Spectroscopy and Differential Emission Measure Diagnostics of a Coronal Dimming Associated with a Fast Halo CME

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Abstract
We study the coronal dimming caused by the fast halo CME (deprojected speed \( v = 1250 \text{ km s}^{-1} \)) associated with the C3.7 two-ribbon flare on 2012 September 27, using Hinode/EIS spectroscopy and Solar Dynamics Observatory (SDO)/AIA Differential Emission Measure (DEM) analysis. The event reveals bipolar core dimmings encompassed by hook-shaped flare ribbons located at the ends of the flare-related polarity inversion line, and marking the footpoints of the erupting filament. In coronal emission lines of log \( T[K] = 5.8–6.3 \), distinct double-component spectra indicative of the superposition of a stationary and a fast upflowing plasma component with velocities up to 130 km s\(^{-1}\) are observed at these regions, which were mapped by the scanning EIS slit close in time to their impulsive dimming onset. The outflowing plasma component is found to be of the same order as and even dominant over the stationary one, with electron densities in the upflowing component of \( 2 \times 10^9 \text{ cm}^{-3} \) at log \( T[K] = 6.2 \). The density evolution in core-dimming regions derived from SDO/AIA DEM analysis reveals impulsive reductions by 40\%–50\% within \( \lesssim 10 \) minutes and remains at these reduced levels for hours. The mass-loss rate derived from the EIS spectroscopy in the dimming regions is of the same order as the mass increase rate observed in the associated white-light CME (1 \( \times 10^{12} \text{ g s}^{-1} \)), indicating that the CME mass increase in the coronagraphic field of view results from plasma flows from below and not from material piled up ahead of the outward-moving and expanding CME front.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – techniques: spectroscopic
Supporting material: animations

1. Introduction
Coronal dimmings are regions that undergo an abrupt reduction in the solar extreme-ultraviolet (EUV) and/or soft X-ray emission, cotemporal with the launch of a coronal mass ejection (CME). “Abrupt depletions” of localized regions in the inner corona were first discussed by Hansen et al. (1974) based on Mauna Loa white-light coronagraph data in association with a H\( \alpha \) prominence eruption and were already presumed to be due to the expulsion of coronal material.

Observations of coronal dimmings in soft X-rays with the Yohkoh SXT (Hudson et al. 1996; Sterling & Hudson 1997) and in the EUV with the Extreme-ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO; Thompson et al. 1998; Zarro et al. 1999) reinforced the interpretation that the reduced emission in coronal dimmings is a result of a density depletion caused by the expansion and evacuation of coronal plasma due to the erupting CME (e.g., Hudson et al. 1996; Harrison & Lyons 2000; Zhukov & Auchère 2004). Coronal dimmings represent the most distinct phenomena associated with CMEs low in the corona and contain important information on their initiation and early evolution, before the CME is observed in coronagraphs. In a recent series of papers, coronal dimmings and the associated CMEs were extensively studied in cotemporal observations from the quasi-quadrature view using the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) and the Extreme-Ultraviolet Imager (EUVI) and COR instruments on board the Solar-Terrestrial Relations Observatory (STEREO). These studies revealed that the maximum extent, the magnetic flux, and the amplitude of the intensity reduction of the dimming region show distinct correlations with the CME mass, whereas the dynamics of the dimming evolution (area growth rate, intensity change rate) is correlated with the CME speed (Dissauer et al. 2018a, 2018b, 2019).

Coronal dimmings are often differentiated into two categories: core and secondary dimmings (Mandrini et al. 2007; Dissauer et al. 2018a). Core (or twin) dimmings are localized areas of strongly reduced emission, located close to the eruption site and rooted in regions of opposite magnetic polarity regions. They are interpreted as marking the footpoints of the erupting flux rope (Hudson et al. 1996; Zarro et al. 1999; Webb et al. 2000) and may reveal de-sharing motions similar to the flare ribbon evolution (Miklenic et al. 2011). On the other hand, the more shallow secondary dimmings are understood to be due to the overlying field that is stretched and partly reconnecting (Thompson et al. 2000; Mandrini et al. 2007; Attrill et al. 2009). Using Differential Emission Measure (DEM) analysis on the multiband AIA EUV imagery, Vanninathan et al. (2018) found significant differences in the plasma properties of the core and the secondary dimming regions, in terms of their depletion depth, rate, and refill time. In the core dimmings, the density dropped impulsively within \(< 30 \) minutes by up to 50\%–70\%, and thereafter stayed at such low levels for more than 10 hr, while the secondary dimmings
evolved more gradually with less strong depletions, and already start to refill 1–2 hr after the start of the event.

Observations of plasma outflows in dimming regions give further evidence that these regions are a result of mass loss and density depletion. However, due to the transient and localized nature of coronal dimmings and the limited spatiotemporal coverage of spectrometers, there exist only a few spectroscopic studies of coronal dimmings. Harrison & Lyons (2000) made the first spectroscopic observation of dimmings using the Coronal Diagnostic Spectrometer (CDS) on board SOHO and showed that the mass loss in dimmings could account for up to 70% of the CME mass. Harra & Sterling (2001) reported significant blueshifts in coronal and transition region lines in CME-associated dimmings, indicative of mass outflows. Harra et al. (2007) presented the first spectroscopic studies of a coronal dimming associated with a halo CME using the Extreme-ultraviolet Imaging Spectrometer (EIS) on board Hinode. They found that the outflows in the dimming regions are highly structured and concentrated in extended loops, with the strongest outflows located at the footpoints of these loops. As shown in Jin et al. (2009), the outflow speeds correlate with the underlying photospheric field strength as well as the magnitude of the dimming.

The plasma outflows in coronal dimming regions are observed at different heights, from the low transition region to the corona (e.g., Jin et al. 2009). As discussed in Tian et al. (2012), spectral lines in coronal dimming regions reveal significant blueshifts and enhanced line widths. The outflow speeds derived from single Gaussian line fits lie mostly in the range of 10–40 km s$^{-1}$. Studying several coronal dimmings, which were well covered in spectroscopic observations by Hinode/EIS, Tian et al. (2012) showed that the coronal emission line profiles in coronal dimmings actually indicate that these are caused by the superposition of a strong background emission component and a relatively weak (of the order of 10%) upflow component with high speeds of $\approx$100 km s$^{-1}$.

In a few events, temperature-dependent outflows were observed. Imada et al. (2007) reported a case of temperature dependence in the outflow speeds on the border of a dimming region. The speed of the flow increased from about 10 km s$^{-1}$ at log $T[K]$ = 4.9 up to 150 km s$^{-1}$ at log $T[K]$ = 6.3. Tian et al. (2012) found that outflows generally do not show any temperature dependence in the majority of the dimming regions and that the temperature-dependent outflows are found only at small regions immediately outside the (deepest) dimming regions.

Finally, we note that the outflows observed from coronal dimmings may also be a relevant parameter in understanding the evolution of CME mass. It has been reported that the CME mass increases from the low corona to 1 au (e.g., Webb et al. 1996; Vourlidas et al. 2000; Tappin 2006; DeForest et al. 2013). Studies of the CME in white-light coronagraph data in the low to mid corona suggest that this increase is predominantly coming from the regions behind the CME and not due to the pile-up (“snow-plow”) of material ahead of the CME front (Vourlidas et al. 2010; Bein et al. 2013; Feng et al. 2015; Howard & Vourlidas 2018). A viable candidate to explain such feeding of mass to the evolving CME from below would be mass flows from the coronal dimming regions (e.g., Temmer et al. 2017).

In this paper, we study Hinode/EIS spectroscopy of a core dimming region that resulted from a fast halo CME, in combination with the plasma diagnostics of the dimming region and its dynamical evolution using the DEM analysis derived from the SDO/AIA EUV filtergrams. As we will demonstrate, localized regions that are “activated” as dimming pixels close in time when mapped by the EIS slit reveal clear double-Gaussian line profiles, where the amount of plasma in the upflowing component can be even larger than that in the stationary background plasma. The estimates of the density and speed of the upflowing plasma will be set in comparison with the increase of mass of the associated CME derived from the STEREO coronagraphs up to a distance of 15 solar radii.

2. Data and Observations

The coronal dimming studied in this paper is associated with an eruptive C3.7 class flare which occurred on 2012 September 27 at (N09°, W33°) in NOAA Active Region 11577. The start of the GOES soft X-ray flare was at 23:36 UT with the maximum reached at 23:57 UT. Despite being only of GOES class C3.7, the event was an extended two-ribbon flare associated with a fast halo CME with a mean projected plane-of-sky speed of about 950 km s$^{-1}$, as listed in the LASCO CME catalog (https://cdaw.gsfc.nasa.gov/CME_list/; Yashiro et al. 2004). Notably, this CME was associated with a magnetic cloud measured in situ at L1 on 2012 October 1 (start time around 00:00 UT) and produced a strong geomagnetic storm with aDst of $-122$ and Kp of 7–.

The full-disk multiband EUV images recorded by the AIA (Lemen et al. 2012) on board the SDO (Pesnell et al. 2012) captured the evolution of this event with high spatial and temporal resolution. The EIS (Culhane et al. 2007) on board Hinode (Kosugi et al. 2007) was pointed at NOAA 11577 and captured part of the western flare ribbons as well as the associated western core dimming region. Thus, this event provides us with an excellent opportunity to study the plasma flows and densities in coronal dimming regions spectroscopically (with EIS) as well as via DEM diagnostics (with AIA).

The AIA instrument on board SDO observes the solar corona in six EUV wavelength bands, centered at 94, 131, 171, 193, 211, and 335 Å, thus providing plasma diagnostics over a temperature range of log $T[K]$ = 5.7–7.0 (Lemen et al. 2012). In addition, AIA observes the lower transition region and upper chromosphere in the He II line centered at log $T[K]$ = 4.7. The observing cadence of the AIA EUV channels is 12 s, and the pixel scale of the CCD is 0.6.

The EIS observations of the event consist of one raster taken between 23:10:27 UT and 00:20:36 UT, covering an area of 302′/5 × 384′/0. The scan was in 101 steps (from right to left) using a slit width of 2″, slit height of 384″, and a pixel size of 1″ in the y-direction. The exposure time for each slit position was 40 s. In total, 25 spectral windows were registered, and the observed spectral lines cover a wide range of temperature of log $T[K]$ = 4.7–7.2. In this study, we focus on the spectral lines where the dimming region is clearly visible and can be compared with AIA images. For this purpose, we selected the following EIS spectral lines: Fe XIII at 196.55 and 202.04 Å (log $T[K]$ = 6.2), Fe XV at 284.16 Å (log $T[K]$ = 6.3), and

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4. See the Richardson and Cane ICME list, http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.txt.
Si VII at 275.37 Å (log $T[K] = 5.8$). The Fe XIII line ratios are used for density measurements. Lines with the signature of blends were not used in this study; this includes the strongest line Fe XII at 195.12 Å. We note that the Fe XV line at 284.16 Å is actually blended with the AlIX 284.03 line. However, as shown in Young et al. (2007), the AlIX line at 284.03 Å only becomes apparent in quiet-Sun conditions, where the Fe XV emission is very weak. In our observations of AR 11577, the signal is strong and dominated by Fe XV emission.

The compensation of all known photometric effects in the EIS spectral data and their calibration to physical units were performed using the eis_prep.pro routine, which is part of SolarSoftWare. The wavelength drift was corrected by the method described in Kamio et al. (2010). As a first approximation, the spectral profiles of the selected lines were fitted by a single Gaussian function with a linear background in order to determine the spectral characteristics of the observed profiles, i.e., spectral amplitude, integrated intensities, background intensities, Doppler shifts, and spectral widths. The EIS data provide no absolute wavelength calibration, and thus the zero reference of the Doppler shifts was calculated as the average value of the Doppler shifts from quiet-Sun regions, which were not directly affected by the flare or dimming. The EIS data recorded at different wavelengths are affected by a spatial offset in the y-direction. This offset was compensated for by the spectral lines under study. Thus, the spatial pixels of the different EIS spectral windows correspond to the same area on the Sun. Finally, the acquired EIS raster was co-aligned with the AIA filtergrams. For this purpose, we used an AIA image recorded in the 211 Å filter to co-align with the EIS Fe XIII 202.04 Å raster, as they both are probing solar plasmas at similar temperatures. We chose the AIA image recorded on 2012 September 28 at 00:06:11 UT, as this corresponds to the time when the EIS slit was scanning the inner part of the triangular-shaped western dimming region, in which we are mostly interested. The position of the EIS raster relative to the AIA image was calculated by applying a spatial cross-correlation on the two images, and we obtained a shift between the nominal EIS and AIA coordinate systems of $x = 11.75'$ and $y = 9.0'$. These corrections were applied to the EIS data, and the coordinate system of AIA was used as reference.

Apart from spectroscopy, DEM analysis on filter images provides an alternative method to retrieve information on the plasma parameters. The added value of the AIA DEM analysis lies in the possibility of studying the dynamic evolution of the plasma parameters in the dimming regions, whereas EIS provides us with a snapshot of the full spectroscopic information. In the present case, we only have one EIS scan available during the event and no information on the pre-event coronal state. We have used the regularized inversion method of Hannah & Kontar (2012, 2013) to derive the DEM from the six AIA EUV filters for every pixel of the image. The AIA images and thus the reconstructed DEM maps have a pixel resolution of 0.6. We use the same approach as described in Vanninathan et al. (2018) to derive for each time step a map of the plasma density. From the retrieved DEM maps, $\phi(T)$, we calculate for each pixel the total emission measure EM and the mean plasma density $n$ using the following expressions:

$$ EM = \int \phi(T) dT, \quad (1) $$

and assuming a filling factor of unity, the mean plasma density is calculated as

$$ n = \sqrt[\frac{EM}{h}], \quad (2) $$

with $h$ the integration height contributing to the optically thin emission in the line of sight. In the case where the integration height $h$ does not vary considerably during the event, its exact value cancels out when calculating the relative changes of the density $n$ with respect to the pre-event state, i.e.,

$$ \frac{n(t)}{n(t_0)} \propto \sqrt[\frac{EM(t)}{EM(t_0)}]. \quad (3) $$

However, we note that during the event, the integration height $h$ might actually change; in particular, it may get larger due to the field line stretching and the expansion of the plasma in the dimming regions. In this case, the density drop we derive according to Equation (3) (i.e., under the assumption of a constant integration height $h$) provides a lower limit, and the actual density drop corresponding to the measured drop in EM might be larger than the estimate we give.

For the analysis of the time evolution of the plasma parameters in selected core dimming regions, the AIA and DEM image sequences were corrected for solar differential rotation to a reference frame recorded before the event start at 23:06 UT.

3. Results

3.1. Event Overview and Magnetic Configuration

Figure 1 and its associated movie give an overview of the evolution of the event in AIA 94 Å (Fe XVIII, log $T[K] = 6.8$), AIA 304 Å (He II, log $T[K] = 4.7$), and 211 Å (Fe XIV, log $T[K] = 6.3$) direct images as well as AIA 211 Å base ratio images. The image sequences illustrate the evolution of the C.7 two-ribbon flare as well as the formation and evolution of pronounced core dimmings. The hook-shaped ends of the flare ribbons encompass the dimming regions as is best visible in the 304 Å filter in Figure 1.

In Figure 2, we show snapshots of the fast halo CME associated with the event as observed by the LASCO C2 (Brueckner et al. 1995) and STEREO COR1 and COR2 (Howard et al. 2008) coronagraphs. Notably, LASCO observes the event as a halo CME with a plane-of-sky speed of 950 km s$^{-1}$ that impacted Earth about four days later and produced a strong geomagnetic storm. The two STEREO satellites were longitudinally separated from Earth by ±105° and observed the CME on the eastern and western limbs, respectively.

As can be seen in Figure 1, the core dimming region located at the southern end of the western flare ribbon is strongly pronounced in all AIA filters, indicative of a broad distribution of plasma temperatures. Notably, the second core dimming region located at the northern end of the eastern flare ribbon appears most pronounced in the cool AIA 304 Å filter mapping the upper chromosphere and lower transition region plasma, and is barely visible in the coronal AIA filters. This is an unusual observation. Dissauer et al. (2018b) reported that coronal dimmings appear strongest in the AIA 211 and 193 Å filters, which are most sensitive to quiet coronal plasma...
temperatures, and only 15% are detectable in the “cool” 304 Å filter. We also note that in all of the AIA filters, both core dimmings also reveal elongations along the outer edge of the two conjugate flare ribbons (see Figure 1, in particular the second row at 23:45 UT). These are associated with the disappearance of the pre-eruptive arcade, as can be most clearly seen in the 211 Å filtergrams (see the movie accompanying Figure 1, 23:06–23:36 UT).

Inspection of Hα filtergrams from the GONG network (not shown) revealed that the event was also associated with the eruption of a long S-shaped filament aligned in the north–south direction, with the slow rise of the filament starting substantially earlier (≤22:30 UT) than the flare. The filament eruption can be also seen in the movie associated with Figure 1, in particular in the AIA 304 and 211 Å filters. The movie shows that the core dimming region located at the hooked ends

Figure 1. Overview of the evolution of the coronal dimming associated with the C7.3 flare and the halo CME of 2012 September 27 in SDO/AIA 94, 304, and 211 Å direct images as well as 211 Å base ratio images. All images are logarithmically scaled. The red lines drawn in the second AIA 211 Å base ratio panel outlines the northern and western borders of the Hinode/EIS raster. The still figure shows snapshots of the event at four time steps (annotated in each panel). The movie shows the event evolution from 2012 September 27, 23:06 UT, to September 28, 00:30 UT. (An animation of this figure is available.)
of the western flare ribbon is located at the northern footpoint of the erupting filament.

In Figure 3, we show a line-of-sight magnetogram from the Helioseismic Magnetic Imager (Scherrer et al. 2012) together with an AIA 304 Å map at 23:45 UT. The contours of the dimming regions extracted from the AIA 304 Å filtergram plotted on top of the two images confirm the bipolar nature of the core dimming region, with the western dimming rooted in positive fields, and the eastern dimming rooted in negative fields. In the second panel of the AIA 211 Å images in Figure 1, we indicate the boundaries of the FOV of the EIS raster (red lines). As can be seen, the triangular-shaped core dimming region located at the southern end of the western flare ribbon was captured by the EIS spectra. It is the main region of interest for the following spectroscopic study.
3.2. EIS Spectroscopy

Figure 4 shows an EIS intensity map in the Fe XIII 202.04 Å spectral line (middle panel) and the corresponding velocity map derived from the single Gaussian fits (right panel) together with an AIA 211 Å image (left panel). The contours plotted on the EIS intensity map are from the AIA 211 Å image and demonstrate the spatial overlap of the structures observed by the two instruments after the co-alignment described in Section 2.

As core dimming regions are suspected to be footpoints of expanding flux ropes, it is expected to see plasma outflows in this area. This aspect is reinforced by the EIS velocity map shown in Figure 4 (right panel). The areas of the strongest blueshifts on the velocity map (indicative of outflows) coincide with the darkest areas on the intensity map, in particular the dark triangular core dimming region as well as the elongations of the dimming region on the outer front of the flare ribbon. The outflow velocities derived from the single Gaussian fits in these regions reveal typical values of some 10 km s$^{-1}$ but can also reach values up to 40–70 km s$^{-1}$. Strong downflows are observed at the location of the flare ribbons, which presumably result from coronal condensation of plasma in the postflare loops.

Comparison with Figure 1 and the associated movie shows that the triangular-shaped western dimming region started to form at about 23:35 UT on 2012 September 27 and is fully pronounced and dark around 23:45 UT. Note that between 23:35 UT and 23:45 UT, material from the erupting filament partially obscured this dimming region (see AIA 211 Å difference images), but thereafter it has moved out of the FOV shown in Figure 1. After 23:45 UT, we can observe that the dimming region is still slightly growing toward the western direction until ∼00:05 UT on 2012 September 28. This growth is most distinctly seen in the evolution of the hooked flare ribbon that forms the western boundary of the dimming region, which we interpret as a signature of magnetic reconnection along the boundary of the newly “opened” fields.

When studying the EIS intensity and velocity maps shown in Figure 4 in relation to the evolution observed in AIA, it is important to note that the EIS slit rastered the FOV from west (start 23:10 UT) to east (end 00:21 UT). This means that the triangular-shaped dimming region (starting at its westernmost segment at x ∼ 570°) is the first time covered by the EIS slit at ∼00:03 UT on 2012 September 28.

Figure 5 shows a zoom into the EIS Fe XIII 202.04 Å intensity and velocity maps, where we inspected the spectral line profiles of the dimming regions. Particular pixels of interest, for which we show the spectral line profiles in Figure 6, are indicated by yellow quadrangles. The top panels of Figure 6 show four spectral profiles in the Fe XIII 202.04 Å line, while the bottom panel shows for the same pixels the line profiles in the Fe XV line at 284.16 Å, both together with the corresponding double-Gaussian fits. The four pixels shown have been covered by the EIS slit at different times, in total about 2 minutes apart. The rightmost pixel was on the EIS slit at about 00:03:30 UT, and the leftmost pixel at about 00:05:40 UT.

The EIS Fe XIII and Fe XV line profiles reveal an interesting behavior. Most of the profiles within the dimming region can be fitted by a single Gaussian. However, as we go toward the regions of strongest blueshifts, we see that a second component starts to develop. All of the spectra shown in Figure 6 reveal a clear double component and can be well fitted by two Gaussians. The primary component is consistent with nearly stationary plasma; the derived speeds in this component are all very small, ranging from −3 to +8 km s$^{-1}$.

The second component reveals upflowing plasma with high speeds. The velocities obtained from this component range from −78 to −135 km s$^{-1}$ for the Fe XIII 202.04 Å line, and −115 to −130 km s$^{-1}$ for the Fe XV 284.16 Å line. Note that in several pixels, the intensity of the second (i.e., upflowing) component matches that of the primary (i.e., stationary) component, and may even overshoot it by almost a factor of 2. Finally, we note that also in the Si VII 275.37 Å line, we identified several pixels in the dimming region that show a
components is obtained for the position and stationary plasmas. The best separation between the two performed in order to separate the emissions from the outflowing plasma. Two-component diagnostics is very close to the Fe XII line at 196.64 Å, which forms at similar temperatures. Thus, the Fe XII 196.64 Å line also shows an outflow component that lies close to the stationary component of the Fe XIII 196.55 line. This affects the density diagnostics for the stationary component. (The density diagnostics for the outflow component is likely not affected.) Therefore, we were very careful with the interpretation of the determined densities, and we give only the values derived for the one EIS pixel where we identified the strongest upflows. It was the only spectrum where we could fit both lines with two components, so that we had some estimate of how much the dynamic component of the Fe XII line is affecting the static component of the Fe XIII line.

As the EIS data consist of only one raster, meaning only one observation per EIS pixel, we use AIA data to study the temporal evolution of the dimming region and the associated density depletion from the reconstructed DEM maps. We have used 3.5 hr of AIA data, which include 30 minutes of preflare to estimate a background level, and continue until 3 hr after the start of the flare.

In Figure 7, we show the time evolution of the plasma density derived in the regions corresponding to the EIS pixels shown in Figures 5 and 6. These values are normalized to the pre-event state, so we can directly assess the percentage density drop within the dimming regions. In the pixels shown, the density drops by 40%–50% and remains at these reduced levels for the whole period shown. The distinct (double) density enhancements observed before the density drop related to the coronal dimming are caused by the erupting filament plasma and the bright ribbon fronts on the outer border of the growing dimming region that come into the pixel’s FOV.

To relate the evolution of the densities reconstructed from the AIA DEM maps (Figure 7) in the 4 pixels indicated in Figure 5 with the corresponding spectra and flows determined from the EIS scan (Figure 6), we need to relate the dynamics observed in AIA with the time at which the EIS slit covered the particular pixels. We first discuss the behavior of the top three pixels plotted in Figure 7, and thereafter the bottom-most one, which is related to different structures as we will show.

In the density evolution retrieved from the DEM maps (Figure 7), we can see that the sharp density drop due to the dimming occurs first in the leftmost (easternmost) pixel, and thereafter in the two neighboring pixels to the right. This is consistent with the expansion of the dimming region toward the west, i.e., from left to right (see Figure 8 and the associated movie). On the other hand, EIS was in scanning mode, and we may expect to see the largest upflow components in those pixels that have been activated as dimming pixels (i.e., the associated fields were “opened”) closest in time to when the EIS slit was mapping them.

The EIS scan was from west to east, and the strongest upflow component is observed at the pixel \((x = 563", y = 44")\), which was covered by the slit at 00:04:16 UT. This is the pixel where we find that the total amount of upflowing plasma is larger than the stationary plasma component. The AIA density evolution shows that in this pixel, the strong drop in the density, indicative of the impulsive dimming onset, starts exactly at that time when it was mapped by the EIS slit. In the neighboring EIS pixel to the left, centered at \(x = 560"\), the impulsive density drop occurred during 23:58 to 00:06 UT, and the EIS slit covered it during this time range at 00:04:58 UT. This

![Figure 5](image.png)

**Figure 5.** EIS intensity (top) and velocity (bottom) maps derived from the Fe XIII 202.04 Å spectral line showing a zoom to the dimming region under study (see green box in Figure 4). The yellow quadrangles mark pixels that correspond to the EIS spectral profiles shown in Figure 6.

double component indicative of upflows with velocities of \(-60 \text{ to } -70 \text{ km s}^{-1}\). In general, the Si VII data is very noisy, making it difficult to obtain line profiles in every pixel.

### 3.3. Density Diagnostics

To estimate the electron densities in the core dimming region under study, we use the intensity ratio of the Fe XIII spectral lines observed at 196.55 and 202.04 Å. We note that the presence of blends in other EIS spectral lines, including the strongest lines of Fe XII at 195.12 Å and Fe XIII at 203.82 Å, renders them complicated to use for our study. Correcting the blends and then fitting double-component profiles require more than three Gaussians, which reduce the accuracy of the results obtained.

As is seen in the spectral line profiles plotted in Figure 6, the EIS spectra in these areas of the core dimming region consist of two components indicative of a static and a fast upflowing plasma. Two-component fitting of both spectral lines was performed in order to separate the emissions from the outflowing and stationary plasmas. The best separation between the two components is obtained for the position \((x = 563", y = 43")\) in the core dimming region. The calculated electron densities for this EIS pixel is \(2.25 \times 10^9 \text{ cm}^{-3}\) for the outflowing plasma and \(1.13 \times 10^9 \text{ cm}^{-3}\) for the stationary plasma.

We note that the Fe XIII line at 196.55 Å used for density diagnostics is very close to the Fe XII line at 196.64 Å, which forms at similar temperatures. Thus, the Fe XII 196.64 Å line also shows an outflow component that lies close to the stationary component of the Fe XIII 196.55 line. This affects the density diagnostics for the stationary component. (The density diagnostics for the outflow component is likely not affected.) Therefore, we were very careful with the interpretation of the determined densities, and we give only the values derived for the one EIS pixel where we identified the strongest upflows. It was the only spectrum where we could fit both lines with two components, so that we had some estimate of how much the dynamic component of the Fe XII line is affecting the static component of the Fe XIII line.

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In the density evolution retrieved from the DEM maps (Figure 7), we can see that the sharp density drop due to the dimming occurs first in the leftmost (easternmost) pixel, and thereafter in the two neighboring pixels to the right. This is consistent with the expansion of the dimming region toward the west, i.e., from left to right (see Figure 8 and the associated movie). On the other hand, EIS was in scanning mode, and we may expect to see the largest upflow components in those pixels that have been activated as dimming pixels (i.e., the associated fields were “opened”) closest in time to when the EIS slit was mapping them.

The EIS scan was from west to east, and the strongest upflow component is observed at the pixel \((x = 563", y = 44")\), which was covered by the slit at 00:04:16 UT. This is the pixel where we find that the total amount of upflowing plasma is larger than the stationary plasma component. The AIA density evolution shows that in this pixel, the strong drop in the density, indicative of the impulsive dimming onset, starts exactly at that time when it was mapped by the EIS slit. In the neighboring EIS pixel to the left, centered at \(x = 560"\), the impulsive density drop occurred during 23:58 to 00:06 UT, and the EIS slit covered it during this time range at 00:04:58 UT. This
finding is consistent with EIS still showing a large upflow component, but less strong than in the previous pixel. Finally, the pixel centered at \( x = 557'' \) reveals its impulsive density drop during 23:53 to 23:57 UT, i.e., before it was covered by EIS at 00:05:39 UT, which is consistent with the even smaller upflow plasma component observed here.

The EIS pixel centered at \( x = 566'' \) is an exception to the timing behavior described above, as its impulsive density drop occurs already during 23:55 to 00:04 UT, i.e., before the westward growing dimming bordered by the bright flare ribbon reached this pixel. Inspection of the movie and still images in Figure 8 reveals that this region dims due to the disappearance of a loop connecting toward the southwest direction. However, this pixel also follows the overall rule to show a significant upflowing plasma component as it was covered by the EIS slit during the phase of impulsive density drop (similar to pixel \( x = 560'' \)).

Finally, we note that the western dimming region under study was formed in most of its extent already at 23:45 UT on 2012 September 27. The strongest upflow components in the dimming region that we measure in the EIS scan refer to the period 00:03 to 00:05 UT on 2012 September 28 when the EIS slit started to actually scan the dimming region. This means we missed the formation and early evolution of the major part of the coronal dimming in the EIS spectra. However, even at these later times, distinct upflows are registered by EIS all over the dimming region (see Figure 3, right panel). The clear two-component spectra, indicative of strong upflowing plasma components, are observed predominantly for those pixels that are located on the newly formed outer dimming segments, behind the propagating bright flare ribbon that surrounds the dimming region.

### 3.4. Mass Evolution of the Associated CME

In the following, we study the mass evolution of the associated white-light CME and compare the outcome to the plasma outflows from the coronal dimming regions. The CME was observed by the coronagraphs on board three satellites located at different positions in the heliosphere: SOHO, STEREO-A, and STEREO-B (see Figure 2). For the CME analysis, we use the COR1 and COR2 coronagraphs on board STEREO-A, which observed the CME close to the limb, i.e., in its plane of sky (for STEREO-A, the source region was located at 72° east). The kinematics of the CME front derived from STEREO-A gives a mean speed of 1250 km s\(^{-1}\). This is higher than the 950 km s\(^{-1}\) listed in the LASCO CME catalog, which is to be expected, as LASCO observed the CME head on as a halo and thus the LASCO measurements mostly reflect the CME expansion and not its propagation speed.

We use the method of Bein et al. (2013) to derive the mass evolution from the STEREO-A coronagraph data. This method accounts for the effect of the occultor disk, which masks part of the CME structure in the low corona depending on the CME direction and 3D structure relative to the viewing direction of the observing spacecraft. From this information, an effective occultation height is derived and is used to separate this “geometric” effect on the derived mass evolution from the physical one.

Figure 9 shows the evolution of the CME mass calculated with this method as a function of height of the CME front. The steep mass increase in the COR1 field of view \((1.4 \times 4 \text{ Rs})\) is due to mass emerging from behind the occulting disk when the CME moves outward, i.e., it is not a real mass increase. A similar trend is seen for the early evolution of CME mass in COR2. We apply the functional fit developed in Bein et al. (2013) to quantify both the effect of the coronagraph occultor lower in the corona and the actual mass evolution. From the fit (shown by the solid red line in Figure 9), we can derive the effective occultation height, the initial CME mass injected \((m_0)\), and a mean rate of increase of the CME mass \(\Delta m\). For the event under study, we obtain a mass increase rate of \((5.4 \pm 0.9) \times 10^{14} \text{ g per solar radius passed by the CME.} \) For a mean CME speed of 1250 km s\(^{-1}\), this corresponds to a mass increase rate of about \((9.7 \pm 1.6) \times 10^9 \text{ g s}^{-1}\).

From the EUV spectral and imaging information provided by EIS and AIA, we can obtain an order-of-magnitude estimate of the mass flux from the dimming outflows. The total area of the dimming regions outlined in Figure 3 is \(A_d = 1.6 \times 10^{15} \text{ cm}^2\). The upflow speeds in the dimming pixels which reveal a clear double-Gaussian component are of the order of \(v_{up} \approx 100 \text{ km s}^{-1}\). The number density in the upflowing plasma derived from EIS spectroscopy is \(n_{up} = 2.25 \times 10^9 \text{ cm}^{-3}\), which relates to a
mass density of $\rho_{up} = 4.8 \times 10^{-15}$ g cm$^{-3}$ using a mean molecular mass for solar abundances of $\mu = 1.27$ (Anders & Grevesse 1989). From these quantities, we can estimate the mass-loss rate related to the upflowing plasma in the dimming region as

$$\frac{dm_{up}}{dt} = A_d \rho_{up} v_{up} = 7.7 \times 10^{11} \text{ g s}^{-1}.$$  \hspace{1cm} (4)

We note that this should probably be considered as an upper estimate, as we assumed the whole dimming region to contribute with the same “strength” (in terms of density of the upflowing plasma and outflow speed) as derived from the EIS pixels that showed the clearest and strongest upflow components. Also, we do not know how long the outflows are actually present as we have only one EIS scan. However, it is

Figure 7. Time evolution of the relative density changes, i.e., actual density divided by its pre-event value, derived from AIA DEM maps for pixels corresponding to the EIS spectra in Figure 6. The segments in red indicate the phase of the impulsive density drop: its start is defined by the data steeply decreasing below 1, and its end is calculated from the time derivative of the curve (defined by the first positive increase). The green vertical lines indicate the time at which the corresponding pixel was covered by the EIS slit.

Figure 8. Evolution of the western dimming region in SDO/AIA 211 Å filtergrams. We show the same zoomed FOV as for the EIS maps in Figure 5. The yellow boxes mark pixels for which we show the EIS spectral profiles in Figure 6. The still figure shows the event at two time steps (annotated in each panel). The animated figure shows the event evolution from 2012 September 27, 23:50 UT to September 30, 01:16 UT. (An animation of this figure is available.)

Figure 9. Mass evolution against height for the CME associated with the C3.7 flare of 2012 September 27, derived from STEREO-A COR1 (red asterisks) and COR2 (blue asterisks) white-light observations. The observing times related to the data points are given in the inset. The dashed red line gives the fit to the COR1 data, the solid red line shows the real mass evolution after accounting for the occultor effect. The derived values for the mass increase per solar radius ($\Delta m$) and the initial CME mass $m_0$ are given in the legend. The dashed line indicates the initial CME mass $m_0$. 

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interesting to note that this order-of-magnitude estimate of the mass-loss rate in the plasma upflows calculated from the coronal dimming regions is of the same magnitude as the mass increase rate observed in the white-light CME.

4. Discussion and Conclusions

In this paper, we studied a coronal dimming caused by the launch of a fast halo CME (deprojected speed of 1250 km s\(^{-1}\)) associated with the C3.7 two-ribbon flare on 2012 September 27, using Hinode/EIS spectroscopy and SDO/AIA DEM analysis. Our main findings and conclusions are the following:

1. We observe bipolar core dimming regions encompassed by hook-shaped flare ribbons located at the ends of the flare-related polarity inversion line (Figure 3). The event is associated with the eruption of a filament, which reveals its footpoints at the core dimming regions formed during its ejection (Figure 1). The dimming region grows in the regions directly behind the expanding hooked parts of the bright flare ribbons. In addition, the core dimming regions also reveal elongations along the outer edges of the two conjugate flare ribbons.

2. Plasma upflows with typical speeds of some 10 km s\(^{-1}\) but up to 40–70 km s\(^{-1}\) (as derived from single Gaussian fits) are observed all over the western core dimming region covered by Hinode/EIS, although parts of it were mapped by the EIS slit \(\geq 20\) minutes after the local dimming formation (Figures 4, 5).

3. Distinct double-component spectra indicative of the superposition of a stationary and a fast upflowing plasma component are observed at those pixels at the growing dimming border, which were mapped by the EIS slit close in time (i.e., within a few minutes) to their impulsive dimming onset (Figure 6). In some EIS pixels, the upflowing plasma component is even dominant over the stationary one (by up to a factor of 2). The velocities derived for the upflowing component are up to \(-130\) km s\(^{-1}\) for the Fe X\(\text{III} 202.04\ \text{Å} \left(\log T [\text{K}]=6.2\right)\) and Fe XV 284.16 Å \(\left(\log T [\text{K}]=6.3\right)\) lines, and up to \(-70\) km s\(^{-1}\) in the Si VII 275.37 Å line \(\left(\log T [\text{K}]=5.8\right)\).

4. Electron density estimates in the core dimming region using the intensity ratio of the EIS Fe X\(\text{III} 196.55\) and 202.04 Å spectral lines give \(2.25 \times 10^9\ \text{cm}^{-3}\) for the outflowing plasma and \(1.13 \times 10^9\ \text{cm}^{-3}\) for the stationary plasma. The dynamics of the relative density changes in core dimming regions derived from SDO/AIA DEM analysis reveals impulsive reductions by \(40\%–50\%\) within \(\leq 10\) minutes. The densities remain at this reduced level for \(>2.5\) hr after their initiation (Figure 7).

5. From the EIS dimming observations, we estimate a mass outflow from the dimming region of about \(8 \times 10^{11}\ \text{g s}^{-1}\). This estimate is close to the mass increase of about \(1 \times 10^{12}\ \text{g s}^{-1}\) observed in the associated white-light CME in the STEREO COR1 and COR2 fields (Figure 9).

The elongated dimmings on the outer front of the flare ribbons can be understood in the frame of the standard 2.5D eruptive flare model, in which the overlying coronal arcade is stretched by the rising CME, causing dimmings at its footpoints (Forbes & Lin 2000; Cheng & Qiu 2016). Subsequently, the arcade field then reconnects and causes the bright flare ribbons at the edge of the elongated dimming regions. In this case, it is expected that the dimming appears before the flare ribbons. In the event under study, we can in fact see how the pre-eruptive arcade associated with the elongated dimmings disappears while the dimming and flare ribbons subsequently form (see the movie accompanying Figure 1, in particular the 211 Å data).

However, to understand the morphology of the core dimming regions encompassed by the hook-shaped (double J-shaped) flare ribbons, and the relation between the local flare ribbon expansion and the growth of the encompassed dimming region, we need the framework of three-dimensional extensions to the standard eruptive flare model (Aulanier et al. 2012; Janvier et al. 2015). In this three-dimensional geometry, the flux rope is surrounded by quasi-separatrix layers (QSLs), i.e., thin layers of steep gradients in field-line connectivities, and the QSL footprints have a curved shape whose endings map to the outer edges of the flux-rope footpoints, which can be related to the hook-shaped flare ribbons (Démoulin et al. 1996; Aulanier & Dudík 2019).

The double-component Hinode/EIS spectra indicating the superposition of stationary and upflowing plasma components in core dimming regions and outflows with velocities up to \(130\) km s\(^{-1}\) support the findings of Tian et al. (2012), who performed an extensive spectroscopic study of several well-observed dimming events. In our case, we find that in pixels that are initiated as dimmings close in time to their mapping by the scanning EIS slit, the outflow components can be of the same order as (and even bigger than) the stationary plasma component, whereas in Tian et al. (2012) the outflow components observed are mostly weak (of the order of \(10\%\) of the stationary component).

The strong outflow component we find in the coronal EIS spectra is consistent with the distinct and impulsive density reductions of \(40\%–50\%\) derived from the SDO/AIA DEM analysis. Similar and even stronger reductions of \(50\%–70\%\) in core dimming regions derived from DEM analysis have been reported in the six events studied in Vanninathan et al. (2018), suggesting that about half and up to two-thirds of the pre-eruption plasma has escaped the core dimming regions. We note that these values are most probably lower estimates, as accounting for an increase of the integration height \(h\) during the event (which may be expected due to the field line stretching and plasma expansion in the dimming regions) would result in even larger density drops calculated from the EM evolution.

We note that there are basically two ways to look at the upflows observed in the dimming regions. Either they are interpreted as mass outflows in the regions where the magnetic field is locally opened and/or expanding due to the erupting CME (e.g., Harrison & Lyons 2000; Harra et al. 2007), or they are interpreted as a source of plasma refilling the corona following an eruption (Tian et al. 2012). In the case under study, we strongly favor the first option for the following reasons: the high upflow speeds derived; the strong upflow component, which is of the same order as the stationary plasma component; and the impulsive reduction of density in the dimming regions associated with strong upflows, which remains at these low levels for hours after the eruption without indication of refilling. The order of magnitude estimates of the mass-loss rate of the plasma flows in the dimming region, which lies in the same range as the mass increase rate in the associated white-light CME, also supports this interpretation.

Bein et al. (2013) studied the mass evolution in the coronagraphic field of view for a set of 25 CMEs. They found a distinct mass increase (of the order of a few percent) in all of the cases, and that the CME center of mass reveals a tendency
to fall backward with respect to the overall outward-moving CME structure. These findings also favor the interpretation that the source of the mass increase is plasma flows from below and not the pile-up of coronal material ahead of the CME (Vourlidas et al. 2010; Feng et al. 2015; Howard & Vourlidas 2018). A similar conclusion was also drawn in the case study by Temmer et al. (2017) from comparison of the area evolution of the core dimming regions and the mass increase in the white-light CME.

Finally, we note that the current case study reinforces the extensive potential of coronal dimmings to better understand and characterize solar eruptions. Coronal dimmings contain important information on the pre-eruptive configuration of CMEs, their initiation and early impulsive evolution, and the relation to the associated flare as well as on some of the CME’s key properties like mass and speed (see also the recent statistical studies by Dissauer et al. 2018b, 2019).

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