was then applied to enhance coronal structures (Druckmüller et al. 2014), thus resulting in the images shown in Figures 1(a) and 2, which have a spatial resolution of 2–3 arcsec.

The solar disk overlays, covering the Moon in both examples, are SDO/AIA color composites from 30.4 (blue/cyan), 17.1 (red), and 19.3 (green) nm images, taken at the same time as the corresponding eclipse observations. The remarkable match between coronal structures in the eclipse white light image and AIA is testimony to the quality of the eclipse data.

The complexity of coronal structures in both images is not surprising given that these two eclipses coincided with the time interval between the two peaks in solar cycle 24, when the average sunspot number, $\langle N \rangle$, was 61.8 ± 22.5 on 2012 November 13 and 77.6 ± 27.9 on 2013 November 3. The first peak in solar cycle 24 occurred on 2011 November with $\langle N \rangle = 96.7 ± 14.6$. The second, larger peak appeared on 2014 February with $\langle N \rangle = 102.3 ± 20.8$. While solar cycles can exhibit a double peak, cycle 24 was unusual, because, unlike previous ones, the second peak was larger than the first (see http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt).

This study focuses on the remarkable tethered prominences captured at high latitudes during both eclipses. These are shown encircled in Figures 1(a) and 2, with detailed close-ups in Figures 1(b), 3(a), (c), and 4(a), (b).

3. Comparison with EUV and White Light Coronagraph Space-based Observations

Given that eclipse images are snapshots of the instantaneous dynamic state of coronal structures, they were complemented in this study by SDO/AIA, SOHO/LASCO C2 and C3, and STEREO COR2 A and COR2 B images prior to and at the time of totality, and also following it. The STEREO COR2 A and COR2 B coronagraphs were used in conjunction with the 2013 eclipse to achieve a 3D perspective of the light-bulb type CME.

The SDO/AIA 30.4, 17.1, and 19.3 nm bandpasses cover a range of temperatures with maxima around 5 × 10^6 K, 10^6 K, and 2 × 10^6 K, respectively. The AIA data were the only ones available at the time of the eclipse observations to provide electron temperature information. However, they have a limited heliocentric radial extent of 1.25 $R_\odot$. The AIA images were processed using the Multiscale Gaussian Normalization technique (MGN; Morgan & Druckmuller 2014), which enhances small-scale structure and overcomes the problem of revealing information in dark and bright regions simultaneously.

The SOHO/LASCO C2 and C3, STEREO/COR2 A and COR2 B coronagraph data were processed in two ways. (1)
The Dynamic Separation Technique (DST, Morgan et al. 2012; Morgan 2015) uses a spatio-temporal deconvolution method to separate the dynamic and quiescent components in a coronograph image, revealing faint dynamic events. It yields superior results compared to simpler running- or base-difference methods. Application of the DST yielded the images

![Figure 1](image.jpg)

Figure 1. (a) The 2012 November 13 total solar eclipse image, colorized in blue, capturing a tethered prominence at PA = 15°, with the corresponding *SDO/AIA* color composite of 30.4 (blue/cyan), 17.1 (red), and 19.3 (green) nm images overlaid over the Moon-obstructed solar disk. (b) Close-up of the tethered prominence (highlighted by small dashes, and its anchor at the Sun indicated by the arrow), with a clear cavity and faint front (identified by the longer dashes) encapsulating it. The arrows point to the likely presence of counter-streaming electron fluxes. Rows (c) through (f), show a time sequence at 2:36, 9:18, 14:30, and 20:37 UT (eclipse time) from the MGN-processed *SDO/AIA* 30.4 (c), 17.1 (d), 19.3 nm (e), and the corresponding color composites (f), with 30.4 in green, 17.1 in red, and 19.3 in magenta. Panels (g) and (h) show “puffs” (see arrows) associated with the prominence as seen in the DST-processed LASCO C2 field of view at 00:24 and 06:24 UT on November 14. (See the associated movies for each of the *SDO* passbands and the color composite.) (Animations (a, b, c, and d) of this figure are available.)
shown in Figures 1(g), (h), 3(h)–(k), 4(h)–(k), and in the left panels in the pairs given in Figure 5. (2) The Normalizing Radial Graded Filter (NRGF, Morgan et al. 2006) is a simple filter applied to coronagraph data for removing the steep radial gradient of brightness in the images to better reveal structure. After applying the NRGF technique, the MGN technique then enhances details. The result of this process yielded the images in the right panels of the pairs shown in Figure 5.

3.1. The 2012 November 13 Total Solar Eclipse

The 2012 November 13 total solar eclipse image (colorized in blue), shown in Figure 1(a), has the cotemporal SDO/AIA color composite from 30.4 (blue/cyan), 17.1 (red), and 19.3 (green) nm images overlaid over the Moon-obstructed solar disk. Coronal structures in this image seem to be defined by the almost continuous distribution of prominences around the solar limb and across the disk, as seen from their characteristic pinkish hue.

Most striking in this example is the high latitude tethered prominence at position angle (PA) 20° (measured counterclockwise from solar north). The details of the close-up in Figure 1(b) reveal a cavity and a faint front encapsulating it. The anchor of the prominence at the Sun is indicated by the arrow. The tethered prominence is highlighted by small dashes, while its faint CME front is identified by the longer dashes, with arrows pointing to the likely locus of counter-streaming electrons fluxes, as first measured in ICMEs (Gosling et al. 1987, 2001; Crooker et al. 2004).

Note that another CME in the southeast sector of the corona was reported about 37 minutes later by Hanaoka et al. (2014) who observed from a cruise ship in the Pacific north of New Zealand. However, it was not present in our eclipse image that was acquired earlier.

The corresponding MGN-processed SDO/AIA images are shown in rows (c) through (f), for a time sequence at 2:36, 9:18, 14:30, and 20:37 UT (eclipse time), for 30.4 (c), 17.1 (d), 19.3 nm (e), and the corresponding color composites (f), with 30.4 in green, 17.1 in red, and 19.3 in magenta. The evolution of the prominence in 30.4 nm, and its coronal environment in 17.1 and 19.3 nm, (which can be followed in the associated movies) reveals considerable rise and twist with the addition of material in all three wavelengths starting from 00:06 UT.

A bowl-shaped structure, akin to a tornado or vortex-type prominence (e.g., Li et al. 2012) forms in 30.4 nm at 2:30 UT (the bowl shape is the cross-section of the vortex). It starts to rise in the form of a very thin tether around 01:48 UT as it reshapes until some of the cool material seems to detach at 14:24 UT. However, it continues to reshape until it dissipates by the time of the eclipse (last frame). The extent of the bowl shape is more pronounced in 17.1 nm starting at 00:06 UT. The structure evolves with more plasma being added at the base of the tether around 14:30 UT, when it starts to rise and eventually exits the SDO field of view. In 19.3 nm, the same bulb-like
Figure 3. (a) Close-up view of the north region of the 2013 November 3 eclipse image. The left oval encircles a tethered prominence eruption with an elongated shroud anchored to the Sun, clearly evident from the pinkish emission in the close-up (c). The right oval encircles the tether of an eruption that was no longer in the eclipse image field of view. The tethered prominence is highlighted by short dotted lines, and the CME envelope is outlined by long dashes, with arrows pointing to the likely locus of counter-streaming electron fluxes. (d)–(g) Time sequence of the corresponding region from SDO/AIA 30.4 (d), 17.1 (e), and 19.3 nm (f), and a color composite of all three in (g), with the same color scheme as in Figure 1, prior to (0:12, 2:18 UT) and at totality (13:52 UT). (h) DST-processed LASCO C2 time sequence at 13:55 UT (just past the eclipse time), when the prominence was captured at the inner edge of the C2 field of view, followed by images at 16:35, 18:35, and 20:35 UT, illustrating the evolution of the tether prominence-CME system until it reached the outer edge of the C2 field of view. (See corresponding movies in all wavelengths, in the color composite and in C2.)

(Animations (a, b, c, d, and e) of this figure are available.)
Figure 4. (a)–(b) Close-up views of the long tethered prominence at PA = 180°, captured with two different cameras during the 2013 November 3 total solar eclipse, complemented in (b) by the corresponding LASCO C2 image, hence the time range shown in that frame. (c) Same as (b) with short and long dashed lines outlining the prominence tether and CME envelope, respectively, with arrows indicating possible counter-streaming electrons. (c)–(e) SDO time sequence at 0:12, 1:18, and 3:18 UT in 30.4 (c), 17.1 (d), and 19.3 nm (e). (f) Their corresponding color composite. (h)–(k) Time sequence of the DST-processed LASCO C2 images prior to the eclipse at 08:47 and 10:47 UT, during the eclipse at 13:55 UT, and 3 hours later at 16:47 UT when the CME exits the field of view. (See corresponding movies for SDO and LASCO C2 panels.)
(Animations (a, b, c, and d) of this figure are available.)
Figure 5. Time sequence evolution of the corona around the time of the 2013 November 3 eclipse as seen in the MGN (right) and DST (left) processed images from LASCO C2 (a)–(f), LASCO C3 (g)–(h), and STEREO/COR2 A (i) and COR2 B (j). Panel (e) is closest in time to the eclipse observations. The arrows point to puff-type CMEs.
It evolves with a denser core forming around 12:12 UT present at 00:06 UT, surrounding the linear 30.4 nm structure. By the time of the eclipse, the 30.4 nm emission had receded, while the bowl shape left the SDO/AIA field of view in both 17.1 and 19.3 nm images. The connectivity between the different temperature filaments within this structure, shown in rows (c) through (e), is even more evident in the color composites given in row (f), and the corresponding movie. Thorough inspection of the MGN- and DST-processed LASCO C2 data showed a faint structureless CME, also known as a "puff" (Alzate & Morgan 2016), traversing the field of view at PA 15°.

3.2. The 2013 November 3 Total Solar Eclipse

The 2013 November 3 total solar eclipse image, shown colorized in blue in Figure 2, is an equally, if not, more complex corona compared to 2012 (see Figure 1(a)). Here too, the cotemporal SDO/AIA color composite from 30.4 (blue/cyan), 17.1 (red), and 19.3 (green) nm images, is overlaid over the Moon-obstructed solar disk. At least three tethered prominences were captured in this image (as shown in the encircling ellipses), with one of them clearly engulfed by a typical light-bulb type CME, with a bright core and a bulbous shell. The details of these tethered structures are given in Figures 3 and 4, and described next within the context of the ancillary SDO/AIA, LASCO C2 and C3, and STEREO data.

3.2.1. North Tethers

A close-up view of the north region of the 2013 November 3 eclipse image is given in Figure 3(a). The left oval encircles a tethered prominence eruption with a very large shroud still anchored to the Sun. Its anchor is clearly evident from the pinkish emission, as also seen in the close-up (c). As in Figure 1(b), the tethered prominence is highlighted by short dotted lines, and its CME envelope is outlined by long dashes, with arrows pointing to the likely locus of counter-streaming electron fluxes. The right oval encircles the tether of an eruption that was beyond the edge of the field of view by the time of the eclipse.

Rows (d), (e), and (f), are a time sequence of the corresponding region as seen in SDO/AIA, 30.4 (d), 17.1 (e), and 19.3 nm (f), and a color composite of all three in (g) (with the same color scheme as in Figure 1), prior to totality (0:12, 2:18 UT) and at totality (13:52 UT). The two tethers in panel (a) correspond to two prominences captured in 30.4 nm, at least 12 hours prior to totality, as seen in the first panel of row (d). Their corresponding coronal “envelopes” presented themselves in 17.1 nm (first panel in row (e)), as a tornado or vortex-type prominence eruption, similar to the 2012 eclipse example in Figure 1, which disappear from the field of view by the time of totality. Only the left one survives, while a tether is all that is left from the right one. Their hotter envelope is clearly seen in 19.3 nm (row (f)), with a denser core centered within the vortices seen in 17.1 nm. The relationship between all three wavelengths is more evident in the color composite shown in row (g). The LASCO C2 time sequence in row (h) starts at 13:55 UT (just past the eclipse time), when the left prominence appeared as the bright core of a CME at the inner edge of the C2 field of view. The core persisted, as seen at 16:35, 18:35, and 20:35 UT, illustrating the evolution of this tethered system until it reached the outer edge of the C2 field of view. (See the corresponding movies in all wavelengths, in the color composite and in C2.)

3.2.2. South Tether

The tethered prominence in the south at PA = 180°, shown in detail in Figure 4(a), resembles the one in the north shown in Figure 3(a). However, the larger field of view of Figure 4(b), captured with a different lens during the eclipse, reveals the presence of a remarkable classic light-bulb type CME, also tethered to the Sun, which is very different from the evolution of the north prominence. Its boundaries and the tether of the prominence are highlighted by long and short dashes, respectively, in Figure 4(c). As in previous examples, the arrows point to the likely presence of counter-streaming electron fluxes.

The evolution of the prominence in the low corona, captured with the 30.4, 17.1, and 19.3 nm SDO/AIA channels (columns (d), (e), and (f) respectively) at 0:12, 1:18, and 3:18 UT, before it exited the field of view, is very different from that in Figure 3. This one appears as a very complex structure, seemingly including sections of a prominence complex extended along the solar limb, as seen in column (d). Evidence for a vortex or tornado shaped prominence appears in the second panel of column (d), followed by the detachment of material, as seen in the last panel. In 17.1 nm, column (e), most of the activity is seen in the structure further to the right. Emission in 19.3 nm (column (f)) is rather diffuse. The connection in the evolution of all three wavelengths is given in column (g). The evolution of this system is more evident in the corresponding movies. The remarkable dynamic evolution of the system is seen in the LASCO C2 time sequence of images shown in the bottom row (panels (h) through (k)), prior to the eclipse at 08:47 and 10:47 UT, at 13:55 UT during the eclipse, and at 16:47 UT about three hours later until the CME exits the field of view. The prominence core (indicated by the arrow in panel (c)) is quite large, and the prominence-CME system clearly indicates that it remained tethered to the Sun.

3.2.3. Evolution of the 2013 CMEs through the LASCO and STEREO Fields of View

Figure 5 provides an overview of the changes in the extended corona prior to, during, and after the 2013 eclipse from the DST and MGN-processed LASCO C2 (a)–(f), C3 (g)–(h), and STEREO COR2 A (i) and COR2 B (j) images. At that time, STEREO A and Earth had a separation angle of 143°, while STEREO B and Earth were separated by 149°. Two oppositely directed CMEs were visible at 13:55 UT in LASCO C2 and at 01:41 UT in LASCO C3, in addition to several puffs, indicated by the arrows.

The emergence of the tip of the light-bulb CME in the south at 09:59 UT in LASCO C2 (panel (c)), clearly expanded substantially with time. The COR2 A and B coronagraph images show the CME in the southeast limb at 19:54 UT, six hours after totality. The structure looks the same in all three sets of images indicating that the three-dimensional aspect of the CME is of the light-bulb type. The extension of the edges of the CME, together with its inner prominence core, down to the inner edge of the occulters in all three coronagraphs, further
supports the finding that this prominence-CME system remained tethered to the Sun. 
In the north, the evolution of the normal CME, i.e., the left oval in Figure 3(a), also shows a tethered prominence-CME system throughout the LASCO C2 field of view and a little later in LASCO C3, with a particularly bright core in both. This system was also visible in STEREO A and B at 19:54 UT, when both CMEs had cleared the edge of their respective occulters. Despite their being faint, remnants of the puffs were also seen in STEREO A and B.

4. Summary and Conclusions

The total solar eclipses of 2012 and 2013, which coincided with a time interval between two maxima in sunspot numbers in Solar Cycle 24, captured exquisite examples of high latitude tethered prominences, all of which had CME envelopes. The tethered prominences presented themselves as helically twisted structures, thinning as they extended away from the corona, with their ends remaining anchored to the Sun, with a particularly bright core in both. This system was also visible in STEREO A and B at 19:54 UT, when both CMEs had cleared the edge of their respective occulters. Despite their being faint, remnants of the puffs were also seen in STEREO A and B.

We speculate that the appearance of the reported tethers as sharply defined, linear rays in the corona, frequently observed in eclipse white light images, suggests that the myriad of such rays might all have their origin in tethered prominence eruptions. If all that is left from the eruption in a given eclipse image is the ray, then the numerous prominence eruptions, with only a small fraction of them leading to a CME, are likely to go unnoticed. Furthermore, when, and if, associated with slow structured and/or unstructured CMEs, traveling at under 100 km s⁻¹, they can readily go unnoticed in the standard CME catalogs. These observations imply that predicting the occurrence and types of CMEs associated with prominence eruptions remains challenging.

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