LETTER

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Energy release in the solar corona from spatially resolved magnetic braids

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It is now apparent that there are at least two heating mechanisms in the Sun's outer atmosphere, or corona[1–5]. Wave heating may be the prevalent mechanism in quiet solar periods and may contribute to heating the corona to 1,500,000 K (refs 1–3). The active corona needs additional heating to reach 2,000,000–4,000,000 K; this heat has been theoretically proposed[6–12] to come from the reconnection and unravelling of magnetic 'braids'. Evidence favouring that process has been inferred[13,14], but has not been generally accepted because observations are sparse and, in general, the braided magnetic strands that are thought[1–3,15–17] to have an angular width of about 0.2 arc seconds have not been resolved[10,18–20]. Fine-scale braiding has been seen[21,22] in the chromosphere but not, until now, in the corona. Here we report observations, at a resolution of 0.2 arc seconds, of magnetic braids in a coronal active region that are reconnecting, relaxing and dissipating sufficient energy to heat the structures to about 4,000,000 K. Although our 5-minute observations cannot unambiguously identify the field reconnection and subsequent relaxation as the dominant heating mechanism throughout active regions, the energy available from the observed field relaxation in our example is ample for the observed heating.

Observations of the solar atmosphere in the visible and infrared spectral ranges have been made from ground-based instruments on ~0.2-arcsec spatial scales, in particular in Hα emission, and these show coherent structures 0.2 arcsec in diameter[21]. But for the ultraviolet and X-ray emission corresponding to temperatures in excess of 100,000 K, there is a paucity of data. Detecting these wavelengths requires the use of instruments outside Earth's atmosphere, and observations so far, including those of the NASA Atmospheric Imaging Assembly[23] (AIA) instrument at present operating on the Solar Dynamics Observatory (SDO), have been limited to a resolution of about 1.0 arcsec. The High-resolution Coronal Imager (Hi-C; see Supplementary Fig. 1) was launched on a sounding rocket on 11 July 2012 and took images of the 1,500,000-Kelvin (1.5-MK) corona with a resolution of 0.2 arcsec (roughly 150 km). The Hi-C passband isolates a very narrow window in the extreme ultraviolet, centred at 193 Å. It is dominated by emission lines of Fe XII with a peak temperature of formation of 1.5 MK. AIA has an identical channel that images the full solar disk (Fig. 1; see also Supplementary Video 1).

The data from Hi-C show evidence of magnetic field braiding and axial twist in loops along their length, reconnection and consequent heating in the low corona, whereas the simultaneous images from AIA/SDO at a resolution of 1.2 arcsec (900 km) do not resolve the braiding. We have studied the intensity of emission in a loop at several AIA wavelengths covering more than two orders of magnitude in temperature (Fig. 2), and found that the twist in the structures increases during the observations (Supplementary Fig. 2 and Supplementary Video 2). After the end of the Hi-C observations, a small flare observed by AIA peaks at the intersection of the converging strands (indicated

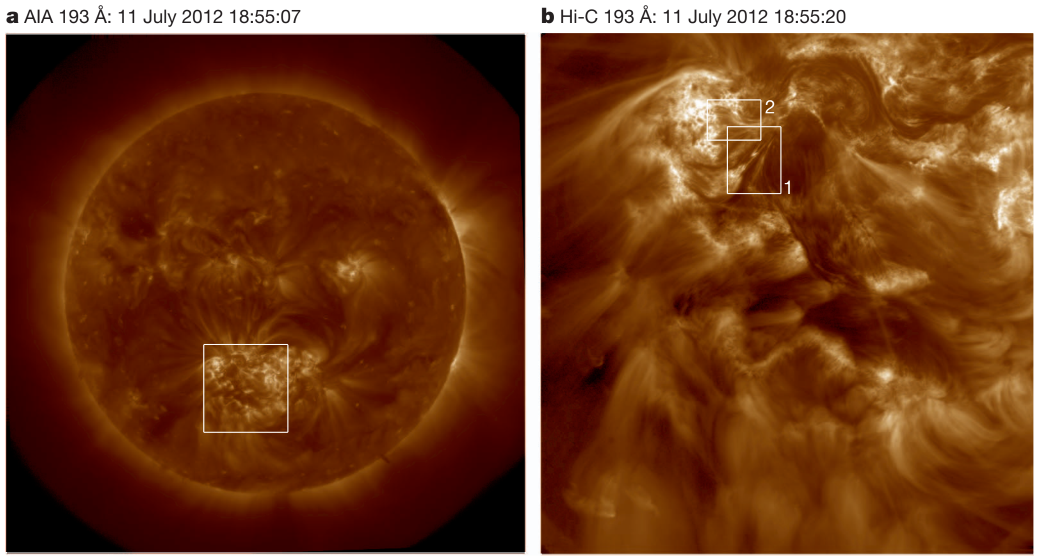

Figure 1 | The 1.5-MK sun. **a**, The co-temporal 1-arcsec-resolution AIA full-sun image (11 July 2012, 18:55 UT) using the 193 Å passband. The field of view for the Hi-C rocket flight is indicated by the box. **b**, The full Hi-C field-of-view image. The two boxes show the locations of the examples that are discussed in the text and shown in Fig. 2 (box 1) and Fig. 3 (box 2). The Hi-C experiment is described in Supplementary Fig. 1.

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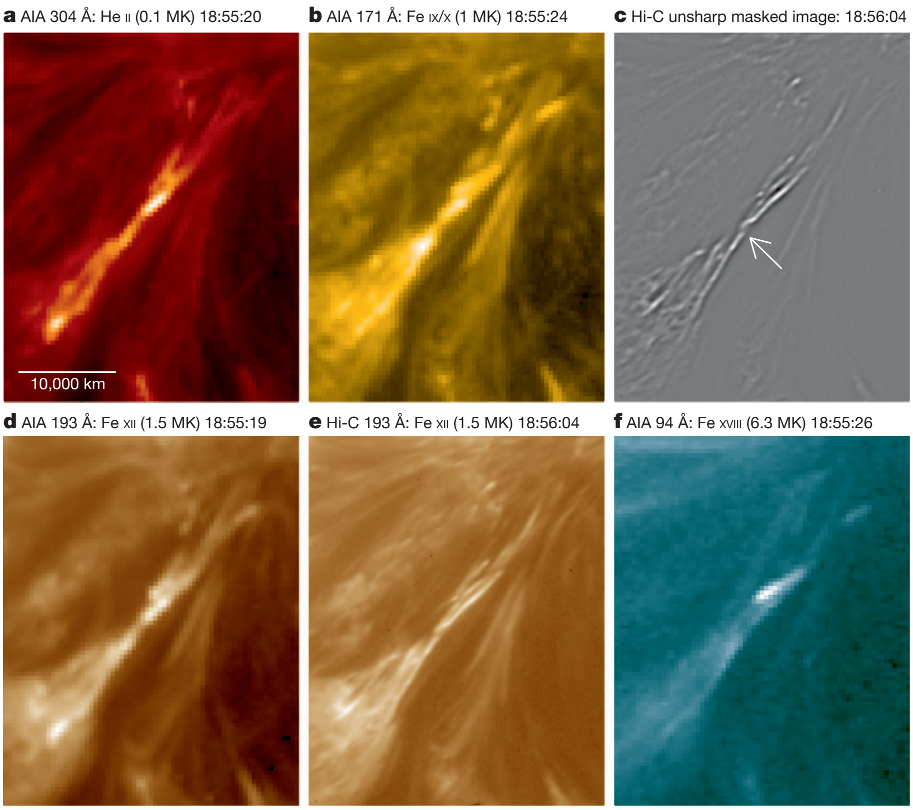

Figure 2 | A coronal loop seen at several different coronal temperatures by AIA and Hi-C. Labels indicate the passbands, the dominant emitting ion and the peak formation temperature of the ion. The image in **c** was constructed by smoothing the original image (**e**) and subtracting the processed image from the original. This 'unsharp mask' version of the Hi-C data enhances the shapes of fine-scale structures in the image relative to the image background. All panels show a narrow magnetic arch that Hi-C resolves to be twisted along its length. The twisted loops converge and appear to intersect (arrow in **c**). A C1.7 flare centred on this intersection is seen in the AIA images about 3 min after the Hi-C flight (Supplementary Video 1).

by an arrow in Fig. 2c, Supplementary Fig. 2 and Supplementary Video 2). At the location of the flare, strong (150 km s^{-1}) outflows of plasma from the reconnection region are observed. These twisting loops are sheared across a polarity inversion line in magnetic field in the photosphere (field strength, 10^3 G; see magnetogram in Supplementary Fig. 3), along which strong shearing flows are present (Supplementary Video 3). Using the Extreme-ultraviolet Imaging Spectrometer[24] observations from the Japan Aerospace Exploration Agency's Hinode spacecraft, we have determined

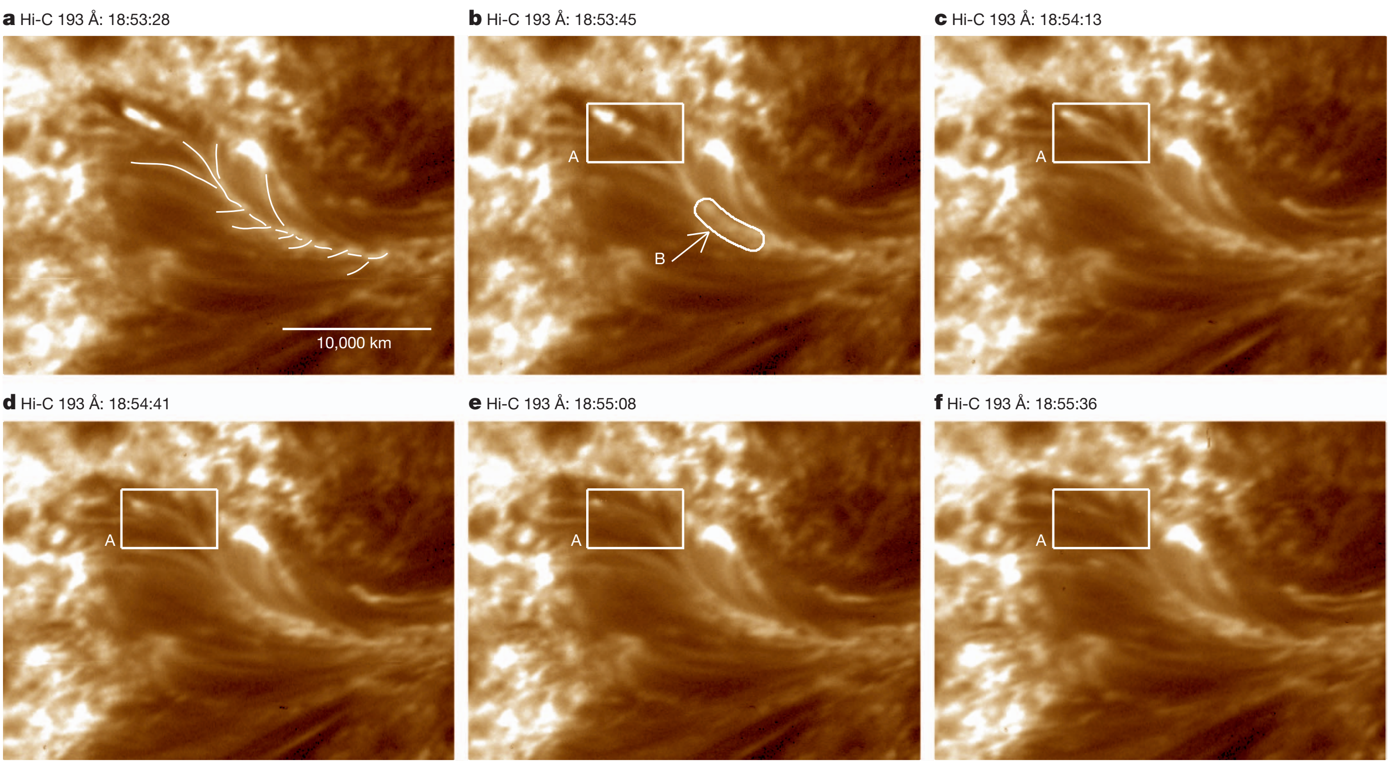

Figure 3 | A time series from Hi-C data. Box A is centred on a location in the braided structure where multiple loops converge and wind about each other. In **a**, we trace along several of the features to guide the eye. As the time sequence proceeds, the loops unwind, as evidenced by the structural changes shown in box A, discernible by comparing **c** with **f** (see also Supplementary Video 2). Area B in **b** highlights a section of the loop ensemble that is found to unwind or simplify during the observation period.

the density of the loops to be $10^{10} e^{-}$ cm^{-3} (where e is electrons) and the peak temperature to be ~7 MK. The structure heats to this peak temperature in 42 s, and then cools in roughly the radiative cooling time, 13 min. The example shown in Fig. 2 is found to generate many such transient events near the location indicated with the arrow (Fig. 2c). AIA data in several passbands show repeated impulsive events, but at the lower resolution of AIA only the increases in intensity are observable—the structural changes in the loops remain unresolved.

In a second example, Hi-C observed a small bundle of loops that are wrapped or braided about each other along their length (Fig. 3). The AIA telescopes also observed this bundle of loops, but saw it as a single structure. The braided loop ensemble is visible over the temperature range 0.1–3 MK. Higher-temperature loops are rooted close to the footpoints of the braided loops, that is, the points at which the loops intersect the photosphere, and are observed in the soft-X-ray range at 4–6 MK. In box A at the end of the braided structure (Fig. 3b), the twist in the loops simplifies and eastward high-speed outflows at 100–150 km s^{-1} along this fan of loops persist throughout the observations (Supplementary Video 3). The bundle's axial field strength estimated from observations is 500 G. We can determine the pitch angle of the twist of the bundle by estimating the number of braids along the length of the bundle (Fig. 3a) and, hence, the strength of the azimuthal component (B_ϕ) of the magnetic field. We count roughly five braids, giving an azimuthal field of order 100 G. The amount of free energy is of order $(B_\phi)^2 V/8\pi$, where V is the volume of the bundle, which we have estimated to be approximately 10^{11} km^3. This yields a total free energy of order 10^{29} erg.

At plasma temperatures of 1 MK, the speed of sound is ~100 km s^{-1} and the observed outflows at ~100 km s^{-1} are therefore indicative of plasma pressure driving mass motion along the field as the plasma is heated locally and expands at the speed of sound into lower-pressure locations along the braided loops. As is the case for the first example, this braided bundle seems to be heated as the free energy stored in the twisting or braiding of the magnetic field is dissipated by means of reconnection. We have summed the emission observed by AIA from the bundle in area B in Fig. 3e to form light curves (Fig. 4; see also Supplementary Video 4). These curves show the duration of the heating and the initial sharp increase in emission and subsequent decay. The event lasts for about 12 min, for the return from the peak to the basal emission level. The radiated energy from this event can be calculated from the light curves and density and is found to be ~10^{26} erg: about ~0.1% of the stored energy in the braided ensemble is converted into

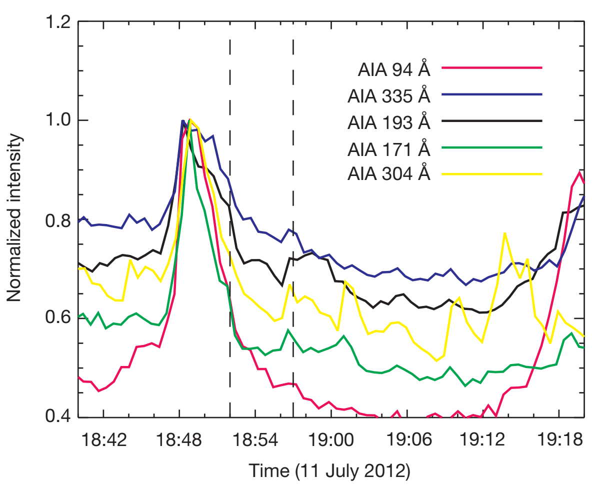

Figure 4 | The light curves for example two. The light curves from multiple AIA channels for area B in Fig. 3b show the increase in intensity for the braided ensemble of loops just before the Hi-C flight. The start and end of the Hi-C flight are indicated by the vertical dashed lines in the plot. The intensities for all passbands decrease over a 10-min period. The heating process shown here repeats several times per hour over the 12 or more hours the structure is present in the AIA data.

thermal energy to power the observed radiation. This braided bundle of loops, seen in the AIA data as a single broader loop, is observed for over 12 h and brightens repeatedly over the AIA observation period.

Several instances of braiding and loop-to-loop interaction were visible to Hi-C during its brief flight: the two examples seen here are the clearest. These observations demonstrate that the active region corona, at a spatial scale of approximately 150 km, is replete with current-laden locations that provide sites for the dissipation of magnetic free energy. The observations show magnetic fields that are braided, and not simply twisted. By reconnecting, presumably at current sheets between entwined flux strands, the braided loops release energy into the corona. The braiding is driven by the ubiquitous small-scale, convection-driven motion of the photospheric feet of the magnetic field, and thus provides a d.c. (that is, non-wavelike) energy source for the corona.

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Supplementary Information is available in the online version of the paper.

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