Energy Release in the Solar Atmosphere from a Stream of Infalling Prominence Debris

A. R. Inglis1,2, H. R. Gilbert1, and L. Ofman1,2

1 Solar Physics Laboratory, Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
2 Physics Department, The Catholic University of America, Washington, DC 20064, USA

Received 2017 August 2; revised 2017 September 13; accepted 2017 September 14; published 2017 September 27

Abstract

Recent high-resolution and high-cadence extreme-ultraviolet (EUV) imaging has revealed a new phenomenon, impacting prominence debris, where prominence material from failed or partial eruptions can impact the lower atmosphere, releasing energy. We report a clear example of energy release and EUV brightening due to infalling prominence debris that occurred on 2011 September 7–8. The initial eruption of material was associated with an X1.8-class flare from AR 11283, occurring at 22:30 UT on 2011 September 7. Subsequently, a semicontinuous stream of this material returned to the solar surface with a velocity $v > 150 \text{ km s}^{-1}$, impacting a region remote from the original active region between 00:20 and 00:40 UT on 2011 September 8. Using the Solar Dynamics Observatory/Atmospheric Imaging Assembly, the differential emission measure of the plasma was estimated throughout this brightening event. We found that the radiated energy of the impacted plasma was $L_{\text{rad}} \sim 10^{27} \text{ erg}$, while the thermal energy peaked at $\sim 10^{28} \text{ erg}$. From this we were able to determine the mass content of the debris to be in the range $2 \times 10^{14} \text{ g} < M < 2 \times 10^{15} \text{ g}$. Given typical prominence masses, the likely debris mass is toward the lower end of this range. This clear example of a prominence debris event shows that significant energy release takes place during these events and that such impacts may be used as a novel diagnostic tool for investigating prominence material properties.

Key words: Sun: activity – Sun: prominences – Sun: filaments

Supporting material: animation

1. Introduction

It has been known for some time that solar prominences, or filaments, exhibit a wide range of eruptive behavior, up to and including the full ejection of significant material from the solar corona into the heliosphere. More commonly, either a partial or failed eruption is observed (Gilbert et al. 2007), where some or all of the eruptive prominence debris fails to escape the solar atmosphere and falls back toward the surface. These types of prominence eruptions are closely associated with coronal mass ejections and are key toward improving our understanding of coronal mass ejection (CME) initiation.

Despite decades of research, several properties of prominences remain poorly constrained (see Labrosse et al. 2010; Mackay et al. 2010 for recent reviews). For example, a novel method of determining prominence mass was presented by Gilbert et al. (2005), yet the uncertainties in column density remained substantial. Additionally, the filling factor of prominences, as with many other solar phenomena, remains poorly known (Kucera et al. 1998). In recent years, however, increased availability of state-of-the-art solar instrumentation, including those on board the Solar Dynamics Observatory (SDO), Solar TERrestrial RElations Observatory (STEREO), and Interface Region Imaging Spectrograph (IRIS), has dramatically increased the potential for detailed studies of this phenomenon.

In particular, recent observations have shown that descending prominence debris from failed eruptions can cause substantial energy release and plasma heating upon impact with the solar atmosphere (e.g., Gilbert et al. 2013; Reale et al. 2013, 2014). This energy release is directly observable by SDO at extreme-ultraviolet (EUV) wavelengths via the Atmospheric Imaging Assembly (AIA), providing a new diagnostic opportunity for understanding the properties of CME-associated material and probing the response of the solar atmosphere. The best example of this phenomenon observed to date is the flare- and CME-associated 2011 June 7 eruption (Innes et al. 2012, 2016; Li et al. 2012; Gilbert et al. 2013; Inglis & Gilbert 2013; Reale et al. 2013; Carlyle et al. 2014; van Driel-Gesztelyi et al. 2014; Yardley et al. 2016), where localized EUV brightening was observed at multiple impact points due to descending prominence debris. Such brightening patches are spatially and temporally resolved by SDO/AIA at multiple wavelengths, indicating that the plasma is multithermal and heated to several MK (Gilbert et al. 2013; Reale et al. 2013). Reale et al. (2013) compared these observations with the process of stellar accretion observed at UV and X-ray wavelengths. Recently, such EUV brightening was observed in another flare by Li & Ding (2017).

Other phenomena sometimes compared to prominence debris include sequential chromospheric brightenings (SCBs; Balasubramaniam et al. 2005; Kirk et al. 2012, 2017) and coronal rain in active regions (Antolin et al. 2012, 2015; Vashalomidze et al. 2015). Both of these phenomena are substantially different; SCBs generally only occur only in the parent active region of the eruption, while the small descending blobs associated with coronal rain have much lower downward speeds than eruptive prominence debris, do not cause observable emission due to impacting in the solar atmosphere, and are not associated with prominence or CME material.

In this work, we present a new case study of prominence debris impacting the lower atmosphere, from 2011 September 7 to 8. To the best of our knowledge, this is only the second example of this phenomenon subject to detailed study and the most energetic observed to date. This event took the form of a single, near-continuous material stream leading to continuous brightening of the same atmospheric region at multiple wavelengths. By examining the energetic and kinematic properties of this event, we constrain the properties of the incoming stream, including the total mass of the deposited...
material. In Section 2, we describe the initial observations of this eruption, while in Section 3, we present the methodology for estimating the radiated and thermal energy of the plasma and infer the prominence mass. The implications of these estimates are discussed in Section 4.

2. Observations

The initial prominence eruption occurred at ∼22:32 UT on 2011 September 7, as part of an X1.8-class solar flare originating from AR 11283 (e.g., Zharkov et al. 2013). This event was also associated with a non-geoeffective CME. Figure 1(a) shows the partially eruptive prominence material shortly after flare onset, at 22:58 UT. From this it is clear that a large amount of cool material was energized during the flare impulsive phase. However, despite the large energy release during this event, a substantial amount of material fails to escape the Sun and returns to the solar surface two hours after flare onset, at ∼00:20 UT on 2011 September 8. The impact point of the stream is substantially removed from the original active region and is indicated by the white box in Figure 1(a).

The main stream of descending material is shown in Figures 1 (b)–(d). These show successive snapshots of the stream just prior to impact with the lower corona. Figure 1(d) shows the beginning of the atmospheric brightening due to this material, indicating that the plasma is being substantially heated.

3. Analysis and Results

3.1. Impact Evolution

Figure 2 shows the evolution of the bright region caused by the impacting prominence stream as observed by SDO/AIA. Panels (a)–(d) show the appearance of the bright region at four different times. Clearly, the bright source undergoes substantial evolution over time during the stream impact. Hence, it is necessary to construct a scheme to estimate the area of the brightening at any given time. To achieve this, we first find the point in both space and time corresponding to the maximum brightening value in the SDO/AIA 193 Å channel. From this we establish a threshold of 5% of this maximum for a pixel to be included in the bright region. Using this threshold, for each image frame we find the point of maximum intensity in the brightening region and expand in all directions until the threshold is reached. Thus, for each frame we are able to estimate the area of the instantaneous bright, heated plasma. The white contour in panels (a)–(d) shows the area defined by this scheme during the selected times. Figures 2(e)–(g) show the full evolution of this brightening region over time. Figure 2(e) shows the integrated flux from a constant area that encompasses the entire brightening at all times (shown as box A in panel (a)). This illustrates that all six EUV channels experience an increase in flux during impact. However, the 171 Å flux peaks slightly later than most other channels,
reaching a maximum at \( \sim 00:26 \) UT, compared with \( \sim 00:25 \) UT for the 211 Å and 335 Å emission, consistent with cooling of the bright plasma following impact. Figure 2(f) shows instead the pixel-averaged, normalized flux in each channel within the contoured region only. Although the majority of channels show an increase in flux on a per-pixel basis, the 94 and 171 Å channels are exceptions, indicating that the increased brightening in these channels is due almost entirely to the increasing size of the bright area, rather than increasing flux in each pixel. This is highlighted in Figure 2(g), which shows the estimated area in cm\(^2\) of the bright region as it evolves. Together, these panels show that substantial brightening begins at \( \sim 00:20 \) UT, peaking at \( 00:26 \) UT, with emission continuing until \( \sim 00:40 \) UT. The impact area of the 2011 September 7–8 event is much larger than the brightenings observed on 2011 June 7; from Figure 2(f) we see that the area peaks at \( \sim 6 \times 10^{18} \) cm\(^2\). For comparison, the largest of the impacts observed on 2011 June 7 was \( \sim 1.3 \times 10^{18} \) cm\(^2\).

The descending prominence debris is visible in several consecutive AIA image frames prior to impact with the lower corona, as shown in Figure 1. Thus, we can estimate the plane-of-sky velocity of the infalling material. Although the true observing angle of the material stream cannot be determined due to a lack of triangulation, plane-of-sky measurements can place a lower limit on the stream velocity. In Figure 3(a), we estimate the position of a distinct piece of the descending stream in successive AIA 193 Å images. These locations are shown by the white diamond marks, propagating from solar west to east. In Figure 3(b), we perform a linear fit to these positions, finding the best-fit plane-of-sky velocity \( v \sim 150 \) km s\(^{-1}\). However, there is large uncertainty due to projection effects; for example, if the material was actually propagating at \( 45^\circ \) in the z-direction, the true velocity would be \( \sim 220 \) km s\(^{-1}\). Nevertheless, these values are similar to estimates of material velocity found by Gilbert et al. (2013) for the 2011 June 7 event, who used triangulated measurements from AIA and STEREO-A, finding \( v \sim 150–300 \) km s\(^{-1}\). For the same event, Reale et al. (2013)
estimated $v \approx 300\text{–}450\,\text{km}\,\text{s}^{-1}$. For the 2011 September 7–8 event, the material also does not appear to experience significant acceleration during this time period, suggesting it may have already reached critical velocity.

3.2. Differential Emission Measure, Energetics, and Mass Estimation

Given the enhancements in emission from multiple SDO/AIA channels, we can investigate the energy release during the impact process by estimating the differential emission measure (DEM) of the bright plasma. To estimate the DEM, we use the forward-fitting technique developed by Aschwanden et al. (2013), which was used by Gilbert et al. (2013) to estimate the energy of prominence debris impacts in the 2011 June 7 event. We choose a DEM distribution of the form

$$\text{DEM}(T) = \text{EM}_0 \exp \left( \frac{\log T - \log \langle T \rangle}{2\sigma^2} \right),$$

(1)
i.e., a Gaussian emission measure distribution with peak temperature $\langle T \rangle$ and width $\sigma$, as utilized by Aschwanden et al. (2013, 2015).

The temperature response functions of the AIA channels are the source of significant uncertainty (e.g., Aschwanden et al. 2013), particularly the 94 and 131 Å channels at low temperatures. In order to account for this, we include a 25% uncertainty in the measured AIA flux due to instrument response, as suggested by Boerner et al. (2012) and Guennou et al. (2012a, 2012b). This is combined in quadrature with the statistical uncertainty associated with the AIA flux measurements.

The best fit to the observed flux is achieved at each time interval via a search over the parameter space given by the variables $\text{EM}_0$, $\langle T \rangle$, and $\sigma$ using the $\chi^2$ test. Figure 4 shows examples of the best-fit DEM results at three different times, near the start, peak, and end of the brightening. This shows that the majority of the brightening comes from increased EM at moderate temperatures, with $\log \langle T \rangle \approx 6.4$.

Given a DEM, we can estimate the radiative losses from the plasma via (e.g., Aschwanden 2005)

$$\frac{dL_{\text{rad}}}{dt} = \int_{\text{fl}}^{\text{ts}} \text{DEM}(T') \times \Lambda(T) \, dT \, \text{erg s}^{-1},$$

(2)

where $\Lambda(T)$ is the radiative loss function and $\text{DEM}(T') = \text{DEM}(T) \times A$ is the differential emission measure multiplied by the emitting area $A$, and hence is in units of $\text{cm}^{-3}\,\text{K}^{-1}$. Here, $\log \langle T \rangle = 5.5$, and $\log T_1 = 7.0$. To find the total energy radiated, we estimate $\Lambda(T)$ using the CHIANTI database (Landi et al. 2012; Del Zanna et al. 2015) assuming coronal abundances, and integrate Equation (2) over the duration of impacting stream; hence,

$$L_{\text{rad}} = \int_{t_0}^{t_1} \frac{dL_{\text{rad}}(t)}{dt} \, dt,$$

(3)

where $t_0 = 00:20\,\text{UT}$ and $t_1 = 00:40\,\text{UT}$.

Using the DEM, it is also possible to calculate the peak thermal energy $U_{\text{th}}$. For an isothermal plasma; this is given by (e.g., Veronig et al. 2005; Hannah et al. 2008; Emslie et al. 2012; Inglis & Christie 2014; Warmuth & Mann 2016)

$$U_{\text{th}} = 3k_B T \sqrt{\text{EM}_{\text{tot}} f V},$$

(4)

where $\text{EM}_{\text{tot}}$ is the total emission measure in $\text{cm}^{-3}$ of the plasma with temperature $T$, $V$ is the plasma volume, and $f$ is the plasma filling factor. For a multithermal plasma, we must account for the energy at all $T$. Hence, Equation (4) becomes (Inglis & Christie 2014; Aschwanden et al. 2015),

$$U_{\text{th}} = 3k_B V^{1/2} \frac{\int \text{DEM}(T') \times TDV}{\text{EM}_{\text{tot}}^{1/2}},$$

(5)

where $\text{DEM}(T')$ is the differential emission measure expressed in $\text{cm}^{-3}\,\text{K}^{-1}$ as before, and a filling factor $f = 1$ is assumed. The temperature bounds are the same as in Equation (2). For both Equations (4) and (5) the volume $V$ must be estimated, which is complicated by a lack of observational information of the source in the $z$-direction. In this work, we use the simple estimate $V \sim A^{3/2}$; hence, the estimated volume varies over time with the area (see Figure 2).

Figure 5 shows the energetic properties of the debris impact region, the same region illustrated by the white contours in Figure 2. Panel (a) illustrates the estimated radiated energy rate $dL/dt$ as a function of time. The radiated losses show an order of magnitude increase, beginning at 00:20 UT. This coincides with a substantial increase in the estimated area of the impact region (see Figure 2); on a per-pixel basis, the increase in emission is smaller, approximately a factor $\sim 2$. Hence, as Figure 5(b) shows, the increase in radiated energy is a combination of increased flux and the enlargement of the emitting region itself. Figure 5(c) shows the estimated instantaneous thermal energy during this event, peaking at $\sim 10^{38}$ erg.
We can compare these energetic properties with the previous observations of impacting prominence debris from the 2011 June 7 event (Gilbert et al. 2013; Reale et al. 2013). In Gilbert et al. (2013), the radiated energy was estimated for five observable brightening regions affected by impacting debris. Combining all of these regions, the estimated total radiated energy $L_{\text{rad}}$ was $\sim 4 \times 10^{25}$ erg. For the 2011 September 7–8 observation, we find from integrating Figure 5(a) that the total energy radiated is $\sim 10^{27}$ erg, at least a factor of 2 higher. This is consistent with the observations for two reasons: first, the 2011 September 7–8 observation consists of a relatively continuous material stream that impacts a larger area than the 2011 June 7 impacts, and second, the brightening duration is substantially longer, with significant emission lasting for $\sim 20$ minutes.

However, the total estimated radiated energy loss is an order of magnitude lower than estimated peak thermal energy of the plasma $U_{\text{th}}$. This could be the result of two major factors. First, when calculating the thermal energy, a value of $f \sim 1$ was assumed for the plasma filling factor; however, the true value of $f$ is unknown and may be substantially less than unity (e.g., Cargill & Klimchuk 1997; Guo et al. 2012). This, combined with uncertainties in the plasma volume $V$, leads to a large uncertainty in the estimate of $U_{\text{th}}$, possibly an overestimate. The second factor is that conductive losses could play an important role in the energy evolution of the bright plasma.

Despite these uncertainties, we can use these energy estimates to constrain the minimum and maximum kinetic energy, and thus the mass, of the impacting prominence material. We can assume that the estimate of $L_{\text{rad}}$ gives us a lower limit on the kinetic energy requirement from the infalling prominence material. Hence, $KE \gtrsim 10^{27}$ erg. Given our plane-of-sky velocity estimate of the falling material of $v \sim 150$ km s$^{-1}$, we can estimate the minimum value of mass $m$ required to produce this kinetic energy. From this we estimate $m_{\text{low}} \sim 2 \times 10^{14}$ g. Alternatively, we can assume that conductive losses play a significant role in the energy budget of this event and that the estimate of $U_{\text{th}}$ provides a good approximation of the total energy deposited by the prominence material. In this case, we find that $KE \sim 10^{28}$ erg, which requires $m_{\text{high}} \sim 2 \times 10^{15}$ g.

4. Conclusions

We have analyzed a new example of energy release and EUV brightening due to prominence debris, occurring on 2011 September 8 at $\sim 00:20$ UT. This event occurred following the large X-class flare from AR 11283 beginning at $\sim 22:30$ UT on 2011 September 7. During the eruption, a large amount of cool material was ejected from the active region. Some of that material failed to escape the solar atmosphere, resulting in a descending stream of prominence debris that impacted the atmosphere at a site substantially removed from the original AR. This caused an extended EUV brightening lasting for $\sim 20$ minutes between 00:20 UT and 00:40 UT.

Due to the brightening of emission in multiple optically thin AIA channels during impact, we were able to estimate the DEM of the plasma as a function of time throughout the event and, consequently, the peak thermal energy and radiated energy of the plasma (see Figure 5). We found the peak value of thermal energy to be $U_{\text{th}} \sim 10^{28}$ erg. The estimated total radiated energy was an order of magnitude smaller, at $L_{\text{rad}} \sim 10^{27}$ erg. The disparity between these values may be due either to the importance of conductive losses in the plasma, or the uncertainty in the plasma volume $V$ and the filling factor $f$, both of which affect the estimate of $U_{\text{th}}$. Comparing these values to estimates from the well-known 2011 June 7 event (e.g., Gilbert et al. 2013; Reale et al. 2013), we see that the 2011 September 7–8 event was more energetic overall, lasting for longer and radiating more energy.

Using SDO/AIA images we also estimated the plane-of-sky velocity of the descending stream at $v \sim 150$ km s$^{-1}$. Using this as a lower limit on the true material velocity, we constrain the kinetic energy and mass requirements of the prominence material in order to explain the observed brightening. We estimate that $10^{27} < KE < 10^{28}$ erg and $2 \times 10^{14} < m < 2 \times 10^{15}$ g. This is substantially greater than the estimate of mass obtained for the prominence debris from 2011 June 7 (Gilbert et al. 2013), consistent with the larger energy release from this event.

We can compare this mass range estimate with the typical mass values expected from solar prominences, which range from $5 \times 10^{12} - 10^{15}$ g (Labrosse et al. 2010), based on a wide range of possible prominence volumes. Similar estimates of $m \sim 10^{14} - 2 \times 10^{15}$ g were found by Gilbert et al. (2006). Given these estimates, a debris mass of $10^{15}$ g seems unphysical, as this approaches the mass of an entire prominence. Hence, the value of $m$ derived from $U_{\text{th}}$ for this event may be an overestimate due to uncertainty on the plasma filling factor $f$ and volume $V$, which introduces large uncertainty into the estimate of $U_{\text{th}}$ (see Equations (4) and (5)). The radiated energy estimate, however, does not depend on the plasma volume and may provide a more realistic estimate of the impacting material. Another uncertain factor is the velocity $v$; the true value could be higher than the estimated plane-of-sky velocity, lowering the mass required to explain the observations. Hence, we conclude that the mass of impacting prominence debris is of the order of $m \sim 2 \times 10^{14}$ g.

This observation shows that prominence debris from partial or failed eruptions can cause significant energy release in the
lower corona, at sites far removed from the initial active region. These observations can constrain the properties of the local coronal plasma and the prominence debris itself. Further study of this type of phenomenon would help to better constrain the energetic and kinematic properties of these events.

L.O. would like to acknowledge support by NASA Cooperative agreement NNG11PLA10A 670.154 to CUA.

References
Antolin, P., Vissers, G., Pereira, T. M. D., Rouppe van der Voort, L., & Scullion, E. 2015, ApJ, 806, 81
Antolin, P., Vissers, G., & Rouppe van der Voort, L. 2012, SoPh, 280, 457
Aschwanden, M. J. 2005, Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd ed.; Chichester: Praxis)
Aschwanden, M. J., Boerner, P., Ryan, D., et al. 2015, ApJ, 802, 53
Aschwanden, M. J., Boerner, P., Schrijver, C. J., & Malanushenko, A. 2013, SoPh, 283, 5
Balasubramaniam, K. S., Pevtsov, A. A., Neidig, D. F., et al. 2005, ApJ, 630, 1160
Boerner, P., Edwards, C., Lemen, J., et al. 2012, SoPh, 275, 41
Cargill, P. J., & Klimchuk, J. A. 1997, ApJ, 478, 799
Carlisle, J., Williams, D. R., van Driel-Gesztelyi, L., et al. 2014, ApJ, 782, 87
Del Zanna, G., Dere, K. P., Young, P. R., Landi, E., & Mason, H. E. 2015, A&A, 582, A56
Emslie, A. G., Dennis, B. R., Shih, A. Y., et al. 2012, ApJ, 759, 71
Gilbert, H. R., Alexander, D., & Liu, R. 2007, SoPh, 245, 287
Gilbert, H. R., Falco, L. E., Holzer, T. E., & MacQueen, R. M. 2006, ApJ, 641, 606
Gilbert, H. R., Holzer, T. E., & MacQueen, R. M. 2005, ApJ, 618, 524
Guennou, C., Auchère, F., Soubré, E., et al. 2012a, ApJS, 203, 25
Guennou, C., Auchère, F., Soubré, E., et al. 2012b, ApJS, 203, 26
Hannah, I. G., Christe, S., Krucker, S., et al. 2008, ApJ, 677, 704
Inglis, A. R., & Christe, S. 2014, ApJ, 789, 116
Inglis, A. R., & Gilbert, H. R. 2013, ApJ, 777, 30
Innes, D. E., Cameron, R. H., Fletcher, L., Inhester, B., & Solanki, S. K. 2012, A&A, 540, L10
Innes, D. E., Heinrich, P., Inhester, B., & Guo, L.-J. 2016, A&A, 592, A17
Kirk, M. S., Balasubramaniam, K. S., Jackiewicz, J., & Gilbert, H. R. 2017, SoPh, 292, 72
Kirk, M. S., Balasubramaniam, K. S., Jackiewicz, J., McAlister, R. T. J., & Milligan, R. O. 2012, ApJ, 750, 145
Kucera, T. A., Andretta, V., & Poland, A. I. 1998, SoPh, 183, 107
Labrosse, N., Heinzel, P., Vial, J.-C., et al. 2010, SSRv, 151, 243
Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., & Mason, H. E. 2012, ApJ, 744, 99
Li, T., Zhang, J., Yang, S., & Liu, W. 2012, ApJ, 746, 13
Li, Y., & Ding, M. D. 2017, ApJ, 838, 15
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 333
Reale, F., Orlando, S., Testa, P., et al. 2013, Sci, 341, 251
Reale, F., Orlando, S., Testa, P., Landi, E., & Schrijver, C. J. 2014, ApJL, 797, L5
van Driel-Gesztelyi, L., Baker, D., Török, T., et al. 2014, ApJ, 788, 85
Vasalominidze, Z., Kukhianidze, V., Zaqrashvili, T. V., et al. 2015, A&A, 577, A136
Veronig, A. M., Brown, J. C., Dennis, B. R., et al. 2005, ApJ, 621, 482
Warmuth, A., & Mann, G. 2016, A&A, 588, A116
Yardley, S. L., Green, L. M., Williams, D. R., et al. 2016, ApJ, 827, 151
Zharkov, S., Green, L. M., Matthews, S. A., & Zharkova, V. V. 2013, JPhCS, 440, 012046

L. Ofman would like to acknowledge support by NASA Cooperative agreement NNG11PLA10A 670.154 to CUA.

ORCID iDs
A. R. Inglis https://orcid.org/0000-0003-0656-2437
L. Ofman https://orcid.org/0000-0003-0602-6693