Formation of Coronal Mass Ejection and Posteroation Flow of Solar Wind on 2010 August 18 Event

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Abstract

The state of the space environment plays a significant role in the forecasting of geomagnetic storms produced by disturbances of the solar wind (SW). Coronal mass ejections (CMEs) passing through the heliosphere often have a prolonged (up to several days) trail with declining speed, which affects propagation of the subsequent SW streams. We studied the CME and posteroation plasma flows behind the CME rear in the event on 2010 August 18 that was observed in quadrature by several space-based instruments. Observations of the eruption in the corona with EUV telescopes and coronagraphs revealed several discrete outflows followed by a continuous structureless posteroation stream. The interplanetary coronal mass ejection (ICME) associated with this CME was registered by the Plasma and Suprathermal Ion Composition instrument aboard the Solar Terrestrial Relations Observatory between August 20, 16:14 UT and August 21, 13:14 UT, after which the SW disturbance was present over 3 days. Kinematic consideration with the use of the gravitational and drag-based models has shown that the discrete plasma flows can be associated with the ICME, whereas the posteroation outflow arrived in the declining part of the SW transient. We simulated the Fe ion charge distributions of the ICME and post-CME parts of the SW using the plasma temperature and density in the ejection region derived from the differential emission measure analysis. The results demonstrate that in the studied event, the post-ICME trailing region was associated with the posteroation flow from the corona rather than with the ambient SW entrained by the CME.

Unified Astronomy Thesaurus concepts: Solar corona (1483); Solar wind (1534); Solar physics (1476); Solar coronal mass ejections (310)

1. Introduction

Interplanetary plasma consisting mainly of the slow-moving solar wind (SW) represents a medium in which recurrent disturbances of the SW associated with fast quasistationary streams from coronal holes and nonperiodic disturbances associated with coronal mass ejections (CMEs) propagate (Lüst 1963; Russell 2001). Depending on their magnitude and direction, CMEs may give rise to geomagnetic storms and scattering of galactic cosmic rays and produce other perturbations of the entire near-Earth environment. Thus, detection of CME initiation in the solar corona and prediction of its propagation in the heliosphere is one of the most important tasks of space weather forecasting. Such predictions commonly consist of an estimation of the arrival time and speed of the CME front structure toward the observation site without taking into account the posteroation effects. However, very often (see, e.g., Lugaz et al. 2017; Rodkin et al. 2018), due to their large-scale structure, successive CMEs may interact in the heliosphere, which results in a change of their initial kinematic and magnetic parameters. A statistical study of Temmer et al. (2017) in the time period 2011–2015 has shown that CMEs often are followed by a trailing region behind their rear that has declining speed and a duration up to several days, which is much longer than the average CME duration itself (about 1.3 days). As a result, powerful CMEs can cause disturbances of the interplanetary medium, which may lead to significant deviations in the CME arrival times and speeds from those initially predicted, especially in the case of slow CMEs (Möstl et al. 2014; Corona-Romero et al. 2017; Shugay et al. 2018; Ravishankar & Michalek 2019).

The aim of this work is to clarify the nature of the post–interplanetary coronal mass ejection (ICME) perturbation of the SW: whether it is associated with entrainment of the interplanetary medium by the earlier CME or with some post-CME plasma flow from the eruption site. We consider the case of the large eruption that occurred on 2010 August 18 at the western solar limb, which was observed by several space telescopes and coronagraphs that studied formation of the eruption flows in the corona and in the heliosphere and established the correspondence between the flows and the SW disturbances measured in situ. The state of the coronal plasma during the eruption process was determined from the differential emission measure (DEM) analysis performed on the basis of the multiwave EUV images. The DEM function describes the amount of thermal plasma along the line of sight at a given electron temperature retrieved from intensities in spectral bands with different temperature responses. By separating emission in specific temperature ranges, DEM enables us to discern the spatial and temporal dynamics of coronal structures participating in the eruption process (e.g., Grechnev et al. 2019; Saqri et al. 2020; Heinemann et al. 2021). A number of algorithms have been developed to derive a coronal DEM from Solar Dynamic Observatory (SDO)/Atmospheric Imaging Assembly (AIA) images in multiple bandpasses (e.g., Hannah & Kontar 2012; Plowman et al. 2013; Plowman & Caspi 2020). Detailed comparison of different algorithms is beyond the scope of this paper and can be found, for example, in Aschwanden et al. (2015). In our case of the limb eruption we use the method and software described recently in Plowman & Caspi (2020). Using...
the data determined by the DEM analysis (the plasma densities and emission-weighted temperatures), we performed modeling of the Fe ion charge distribution of the plasma outflows “frozen in” at the boundary of the corona for several temporal intervals: in the quiet state before eruption, during the CME formation, and after its liftoff. A comparison of the modeled Fe ion charge states with the measured ones has shown that the post-ICME disturbance of the SW is associated with the post-eruption coronal flow.

2. Data

In the analysis of the eruption plasma in the inner corona at distances up to $1.7 R_\odot$, we used the EUV multilwave length images from the AIA telescope (Lemen et al. 2012) aboard the SDO, the images in the 174 Å band of the Sun Watcher with Active Pixels and Image Processing (SWAP) telescope as a part of the Project for Onboard Autonomy 2 (PROBA2) mission (Seaton et al. 2013), and the images in the 195 Å band from the Extreme-Ultra-Violet Imager (EUVI) as a part of Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI: Howard et al. 2008) aboard the Solar Terrestrial Relations Observatory (STEREO) spacecraft (Kaiser et al. 2008). At the distances 2–30 $R_\odot$, we explore the CME formation from the data of the LASCO C2 and C3 coronagraphs (Brueckner et al. 1995) aboard the Solar and Heliospheric Observatory (SOHO: Domingo et al. 1995). The SW data, including the Fe ion charge distributions, magnetic field, and plasma parameters, were taken from observations with the Plasma and Suprathermal Ion Composition (PLASTIC: Galvin et al. 2008) and the In situ Measurements of Particles and CME Transients (IMPACT: Luhmann et al. 2008) instruments.

3. Description of the Event and Kinematics of Eruption

We investigated the eruption in active region (AR) 11093 on 2010 August 18, when it was seen from the Earth at the western limb. During the preceding days, when this AR crossed the solar disk, it produced a series of eruptions that were studied by several researchers (Vemareddy et al. 2012; Tun & Vourlidas 2013; D’Huys et al. 2017; Lario et al. 2017). On August 18, the most powerful CME (partial halo) was registered above the western limb by LASCO C2 at 05:48 UT and by STEREO-A/COR2 at 05:54 UT. The SolarDemon dimming detection system (Kraakamp & Verbeek 2015) determined that the eruption was accompanied by a large dimming that appeared in the corona above the limb at 05:02 UT and existed at least until 07:02 UT.

This eruption was observed in quadrature from two positions: from the Earth by the SDO/AIA and Proba 2/SWAP EUV telescopes, by the SOHO/LASCO coronagraphs, and from the STEREO-A (hereafter STA) position by the SECCHI/EUVI telescope. The ICME and subsequent post-eruption SW flows were detected in situ by the STA/PLASTIC and IMPACT instruments.

In Figure 1 the images of AR 11093 are shown before eruption on August 18 at 04:00 UT in the AIA 193 Å band (Figure 1a) and in the STA/EUVI 195 Å band (Figure 1b). Figure 1c shows the PFSS-modeled magnetic field structure on 2010 August 14 at 07:00 UT, when the AR was on the solar disk, taken from the Lockheed Martin Solar and Astrophysics Laboratory archive. The magnetic field structure included closed coronal loops and a pseudostreamer (Wang 2015), which separated a small equatorial coronal hole near AR 11093 and the northern polar coronal hole. Westward from the AR, a large filament F was seen, which later participated in the eruption.

At the initial stage of eruption, below a distance of 2 $R_\odot$, when the CME structure was not finally formed, the coronal loops started to move upward (Figure 1d)), which was seen by the EUV SDO/AIA (up to 1.3 $R_\odot$) and PROBA2/SWAP (up to 1.7 $R_\odot$) telescopes. Then, from 2 to 5 $R_\odot$, the eruption plasma was accelerated and transformed from a system of loops to several successive compact structures. At that period, the filament F seen in Figures 1(a) and (b) manifested a draping toward the eruption site along the neutral magnetic line, so it might enrich the eruption plasma by the cold filament material.

Figures 1d–f demonstrate the polar intensity maps of AIA 171 Å (2010 August 18, 05:00:48 UT), LASCO C2 (06:12:07 UT), and LASCO C3 (09:06:05 UT). The position angle counts out clockwise from the north (it corresponds to the ordinary LASCO position angle by the relation $360^\circ\text{–PA}_{\text{LASCO}}$). The apex of the coronal structure seen at the latitude angle of 73° in EUV below 1.3 $R_\odot$ shifted to 115° at $R = 2–5 R_\odot$ (C2) and split into three parts above 10 $R_\odot$ (C3).

We identified the upward plasma flows by two methods. The confined plasma flows were identified as bright ridges on the time–height maps (Figures 1g and h) created from the LASCO C2 and C3 (Figures 1e and f) polar maps.

To select the plasma flows that may contribute to SW, we integrated intensity of the polar maps at each height on the C2 map within the position angles 76°±86° and on the C3 map within 86°±2°. These ranges correspond to inclination of the eruption structure with distance to the STA position near the equator (the Heliocentric Earth Equatorial (HEEQ) latitude of STA for 2010 August 18 was equal to 3°7). According to the WSA-ENLIL-DONKI-HELCATS model, in the ecliptic plane the CME angular width is more than 60°, whereas the STA position is declined from the CME apex on the angle less than 10°. Thus, no corrections for the CME geometry and projection effect were needed. As a result, we obtained the time–distance (T–D) maps shown on Figures 1(g) (the C2 map) and (h) (the C3 map). We distinguished four flows on the C2 map and five flows on the C3 map, which are combined together on Figure 1(i). The flows 1 and 2 seen in C2 and C3 are evidently matched with the initial upward moving structure seen in EUV below 1.3 $R_\odot$. The flows 3, 4, and 5 are seen only on the C2 and C3 maps, so they were originated above 2 $R_\odot$, probably at the streamer’s top. The visibility of all flows diminishes with distance so that they become indistinguishable from background between 10 and 20 $R_\odot$ due to weakening of contrast. Nevertheless, we expected that all flows may appear in SW.

All five flows were originated and accelerated in the corona during the C-class flare up to 09:30 UT. After the end of the flare, the LASCO images showed that the plasma outflow lasted as a continuous structureless stream. We estimated the speed of this continuous flow by analysis of cross correlation between irregularities of intensity in the C3 polar maps at different heights as a function of time between 11:18 UT and

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1. https://www.lmsal.com/solarsoft/archive/sswdb-new/packages/pfss/lib_synop
2. http://helioweather.net/archive/2010/08/
12:54 UT. We found the mean speed of this component to be \( \sim 530 \text{ km s}^{-1} \), which corresponds to its startup from the solar surface at about 10:00 UT. We regard this component as the sixth flow.

We suggested that after the end of the flare the flows were decelerated by two forces: the gravitation force below \( 20 \text{R}_\odot \) and the MHD drag force above that distance (Shen et al. 2012; Grechnev et al. 2019). The gravitational deceleration is described by the formula

\[
v_1^2 = v_0^2 - 2GM_\odot \left( \frac{1}{r_0} - \frac{1}{r_1} \right),
\]

where \( v_0(v_1) \) is the velocity of the flow at the distance of \( r_0(r_1) \) from the Sun’s center, \( G \) is the universal gravity constant, and \( M_\odot \) is the mass of the Sun. In the drag-based model (DBM: Vršnak et al. 2013; Vršnak 2021), deceleration is defined by the magnetic drag force between the flow and the ambient media according to the equation

\[
dv/dt = -\gamma(v-w)(v-w),
\]

where \( v \) is the flow speed, \( w \) is the speed of the ambient SW, and \( \gamma \) is the MHD drag parameter. Integration of this equation along the path from the initial point to the observer gives the

Figure 1. (a) AR 11093 seen on 2010 August 18 before eruption by SDO/AIA in 193 Å at 04:00:07 UT; (b) by STA/EUVI in 195 Å at 04:00:30 UT. (c) The magnetic field map of the Sun in the PFSS approximation for 2010 August 14, 07:00 UT (taken from the database https://www.lmsal.com/solarsoft/archive/sswdb-new/packages/pfss/l1q_synop). (d–f) The polar maps of the coronal structures during eruption in AIA 171 Å (2010 August 18, 05:00:48 UT), LASCO C2 (06:12:07 UT), and LASCO C3 (09:06:05 UT). The position angle counts out clockwise from the north. (g) The time–distance (T–D) slice map of the eruption flows derived from the LASCO C2 polar maps; (h) the same from the LASCO C3 maps; (i) the combined T–D plots of the eruption flows including the AIA 171 Å and SWAP 174 Å (plus signs), C2 (crosses), and C3 (circles) data.
Table 1 presents the initial data and the modeled times and speeds of the SW flows calculated with the base version of DBM in comparison with those measured in situ on STA. We have made a series of calculations and found that the discrete flows 1–3 and 5 well correspond to the ICME density peak with $\gamma = 0.3 \times 10^{-7}$ km$^{-1}$ for the first flow and $0.13 \times 10^{-7}$ km$^{-1}$ for the others (the value averaged over the flows 2–5) and the ambient plasma speed for all flows $w = 445$ km s$^{-1}$.

The spreads in the flow arrival times and speeds are summarized from two parts: uncertainties from the $T-D$ maps due the data discretization shown in the $T_{20}$ and $V_{20}$ columns of Table 1 and the model uncertainties of DBM. Typically, DBM gives the CME arrival times with the uncertainty of 9–14 hr (see the references cited above). However, our investigation, based on the data of 2010–2011 (Rodkin et al., 2018), has shown that in the case of the single ICMEs (not interacted with other SW transients in the heliosphere) the inaccuracy of the DBM results in arrival time amounts of 8 hr, the mean error in speed is $65$ km s$^{-1}$. As a result, for all flows, except flow 4, the difference between the modeled and measured times and speeds did not exceed the final errors in $V_{STA}$ in Table 1. Flow 4 did not fit to the SW data under any calculation parameters, probably because it was rather weak and merged to the main flows.

### 4. DEM Diagnostics of Plasma Flows in the Corona

We investigated variation of the plasma temperature and density in the eruption region using the DEM distribution derived from the AIA EUV images. Intensity fluxes in spectral bands are related to DEM via the expression:

$$F_i = \int_T G_i(T) \text{DEM}(T) \, dT,$$

where $F_i$ is the intensity flux and $G_i(T)$ is the temperature response function of the passband $i$.

To determine DEM for the eruption plasma, we applied the method and software developed by Plowman & Caspi (2020). The integral of DEM over the temperature gives the total emission measure (EM) integrated along the line of sight: $\text{EM} = \int_T \text{DEM}(T) \, dT$. Using the obtained DEM, one can calculate the emission-weighted temperature (e.g., Cheng et al., 2012; Saqri et al., 2020):

Table 1 Kinematic Parameters of the CME and Post-eruption Flows

| № of Flow | $R_{sd}$ ($R_E$) | $T_{sd}$ (Aug 18 (UT)) | $T_{20}$ (Aug 18 (UT)) | $V_{20}$ (km s$^{-1}$) | $T_{STA}$ (UT) | $V_{STA}$ (km s$^{-1}$) | $V_p$ (km s$^{-1}$) |
|-----------|------------------|------------------------|------------------------|------------------------|----------------|------------------------|-------------------|
| 1         | 17.75            | 09:36                  | 10:15 ± 0.22 hr        | 670 ± 26               | Aug 21 00:58 ± 10 hr | 533 ± 66               | 585               |
| 2         | 16.74            | 10:33                  | 11:37 ± 0.24 hr        | 599 ± 23               | Aug 21 03:20 ± 12 hr | 550 ± 69               | 580               |
| 3         | 13.59            | 10:55                  | 12:42 ± 0.28 hr        | 686 ± 32               | Aug 20 22:27 ± 12 hr | 590 ± 70               | 551               |
| 4         | 12.30            | 11:23                  | 13:17 ± 0.33 hr        | 872 ± 69               | Aug 20 12:59 ± 12 hr | 671 ± 75               | 329               |
| 5         | 12.47            | 12:13                  | 14:36 ± 0.37 hr        | 606 ± 48               | Aug 21 05:20 ± 18 hr | 553 ± 80               | 574               |
| 6         | 9.38             | 12:54                  | 16:53 ± 0.40 hr        | 508 ± 56               | Aug 21 19:39 ± 16 hr | 500 ± 77               | 511               |

**Note.** $R_{sd}$ is the maximum distance in the $T-D$, $T_{sd}$ is the time at $R_{sd}$, $T_{STA}$ is the time at $20 R_E$, $V_{20}$ is the speed at $20 R_E$, $V_{STA}$ is the speed at STA modeled by DBM, and $V_p$ is the speed of protons measured at STA.
Figure 2. Polar EM maps for three temperature ranges (A: $5.5 < \log_{10} T < 6.3$; B: $6.3 < \log_{10} T < 6.8$; and C: $6.8 < \log_{10} T < 7.2$) at 05:20 UT and the DEM temperature distribution in the indicated box at three time moments. Red curve: 04:01 UT ($\chi^2 = 0.99$); black curve: 05:20 UT ($\chi^2 = 0.95$); green curve: 10:00 UT ($\chi^2 = 0.94$).

Table 2
The Mean Values of Plasma Density and Emission-weighted Temperature for Five Time Moments in Three Temperature Ranges

| Time  | $N_e$ ($10^9$) | $T_{em}$ (MK) | $N_e$ ($10^9$) | $T_{em}$ (MK) | $N_e$ ($10^9$) | $T_{em}$ (MK) |
|-------|---------------|---------------|---------------|---------------|---------------|---------------|
|       | (cm$^{-3}$)   | (MK)          | (cm$^{-3}$)   | (MK)          | (cm$^{-3}$)   | (MK)          |
| 04:01 | 1.0 ± 0.1     | 1.5 ± 0.4     | 4.8 ± 0.5     | 3.4 ± 0.7     | 3.7 ± 0.2     | ...           |
| 05:20 | 1.3 ± 0.1     | 1.4 ± 0.3     | 3.3 ± 0.2     | 3.6 ± 0.3     | 5.2 ± 1.0     | 10.6 ± 4.5    |
| 05:22 | 1.1 ± 0.1     | 1.4 ± 0.2     | 3.1 ± 0.2     | 3.6 ± 0.4     | 4.6 ± 1.0     | 10.5 ± 4.9    |
| 05:25 | 1.0 ± 0.1     | 1.4 ± 0.3     | 2.5 ± 0.2     | 3.5 ± 0.5     | 3.8 ± 0.5     | 10.6 ± 3.2    |
| 10:00 | 0.8 ± 0.1     | 1.4 ± 0.1     | 2.0 ± 0.4     | 3.3 ± 0.9     | 2.5 ± 0.6     | ...           |

\[
T_{em} = \frac{\int_T T \cdot DEM(T) \, dT}{EM}. \tag{5}
\]

Based on the EM structure, we can estimate the plasma density, assuming that the depth of the structure along the line of sight ($L$) is approximately equal to its visible width (the same method can be found, e.g., in Cheng et al. 2012). So the plasma density can be estimated as

\[
N_e = \sqrt{\frac{EM}{L}}. \tag{6}
\]

To retrieve DEM, we used the AIA/SDO images of the solar corona in six channels (94, 131, 171, 193, 211, 335 Å), which cover a broad temperature range (from $10^3$ to above $10^7$ K). The input error of each pixel in AIA images was calculated using the \texttt{aia_bp\_estimate\_error} routine considering the data obtained during eclipses (Heinemann et al. 2021).

Stray light in some cases can significantly disturb intensities of the AIA images (Wendeln & Landi 2018; Saqri et al. 2020; Heinemann et al. 2021), in particular above the limb, where intensities are fast weakening. In our case, no correction for stray light was needed within the typical error of the DEM reconstruction (about 20%).

The errors may occur in the DEM solution at high flow speeds (over 800 km s$^{-1}$, see Grechnev et al. 2019) due to nonsimultaneity in the registration of images in different AIA channels. In our case, it is possible to compute the DEM without a compensation for its motion, since the flow speeds at distances 1.2 $R_o$ were about 100 km s$^{-1}$.

We analyzed DEM in the AIA field of view for the several moments on 2010 August 18: before the eruption at 04:01 UT, during the development of the solar flare at 05:20 UT, 05:22 UT, and 05:25 UT, when the plasma rose up in the AIA field of view, and in the posteruption stage at 10:00 UT, when the CME left the corona.

In Figure 2, we show the EM polar maps at 05:20 UT in three temperature ranges $5.5 < \log_{10} T < 6.3$ (A), $6.3 < \log_{10} T < 6.8$ (B), and $6.8 < \log_{10} T < 7.2$ (C). The rightmost panel shows variation of the DEM temperature distribution in the indicated box before (04:01 UT), during (05:20 UT), and after (10:00 UT) eruption. The DEM profiles were averaged over the box $1.15 \pm 0.02 R_o$ and $73^o \pm 1^o$ in the position angle, which corresponds to the highest total EM during eruption. The DEM was considered only up to $\log_{10} T = 7.2$ because of the artifacts that appeared due to the low temperature sensitivity of the AIA channels at high temperatures (Plowman & Caspi 2020). To calculate the plasma density in the hottest range ($\log_{10} T > 6.8$), the value of EM integrated over the temperature was doubled, since the DEM distribution at this temperature range included only half of the peak.

In Table 2 we show the mean values of plasma density and emission-weighted temperature in three ranges: $5.5 < \log_{10} T < 6.3$, $6.3 < \log_{10} T < 6.8$, and $6.8 < \log_{10} T < 7.2$. The mean values at 05:20 UT, 04:01 UT, and 10:00 UT were averaged over the box as described above. The box was shifted to 1.17 $R_o$ at 05:22 UT and to 1.20 $R_o$ at 05:25 UT according to the plasma movement. In the quiet conditions, before eruption (04:01 UT) and after eruption (10:00 UT), densities in the hot temperature range ($6.8 < \log_{10} T < 7.2$) were larger than those in the cold range ($5.5 < \log_{10} T < 6.3$), although in the histograms of Figure 2 the relation between the corresponding EM values is reverse. The reason is that in the quiet conditions the depth of the hot structures was much less (more than one order) than that of the cold ones. During the eruption (05:20–05:25 UT), density in the hot range increases due to inflow of the heated plasma of the reconnected surrounding structures.
loops with the medium temperature $6.3 < \log_{10} T < 6.8$. After eruption (at 10:00 UT), densities in all temperature ranges drop down due to liftoff of the CME.

5. Solar Wind Parameters Measured in Situ

Figure 3 shows the SW parameters registered by IMPACT and PLASTIC at STA in the period 2010 August 19–26: the magnetic field magnitude and its Radial-Tangential-Normal (RTN) components, proton speed, density and temperature, and parameters $q_4$, $q_8$, and $q_{12}$ (see the definition of these parameters below in Equation (7)) characterizing the Fe ion charge distribution. The SW disturbance started with the shock on 2010 August 20, 16:14 UT, the ICME on August 20, 16:14 UT–August 21, 13:14 UT (from the STEREO event catalog) followed up to August 25 by a long trailing region with declining speed. The arrivals of the plasma flows given in Table 1 are marked on the proton speed chart. The flows 1, 2, 3, and 5 evidently correspond to the magnetic cloud of the ICME. The fourth flow (not shown on the chart), with the highest speed according to Table 1, should arrive significantly ahead of the ICME, but it was not observed in SW. Most likely, this weak flow decelerated and merged with other discrete flows. The sixth posteruptive flow arrived in the post-ICME part of the transient. It is worth mentioning that the shock time agrees well with the DBM modeling of the CME frontal structure indicated in the LASCO Coordinated Database Analysis Workshops (CDAW) database (start at 05:48 UT, $V_{20} = 1416$ km s$^{-1}$) with $\gamma = 0.3 \times 10^{-7}$ and $w = 330$ km s$^{-1}$.

The ionization state of the SW plasma is "frozen in" in the inner corona at heights where recombination/ionization timescales become dominant over the plasma expansion timescale (see, e.g., Hundhausen et al. 1968; Ko et al. 1997; Goryaev et al. 2020). Since the Fe ions freeze in at the largest heights compared with other abundant elements, the Fe ion composition is the most suitable for characterizing the state of the SW.

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3 http://ipshocks.fi/database
4 https://stereossc.nascom.nasa.gov/data/ins_data/impact/level3/ICMEs.pdf
plasma. In the development of the approach proposed in Goryaev et al. (2020), we introduce here three relative parameters \( q_4, q_8, \) and \( q_{12} \) for characterizing the Fe ion charge distribution as follows:

\[
q_4 = \frac{\sum_{0 \leq Z < 2} n_i Z^2}{\sum_{0 \leq Z < 2} n_i}, \quad q_8 = \frac{\sum_{2 \leq Z < 11} n_i Z^2}{\sum_{0 \leq Z < 2} n_i Z^2}, \quad q_{12} = \frac{\sum_{12 \leq Z \leq 20} n_i Z^2}{\sum_{0 \leq Z < 20} n_i Z^2}, \quad q_4 + q_8 + q_{12} = 1, \tag{7}
\]

where \( n_i \) is the number density of the ion with charge \( Z \). The parameters \( q_4, q_8, \) and \( q_{12} \) correspond conditionally to the \"cold,\" \"middle,\" and \"hot\" parts of the Fe charge distribution.

In contrast to the average charge \( Q_{Fe} \), the differentiation for the parameters \( q_4, q_8, \) and \( q_{12} \) shown in Figure 3 allows one to derive more detailed information on conditions in the SW plasma.

In the period from August 19 to the shock time, the Fe ion charge distribution was characterized by the largest value of \( q_8 > 0.8 \) and the minor \( q_4 \) and \( q_{12} \) values below 0.1, which corresponds to the slow SW. After the shock, the jump of \( q_4 \) to 0.3 indicated the appearance of the sheath cold matter; then, in the ICME part, arrival of the hot eruption plasma led to an increase of \( q_{12} \) to 0.2–0.3. The most interesting anomaly in the Fe ion charge distribution is seen in the period after the rear of the ICME, from August 21, 13:14 UT, to August 23, 00:00 UT. During this post-ICME period, the values of \( q_4 \) were several times higher than that of \( q_{12} \), which means a significant domination of the \"cold\" component in the SW plasma. Development of the dimming in the period from the shock to August 23, 12:00 UT was indicated by a decrease of the medium temperature parameter \( q_8 \). After August 23, 12:00 UT, all charge distribution parameters returned to the slow SW values.

6. Fe Ion Charge Distributions of the Flows in the Corona and in SW around the ICME Event

For our analysis of the ICME event, we considered the four time intervals designated as T1–T4 in Figure 3: 2010 August 19 00:00–2010 August 20 14:00 (T1); 2010 August 20 18:00–2010 August 21 12:00 (T2); 2010 August 21 14:00–2010 August 22 20:00 (T3); and 2010 August 23 06:00–2010 August 25 06:00 (T4). The interval T1 corresponds to the pre-ICME SW, T2 is associated with the passage of the ICME, T3 is related to the post-eruptive SW flows, and T4 is SW returned to pre-ICME conditions. For each time interval we summed the 2 hr Fe ion distributions taken from the STA/PLASTIC database.

Figure 4(a) shows the number of counts of Fe ions with the charge \( Z \) summed over the intervals T1–T4. The distributions for the intervals T1 (green) and T4 (yellow) have similar shapes peaked at \( Z = 9 \), because these are probably associated with the slow component of SW. Although the distributions for T2 (red) and T3 (blue) intervals are associated with different SW types, these are peaked at the same value \( Z = 8 \). Also, T2 distribution has the noticeable high charge tail with \( Z \geq 12 \), which is evidence for the ICME event.

We modeled the evolution of the Fe ion charge state and frozen-in conditions for the CME event on 2010 August 18 to compare with the in situ observations of the associated ICME. To determine a frozen-in charge state, we solved a system of balance equations with the preset profiles of plasma electron temperature \( T_e \), density \( N_e \), and bulk velocity \( V \) as functions of distance (see details in Rodkin et al. 2017; Grechnev et al. 2019). We performed three sets of calculations for the initial times from Table 2: 04:01 UT (hereafter case 1), 05:20 UT (case 2), and 10:00 UT (case 3). The bulk velocities \( V \) for the three cases were derived from the kinematic measurements. For the electron densities \( N_e \) we used the plausible geometry of the expansion of the SW plasma in the corona: \( N_e \sim 1/h^2 \) (\( h \) is the height above the solar surface) for cases 1 and 3 (the slow SW flowing from streamers) and \( N_e \sim 1/r^6 \) (\( r \) is the heliocentric distance) for case 2 (CME flux rope).

For deriving the final frozen-in Fe ion charge distributions in three mentioned cases we used the following procedure. According to Table 2, the SW flow for each case consists of two (cases 1 and 3) or three (case 2) plasma components, which hereafter are called the \"cold,\" \"middle,\" and \"hot\" ones according to temperature regimes. For each case, the frozen-in charge distributions are then calculated separately for all components, and the final total distribution \( n_Z \) for each case is given by mixing plasma components

\[
n_Z = \frac{n_z^{(c)} N_e^{(c)} L^{(c)} + n_z^{(m)} N_e^{(m)} L^{(m)} + n_z^{(h)} N_e^{(h)} L^{(h)}}{N_e^{(c)} L^{(c)} + N_e^{(m)} L^{(m)} + N_e^{(h)} L^{(h)}}, \tag{8}
\]

for case 2 (CME plasma) and

\[
n_Z = \frac{n_z^{(c)} N_e^{(c)} L^{(c)} + n_z^{(m)} N_e^{(m)} L^{(m)}}{N_e^{(c)} L^{(c)} + N_e^{(m)} L^{(m)}}, \tag{9}
\]

for cases 1 and 3 (without the hot components), where \( n_z^{(c)}, n_z^{(m)}, n_z^{(h)} \) are the partial final distributions for cold, middle, and hot plasma components; and \( N_e^{(c)}, N_e^{(m)}, N_e^{(h)} \) and \( L^{(c)}, L^{(m)}, L^{(h)} \) are the corresponding plasma densities and depths along the line of sight. We did not take into account the hot component for the pre- and post-reruption conditions due to large uncertainties in the DEM hot wing at the temperatures \( T_e > 7 \). A similar two-plasma model was used by Gruesbeck et al. (2012) for possibly interpreting ICME observations with very low and high charge state ions.

Figures 4(b)–(d) show the comparison of the calculated relative (normalized to unity) Fe ion distributions with the measured ones for the T1–T4 intervals. As is seen, the modeled distributions agree well with the measurements. Nevertheless, the modeled distributions overestimate the high charge states with \( Z \geq 16 \) for all cases, especially for case 2, which is associated with the ICME. It may be related to the overestimation of the high-temperature part of DEM distributions in the reconstruction procedure. The high charge peak for the Fe\(^{16+}\) ion is caused by the smaller recombination rates compared with the ions in lower charge states (see Goryaev et al. 2020). The comparison of \( q_4, q_8, q_{12} \) parameters for the modeled and measured Fe ion distributions is shown in...
Table 3. It is also seen that $q_4$ and $q_8$ parameters have a very good agreement with the measured ones, while the modeled $q_{12}$ values are overestimated about two times. Furthermore, the modeling enables the interpretation of the difference in behavior of the $q_4$ and $q_{12}$ parameters in cases 1 (T1) and 3 (T3) (see Figure 3) as follows. In the preeruption state (case 1) the mean values of $q_4 = 0.059$ and $q_{12} = 0.077$ corresponded to the frozen-in conditions, where the plasma transforms from a collisional to collisionless state. It occurred at the heights of $h \approx 4-5 R_e$ with the plasma electron temperature of $T_e \approx 1$ MK typical for the quiet slow SW. In the posteruption state (case 3) $q_4 = 0.217$, $q_{12} = 0.061$, and $T_e \approx 0.5$ MK, so the “cold” plasma dominates. According to the model results, this increase of the “cold” component is explained not only by depletion of the highly charged ions after the CME liftoff but also by the absence of heating after the flare ending. The last panel in Figure 3 and the data from Table 3 show that the SW plasma in the T4 interval finally returns to the pre-ICME state, as in the T1 interval.

### Table 3

| Time Interval № | $q_4$ (Measured ± Modeled) | $q_8$ (Measured ± Modeled) | $q_{12}$ (Measured ± Modeled) |
|-----------------|-----------------------------|-----------------------------|-------------------------------|
| 1               | $0.059 \pm 0.020$           | $0.053 \pm 0.013$           | $0.864 \pm 0.207$             |
| 2               | $0.229 \pm 0.035$           | $0.250 \pm 0.112$           | $0.600 \pm 0.083$             |
| 3               | $0.217 \pm 0.049$           | $0.218 \pm 0.016$           | $0.722 \pm 0.144$             |
| 4               | $0.089 \pm 0.028$           | $0.836 \pm 0.199$           | $0.074 \pm 0.038$             |

Note. The parameters for the time intervals 1–3 are compared with the modeled ones.

Table 3. It is also seen that $q_4$ and $q_8$ parameters have a very good agreement with the measured ones, while the modeled $q_{12}$ values are overestimated about two times.

Furthermore, the modeling enables the interpretation of the difference in behavior of the $q_4$ and $q_{12}$ parameters in cases 1 (T1) and 3 (T3) (see Figure 3) as follows. In the preeruption state (case 1) the mean values of $q_4 = 0.059$ and $q_{12} = 0.077$ corresponded to the frozen-in conditions, where the plasma transforms from a collisional to collisionless state. It occurred at the heights of $h \approx 4-5 R_e$ with the plasma electron temperature of $T_e \approx 1$ MK typical for the quiet slow SW. In the posteruption state (case 3) $q_4 = 0.217$, $q_{12} = 0.061$, and $T_e \approx 0.5$ MK, so the “cold” plasma dominates. According to the model results, this increase of the “cold” component is explained not only by depletion of the highly charged ions after the CME liftoff but also by the absence of heating after the flare ending. The last panel in Figure 3 and the data from Table 3 show that the SW plasma in the T4 interval finally returns to the pre-ICME state, as in the T1 interval.

### 7. Discussion and Conclusion

The analysis of the eruption in AR 11093 that occurred on 2010 August 18 and the associated SW transient detected by STA on 2010 August 20–23 has yielded the following results.
The CME flux rope was formed during the C-class flare from several discrete plasma flows originating in the region of AR 11093 with the pseudostreamer nearby. According to the AIA, SWAP EUV images, and LASCO C2–C3 time–height maps, the first flow started at $R = 1.15 \ R_\odot$, and others started at $2.2 \ R_\odot$ and higher, as the streamer blowout blobs like those observed recently by the Parker Solar Probe (Lario et al. 2020; Rouillard et al. 2020) probably started. After the end of the flare, the plasma outflow transformed into the unstructured stream, whose speed was determined by correlation of irregularities at different heights. To predict the arrival times and speeds of the flows at STA, we applied the gravitation and DBM kinematic models. The drag parameters and ambient plasma speed were found in grid calculations under a condition of minimal difference between the modeled flow speeds and the measured in situ proton speeds at the arrival times. Then the optimal values of the drag parameter and the ambient plasma speed were obtained by averaging the values for all flows except the fastest, flow 4, which probably was decelerated and merged with other flows. As a result, we ascertained that the discrete flows that started during the eruption appeared in SW as components of the ICME, whereas the unstructured flow that started after eruption appeared in the ICME trailing region. Thus, we showed that DBM is well applicable to the propagation of the multicomponent CME structure and also to the posteruption flow. The ambient plasma speed was found to be of 445 km s$^{-1}$ for all flows (except flow 4), and the $\gamma$ value amounted to 0.3 for the frontal flow 1 and 0.13 for other flows. Such a difference in $\gamma$ means that the drag force diminished for the flows passed behind the CME front along the same open magnetic field lines. The open magnetic field structure in the ICME trailing region was first described by Neugebauer et al. (1997).

To understand the origins of the SW flows, we analyzed the Fe ion charge distribution of SW and confronted it with parameters of the coronal plasma. First, we determined the plasma EM in the eruption region with the use of DEM in the time intervals corresponding to the preeruption, eruption, and posteruption conditions. The largest EM in all temperature bands was determined in the preeruption stage (at 04:01 UT). During the eruption (05:20–05:25 UT), the EM values dropped down on about one order in the middle temperature range ($6.3 < \log_{10} T < 6.8$) and in the hot range ($6.8 < \log_{10} T < 7.2$) because of the uncompensated plasma outflow from the dimming region. In the cold channel ($5.5 < \log_{10} T < 6.3$) the EM value dropped down less than three times. Such a smaller decrease can be explained by an additional inflow of the cold plasma by interchange reconnection of the cold loops seen in the AIA 171 Å and SWAP 174 Å with the open magnetic lines of the flux rope (Owens et al. 2020) and by drainage of the cold filament matter to the eruption site. Drainage of the filament mass before eruption was described by Martin et al. (2008), Bi et al. (2014), Zhang et al. (2017), and Jenkins et al. (2018).

Using the obtained plasma parameters, we have modeled the frozen-in Fe ion charge distributions in the studied coronal flows and calculated the values of the $q_4$, $q_8$, and $q_{12}$ parameters averaged over four time intervals T1–T4. For all the intervals, the modeled values agreed with the measured ones within the errors. A small excess of the measured $q_8$ with respect to the modeled values may be related to the contribution of the surrounding coronal structures not associated with the eruption. The observed anomalous divergence between the $q_4$ and $q_{12}$ values in the post-ICME trailing region can be explained by inflow of the cold plasma in the absence of heating after the solar flare end. As a result, the SW ion state in the post-ICME tail in the interval 2010 August 21, 14:00 UT–2010 August 22, 20:00 UT significantly differs from the state of the slow ambient SW before 2010 August 20, 14:00, and after 2010 August 23, 06:00 UT.

In conclusion, the results demonstrate that in the studied CME event of 2010 August 18–23, the post-ICME SW disturbance was caused by the posteruption coronal flow from the dimming region and cannot be associated with the ambient SW entrained by the CME.

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