Magnetic reconnection between a solar filament and nearby coronal loops

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Figures S1-S9
Movies M1-M4
Figure S1. Evolution of filaments observed by SDO (a-c) and STEREO-B (d-f).
Panels (a-c) and (d-f) separately show SDO/AIA (a-c) and STEREO-B/EUVI (d-f) 304 Å images before (a and d), during (b and e), and after (c and f) the filament eruption. The red rectangle in (a) is the field of view (FOV) in Fig. 1, and the green rectangle in (a) the FOV in Movies M1 and M4. The cyan rectangle in (b) is the FOV in Fig. S4a, and the blue rectangle in (d) the FOV in Fig. S3 and Movie M2. The pink solid arrows in (b) and (e) mark the outward erupting filament part. Two nearby filaments, FE and FS, are separately located to the east and south of the filament we studied. A long time before the eruption, these three filaments remain unchanged. The northern part of the filament erupts, and reconnects with its nearby coronal loops.
However, the southwestern part of the filament does not erupt. Comparing panels (c) and (f) to (a) and (d), we find that these two nearby filaments FE and FS remain unchanged during the whole process. Panels (b) and (e) show that the newly reconnected filament F1 forms orthogonally above FE by observing from two viewing points. This indicates that F1 and FE are different filaments. The northern part of the erupting filament reappears at the same position after the eruption. This shows that only the upper, rather than the lower, part of the northern part of filament erupts. Thereafter, these three filaments remain unchanged for a long time.

**Figure S2.** Positions of the SDO and STEREO A and B satellites at 01:00:00 UT on January 1, 2012. The dotted circle represents the Earth orbit at 1 AU. The angles between these three satellites are denoted by the numbers in the plot. E and W show the directions, i.e., east and west, in the FOV of SDO. The red diamond marks the general location of the filament we studied. As the filament is located near the northeastern limb in the FOV of SDO/AIA images, it can also be observed by STEREO-B, but not by STEREO-A.
**Figure S3. Evolution of the filament observed by STEREO-B.** Panels (a-c) separately show EUVI 304 Å images before (a), during (b), and after (c) the magnetic reconnection. A blue circle in (c) encloses the southern footpoints of the newly reconnected filament F1. This circle is pointing at roughly the same location as the circle at the footpoint of F1 in Fig. 2c. Similar to Fig. S1, the pink solid arrow in (c) marks the outward erupting part of the filament. Similar to Figs. 1 and S1, two nearby filaments FE and FS are located to the east and south of the filament we analyzed, respectively. Because of the separation angle of 111º between STEREO-B and SDO (see Fig. S2), this view is in approximate quadrature. The eruption of the filament can be followed through this image sequence. In particular, panel (c) shows the filament after the reconnection, now connected to a new footpoint highlighted by the blue circle. A two-ribbon flare, marked by two cyan arrows in (c), and post-flare loops are associated with this filament eruption. The FOV is indicated by the blue rectangle in Fig. S1d.
Figure S3. Evolution of the filament observed by STEREO-B. Panels (a-c) separately show EUVI 304 Å images before (a), during (b), and after (c) the magnetic reconnection. A blue circle in (c) encloses the southern footpoints of the newly reconnected filament F1. This circle is pointing at roughly the same location as the circle at the footpoint of F1 in Fig. 2c. Similar to Fig. S1, the pink solid arrow in (c) marks the outward erupting part of the filament. Similar to Figs. 1 and S1, two nearby filaments FE and FS are located to the east and south of the filament we analyzed, respectively. Because of the separation angle of 111º between STEREO-B and SDO (see Fig. S2), this view is in approximate quadrature. The eruption of the filament can be followed through this image sequence. In particular, panel (c) shows the filament after the reconnection, now connected to a new footpoint highlighted by the blue circle. A two-ribbon flare, marked by two cyan arrows in (c), and post-flare loops are associated with this filament eruption. The FOV is indicated by the blue rectangle in Fig. S1d.

Figure S4. Filament eruption observed by SDO/AIA. Panel (a) displays an AIA 304 Å image at 00:49:20 UT with the FOV as indicated in Fig. S1b (cyan rectangle). Panels (b-c) display time-space plots of a series of AIA 304 Å images, respectively for the time evolution along lines AB (b) and CD (c) marked in (a). The green arrows in (a) and (c) mark the current sheets, a dotted line in (b) the filament eruption, and the blue arrows in (c) the filament threads. Panel (b) shows that the filament rises slowly at the beginning, and then accelerates and erupts. It stops erupting after the reconnection. The erupting speeds and acceleration are measured from this panel. During the eruption, the filament is dispersed into threads when viewed from above, marked by blue arrows in (c). When these threads encounter the loops, they become bright current sheets at the interfaces, denoted by green arrows in (a) and (c). Due to the filament eruption, the current sheets move toward the southeast (toward lower left in panel a), and some of them merge (c; see also Fig. S8d). For comparison the green rectangle in (a) shows the FOV of Figs. 2(a-c) and S6, the cyan rectangle the FOV of Fig. S5(a-b), and the black rectangle the FOV of Figs. S8(a-b) and Fig. S9a.
Figure S5. Propagation of the brightening at the southern footpoints of F1 observed by SDO/AIA. Panels (a-b) show AIA 304 Å images with the FOV as indicated in Fig. S4a (cyan rectangle). Panel (c) displays a time-space plot of a series of AIA 304 Å images along the line EF marked in (b). The yellow and blue arrows in (b) denote the filament footpoints and threads, respectively. The blue ellipse in (b) encloses the footpoint region. The yellow dotted line in (c) indicates the apparent propagation of the brightening at the footpoint with a speed of about 70 km s\(^{-1}\). As noted in the main text, the magnetic flux of the southern footpoint region of F1 is measured in the footpoint region of F1 (blue ellipse in b). For more details see Fig. S6.

Figure S6. Magnetic flux and energy budget during the reconnection. An HMI line-of-sight (LOS) magnetogram, with the same FOV as in Figs. 2a-2c (see also the green rectangle in Fig. S4a), displays the general magnetic field information during the reconnection. The blue and cyan dotted lines represent the erupting filament L3 and its nearby coronal loops L2 during the reconnection as displayed in Fig. 2b. The red and green dashed lines denote the newly reconnected filaments F1 and F2 after the reconnection as displayed in Fig. 2c. Similar to Fig. S5b, the blue ellipse encloses the southern footpoint region of F1. As L3 (blue dotted line) totally reconnects with L2 (cyan dotted line) and forms the newly reconnected filaments F1 (red dashed line) and F2 (green dashed line), the magnetic flux of L3 has to equal that of L2. F1 connects the northern footpoints of L3 and the eastern footpoints of L2, and thus the magnetic flux of F1 equals that of L3, and also the flux of the reconnected L2. In the southern footpoint region of F1 (blue ellipse), we measure the negative magnetic flux by integration over the blue ellipse. By this we obtain a value of \((8.5\pm1.5)\times10^{19}\) Mx. Under the assumption that the magnetic field is roughly vertical at the solar surface, we correct for the projection effect, and get the corrected magnetic flux of \((1.2\pm0.2)\times10^{20}\) Mx for F1. As L1 shares the footpoint region with L2, and it remains unchanged during the reconnection...
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process (see Figs. 2a-2c), we assume that half of the magnetic flux, \((6.0\pm1.0)\times10^{19}\) Mx, is the flux of \(L_2\). The total reconnected flux of \(L_3\) and \(L_2\) is then twice of that of \(L_2\), \((1.2\pm0.2)\times10^{20}\) Mx. The reconnection process lasts for about \(11\pm2\) minutes. Then the mean magnetic reconnection rate can be calculated as \((2.0\pm0.7)\times10^{17}\) Mx s\(^{-1}\). This is lower than reconnection rates previously calculated from X- and M-class flares, as noted in the main text.

Based on these observations we can estimate the mean magnetic energy release rate \(\text{ME}_r\) through \(\text{ME}_r = \frac{B^2}{8\pi} \times \frac{V}{\tau}\). Here \(B\) is coronal magnetic field strength, \(V\) volume, and \(\tau\) time duration. We assume the current sheet is a cuboid with length of \(L\), and width and height of \(R\). Then the volume is \(V=L \times R \times R\). For the mean length of the current sheets we use \(L=36''=2.6\times10^9\) cm, and we estimate the full width at half maximum of current sheet region as \(R=18''=1.3\times10^9\) cm. For the magnetic field strength we obtain a value of \(B=71\pm12\) G, similar to a typical value of \(B=75\) G, and estimate the duration of the event based on our observations to be \(\tau=11\pm2\) minutes. Then \(\text{ME}_r\) equals to \((1.5\pm0.7) \times 10^{27}\) erg s\(^{-1}\).

We can roughly calculate the mean thermal energy release rate \(\text{TE}_r\) through \(\text{TE}_r = \frac{3}{2} n_p k_B V \times (\delta T / \delta \tau)\). Here \(n_p\) is mean number density in reconnection region, \(k_B\) Boltzmann’s constant, and \((\delta T / \delta \tau)\) the temperature increase with time. We use \(n_p = \sqrt{\frac{\text{EM}}{R}}\) to estimate \(n_p\) depending on EM maps obtained. The mean EM in current sheet region is about \((1.6\pm0.5) \times 10^{27}\) cm\(^{-5}\). Then \(n_p = (1.1\pm0.2) \times 10^9\) cm\(^{-3}\). We estimate the temperature increase of plasma based on the temperature maps derived from the EM analysis and find \((\delta T / \delta \tau) = 0.35\pm0.25\) MK/s. This yields \(\text{TE}_r = (4.0\pm3.1) \times 10^{26}\) erg s\(^{-1}\). The errors we have used above are mainly from the statistical distributions of the measurements.

From these calculations, we conclude that the mean magnetic energy release rate \(\text{ME}_r\) is consistent with the mean thermal energy release rate \(\text{TE}_r\). Naturally, all are less than those previously obtained in X- and M-class flares, as noted in the main text, because here we observe not a full flare, but a smaller energetic event. It should be noted that during a reconnection event only a (small) fraction of the released magnetic energy is converted directly in heating of the plasma. Thus it is expected that the rate of thermal energy increase we estimate here is lower than the rate of magnetic energy conversion derived above.
Figure S7. Coronal mass ejection (CME) associated with the filament eruption. The two panels show SOHO/LASCO C2 (a) and STEREO-B SECCHI COR1 (b) running difference images. A narrow CME is observed associated with the filament eruption. This suggests that part of the filament erupts successfully (see also the pink solid arrows in Figs. S1b, S1e, and S3c). The main filament eruption is associated with a two-ribbon flare, post-flare loops, and a narrow CME, and causes the encounter and reconnection of erupting filament L3 and its nearby coronal loops L2. However, the reconnection between L3 and L2 keeps L3 from erupting outward (see Fig. S4b).
Figure S8. Evolution of current sheets and plasmoids observed by SDO/AIA.

Panels (a-b) show AIA 171 Å images (FOV outlined in Fig. S4a as black rectangle). Panels (c-d) display time-space plots of a series of AIA 171 Å images along the lines GH (c) and IJ (d) as marked in (a) and (b), respectively. The dotted and dashed lines in (c) separately denote the motions of the plasmoids and the newly reconnected filament threads. The green arrows and red dotted lines in (d) show the current sheets and their sideward motions. The respective speeds are denoted by the numbers (in km s⁻¹) in the plots. Plasmoids mostly move toward northeast, i.e., upper left in panel (b). So in general the plasmoids tend to move toward the erupting filament. In contrast, the current sheets move toward the southeast (lower left) due to the filament eruption (see also Fig. S4c). At least twelve individual current sheets are detected from panel...
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Figure S9. Measurements of current sheets and plasmoids observed by SDO/AIA. Panel (a) displays a snapshot AIA 171 Å image at 00:50:48 UT, with the same FOV of Figs. S8(a-b). Panels (b-d) display histograms of properties of current sheets and plasmoids observed during about 11 minutes of the reconnection of the filament and the loops. These are the length (b) and the width (c) of current sheets, and the width of plasmoids (d). In (a), the green pluses mark two endpoints of a current sheet, the blue contours and green dotted lines denote the boundaries of two plasmoids and a current sheet, respectively, and the blue and green arrows the widths.

Note that the spatial scale of the AIA images is about 0.6"/pixel and the spatial resolution is about 1.4". Thus the width of the observed current sheet (c) and of the
plasmoids (d) might be well below the size we estimate here. Strictly speaking, our estimates of these widths should be considered as upper limits only.

**Movie M1. SDO observations of the temporal evolution of magnetic reconnection between the erupting filament and its nearby coronal loops.** The panels show emission from the hot corona down to the cool chromosphere and the magnetic field on the solar surface according to the following table:

<table>
<thead>
<tr>
<th>AIA 94 Å</th>
<th>AIA 335 Å</th>
<th>AIA 211 Å</th>
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<tbody>
<tr>
<td>Fe XVIII</td>
<td>Fe XVI</td>
<td>Fe XIV</td>
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<td>2.5 MK</td>
<td>1.9 MK</td>
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<table>
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<th>AIA 171 Å</th>
<th>AIA 131 Å</th>
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<tbody>
<tr>
<td>Fe XII</td>
<td>Fe IX</td>
<td>Fe VIII</td>
</tr>
<tr>
<td>1.5 MK</td>
<td>0.9 MK</td>
<td>0.6 MK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fe XXI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0 MK</td>
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</table>

<table>
<thead>
<tr>
<th>AIA 304 Å</th>
<th>AIA 1600 Å</th>
<th>HMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>He II</td>
<td>Chromosphere</td>
<td>LOS magnetograms</td>
</tr>
<tr>
<td>0.05 MK</td>
<td>0.01 MK</td>
<td>surface</td>
</tr>
</tbody>
</table>

The time cadence is 1 minute for AIA images, and 3 minutes for HMI LOS magnetograms. The FOV is indicated as green rectangle in Fig. S1a. The black boxes in all panels show the FOV of Figs. 2(a-c), and the white boxes that of Figs. 2(d-f) of the main text.

**Movie M2. STEREO-B SECCHI EUVI observations of the temporal evolution of the eruption and reconnection of the filament.** This shows the erupting filament roughly at quadrature to AIA observations (see Fig. S2), so the erupting filament is seen from the northwestern side. The two panels show plasma at about 0.05 MK at 304 Å (left) and at about 1.5 MK at 195 Å (right) at the same FOV as Fig. S3 (blue rectangle in Fig. S1d). The time cadence is 10 minutes and 5 minutes, respectively.

**Movie M3. SDO observations of the temporal evolution of current sheets.** Similar to Movie M1, but for a smaller FOV (white boxes in Movie M1, same as Figs. 2d-2f and Figs.4a-4b). In particular the time cadence is higher, now at 12 s. Here we replaced the two bottom right panels by the emission measure (EM) and the temperature (TE) maps. The EM and TE maps show the temporal evolution of Figs. 4a-4b in the main text.

**Movie M4. Composite multi-color images showing the magnetic reconnection process between the erupting filament and the nearby coronal loops.** The movie shows a composite of AIA images in different wavelength channels (and thus at different plasma temperatures): the red channel shows 335 Å (~2.5 MK), the green 193 Å (~1.5 MK), and the blue 304 Å (~0.05 MK). The FOV is the same as in Movie M1 (green rectangle in Fig. S1a), but here the cadence is faster at 12 s.