On-disk Solar Coronal Condensations Facilitated by Magnetic Reconnection between Open and Closed Magnetic Structures

Leping Li1,2, Hardi Peter3, Lakshmi Pradeep Chitta3, and Hongqiang Song4

1 CAS Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
2 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
3 Max Planck Institute for Solar System Research, D-37077 Göttingen, Germany
4 Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, and Institute of Space Sciences, Shandong University, Weihai, Shandong 264209, People’s Republic of China

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Abstract

Coronal condensation and rain are a crucial part of the mass cycle between the corona and chromosphere. In some cases, condensation and subsequent rain originate in the magnetic dips formed during magnetic reconnection. This provides a new and alternative formation mechanism for coronal rain. Until now, only off-limb, rather than on-disk, condensation events during reconnection have been reported. In this paper, employing extreme-ultraviolet (EUV) images of the Solar Terrestrial Relations Observatory (STEREO) and Solar Dynamics Observatory (SDO), we investigate the condensations facilitated by reconnection from 2011 July 14–15, when STEREO was in quadrature with respect to the Sun–Earth line. Above the limb, in STEREO/EUV Imager (EUVI) 171 Å images, higher-lying open structures move downward, reconnect with the lower-lying closed loops, and form dips. Two sets of newly reconnected structures then form. In the dips, bright condensations occur in the EUVI 304 Å images repeatedly, which then flow downward to the surface. In the on-disk observations by SDO/Atmospheric Imaging Assembly (AIA) in the 171 Å channel, these magnetic structures are difficult to identify. Dark condensations appear in the AIA 304 Å images, and then move to the surface as on-disk coronal rain. The cooling and condensation of coronal plasma is revealed by the EUV light curves. If only the on-disk observations were be available, the relation between the condensations and reconnection, shown clearly by the off-limb observations, could not be identified. Thus, we suggest that some on-disk condensation events seen in transition region and chromospheric lines may be facilitated by reconnection.

Unified Astronomy Thesaurus concepts: Solar magnetic reconnection (1504); Plasma physics (2089); Solar corona (1483); Solar ultraviolet emission (1533); Solar magnetic fields (1503)

Supporting material: animations

1. Introduction

Condensation of hot solar coronal plasma is a widely observed phenomenon, which is best seen at the solar limb. Solar filaments/prominences are one of the prominent examples of coronal plasma condensation (Pneuman 1983; Mackay et al. 2010; Xia et al. 2014). Formation of a prominence is generally initiated when coronal plasma is trapped in the dips of helical magnetic fields over polarity inversion lines. As the radiative losses from the trapped plasma exceed the heat input into the system, thermal instability is triggered, which further leads to rapid plasma cooling and condensation at coronal heights. The resulting condensed, dense plasma provides the mass of a prominence (Parker 1953; Field 1965; Pneuman 1983). The extreme-ultraviolet (EUV) images recorded by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), revealed events of cooling and condensation of coronal plasma during the formation of prominence in a loop system (Liu et al. 2012) and a coronal cavity (Berger et al. 2012), respectively. Similarly, coronal rain, which is seen as plasma draining through magnetic loops, is another manifestation of condensation (Müller et al. 2003, 2004; Fang et al. 2013; Oliver et al. 2016). It appears frequently in post-flare loops and non-flaring active region (AR) closed loops (see a review in Antolin 2020, and references therein). Quiescent coronal rain in AR closed loops forms due to thermal nonequilibrium when hot, dense plasma trapped by loops rapidly cools and condenses. Under the effect of gravity, the cool condensation subsequently falls from the corona along one or both legs of the loops to the surface as coronal rain (Müller et al. 2003, 2004; Li et al. 2015; Froment et al. 2018). In this case, the hot, dense plasma could be supplied through heating events concentrated at/near the loop footpoints (Froment et al. 2017; Chitta et al. 2018). Alternatively, impulsive heating, occurring anywhere along a field line, could also trigger thermal instability and the subsequent formation of coronal rain (Kohutova et al. 2019). Employing multiwavelength images, the cooling and condensation events of coronal plasma in AR closed loops have been reported during the formation of coronal rain (Schrijver 2001; Antolin & Rouppe van der Voort 2012; Vashalomidze et al. 2015).

One widely investigated concept of condensation relies on the thermal properties of the plasma alone, which is independent of the magnetic field, its topology, and evolution (Müller et al. 2003, 2004). In this scenario, the loss of thermal equilibrium between heat input, heat conduction, and radiative losses solely causes catastrophic cooling of plasma (Fang et al. 2013; Xia et al. 2014). However, a reconnection-condensation model for the formation of a prominence with in situ radiative condensation triggered by magnetic reconnection has been numerically simulated (Kaneko & Yokoyama 2015, 2017). In line with these simulations, using SDO/AIA and Solar TERRrestrial RELations
Observatory (STEREO; Kaiser et al. 2008)/EUV Imager (EUVI; Howard et al. 2008) multiwavelength images, we recently reported condensation events facilitated by reconnection between open and closed magnetic structures (Li et al. 2018a, 2018b, 2019, 2020). Here, the magnetic reconnection is inferred from the reconfiguration of magnetic field topology as captured by the evolution of coronal structures, e.g., loops, as the magnetic flux is frozen into plasma in the solar corona (Priest & Forbes 2000; Li & Zhang 2009; Liu et al. 2010; Tian et al. 2014; Li et al. 2016a, 2016b, 2016c; Cheng et al. 2018; Yan et al. 2018; Shen et al. 2019). The simulations and observations suggest that the thermal evolution, e.g., coronal condensation, and the evolution of the magnetic field, e.g., magnetic reconnection, have to be treated together and cannot be separated (Kaneko & Yokoyama 2015, 2017; Li et al. 2018a, 2019, 2020).

In a recent study, we presented observations that show a sequence of events from the formation of magnetic dips high in the corona to plasma condensations and subsequent rain along with signatures of reconnection (Li et al. 2018a). This concerns a system of magnetic structures, lasting for several days, out of the northwestern solar limb observed on 2012 January 19. The higher-lying open structures move down toward the surface, and reconnect with the lower-lying closed loops. Two sets of newly reconnected structures then form, and recontract away from the reconnection region. During the reconnection process, a magnetic dip forms in the higher-lying open structures. Coronal plasma surrounding the dip converges into the dip, resulting in the enhancement of plasma density. In the dip, thermal instability of plasma, triggered by the enhancement of density, occurs, and the coronal plasma rapidly cools and condenses. A transient prominence then forms, and facilitates a speedup of the reconnection. Due to the successive reconnection, the condensation, without support from underlying structures, falls to the surface along the newly reconnected closed loops, and also along the higher-lying open structures, as coronal rain. These observations form the basis for the proposal of a new and alternative mechanism for the formation of coronal rain along open field lines facilitated by interchange reconnection (Li et al. 2018a).

Formation of plasma condensations in the magnetic dips is coupled with quasiperiodic fast magnetooacoustic waves that originate from the reconnection region and propagate upward across the dips of higher-lying open structures (Li et al. 2018b). This indicates that most of the magnetic energy may be converted to wave energy through reconnection. Such repeated condensation events facilitated by reconnection between open and closed structures were observed over an extended period of time (e.g., 15 events in the long-term evolution of the same magnetic structure system during 2012 January 16–20; see Li et al. 2019). However, no condensation, and thus no subsequent coronal rain, is detected in one of the repeated reconnection events. This suggests that not every reconnection event will lead to the formation of condensation (Li et al. 2019). Moreover, 79 other similar reconnection and condensation events were identified above the limb at different times and different places during the month of 2012 January, employing the AIA observations with a much longer time cadence of 14 minutes (Li et al. 2019). The condensation, and hence the coronal rain, facilitated by reconnection is a common, rather than a special, phenomenon in the corona. Recently, using Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) and AIA images and spectra, we analyzed a coronal rain event with loop-like paths in the transition region and chromospheric lines, e.g., Si IV 1394 Å and Mg II k 2796 Å, and found that it originates from the condensations facilitated by reconnection between open and closed structures (Li et al. 2020). Some of the coronal rain events observed at chromospheric temperatures thus could be explained by the formation mechanism of coronal rain, where the condensation is facilitated by interchange reconnection. Moreover, the interval of the occurrence of repeated coronal rain events is obtained as being in the range of 4.6–10.4 hr with a mean value of 6.6 hr (Li et al. 2020). This interval of recurrence is identical with periods of quiescent coronal rain in AR closed loops (Auchère et al. 2018; Froment et al. 2020). However, different from the periodicity of coronal rain in AR closed loops that is driven by thermal nonequilibrium, the global topological changes caused by reconnection clearly play a role in this repetition, as the repetition observed in the coronal rain along open structures closely follows the formation of dips (Li et al. 2020).

Coronal rain events occurring at/near null points and associated dips have been reported (Li et al. 2012; Reeves et al. 2015; Li et al. 2018a, 2018b, 2019, 2020; Mason et al. 2019). They belong to quiescent coronal rain, as no associated flare is observed during the reconnection and condensation process (Li et al. 2018a, 2018b, 2019, 2020). Quite different from the quiescent coronal rain events along closed loops in non-flaring AR reported previously (Schrijver 2001; Antolin & Rouppe van der Voort 2012; Vlashalomidze et al. 2015; Kohutova et al. 2019), the quiescent coronal rain here occurs in the dips of open structures. Because of this, their dynamics at coronal heights are quite different (see more details in Li et al. 2020). The main difference is that in the case of coronal rain occurring in AR closed loops, it is mostly observed to fall toward the surface along one or both loop legs (Antolin 2020). In contrast, condensation that forms in the dips of open structures accumulates, expands, and flows along the supporting field as a prominence, and moves together with the evolution of dips, before it falls toward the surface (Li et al. 2018a, 2019, 2020). Furthermore, the coronal rain in AR closed loops is driven by thermal nonequilibrium promoted by footpoint-concentrated heating events (Müller et al. 2003, 2004; Antolin 2020). On open field lines, Mason et al. (2019) suggested that thermal nonequilibrium is not expected to occur. In contrast, in their 3D MHD models Kohutova et al. (2020) found condensations also on magnetic field lines that reach the top of the computational domain at 14.4 Mm above the photosphere and can therefore be considered locally open. Here, the loss of thermal equilibrium seems to be induced in a similar fashion to that in closed loops, i.e., by the gradual increase of density due to an evaporated upflow driven by footpoint heating. This magnetic configuration of Kohutova et al. (2020) is quite different from large-scale open structures with dips where an enhancement in local density through reconnection facilitates the loss of thermal equilibrium (Li et al. 2018a, 2018b, 2019, 2020; Mason et al. 2019). All these results point to a new class of quiescent coronal rain along open structures in comparison with that in AR closed loops (see more details in Li et al. 2020).

Until now, owing to the ease of detection, the reported condensation events facilitated by reconnection between open and closed structures are all seen above the solar limb (Li et al. 2018a, 2018b, 2019, 2020; Kohutova et al. 2019; Mason et al. 2019). Whether the condensation facilitated by reconnection
can still be observed further on the disk, and how it performs, are open questions. To answer these questions, in this study, we investigate the condensation events facilitated by reconnection both above the limb and on the disk. Comparing the off-limb events, how the magnetic fields, associated with the magnetic structure system, distribute and evolve can be investigated by employing the on-disk events. The observations and method are described in Section 2, the results are shown in Section 3, and a summary and discussion are given in Section 4.

2. Observations and Method

AIA on board the SDO is a set of normal incidence imaging telescopes designed to acquire images of the solar atmosphere at 10 wavelength bands. EUVI on board STEREO provides solar images in four EUV channels of 171, 195, 284, and 304 Å. Here, different channels show plasma at different temperatures, e.g., 171 Å peaks at ~0.9 MK (Fe IX), 131 Å peaks at ~0.6 MK (Fe VIII), ~10 MK (Fe XXI), and 304 Å peaks at ~0.05 MK (He II). In this study, we employ AIA 171, 131, and 304 Å images, and EUVI A and B 171 and 304 Å images to investigate the evolution of magnetic structures and condensations. Here, to better show the evolution, the EUVI A and B 171 Å images and the AIA 304 Å images are enhanced by using the Multiscale Gaussian Normalization (MGN) technique (Morgan & Druckmüller 2014). Spatial sampling of the employed AIA and EUVI images is 0.6" pixel⁻¹ and 1.6" pixel⁻¹, respectively. The time cadence of the AIA EUV images is 12 s, while that of the EUVI images is nonuniform. Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) line-of-sight (LOS) magnetograms on board the SDO, with time cadence and spatial sampling of 45 s and 0.5" pixel⁻¹, are also used to study the evolution of associated photospheric magnetic fields.

The SDO and STEREO A and B satellites observe the Sun generally at different angles. The positions of these three satellites at 00:14 UT on 2011 July 15 are shown in Figure 1. In order to find the on-disk condensations facilitated by reconnection between open and closed structures in the field of view (FOV) of SDO, we chose a period of time, i.e., from 2010–2011 September, when the viewing direction of SDO is mostly perpendicular to those of STEREO A and B. During this time period, we examine the evolution of magnetic structures out of the eastern (western) limb by using the EUVI A (B) 171 and 304 Å images to find the off-limb condensation events facilitated by reconnection in the FOV of STEREO A (B). Under an almost orthogonal viewing angle of SDO, the off-limb condensation events facilitated by reconnection in STEREO A and B FOVs are hence located on the disk in the FOV of SDO. In this study, the condensation events facilitated by reconnection between open and closed structures from 2011 July 14–15 above the southeastern (southwestern) limb in the EUVI A (B) images are chosen for analysis (see the red diamond in Figure 1). During this time period, the time cadence of the EUVI A (B) 171 Å images ranges from 30 s to 258 (120) minutes with the most value of 75 s, and that of the EUVI A (B) 304 Å images varies from 2.5 minutes to 250 (10) minutes with two most values of 2.5 and 10 minutes.

Figure 1. Positions of the STEREO A and B and SDO satellites at 00:14 UT on 2011 July 15. The angles between these three satellites are denoted by the numbers in the plot. The dotted circle represents the Earth orbit at 1 au. East and west separately show the east and west directions in the FOV of SDO. The red diamond marks the general location of the coronal structures we studied. See Section 2 for details.
3. Results

3.1. Off-limb Coronal Condensations Facilitated by Reconnection between Open and Closed Structures Observed by STEREO

From 2011 July 14–15, the long-term evolution of a set of higher-lying open structures L1 is observed above the southwestern (southeastern) limb in the EUVI B (A) 171 Å images, see Figures 2(a)–(b). The NOAA AR 11250 is located to the north of the structures, see Figures 2(a)–(b). A filament lies underneath the structures of L1, see Figure 2(b). The structures of L1 move down toward the surface, with obvious structural changes, and interact with the lower-lying closed loops, L2, see Figures 3(a) and (d) and the online animated version of Figure 3. Along the AB direction in the red rectangle in Figure 3(a), a time slice of the EUVI B 171 Å images is made, and displayed in Figure 4(a). The downward motion of structures L1 is clearly detected perpendicular to the LOS with a mean speed of \(0.7 \text{ km s}^{-1}\), see the red dotted line in Figure 4(a). The structures L1 and L2 interact and give rise to a pair of new structures, L3 and L4. This process is consistent with magnetic reconnection at the interface of structures L1 and L2, see Figures 3 and the online animated version of Figure 3.

Due to the downward motion of structures L1, a magnetic dip forms in structures L1, see Figures 3 and the online animated version of Figure 3. Condensations of coronal plasma appear in the EUVI A and B 304 Å images at the north edge of the dip. They then flow down along both legs of the newly reconnected closed loops L4, and also the leg of higher-lying open structures L1, to the surface as coronal rain, and finally disappear, see Figures 3 and the online animated version of Figure 3. Along the CD direction in the green box in Figure 3(b), a time slice of the EUVI B 304 Å images is made and shown in Figure 4(b). Multiple flows of the condensations are evidently identified.
with speeds ranging from 15–30 km s\(^{-1}\), see the green dotted lines in Figure 4(b).

During the 2 days, condensations take place repeatedly five times. General information on the repeated condensation events is listed in Table 1. Parameters, including the start time, the end time, the appearance time, and the lifetime of the condensations are measured and listed in Table 1. The lifetimes of condensations range from 1.5–10.2 hr. Because the time cadences of EUVI A and B 304 Å images here are nonuniform, those surrounding the measured parameters are chosen as measurement errors, e.g., ±0.2 hr is taken as the measurement error of the appearance time in the EUVI A 304 Å images for the first condensation event, see Table 1. Additionally, due to the longer, nonuniform time cadences of the EUVI A and B 304 Å images, the downward flow of the second condensation event along the north leg of loops L4 and/or the leg of structures L1 looks like a chromospheric surge, see the online animated version of Figure 3. We carefully check the simultaneous associated AIA 304 Å images, see the online animated version of Figure 5, and only detect the northward, rather than the southward, flows, see Section 3.2. This indicates that the coronal rain, rather than the chromospheric surge, takes place during the second condensation event. In the intervals between any two neighboring reconnection and condensation events, the higher-lying open structures L1 remain quiescent, and show inclined structures, see Figures 3(c) and (f). Without reconnection between the open and closed structures, no formation of dip in the higher-lying open structures, and no cooling and condensation of coronal plasma is observed (Li et al. 2018a, 2018b, 2019, 2020).

In the purple rectangles in Figures 3(a) and (b), the light curves of the EUVI B 171 and 304 Å channels for the second reconnection and condensation event are calculated and displayed in Figure 4(c) as blue and purple squares and lines.
Here, we show the observed values as squares on the lines, clearly showing the time cadences of the EUVI B images. In the blue rectangle in Figure 3(d), the light curve of the EUVI A 171 Å channel is measured and shown in Figure 4(c) as green diamonds and lines. The light curve of the EUVI A 304 Å channel is, however, not calculated, as the time cadence of the EUVI A 304 Å images during the time period is nonuniform. The EUVI B and A 171 Å light curves increase, reach their peaks, and then decrease, see the blue and green lines in Figure 4(c). They peak at 18:14 UT on 2011 July 14, see the vertical blue dotted and green dashed lines in Figure 4(c). Similar to the EUVI B and A 171 Å light curves, the light curve
of the EUVI B 304 Å channel also increases, reaches the peak, and then decreases. It, however, peaks at 20:36 UT on 2011 July 14, about 2.4 hr after the peaks of the EUVI B and A 171 Å light curves, see the purple vertical dotted line in Figure 4(c). This progressive appearance of emission first in the 171 Å channel and then in the 304 Å channel is consistent with plasma cooling and condensation (Viall & Klimchuk 2012). The plasma in the dip of structures L1 cools down from \( \sim 0.9 \) MK, the characteristic temperature of the 171 Å channel, to \( \sim 0.05 \) MK, the characteristic temperature of the 304 Å channel, in about 2.4 hr for the EUVI B. The peak times of the EUVI A 171, B 171, and B 304 Å light curves, and the cooling times from the 171 Å channel to the 304 Å channel are listed in Table 2. Similarly, the time cadences surrounding the measured parameters are considered as measurement errors, see Figure 4(c) and Table 2. Taking the measurement errors into account, identical results of the parameters are obtained for both EUVI A and B, see Table 2. For the other reconnection and condensation events, a similar evolution of the EUVI 171 and 304 Å light curves is obtained. In this study, even though the time cadences of the EUVI A and B observations are longer and nonuniform, the signatures of reconnection and condensations are clearly identified, see Figures 3 and 4 and the online animated version of Figure 3.

### 3.2. On-disk Coronal Condensations Facilitated by Reconnection between Open and Closed Structures Observed by SDO

In consideration of the separation angles between the three satellites of SDO and STEREO A and B, see Figure 1, combining the evolution of the 171 Å structures in EUVI A and B, we identify the same structures in the AIA 171 Å images on the disk, see Figure 2(c). The identification is confirmed as the observed structures in the AIA 171 Å channel are located such that the AR 11250 is located to the north of the structures L1, and the filament is lying underneath the structures L1, see Figure 2(c). As the structures are located on the disk in the FOV of SDO, their associated photospheric magnetic fields are thus observed in HMI LOS magnetograms, see Figure 2(d). The open structures L1 and L3 root in positive magnetic field concentrations, enclosed separately by the blue circles and ellipses in Figure 5. For the magnetic fields enclosed by the

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Figure 5. Coronal condensations facilitated by magnetic reconnection between open and closed structures observed by SDO. (a) and (b) AIA 171 Å, (c) and (d) 131 Å, (e) and (f) 304 Å images, and (g) and (h) HMI LOS magnetograms. Here, the AIA 304 Å images in (e) and (f) are enhanced employing the MGN technique. The blue circles and ellipses separately enclose the endpoints of structures L1 and L3. The blue solid arrows in (a) and (c) mark the bright emission in the AIA 171 and 131 Å channels, and the green solid arrows in (e) and (f) denote the condensations. The cyan dotted lines in (e) and (g) represent the filament underneath the structures L1. The cyan rectangle in (e) shows the FOV of Figures 6(a) and (b). The blue rectangles in (b), (d), and (f) mark the regions of the light curves of the AIA 171, 131, and 304 Å channels as displayed in Figure 7 by the red, green, and blue lines. The FOV is denoted by the blue rectangle in Figure 2(c). An animation of the unannotated SDO observations is available. It covers 16 hr starting at 13:00 UT on 2011 July 14, and the time cadence is 1 minute. See Section 3.2 for details. (An animation of this figure is available.)
blue circles, many dynamics, e.g., the motion, separation, convergence, and rotation, are detected, see the online animated version of Figure 5. Moreover, a mean magnetic field strength of 100 G and a total magnetic flux of $4 \times 10^{11}$ Mx are measured for the structures L1. The filament, underneath the structures L1, is located above the polarity inversion line between opposite polarity magnetic fields, see the cyan dotted lines in Figures 5(e) and (g). The loops L2 are difficult to observe on the disk in the AIA 171 Å images. According to the EUVI A and B 171 Å observations, see Section 3.1, they should connect the positive magnetic field concentration, the endpoint of structures L3, and the negative magnetic field concentrations, located between the endpoints of open structures L1 and L3. Moreover, the endpoint of loops L2, rooting in the negative magnetic field concentrations, is located closer to the other endpoint of loops L2 than to the endpoint of structures L1.

Due to the SDO viewing angle, the almost LOS downward motion of structures L1 is difficult to detect in the AIA images. Nevertheless, a bright emission feature appears at the north edge of the dip of structures L1 in the AIA 171 and 131 Å images, marked by blue solid arrows in Figures 5(a) and (c). Here, the AIA 131 Å emission shows plasma with the lower characteristic temperature ($\sim$0.6 MK) of the AIA 131 Å channel because there is no associated bright emission identified in the AIA higher-temperature channels, e.g., 94, 335, 211, and 193 Å. Subsequently, the leg of structures L1 appears, see Figures 5(a) and (c) and the online animated version of Figure 5. We measure the width of structures L1 in the dip region, and get a value of $\sim$22 Mm. Assuming that the structures L1 are cylinder in the dip region, with a diameter of 22 Mm, we calculate the magnetic field strength of structures L1 in the dip region using the total magnetic flux of structures L1 ($4 \times 10^{11}$ Mx), and obtain a mean value of 10 G. The newly reconnected open structures L3 then form, see Figures 5(b) and (d). At the same time, part of the leg of structures L1 turns into the north leg of the newly reconnected closed loops L4 through reconnection with loops L2. However, they are not distinguished from each other, due to the viewing angle of SDO, see Figures 5(b) and (d).

Dark condensations are detected in the AIA 304 Å images, with the width of $\sim$1.4", that flow along the leg of structures L1 and the north leg of loops L4 (toward their north endpoints), denoted by green solid arrows in Figures 5(e) and (f). Similar as in the STEREO observations, cooling and condensation of coronal plasma in the dip is thus identified on the disk with AIA. In order to better show the condensations, the AIA 304 Å image in the cyan rectangle in Figure 5(e) is enlarged in Figure 6(a). Here, the blue dashed--dotted lines in Figures 6(a) and (b) enclose the AIA 131 Å structures L1 and L4, showing the moving path of condensations. Along the green dotted line EF in Figure 6(a), a time slice of the AIA 304 Å images is made and displayed in Figure 6(c). Multiple flows of the condensations are identified, denoted by green solid arrows in Figure 6(c), with moving speeds ranging from 37–72 km s$^{-1}$, see the cyan dashed lines in Figure 6(c). Here, besides the dark features, some bright features are also detected, see Figure 6(c). This may be caused by the multithermal character of coronal rain.

In the blue rectangles in Figures 5(b), (d), and (f), the light curves of the AIA 171, 131, and 304 Å channels are calculated and displayed in Figure 7 as red, green, and blue lines. Here,

Figure 6. Temporal evolution of the coronal condensations facilitated by magnetic reconnection between open and closed structures observed by SDO. (a) AIA 304 Å and (b) 131 Å images, and (c) a time slice of the AIA 304 Å images along the green dotted line EF in (a). Here, the AIA 304 Å image in (a) is enhanced using the MGN technique. Same as in Figures 5(e) and (f), the green solid arrows in (a) and (c) denote the condensations. The blue dashed--dotted lines in (a) and (b) enclose the structures L1 and L4 in (b). The cyan dashed lines in (c) enclose the motions of condensations. The moving speeds are denoted by the numbers in (c). The FOV of (a) and (b) is denoted by the cyan rectangle in Figure 5(e). An animation of the AIA 304 Å images (panel (a)) is available. It covers 80 minutes starting at 20:00 UT on 2011 July 14, and the time cadence is 1 minute. See Section 3.2 for details.

(An animation of this figure is available.)
the inverse of the AIA 304 Å light curve is used, as the condensations in the AIA 304 Å images show dark absorption features. All three AIA EUV light curves increase, reach the peaks, and then decrease. They, however, peak separately at 19:35 UT, 20:08 UT, and 20:34 UT on 2011 July 14, marked by the red, green, and blue vertical dotted lines in Figure 7. The fact that the AIA 131 Å light curve peaks later than the AIA 171 Å light curve also supports that the AIA 131 Å emission represents plasma with the lower characteristic temperature (∼0.6 MK) of the AIA 131 Å channel, cooler than the emitting plasma detected by the AIA 171 Å channel (∼0.9 MK). The cooling of plasma, always shown by the AIA EUV light curves in the corona (Viall & Klimchuk 2012), in the dip of open structures L1 is hence clearly detected. Here, the plasma cools down from ∼0.9 MK, the characteristic temperature of the AIA 171 Å channel, to ∼0.6 MK, the lower characteristic temperature of the AIA 131 Å channel, in 33 minutes, and then to ∼0.05 MK, the characteristic temperature of the AIA 304 Å channel, in another 26 minutes, see the second condensation event in Table 2. A similar evolution of the AIA EUV light curves is obtained for the other reconnection and condensation events. For the five condensation events, the plasma in the dip

![Figure 7](image)

Figure 7. The AIA 171 and 131 Å light curves (red and green lines) and the inverse of the AIA 304 Å light curve (blue line) in the blue rectangles in Figures 5(b), (d), and (f). The red, green, and blue vertical dotted lines separately mark the peaks of the AIA 171, 131, and 304 Å light curves; see the second condensation event in Table 2. Similar to Figure 4(c), the purple squares and lines represent the EUVI B 304 Å light curve. See Section 3.2 for details.

| Event | Instrument | Peak Time (UT) | Cooling Time (hr) |
|-------|------------|----------------|-------------------|
|       |            | 171 Å | 131 Å | 304 Å | 171–131 Å | 131–304 Å | 171–304 Å |
| 1     | EUVI A     | …    | …    | 14 04:26 ± 0.2 hr | …    | …    | …    |
|       | EUVI B     | 14 02:14 ± 2 hr | …    | 14 04:26 ± 0.2 hr | …    | …    | 2.2 ± 2.2 |
|       | AIA        | 14 01:49 | 14 02:01 | 14 04:46 | 0.2    | 2.75  | 2.95  |
| 2     | EUVI A     | 14 18:14 ± 4.3 hr | …    | …    | …    | …    | …    |
|       | EUVI B     | 14 18:14 ± 0.7 hr | 14 20:36 ± 0.2 hr | …    | …    | 2.4 ± 2.2 |
|       | AIA        | 14 19:35 | 14 20:08 | 14 20:34 | 0.55  | 0.43  | 0.98  |
| 3     | EUVI A     | 15 00:14 ± 2 hr | …    | …    | …    | …    | …    |
|       | EUVI B     | 15 00:14 ± 0.7 hr | 15 01:51 | …    | …    | 1.6 ± 0.7 |
|       | AIA        | 15 00:23 | 15 00:33 | 15 01:59 | 0.17  | 1.43  | 1.6   |
| 4     | EUVI A     | …    | …    | 15 08:16 ± 2 hr | …    | …    | …    |
|       | EUVI B     | …    | …    | 15 07:54 | …    | …    | …    |
|       | AIA        | 15 06:25 | 15 06:33 | 15 07:56 | 0.13  | 1.38  | 1.52  |
| 5     | EUVI A     | …    | …    | 15 16:46 ± 0.2 hr | …    | …    | …    |
|       | EUVI B     | 15 14:14 ± 2 hr | 15 16:26 ± 0.2 hr | …    | 2.2 ± 2.2 |
|       | AIA        | 15 13:52 | 15 14:55 | 15 16:09 | 1.05  | 1.23  | 2.28  |

Note. Similar to Table 1, the 14 and 15 in the front of the Columns 3–5 separately represent the dates of 2011 July 14 and 15. For the second event, the peak times of the STEREO/EUVI A 171 Å, B 171 Å, and B 304 Å light curves are marked by the vertical green dashed, blue dotted, and purple dotted lines in Figure 4(c), and those of the SDO/AIA 171, 131, and 304 Å light curves are denoted by the red, green, and blue vertical dotted lines in Figure 7.
cools down from $\sim$0.9 MK to $\sim$0.6 MK in 0.13–1.05 hr, and then to $\sim$0.05 MK in another 0.43–2.75 hr, see Table 2. More details on the repeated reconnection and condensation events above the limb are revealed in Li et al. (2019, 2020). To compare with the STEREO observations, we overlay the EUVI B 304 Å light curve in Figure 4(c) on Figure 7 as purple squares and lines. Even though the condensation in the AIA 304 Å images shows dark absorption feature, and is affected by the underneath background emission, the AIA 304 Å light curve shows similar temporal evolution to the light curve of the EUVI B 304 Å channel, see Figure 7. Both of them peak at almost the same time. In consideration of the measurement errors, consistent parameters, i.e., the peak and cooling times, are obtained from the AIA and EUVI A and B observations, see Table 2.

4. Summary and Discussion

Employing EUV images and LOS magnetograms of STEREO A and B and SDO, we investigate the condensation events facilitated by reconnection between open and closed structures both above the limb and on the disk from 2011 July 14–15. In the EUVI B (A) 171 Å images, the higher-lying open structures L1 above the southwestern (southeastern) limb move down toward the surface, with the formation of a magnetic dip, and interact with the lower-lying closed loops L2. Reconnection between the structures L1 and L2 takes place at the interface, and forms the newly reconnected structures L3 and L4. Five bright condensation events appear repeatedly in the EUVI A and B 304 Å images at the north edge of the dip of structures L1, and move downward to the surface along both legs of the loops L4 and the leg of structures L1. In the AIA 171 Å images, due to the viewing angle, the whole system of reconnection structures is not totally detected on the disk. Only part of the structures L1, L3, and L4 are identified. Bright emission appears in the AIA 171 and 131 Å images at the north edge of the dip of structures L1. Dark condensations subsequently occur in the AIA 304 Å images, and then flow downward to the surface along the north leg of structures L1 and L4. The cooling and condensation process of coronal plasma in the dip of structures L1 is evidently observed, also identified from the EUVI 171 and 304 Å and the AIA 171, 131, and 304 Å light curves.

According to the EUVI A and B and AIA EUV images and the HMI LOS magnetograms, schematic diagrams, adapted from Figure 6 of Li et al. (2018a), are provided to describe the reconnection between structures and the condensations of plasma from three different observing angles in Figure 8. Reconnection between the field lines of structures L1 and L2, see red stars between the green and blue lines in Figure 8, forms a magnetic dip in structures L1, marked by red solid arrows in Figure 8. The surrounding plasma is gathered into the dip, leading to the enhancement of the plasma density. Triggered by the enhancement of the density, thermal instability takes place locally in the dip, driving the plasma to cool catastrophically and condense, see large orange ellipses in Figure 8. Due to the successive reconnection, the condensations fall along the field lines of structures L1 and L4 to the surface as coronal rain, see small orange ellipses along the lines in Figure 8.

Similar coronal condensation events facilitated by reconnection between open and closed structures above the limb observed by STEREO are presented (see Section 3.1). The repeated condensation events last for 1.5–10.2 hr, consistent with the lifetimes of condensations in Li et al. (2018a, 2018b, 2019, 2020). The speed of the movement (0.7 km s$^{-1}$) of the structures L1 and the falling speed (15–30 km s$^{-1}$) of condensations are, however, smaller than those in Li et al. (2018a, 2018b, 2019, 2020). This may be caused by the longer time cadences of the EUVI A and
B 171 and 304 Å images than those of the AIA 171 and 304 Å images, see Section 2. Identical to Li et al. (2019, 2020), a filament is located under the higher-lying open structures L1, see Figures 2 and 8. This kind of magnetic system, consisting of the higher-lying open structures and lower-lying filament, may be prone to the condensations facilitated by reconnection between open and closed structures.

On-disk condensation events facilitated by reconnection between open and closed structures are first reported (see Section 3.2). Similar to those off-limb condensations facilitated by reconnection previously investigated (Li et al. 2018a, 2018b, 2019, 2020), bright emission in the AIA 171 Å and 131 Å images is detected on the disk during the cooling and condensation process. However, the AIA 171 Å structures are difficult to observe on the disk before the reconnection takes place. Moreover, dark, rather than bright, condensations are identified in the AIA 304 Å images on the disk, consistent with the on-disk quiescent coronal rain in AR closed loops in Hα against a bright background (Antolin et al. 2012; Antolin & Rouppe van der Voort 2012; Ahn et al. 2014). The speed of the movement (37–72 km s\(^{-1}\)) of the on-disk condensations in the AIA 304 Å images is larger than that (15–30 km s\(^{-1}\)) of the off-limb condensations in the EUVI 304 Å images, but identical to those of the off-limb condensations in the AIA 304 Å images (Li et al. 2018a, 2018b, 2019, 2020), due to the time cadences of respective observations. Even though the structures and condensations on the disk are affected by the underneath background emission, similar cooling times from ∼0.9 MK to ∼0.6 MK (0.13–1.05 hr), and then to ∼0.05 MK (0.43–2.75 hr) are clearly identified to those of the off-limb bright condensations facilitated by reconnection in Li et al. (2018a, 2018b, 2019, 2020) (see Figure 7 and Table 2).

On-disk condensations facilitated by reconnection between open and closed structures at high coronal altitudes are suggested to explain some of the flows, e.g., coronal rain in the chromospheric lines on the disk. Recently, employing IRIS and AIA observations, we proposed that some of the off-limb coronal rain events with loop-like paths in the transition region and chromospheric lines originate from the condensations facilitated by interchange reconnection (Li et al. 2020). In this study, the coronal plasma would cool all the way down to the chromospheric temperatures, as reported in Li et al. (2020), the chromospheric flows associated with the downflows of condensations then could be observed in the chromospheric lines. Using Hα line center images of the full-disk Hα telescope at the Huairou Solar Observing Station, the chromospheric flows associated with the on-disk condensations are examined. On account of the width of condensations (∼1.4\(^{\circ}\)), the larger spatial sampling of Hα images (∼0.9\(^{\prime}\) pixel\(^{-1}\)), and the influencing factors of ground-based telescopes, e.g., cloud and atmospheric turbulence, no associated chromospheric flow is evidently detected. To verify our suggestion, higher spatial resolution chromospheric observations, e.g., data from the New Vacuum Solar Telescope (Liu et al. 2014) or the Daniel K. Inouye Solar Telescope, are needed in the future works.

Similar results of the on-disk condensations are obtained to those of the on-disk quiescent coronal rain in AR closed loops in Hα (see Section 3.2). If we considered the AIA 304 Å observations alone, the on-disk condensation, and hence coronal rain events we report here would resemble those occurring in magnetically closed field lines (Antolin & Rouppe van der Voort 2012; Antolin et al. 2012; Ahn et al. 2014), which are generally interpreted as a manifestation of the heating-condensation cycles due to thermal nonequilibrium (Schrijver 2001; Müller et al. 2003, 2004; Antolin 2020). However, combining the observations of SDO and STEREO A and B at different viewing angles, we find that the on-disk coronal rain in this study corresponds to the downflows of condensations facilitated by reconnection between open and closed structures. Similarly, if we analyze only the on-disk observations as recorded by the AIA as shown in Figure 7, it appears that the structures gradually brighten first in the 171 Å channel and then in the 131 Å channel. Such sequential appearance of coronal structures in the AIA channels sensitive to emission from progressively cooler plasma could be interpreted as a case of loop cooling after nanoflare heating (e.g., Viall & Klimchuk 2012; Li et al. 2015), for instance. In contrast, by employing observations from multiple vantage points, we show that the on-disk structure brightening in the AIA images is actually due to cooling and condensation of plasma facilitated by reconnection in the high corona that is not necessarily regulated by any heating mechanism. To search for the origination of structures harboring on-disk flow, e.g., coronal rain, in the transition region or chromospheric lines, observations from different viewing angles are thus quite important. If there is no observation from other viewing angles, evolution of the associated structures, that may be difficult to observe on the disk, in multlwavelength images during the cooling and condensation process needs to be examined because the condensation facilitated by reconnection cools down from ∼0.9 MK, the characteristic temperature of the 171 Å channel, rather than from the higher temperatures.

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ORCID iDs
Leping Li @ https://orcid.org/0000-0001-5776-056X
Hardi Peter @ https://orcid.org/0000-0001-9921-0937
Lakshmi Pradeep Chitta @ https://orcid.org/0000-0002-9270-6785
Hongqiang Song @ https://orcid.org/0000-0001-5705-661X

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