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the base of the north part of the arcade (region B). Therefore, we can distinguish directly regions where the emission measure distribution along the line of sight is broader and whether the plasma excess is cool or hot.

Superimposing the CIFR map with an emission map in the TRACE 171 A filter, which is sensitive mostly to cooler plasma around 1 MK, we see that this scenario is reliable (Fig. 3): The dimmed spots (D and B) clearly correspond to bright regions in the TRACE image, i.e., there is an excess of cool plasma along the line of sight.

The CIFR map (Fig. 2) shows directly the existence of thermally coherent thin magnetic structures and that hot coronal loops are highly transversally structured. According to theoretical conjectures (*5*, *12*), the tangling of magnetic flux tubes is a prerequisite for magnetic energy release. In this perspective, the tightness and entwining of the thin thermal structures on the left side of the core loop arcade are a direct indication that this region is the probable site of frequent major heating episodes.

References and Notes

1. G. S. Vaiana, A. S. Krieger, A. F. Timothy, *Solar Phys.* **32**, 81 (1973).
2. E. N. Parker, *Astrophys. J.* **330**, 474 (1988).
3. P. J. Cargill, *Astrophys. J.* **422**, 381 (1994).
4. P. J. Cargill, J. A. Klimchuk, *Astrophys. J.* **605**, 911 (2004).
5. J. A. Klimchuk, *Solar Phys.* **234**, 41 (2006).
6. K. P. Dere, H. E. Mason, *Solar Phys.* **144**, 217 (1993).
7. S. Tsuneta *et al.*, *Publ. Astron. Soc. Jpn.* **44**, L63 (1992).
8. T. Yoshida, S. Tsuneta, *Astrophys. J.* **459**, 342 (1996).
9. L. Golub *et al.*, *Solar Phys.* **243**, 63 (2007).
10. J. F. Vesecky, S. K. Antiochos, J. H. Underwood, *Astrophys. J.* **233**, 987 (1979).
11. S. Serio, G. Peres, G. S. Vaiana, L. Golub, R. Rosner, *Astrophys. J.* **243**, 288 (1981).
12. M. C. López Fuentes, J. A. Klimchuk, P. Démoulin, *Astrophys. J.* **639**, 459 (2006).

13. Hinode is a Japanese mission developed and launched by the Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency, with the National Astronomical Observatory of Japan as domestic partner and NASA and Science and Technology Facilities Council (UK) as international partners. It is operated by these agencies in cooperation with the European Space Agency (ESA) and the Norwegian Space Centre (Norway).

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REPORT

Continuous Plasma Outflows from the Edge of a Solar Active Region as a Possible Source of Solar Wind

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The Sun continuously expels a huge amount of ionized material into interplanetary space as the solar wind. Despite its influence on the heliospheric environment, the origin of the solar wind has yet to be well identified. In this paper, we report Hinode X-ray Telescope observations of a solar active region. At the edge of the active region, located adjacent to a coronal hole, a pattern of continuous outflow of soft-x-ray–emitting plasmas was identified emanating along apparently open magnetic field lines and into the upper corona. Estimates of temperature and density for the outflowing plasmas suggest a mass loss rate that amounts to ~1/4 of the total mass loss rate of the solar wind. These outflows may be indicative of one of the solar wind sources at the Sun.

Since early studies on comet tail orientations in the middle of the twentieth century (*1*, *2*), it has been widely perceived that the interplanetary space around the Sun, the heliosphere, is permeated with continual but varying flows of charged particles: This material flow is the solar wind (*3*, *4*). A huge amount of material is expelled from the Sun in the solar wind, at a rate reaching as high as 1×10^{12} g s^{-1}, into the heliosphere. It extends beyond Jupiter, showing a variety of interactions with planets, including Earth. Observations with space-borne instruments have so far revealed various basic features of the solar wind, such as the existence of two distinct categories of wind velocities: one, the fast solar wind, with velocity as high as ~800 km s^{-1}, and the other, the slow wind, with velocity ~300 km s^{-1}. Nonetheless, at least two fundamental issues remain unresolved: One is the location of the source of the outflows (i.e., the source regions) on the Sun, and the other is the acceleration mechanism of the flows after departing the solar surface.

It is now well recognized that the fast solar wind originates from (polar) coronal holes (*5*, *6*). Recent observations with the Solar and Heliospheric Observatory (SOHO) satellite have enabled us to investigate polar coronal holes with line-of-sight Doppler measurements (*7*, *8*). However, imaging observations of the outflowing material are still rare. The situation is even more uncertain for the case of the slow solar wind, in which multiple source regions have been postulated, such as the boundary of polar coronal holes, helmet streamer structures (from near the top of closed loop structures in the solar corona) (*9*, *10*), or from the edge of active regions (*11*). But again, no clear identification of the source outflow has so far been made.

In this paper, we report imaging observations of a solar active region made with the X-ray Telescope (XRT) (*12*) aboard the Hinode (*13*) satellite. XRT is a grazing incidence soft-x-ray imager that achieves high angular resolution (consistent with 1 arcsec pixel size) with broad and continuous temperature coverage for coronal plasmas ranging from 1 million kelvin (MK) to 10 MK. The XRT observations presented here reveal a pattern of continuous outflow of soft-x-ray–emitting plasmas along apparently open field lines from the edge of an active region butting up adjacent to a coronal hole. Furthermore, the observations from XRT are strongly supported by observations with the Extreme Ultraviolet (EUV) Imaging Spectrometer (EIS) (*14*), also aboard Hinode, which detected persistent upward Doppler motions of coronal plasmas from the apparent outflowing region throughout the XRT observation interval. We assert that these observations are possibly the first identification of outflowing solar wind material.

XRT observed the active region NOAA AR 10942 for 3 consecutive days, from 20 to 22 February 2007, over which period the region was

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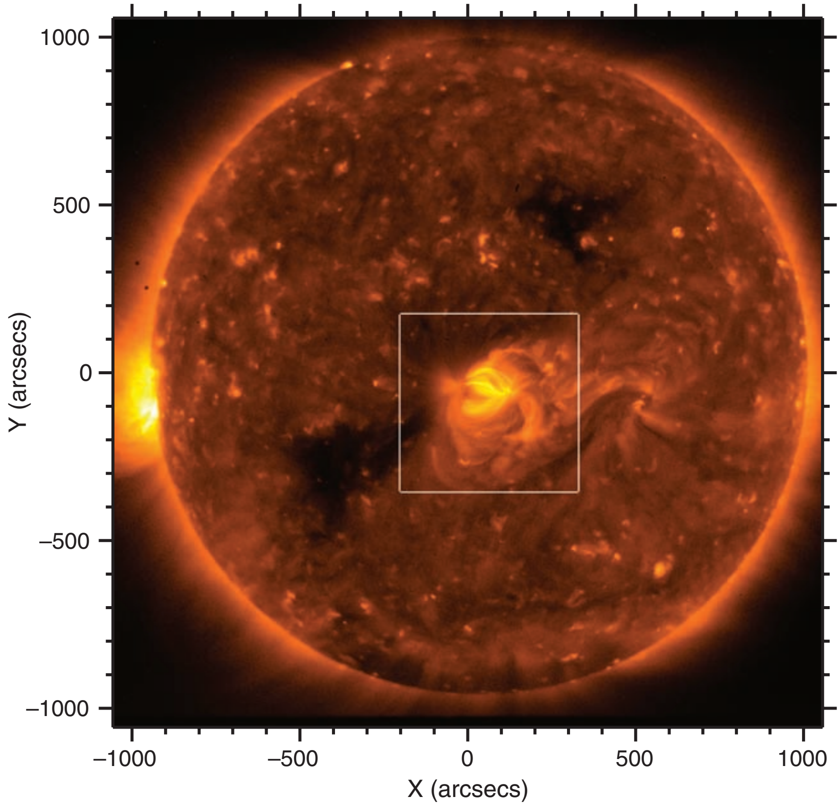

Fig. 1. A full-Sun image taken with the Ti-poly filter of the XRT at 11:13:45 UT on 22 February 2007, shown with a logarithmic intensity scale. Solar north is up and east to the left in this and in all solar images in this paper. Exposure duration is 8 s. The square box indicates the area shown in Fig. 2 and movie S1. The box location on the Sun moves westward with time while the spacecraft pointing tracks solar rotation.

located east of solar disk center near the equator. The observations were chiefly made with XRT's titanium-on-polyimide (Ti-poly) filter, with the size of the readout area on the charge-coupled device (CCD) being 512 pixels by 512 pixels, which was sufficient to cover the entire active region and the surrounding corona. The focus position of the telescope was set to provide the highest angular resolution across the region. XRT also made a series of full-Sun exposures about every 6 hours with Ti-poly and thin-aluminum–on–mesh (thin-Al–mesh) filter pairs, with which fainter (nonactive region) coronal features can be well imaged. The active region was located just west of a large coronal hole (Fig. 1). The coronal hole was long-lived, being present at least one solar rotation both before and after the observation period.

A prominent feature seen in the XRT images (movie S1) is a pattern of plasma outflow along a bundle of fanlike magnetic field lines emanating from a region located at the east edge of the active region. At least the left (east) half of the field line bundle (Fig. 1) is likely to be opened, that is, extending into the outer corona. This outflowing feature was continuously present throughout the entire 3-day observation period. In an attempt to estimate transverse velocity (velocity in the plane orthogonal to the line-of-sight direction) of the outflow, we created a time-distance plot from the Ti-poly images. The time-distance plot in Fig. 2 shows patterns in the flow with transverse velocity ranging between 100 to 170 km s^{-1}, with a typical value of 140 km s^{-1}.

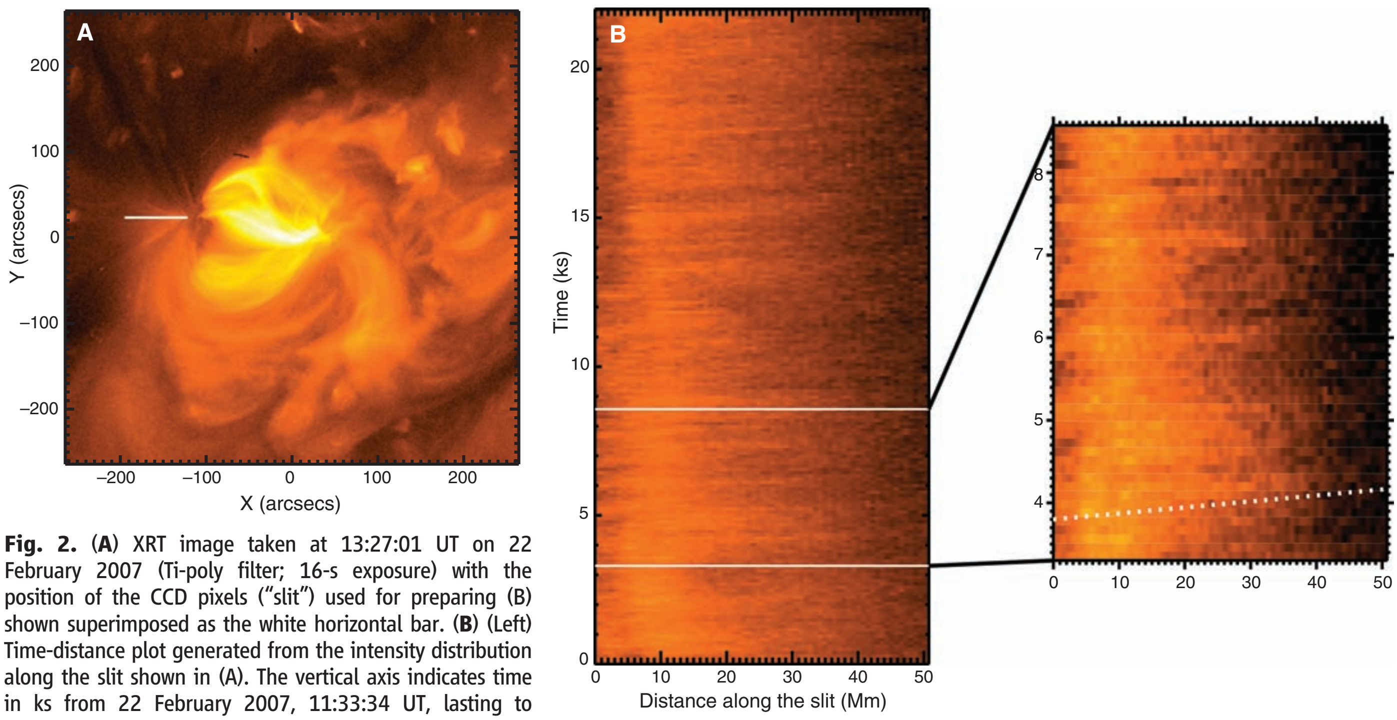

Fig. 2. (**A**) XRT image taken at 13:27:01 UT on 22 February 2007 (Ti-poly filter; 16-s exposure) with the position of the CCD pixels ("slit") used for preparing (B) shown superimposed as the white horizontal bar. (**B**) (Left) Time-distance plot generated from the intensity distribution along the slit shown in (A). The vertical axis indicates time in ks from 22 February 2007, 11:33:34 UT, lasting to 17:40 UT. The horizontal axis gives distance along the slit in Mm measured from the west (right) edge of the slit toward east (left). (Right) Expanded display for the interval indicated by the two white lines in the left image (12:28:36 to 13:56:28 UT). The dotted line represents west-to-east transverse velocity of 140 km s^{-1}.

Whereas the observation was mostly made with the Ti-poly filter for the 3 days, imagery of the region with the thin-Al–mesh filter was also made on 21 February (10:42 to 23:59 UT). By using pairs of images taken with both filters, we can determine an estimate of the physical properties of the plasma with the filter-ratio method (*15*). For the source region, we estimated the temperature ~1.1 MK and emission measure ~7.9×10^{42} cm^{-3} for a volume that corresponds to a single CCD pixel times line-of-sight depth (Fig. 3). Assuming a line-of-sight depth of 1.5 Mm, this gives a density of the region of ~3.2×10^{9} cm^{-3}. With the typical transverse outflow velocity of 140 km s^{-1}, a crude estimate on the amount of the outflowing material per unit time is then ~2.8×10^{11} g s^{-1}. If all the outflowing material were to escape to the interplanetary space along open field lines, this would be equivalent to ~1/4 of the total mass loss rate for the solar wind.

The source region of the outflows, which corresponds to an ensemble of small sunspots (or pores) as seen by the Solar Optical Telescope (SOT) (*16*, *17*) aboard Hinode, does not show any particular brightening activities in soft x-rays associated with the outflows. This is also the case throughout the entire observation period.

In the XRT images, the fanlike field lines along which materials show outflowing motion do not have obvious corresponding conjugate footpoints on the east side. This, however, does not immediately imply that the field lines open out into interplanetary space, because it is possible that these fields form large-scale closed loops but only a portion of such loops is visible in soft x-rays because of temperature and/or density distributions along the loops. On the other hand, computations show (Fig. 4) that potential field lines from the source region at the active region–coronal hole boundary reach the source surface, indicating open field lines. This suggests that at least a fraction of the outflowing material along the fanlike field lines escapes into interplanetary space, resulting in the solar wind.

It has been reported, on the basis of observations with the Transition Region and Coronal Explorer (TRACE) observatory (*18*)

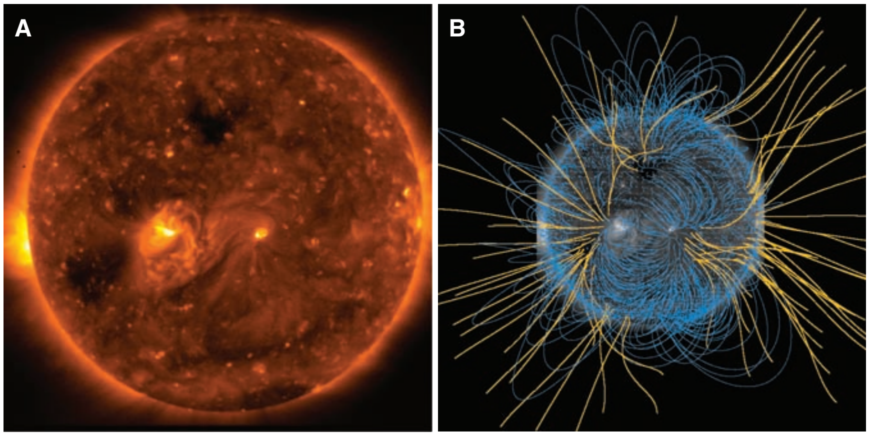

Fig. 4. (**A**) XRT full-Sun image displayed with a logarithmic intensity scale at 00:02:13 UT on 21 February 2007, taken with the thin-Al–mesh filter (4-s exposure). The active region NOAA AR 10942 is slightly to the east of Sun center. (**B**) Potential field lines calculated from a magnetogram taken by SOHO Michelson Doppler Imager (MDI) at 00:03:02 UT on 21 February 2007, with the source surface set at 2.5 solar radii. Field lines reaching the source surface, i.e., those considered to open out into interplanetary space, are shown in yellow, whereas closed lines are shown in blue. The field lines are overlaid on the same XRT image as that in (A). Because of lack of magnetogram data for the polar regions, field lines emanating from the polar regions should not be regarded as valid (such regions were filled with a null magnetic signal when performing the potential field calculation).

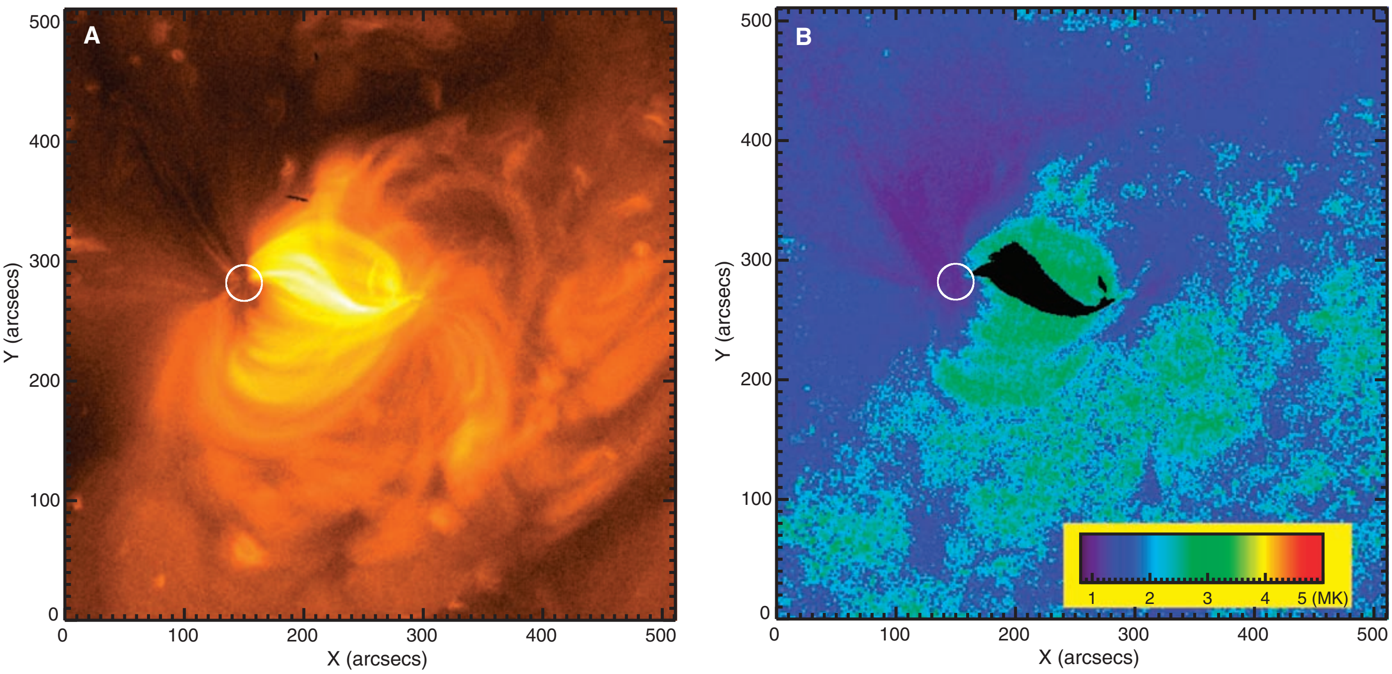

Fig. 3. (**A**) XRT image of NOAA AR 10942 taken at 23:57:45 UT on 21 February 2007 with the Ti-poly filter. The source region of the outflows is shown by the circle, whose radius is 10.9 Mm. (**B**) Map of filter-ratio temperatures for the same area as in (A), derived from a pair of images taken with the thin-Al–mesh and Ti-poly filters at 23:57:14 and 23:57:45 UT, respectively, on 21 February 2007. Exposure duration for each image is 16 s. Black areas in the active region correspond to saturated CCD pixels in the thin-Al–mesh image, where filter-ratio temperatures could not be derived with this pair of images. The white circle indicates the same region as (A).

and the EUV Imaging Telescope (EIT) (*19*) aboard SOHO, that traveling disturbances exist along fanlike coronal magnetic field lines and that these have been identified as slow magneto-acoustic waves with period of 3 min (*20*, *21*). Meanwhile, it has been argued that there are flows along coronal loops as observed by TRACE and SOHO, with velocities of several tens of km s^{-1} in emission lines at temperatures around 0.6 to 1 MK (*22*, *23*). Although the relationship between the flow pattern reported in this study and the wave phenomena seen with TRACE and EIT is a subject for subsequent studies, EIS aboard Hinode, with which line-of-sight Doppler velocities of coronal plasmas can be measured, also identified upward Doppler velocities of ~50 km s^{-1} in a coronal emission line (Fe XII) at the outflowing region in each of the 3 days of the XRT observations (EIS data from 23:45 UT on 20 February, 05:32 UT on 21 February, and 18:08 UT on 22 February, with the last one indicating velocity possibly as high as ~90 km s^{-1}). These Doppler velocities may be consistent with the typical transverse velocity of 140 km s^{-1} obtained from XRT, considering the inclination of the field lines. The EIS upward Doppler signatures add support to the interpretation of the XRT observations as evidence for the presence of outflowing plasmas.

The assertion that the observed outflows are a possible source of the solar wind is also supported by interplanetary scintillation tomographic observations of the solar wind (*11*), which argue that the low-speed solar wind is most likely associated with regions that include rapidly expanding open magnetic flux adjacent to active regions. Furthermore, in situ measurements of solar wind particles and magnetic field with the Advanced Composition Explorer (ACE) satellite support the idea that one of the sources of the slow solar wind resides in boundaries between coronal holes and active regions (*24*). The striking resemblance in the magnetic field configuration proposed in those studies and the present observations suggest that the observed outflows correspond to one of the sources of the slow solar wind.

References and Notes

1. C. Hoffmeister, *Z. Phys.* **22**, 265 (1943).
2. L. Biermann, *Z. Phys.* **29**, 274 (1951).
3. S. Chapman, *Smithson. Contrib. Astrophys.* **2**, 1 (1957).
4. E. N. Parker, *Astrophys. J.* **128**, 664 (1958).
5. G. Noci, *Sol. Phys.* **28**, 403 (1973).
6. B. Bell, G. Noci, *J. Geophys. Res.* **81**, 4508 (1976).
7. D. M. Hassler *et al.*, *Science* **283**, 810 (1999).
8. C.-Y. Tu *et al.*, *Science* **308**, 519 (2005).
9. Y.-M. Wang *et al.*, *Astrophys. J.* **498**, L165 (1998).
10. J. T. Gosling *et al.*, *J. Geophys. Res.* **86**, 5438 (1981).
11. M. Kojima *et al.*, *J. Geophys. Res.* **104**, 16993 (1999).
12. L. Golub *et al.*, *Sol. Phys.* **243**, 63 (2007).
13. T. Kosugi *et al.*, *Sol. Phys.* **243**, 3 (2007).
14. J. L. Culhane *et al.*, *Sol. Phys.* **243**, 19 (2007).
15. H. Hara, S. Tsuneta, J. R. Lemen, L. W. Acton, J. M. McTiernan, *Publ. Astron. Soc. Jpn.* **44**, L135 (1992).
16. K. Ichimoto and the Solar-B Team, *J. Korean Astron. Soc.* **38**, 307 (2005).
17. T. Shimizu, in *The Solar-B Mission and the Forefront of Solar Physics*, T. Sakurai, T. Sekii, Eds., ASP Conference Series vol. 325 (Astronomical Society of the Pacific, San Francisco, CA, 2004), pp. 3–13.
18. B. N. Handy *et al.*, *Sol. Phys.* **187**, 229 (1999).
19. J.-P. Delaboudinière *et al.*, *Sol. Phys.* **162**, 291 (1995).
20. I. De Moortel, J. Ireland, R. W. Walsh, *Astron. Astrophys.* **355**, L23 (2000).
21. E. Robbrecht *et al.*, *Astron. Astrophys.* **370**, 591 (2001).
22. A. R. Winebarger, E. E. DeLuca, L. Golub, *Astrophys. J.* **553**, L81 (2001).
23. A. R. Winebarger, H. Warren, A. van Ballegooijen, E. E. DeLuca, L. Golub, *Astrophys. J.* **567**, L89 (2002).
24. Y.-K. Ko *et al.*, *Astrophys. J.* **646**, 1275 (2006).
25. We are grateful to K. Fujiki of Solar-Terrestrial Environment Laboratory, Nagoya University, and T. K. Suzuki of the University of Tokyo for stimulating discussions on the observed features of the solar wind, the SOHO MDI team for providing full-Sun magnetogram data, and A. C. Sterling of the NASA Marshall Space Flight Center for improvement of the manuscript. Hinode is a Japanese mission developed and launched by ISAS/JAXA, collaborating with NAOJ as a domestic partner and NASA and Science and Technology Facilities Council (STFC) (UK) as international partners. Scientific operation of the Hinode mission is conducted by the Hinode science team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the postlaunch operation is provided by JAXA and NAOJ (Japan), STFC (UK), NASA (USA), European Space Agency, and Norwegian Space Centre (Norway). U.S. members of the XRT team are supported by NASA contract NNM07AA02C to the Smithsonian Astrophysical Observatory. Lastly, we would like to express our sincere gratitude to the late T. Kosugi, former project manager of the Hinode mission at ISAS/JAXA, whose years of outstanding effort led to the success of this mission.

Supporting Online Material

www.sciencemag.org/cgi/content/full/318/5856/1585/DC1
Movie S1

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REPORT

Slipping Magnetic Reconnection in Coronal Loops

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Magnetic reconnection of solar coronal loops is the main process that causes solar flares and possibly coronal heating. In the standard model, magnetic field lines break and reconnect instantaneously at places where the field mapping is discontinuous. However, another mode may operate where the magnetic field mapping is continuous but shows steep gradients: The field lines may slip across each other. Soft x-ray observations of fast bidirectional motions of coronal loops, observed by the Hinode spacecraft, support the existence of this slipping magnetic reconnection regime in the Sun's corona. This basic process should be considered when interpreting reconnection, both on the Sun and in laboratory-based plasma experiments.

Magnetic reconnection is a diffusive magnetohydrodynamic (MHD) process, through which magnetic loops exchange their connections at large scales (*1*). In magnetic loops whose footpoints are both rooted in a dense conducting layer, which is the case in the solar atmosphere (*2*, *3*), reconnection also redistributes field-aligned electric currents far from where they were located early on (*4*–*6*). When reconnection occurs across layers where the magnetic mapping is discontinuous (which naturally results from existing magnetic null points), magnetic loops instantaneously exchange their large-scale connections by pairs. This is always true, regardless of the rate of magnetic flux being transferred through the local reconnection site. It is the standard reconnection model, and it is used to model solar flares in general. However, solar observations, combined with theoretical reconstructions of the coronal magnetic field, show that brightenings related to solar flares are often not associated with mapping discontinuities but rather with so-called quasi-separatrix layers (QSLs), across which the magnetic mapping has very sharp spatial gradients, although still being continuous (*7*–*9*). Whether magnetic reconnection, instead of simple magnetic diffusion, occurs in QSLs, and, if so, what are its large-scale consequences, have been debated for more than 10 years, because the absence of mapping discontinuities in QSLs forbids the occurrence of standard reconnection.

Three-dimensional (3D) MHD simulations that included collisional diffusive terms in Ohm's

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