THE INCONVENIENT TRUTH ABOUT CORONAL DIMMINGS

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ABSTRACT

We investigate the occurrence of a coronal mass ejection (CME)-driven coronal dimming using unique high-resolution spectral images of the corona from the Hinode spacecraft. Over the course of the dimming event, we observe the dynamic increase of nonthermal line broadening in the 195.12 Å emission line of Fe XII as the corona opens. As the corona begins to close, refill and brighten, we see a reduction of the nonthermal broadening toward the pre-eruption level. We propose that the dynamic evolution of the nonthermal broadening is the result of the growth of Alfvén wave amplitudes in the magnetically open rarefied dimming region, compared to the dense closed corona prior to the CME. We suggest, based on this proposition, that, as open magnetic regions, coronal dimmings must act just as coronal holes and be sources of the fast solar wind, but only temporarily. Further, we propose that such a rapid transition in the thermodynamics of the corona to a solar wind state may have an impulsive effect on the CME that initiates the observed dimming. This last point, if correct, poses a significant physical challenge to the sophistication of CME modeling and capturing the essence of the source region thermodynamics necessary to correctly ascertain CME propagation speeds, etc.

Key words: solar wind – Sun: chromosphere – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: magnetic fields

1. INTRODUCTION

Coronal dimmings, or “transient coronal holes” as they are sometimes known, have provoked great curiosity in the solar physics community since their initial observation with Skylab (Rust & Hildner 1976; Rust 1983). They were first noticed as a rapid intensity reduction of the soft X-Ray corona around active regions, and have subsequently been connected to coronal mass ejections (CMEs; see e.g., Hudson et al. 1996; Forbes 2000; Kahler & Hudson 2001). Indeed, coronal dimmings are now viewed as the residual footprint of the CME in the corona (e.g., Thompson et al. 2000), the radio and plasma signatures of which are observed in interplanetary space (e.g., Cane 1984; Neugebauer et al. 1997; Attrill et al. 2008). The connection between dimming and CME has been quantitatively fortified by the recent statistical surveys of Reinard & Biesecker (2008) and Bewsher et al. (2008) using extreme-ultraviolet (EUV) instrumentation on the Solar and Heliospheric Observatory (SOHO) spacecraft (Fleck et al. 1995). The former of these surveys indicates that at least 50% of front-sided CMEs have associated dimming regions, while the latter stressed that the relationship between the two phenomena is one that grows considerably when only narrowband spectroscopic observations are considered. Therefore, rigorously establishing the poorly understood physical connection between CMEs and coronal dimmings using detailed spectroscopic measurement is a must.

We focus our analysis on observations of NOAA Active Region 10930 (NOAA AR 10930) from the Extreme-Ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007 on Hinode (Kosugi et al. 2007) between 19:00UT 2006 December 14 and 06:00UT 2006 December 15. This time period saw an X-Class flare and a ~1000 km s⁻¹ halo CME¹ emanating from this complex active region at around 20:12 UT (relative to SOHO/EIT imaging; Delaboudinière et al. 1995). In this paper, we expand on the analysis of Harra et al. (2007), exploiting rare detailed spectroscopic measurements of a dimming region. EIS provides a tantalizing look at the dynamic behavior of EUV emission lines and their nonthermal line widths, in particular, over the course of the eruption. The interpretation of the dynamic evolution of the nonthermal line widths presented in this paper forms a challenge to the rapidly increasing sophistication of numerical CME models, in that they need to cope with the complex thermodynamics of the CME source region.

2. OBSERVATIONS & DATA ANALYSIS

The data set of interest comprises of three spectroheliogram “raster” observations (19:20–21:34UT, 01:15–03:30, 04:10–06:24UT), targeted at the following edge of the active region that is the source of the event studied. Each EIS raster is comprised of 256 horizontal (west to east) mirror mechanism steps with the 1” slit at a spacing of 1” and a height of 256”, and has information in a nine 24 pixel wide spectral window. At a spectral resolution of 22.3 mÅ and wavelength of 195 Å, one pixel on the detector is equivalent to a velocity of ~34 km s⁻¹.

For brevity, we present the analysis of the Fe XII 195.12 Å emission line as the EIS rasters can be supported by the broadband imaging from SOHO/EIT in the 195 Å passband at its regular 12 minute “CME Watch” cadence. The analysis of other strong and (relatively) spectrally clean emission lines observed in this period (Fe XIII 202.04 Å and Fe XV 284.16 Å) will be published in a later article (McIntosh 2009).

Once the data are reduced, we need to extract the physical measurements from the emission-line spectra. To do this, we choose to fit the spectral profiles at each spatial pixel at each raster step with a single Gaussian (assuming a linear continuum background variation in the spectral window) and, to ensure the highest quality fits, we use a combination of genetic algorithm (e.g., McIntosh et al. 1998) and downhill convergence methods.

¹ The CME properties were automatically derived from SOHO/LASCO data by the NASA/GSFC CDAW (http://cdaw.gsfc.nasa.gov/) and the Royal Observatory of Belgium/SIDC CACTUS (Robbrecht & Berghmans 2004; http://www.sidc.be/cactus/) catalogues.
Figure 1. Contextual pre-CME images of NOAA AR 10930 from SOHO and Hinode. We show the closest EIT 195 Å image to the start of the first EIS raster—shown inset as the peak intensity of the Fe XII 195.12 Å emission line. See the online edition of the journal to see a movie of the dimming evolution.

Upon completion of the Gaussian fitting process, we have spatial maps of the line (peak) intensity, line position, and $1/e$ width $w_{1/e}$ of the profile (measured in spectral pixels). The map of the nonthermal line width $v_{\text{nt}}$ (in km s$^{-1}$) of the emission-line profile is determined using the quadratic relationship

$$v_{\text{nt}} = c \frac{D_s}{\lambda_0} \sqrt{w_{1/e}^2 - w_{\text{inst}}^2 - w_{\text{th}}^2},$$

where $w_{\text{inst}}$ is the instrumental width (taken to be 2.5 pixels full-width half-max; Doschek et al. 2007), $w_{\text{th}} = \sqrt{2k_B T_e/m_{\text{ion}}}$ is the thermal width for an ion of mass $m_{\text{ion}}$ and peak formation temperature of $T_e^*$ (assuming that the ion and electron temperatures are equal), $\lambda_0$ (195.12 Å) is the rest wavelength of the line, $D_s$ (22.3 mÅ) is the spectral pixel scale, and $c$ is the speed of light.

In order to compare the three EIS rasters, as well as with the broadband EIT images, we must derotate the coordinates of each slit position to the start time of the first raster using the mapping method of McIntosh et al. (2006). An example is shown in Figure 1, where the monochromatic EIS image is inlaid in the closest EIT image to the start of the first raster (19:13UT).

3. RESULTS

Figure 2 shows the evolution of the Fe XII line intensities before (19:20UT; panel A), and at two stages during (01:15; panel B—04:10UT; panel C), the dimming event. Panel D shows the percentage change in the line intensity between the pre- and first post-eruption rasters [(B – A)/A], while panels E and F show the percentage intensity change between pre- and second post-eruption rasters [(C – A)/A] and that between the two post-eruption rasters [(C – B)/B]. The white contours overlapped on panels D and E isolate the strongest dimming region, where we see a reduction in intensity of 75%. In fact, we see that, from EIS’ perspective, there is a sizable reduction in intensity to the south and east of AR 10930; much of that area shows a drop in intensity between 25 and 50%, which would classify this event as a “deep” dimming in the terminology of Attrill et al. (2007).

We should note here that the choice of a 75% reduction in intensity is arbitrary, but that it outlines a region of significant change of the emission from magnetic field lines rooted in the region running from [440", –200"] to [480", –120"]). In panel F of Figure 2, we see that the intensities are increasing over almost the entire region, recovering slowly as is typical of coronal dimmings (Reinard & Biesecker 2008; Attrill et al. 2008). This behavior has been associated with the closure of the overlying corona and return of plasma heating to the region (see e.g., McIntosh et al. 2007). We use the observed intensity drop to compute a rough estimate of the drop in electron density in the dimming region. For a resonance line whose intensity varies as $n_e^2$, a 75% reduction in emission corresponds to a 44% reduction of electron density. The apparent intensity drop and slow recovery of the region are mirrored by the SOHO/EIT image sequence (see the online version of the journal for movie accompanying Figure 1).

Figure 3 mirrors Figure 2, except it shows the evolution of the Fe XII nonthermal line width ($v_{\text{nt}}$) before (panel A) and over the course of the dimming event (panels B and C). Again, panels D through F show the percentage change in $v_{\text{nt}}$ between the pre- and first post-eruption rasters [(B – A)/A], the pre- and second post-eruption rasters [(C – A)/A], and between the two post-eruption rasters [(C – B)/B]. Immediately, we see a dynamic evolution of $v_{\text{nt}}$ in the contour-outlined dimming region over the course of the event. Comparing panels A and B (and D), we see a large increase (~15%) in $v_{\text{nt}}$, largely concentrated in and around the perimeter of the 75% reduction contour. As the dimming event progresses (comparing panels C, A and E), there continue to be regions of difference in $v_{\text{nt}}$ late in the lifetime of the dimming, becoming more spatially compact and following the contraction of the intensity decrease contour. In panel F, we see that $v_{\text{nt}}$, much as in Figure 2, appears to be slowly recovering to pre-eruption levels, and we find that other (spectrally clean) coronal spectral lines observed by EIS in this region exhibit the same dynamic behavior of $v_{\text{nt}}$.

4. DISCUSSION & CONCLUSION

Harra et al. (2007) reported on the considerable (relative) blueshifted Doppler velocities (~40 km s$^{-1}$) that emanated from the dimming region and are indicative of significant coronal outflows while the region is open. We believe that these outflows are real, are consistent with the measurements discussed above, and reinforce our belief that the transient dimmings are really short-lived coronal holes. Unfortunately, the relative nature of the EUV Doppler measurements leaves some ambiguity in the absolute magnitude of these flows. However, we have
Figure 2. Phases of the coronal dimming observed in the \( \text{Fe XII} \) 195.12 Å emission-line intensity observed by EIS. Panels A through C show the line intensity before, at the peak, and near the end of the dimming event, while panels D through F, respectively, show the percentage change in intensity between panels A and B, C and A, and C and B. The solid white contours in panels D and E indicate a 75% reduction in intensity.

Figure 3. Phases of the coronal dimming observed in the nonthermal line width of the \( \text{Fe XII} \) 195.12 Å emission line observed by EIS. Panels A through C show the line width before, at the peak, and near the end of the dimming event, while panels D through F, respectively, show the percentage change in line width between panels A and B, C and A, and C and B. The solid white contours in panels B and C and the black contours in panels D and E indicate a 75% reduction in intensity (from Figure 2).

demonstrated that the nonthermal line widths of these hot coronal emission lines also evolve dynamically, and are very responsive to the large-scale CME-related intensity fluctuations that historically constitute a coronal dimming event.

The rapid growth of the coronal nonthermal line widths appears to be tied to the post-CME evacuation of the dimming region. Further, this rapid growth of nonthermal line widths is followed by a slow decrease, with values beginning to approach their pre-eruption levels—a result of the closing and gradual filling of the corona as the CME cuts its magnetic ties with the Sun (Reinard & Biesecker 2008; Attrill et al. 2008).
In an effort to explain this evolution, we invoke the ubiquitous presence of Alfvénic plasma motions in the chromosphere (e.g., De Pontieu et al. 2007) and corona (e.g., Tomczyk et al. 2007) and their likely connection to the nonthermal line widths measured in the upper atmosphere (e.g., Tomczyk et al. 2007; McIntosh et al. 2008). The observed increase in nonthermal line width in the dimming region is consistent with subresolution density drops, by a factor of $\delta \rho^{1/4}$. Further, as the corona begins to refill, the wave amplitudes should shrink back to their nominal (pre-event closed magnetic topology) value, precisely as we have observed in this instance. We stress that the dynamic behavior of the 195.12 Å nonthermal line widths is mimicked in the other spectrally isolated EIS lines studied for this event, but not shown in this paper (McIntosh 2009).

The likely role of Alfvén waves in the acceleration of the fast solar wind (Suzuki & Inutsuka 2005; De Pontieu et al. 2007; Cranmer et al. 2007; Verdini & Velli 2007) that originates from the dimming region should correlate strongly with the speed of the CME. Such wind streams should “switch-on” on a timescale commensurate with the speed of the CME. This implies that the dimming regions are sources of fast wind streams blowing behind—in the magnetic envelopes of—CMEs. Such wind streams should “switch-on” on a timescale commensurate with the Alfvén crossing time of the region and “blow” for a length of time commensurate with that required for the open magnetic flux behind the CME to close. If this conjecture is indeed true, we would expect that the amount of an unsigned magnetic flux in the dimming region should correlate strongly with the speed of the event. In particular, CME propagation speeds are highly variable, and the dimming region-initiated wind stream on the CME remains to be seen. The hypothesis presented is one that we hope to directly test when the Coronal Multichannel Polarimeter (CoMP; Tomczyk et al. 2007, 2008) instrument begins regular observation from the Mees Solar Observatory on Haleakula early in 2009.

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