EXTENDED PDF FORMAT
SPONSORED BY
usb
www.usbweb.com

Evidence for Alfvén Waves in Solar X-ray Jets

J. W. Cirtain, *et al.*

Science **318**, 1580 (2007);
DOI: 10.1126/science.1147050

The following resources related to this article are available online at www.sciencemag.org (this information is current as of June 5, 2008):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/318/5856/1580

Supporting Online Material can be found at:
http://www.sciencemag.org/cgi/content/full/318/5856/1580/DC1

A list of selected additional articles on the Science Web sites **related to this article** can be found at:

http://www.sciencemag.org/cgi/content/full/318/5856/1580#related-content

This article has been **cited by** 3 article(s) on the ISI Web of Science.

This article has been **cited by** 2 articles hosted by HighWire Press; see:
http://www.sciencemag.org/cgi/content/full/318/5856/1580#otherarticles

This article appears in the following **subject collections**:
Astronomy
http://www.sciencemag.org/cgi/collection/astronomy

Information about obtaining **reprints** of this article or about obtaining **permission to reproduce this article** in whole or in part can be found at:
http://www.sciencemag.org/about/permissions.dtl

Downloaded from www.sciencemag.org on June 5, 2008

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2007 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.

3. J. M. Malherbe, B. Schmieder, E. Ribes, P. Mein, *Astron. Astrophys.* **119**, 197 (1983).
4. G. Simon, B. Schmieder, P. Démoulin, A. I. Poland, *Astron. Astrophys.* **166**, 319 (1986).
5. B. Schmieder, M. A. Raadu, J. E. Wiik, *Astron. Astrophys.* **252**, 353 (1991).
6. S. F. Martin, *Sol. Phys.* **182**, 107 (1998).
7. J. B. Zirker, O. Engvold, S. F. Martin, *Nature* **396**, 440 (1998).
8. J. Chae, C. Denker, T. J. Spirock, H. Wang, P. R. Goode, *Sol. Phys.* **195**, 333 (2000).
9. J. T. Karpen, S. K. Antiochos, J. A. Klimchuk, *Astrophys. J.* **637**, 531 (2006).
10. C. J. Schrijver *et al.*, *Sol. Phys.* **187**, 261 (1999).
11. S. Patsourakos, J. C. Vial, *Sol. Phys.* **208**, 253 (2002).
12. T. Kosugi *et al.*, *Sol. Phys.* **243**, 3 (2007).
13. S. Tsuneta *et al.*, http://arxiv.org/abs/0711.1715.
14. Y. Suematsu, R. Yoshinaga, N. Terao, T. Tsubaki, *Publ. Astron. Soc. Jpn.* **42**, 187 (1990).
15. M. Kuperus, M. A. Raadu, *Astron. Astrophys.* **31**, 189 (1974).
16. J. L. Leroy, V. Bommier, S. Sahal-Bréchot, *Astron. Astrophys.* **131**, 33 (1984).
17. T. Hirayama, *Sol. Phys.* **100**, 415 (1985).
18. V. M. Nakariakov, E. Verwichte, *Living Rev. Sol. Phys.* **2**, 3 (2005).
19. A. J. Díaz, R. Oliver, J. L. Ballester, *Astrophys. J.* **580**, 550 (2002).
20. T. Hirayama, in *Coronal and Prominence Plasma*, A. I. Poland, Ed., NASA Conference Publication No. 2442 (NASA, Washington, DC, 1986).
21. E. Tandberg-Hanssen, J. M. Malville, *Sol. Phys.* **39**, 107 (1974).
22. E. Wiehr, G. Stellmacher, *Astron. Astrophys.* **247**, 379 (1991).
23. G. L. Withbroe, R. W. Noyes, *Annu. Rev. Astron. Astrophys.* **15**, 363 (1977).
24. I. De Moortel, J. Ireland, A. W. Hood, R. W. Walsh, *Astron. Astrophys.* **387**, L13 (2002).
25. C. J. Schrijver, M. J. Aschwanden, A. M. Title, *Sol. Phys.* **206**, 69 (2002).
26. M. J. Aschwanden, B. De Pontieu, C. J. Schrijver, A. M. Title, *Sol. Phys.* **206**, 99 (2002).
27. D. Banerjee, R. Erdélyi, R. Oliver, E. O'Shea, *Sol. Phys.* **tmp**, 136 (2007).
28. Y. Lin, O. Engvold, L. H. M. Rouppe van der Voort, M. van Noort, *Sol. Phys.* **tmp**, 71 (2007).
29. S. Koutchmy, Y. D. Zugzda, V. Locans, *Astron. Astrophys.* **120**, 185 (1983).
30. H. Hara, K. Ichimoto, *Astrophys. J.* **513**, 969 (1999).

31. The authors thank H. Shibahashi, T. Sekii, R. Erdélyi, and V. Nakariakov for comments. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and Science and Technology Facilities Council (STFC) (UK) as international partners. It is operated by these agencies in cooperation with European Space Agency and Norwegian Space Centre (Norway). This work was carried out at the NAOJ Hinode science center, which was supported by the Grant-in-Aid for Creative Scientific Research, the Basic Study of Space Weather Prediction (head investigator, K.S.) from the Ministry of Education, Culture, Sports, Science, and Technology, Japan, donation from Sun Microsystems Incorporated, and NAOJ internal funding. The National Center for Atmospheric Research is sponsored by NSF. T.J.O. is supported by research fellowships from the Japan Society for the Promotion of Science for Young Scientists.

Supporting Online Material
www.sciencemag.org/cgi/content/full/318/5856/1577/DC1
Movie S1

21 May 2007; accepted 6 November 2007
10.1126/science.1145447

REPORT

Evidence for Alfvén Waves in Solar X-ray Jets

J. W. Cirtain,[1,2]* L. Golub,[1] L. Lundquist,[1] A. van Ballegooijen,[1] A. Savcheva,[1] M. Shimojo,[3] E. DeLuca,[1] S. Tsuneta,[4] T. Sakao,[5] K. Reeves,[1] M. Weber,[1] R. Kano,[4] N. Narukage,[5] K. Shibasaki[3]

Coronal magnetic fields are dynamic, and field lines may misalign, reassemble, and release energy by means of magnetic reconnection. Giant releases may generate solar flares and coronal mass ejections and, on a smaller scale, produce x-ray jets. Hinode observations of polar coronal holes reveal that x-ray jets have two distinct velocities: one near the Alfvén speed (~800 kilometers per second) and another near the sound speed (200 kilometers per second). Many more jets were seen than have been reported previously; we detected an average of 10 events per hour up to these speeds, whereas previous observations documented only a handful per day with lower average speeds of 200 kilometers per second. The x-ray jets are about 2×10^3 to 2×10^4 kilometers wide and 1×10^5 kilometers long and last from 100 to 2500 seconds. The large number of events, coupled with the high velocities of the apparent outflows, indicates that the jets may contribute to the high-speed solar wind.

The solar corona provides an opportunity to study the interactions of high-temperature electrically conducting gas, plasma, and a dynamic magnetic field. The constant emergence and cancellation of the magnetic field create a multitude of energetic changes in magnetic topology that can inject enormous amounts of energy into the plasma. It is thought that magnetic reconnection is involved in releasing energy to produce solar flares and coronal mass ejections (CMEs). X-ray jets, in which a burst of hot plasma is driven into the solar corona along an open magnetic field line, are thought to be a different manifestation of the reconnection process. It appears as though at least some fraction of these outflows has sufficient kinetic energy to leave the corona and propagate into the inner heliosphere.

Two types of outflows are possible during the post–magnetic reconnection phase of a jet. In the first case, an outflow at the local sound speed (v_c), resulting from energy deposition that rapidly heats the dense chromospheric plasma, expands into the overlying low-pressure corona. The sound speed is governed by the equation

$$v_c = \left(\frac{2\gamma k T^{1/2}}{m_p}\right)^{1/2} \tag{1}$$

Here, T is the temperature at the location of energy deposition, k is the Boltzmann constant, γ is the ratio of specific heat capacities, and m_p is the proton mass. The average temperature of jets and the related footpoint flares is 6 million K (*1*, *2*), a temperature estimate consistent with our observations, which also show that the loop density in the coronal hole before the jet is 3×10^8 cm^{-3}. The initial velocity of the conduction front would be 400 km s^{-1}.

The second case is when plasma is accelerated by the formation of an Alfvén wave during the relaxation of the magnetic field, and the plasma is forced to flow out along the field at about the Alfvén speed, v_a, given by

$$v_a = B_0/\sqrt{4\pi\rho} \tag{2}$$

where B_0 is the magnetic field strength, and ρ is the mass density. Assuming that the magnetic field is of the order of 10 gauss, the Alfvén velocity of the plasma before the subsequent evaporation should be ~ 1000 km s^{-1}.

These observations of coronal jets provide useful insight into the formation of hot, collimated, high-velocity outflows, which are likely a large-scale contributor to the mass loading of the fast solar wind. The first models for the existence of the solar wind were provided by Parker and Chapman (*3*, *4*). Previous work (*5*–*9*) has suggested that Alfvén waves may play an important role in driving the solar wind. Using observations from the NASA mission Ulysses, Wang (*10*) found that the fast solar wind originated from the polar coronal holes and was nearly continuously present, but there was no direct evidence for the mechanism producing the fast wind.

---

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA. [2] Marshall Space Flight Center, National Aeronautics and Space Administration (NASA) VP62, Huntsville, AL 35812, USA. [3] Nobeyama Solar Radio Observatory, Nobeyama, Nagano 384–1305, Japan. [4] National Astronomical Observatory of Japan (NAOJ), Mitaka, Tokyo 181–8588, Japan. [5] Institute of Space and Astronautical Science, (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Kanagawa 229–8510, Japan.

*To whom correspondence should be addressed. E-mail: Jonathan.W.Cirtain@nasa.gov

X-ray jets have been identified in polar coronal holes, in "quiet" Sun, and from within active regions (*1*, *2*, *10*–*14*). Shibata *et al*. (*2*) found that the jets were a transient x-ray source with essentially collimated motion outward along the coronal magnetic field from the initiation site. The observed outflow velocity in these studies was typically 200 to 600 km s^{-1}. These jets were reported to have lengths of 1×10^5 to 10×10^5 km and collimated widths of 1×10^4 km. Other observations of polar jets by means of instruments such as the High-Resolution Telescope and Spectrograph (HRTS) (*13*, *14*) have reported that extreme ultraviolet jets, so-called chromospheric jets, do not have physical characteristics similar to the x-ray jets reported by Shibata and others or to the x-ray jets studied in this report. The relationship between the lower-temperature jets (observed with emission lines formed near 1.0×10^4 K) and x-ray jets (formed above 2.0×10^6 K) remains unclear.

Hinode (formerly Solar-B) is in polar orbit about Earth, following the day-night terminator and thus providing nearly continuous observations of the Sun. Here we report Hinode X-ray Telescope (XRT) observations of polar coronal hole jets and show that at least some jets have two velocity components. According to current theories of magnetic reconnection, an Alfvén wave should be generated by the reconnected magnetic field line as it proceeds from a highly curved geometry to a relaxed configuration. This Alfvén wave could drive plasma along the field at speeds of 600 to 1000 km s^{-1}, depending on the local plasma density and field strength. We have observed several such outflow (radial) velocities for some large jets. The energy released by reconnection will subsequently heat the plasma, which expands into the corona at v_c. We have also observed this component of the process and can clearly differentiate it from the high-speed component.

XRT collected >9000 images during 10 different 6- to 8-hour continuous observations [Figs. 1 and 2, supporting online material (SOM) text, and SOM movies S1 and S2]. Both north and south polar coronal holes were studied. XRT images had a 1024-by-512 arc second field-of-view (7.68×10^5 by 3.84×10^5 km), with one image taken every 30 s. The observed jets are typically 2×10^3 to 2×10^4 km wide and greater than 1×10^5 km long.

We define the axis of a jet to be a line beginning at the initiation site of the jet and extending in the outflow direction. We determined the x-ray intensity along this line from many sequential images. This measure of intensity along the jet axis is plotted as a column and shows the x-ray intensity variation along the jet axis at one instant in time. By "stacking" these columns from sequential images along the *x* axis of the plot, a representation of the intensity variation in distance and time is created (Fig. 3A). The slope of an intensity front in this type of plot determines the velocity of the outflowing plasma.

Using this technique, we examined four jets in detail. There are multiple velocity components for each of the jets. One component of the jet velocity is consistent with the previously reported spatio-temporal average velocity of ≈ 200 km s^{-1} (*1*). However, a much higher velocity is also observed, roughly ~ 800 km s^{-1} at the start of each event. We interpret this as evidence for material being ejected at v_a during the relaxation of the magnetic field

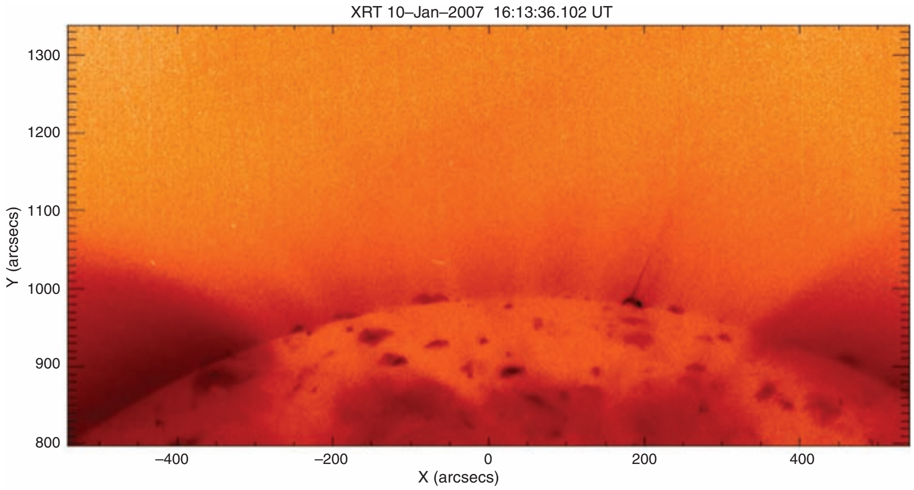

Fig. 1. Hinode XRT false-color image of the north polar coronal hole. A typical jet is seen in the center of this image (movie S2).

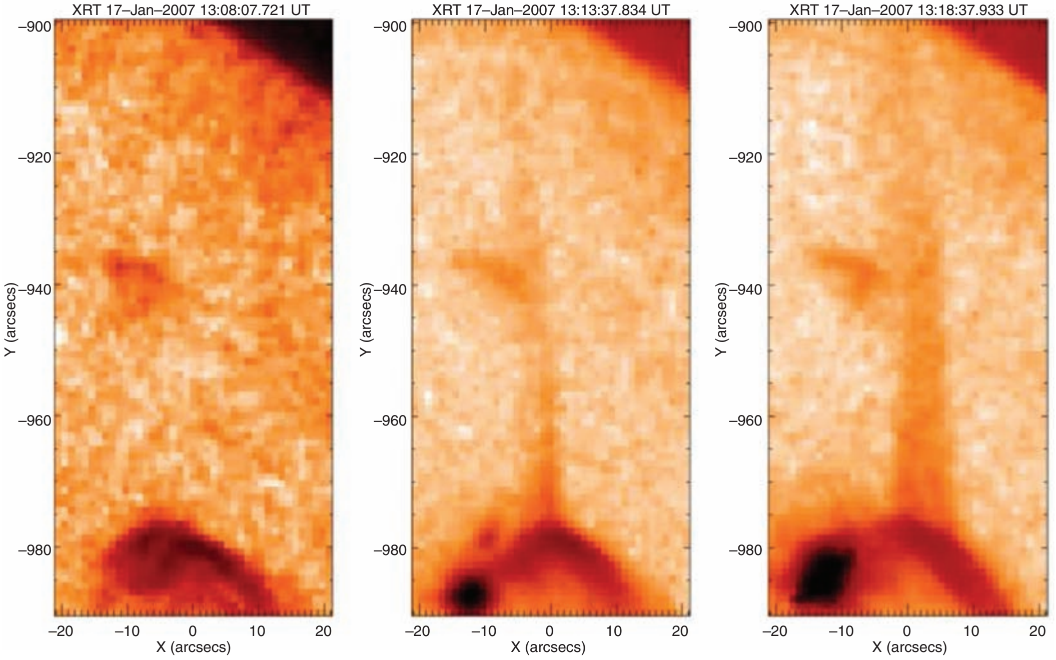

Fig. 2. Hinode XRT false-color images of three stages of a jet's evolution (movie S1).

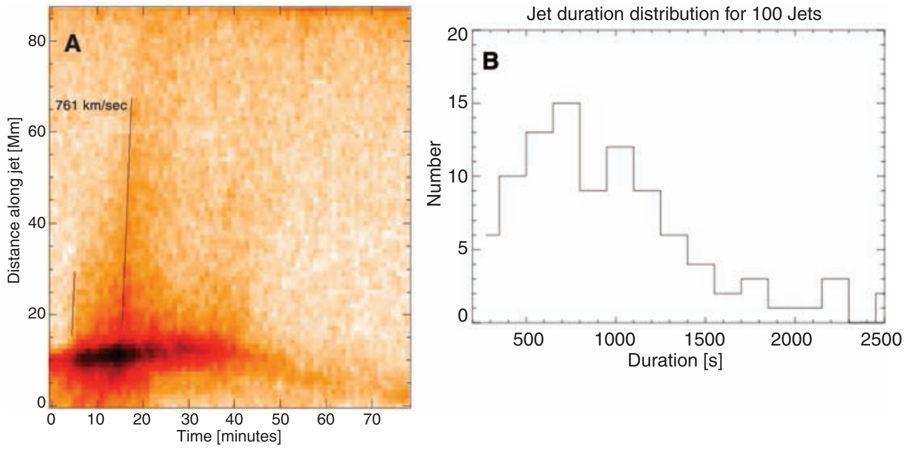

Fig. 3. (**A**) A time-distance plot for the jet shown in Fig. 2. (**B**) Histogram showing the distribution in lifetimes for 100 jets.

after reconnection. We have also found that this high-speed mass flow sometimes occurs multiple times per jet; presumably, there is an Alfvén wave generated during each burst of reconnection.

Alfvén waves are created when the magnetic field is subjected to transverse motions. In the low-β corona, this occurs during reconnection. These transverse motions could be observed in jets as the plasma is constrained to move with the magnetic field. Previous observations with instruments from the Transition Region and Coronal Explorer, Yohkoh, and other missions lacked the imaging cadence and dynamic range to capture these oscillations. We have observed such transverse oscillations for jets (movie S1) using the Hinode XRT. These oscillations have a period of about 200 s and a peak-to-peak magnitude of 8000 km. These observations of the transverse motion of the jet relative to the jet outflow direction are further evidence for Alfvén wave creation during reconnection.

We also found that the frequency of jet formation is at least an order of magnitude greater than that which has been previously reported (*10*–*12*). These previous studies found only a few events per day, primarily resulting from reduced cadence and longer exposures. Our Hinode XRT observations indicate an average of 10 jet events per hour during 100 hours of observations (movie S2). We found that jets frequently occur from the same x-ray bright points or from bright points that formed extremely close to the locations of previous jet-initiation sites, whereas other jets occur from transient x-ray bright points. The x-ray jets in our observations have lifetimes ranging from 100 to 1500 s, much longer than the typical 10- to 100-s lifetimes of the chromospheric jets (*13*, *14*). The histogram in Fig. 3B shows the distribution of jet lifetimes for 100 events observed during the study. No correlation is yet available regarding the location of the bright points, jet formation, and distance from the coronal hole boundary.

Given the increased number of jets observed, we have performed a simple calculation of the impact on the mass loading to the fast solar wind. Each event has an average m_p loss of 1×10^{37}. For both north and south polar coronal holes, XRT recorded, on average, 10 jets per hour. This produces a net flux of 1×10^{12} protons m^{-2} s^{-1} at 1 astronomical unit. Current estimates of the average solar wind flux are only a factor of 10 more than the value of this jet mass-loading contribution (*5*, *10*).

XRT has shown that there is a similarity between these small-scale eruptive events (jets) and the flares/CMEs from active regions, in the sense that both phenomena may involve topological changes to the coronal magnetic field via reconnection, thus providing the energy for both heating and accelerating coronal plasma. This correspondence between events that differ in energy by three to four orders of magnitude may serve as a prototype for the formation of other astrophysical jets, where the energy released is many orders of magnitude greater still.

References and Notes

1. M. Shimojo *et al.*, *Publ. Astron. Soc. Jpn.* **48**, 123 (1996).
2. K. Shibata *et al.*, *Publ. Astron. Soc. Jpn.* **44**, L173 (1992).
3. E. N. Parker, *Astrophys. J.* **128**, 664 (1958).
4. S. Chapman, *Smithson. Contrib. Astrophys.* **2**, 1 (1957).
5. S. R. Cranmer, G. B. Field, J. L. Kohl, *Astrophys. J.* **518**, 937 (1999).
6. S. R. Cranmer, A. A. van Ballegooijen, *Astrophys. J. Suppl. Ser.* **156**, 265 (2005).
7. S. R. Cranmer, A. A. van Ballegooijen, R. J. Edgar, *Astrophys. J. Suppl. Ser.* **171**, 520 (2007).
8. W. H. Matthaeus, G. P. Zank, S. Oughton, D. J. Mullan, P. Dmitruk, *Astrophys. J.* **523**, L93 (1999).
9. M. Velli, *Astron. Astrophys.* **308**, 228 (1993).
10. Y.-M. Wang, *Astrophys. J.* **410**, L123 (1993).
11. B. E. Wood, M. Karovska, J. W. Cook, R. A. Howard, G. E. Brueckner, *Astrophys. J.* **523**, 444 (1999).
12. D. Dobrzycka, S. R. Cranmer, J. C. Raymond, D. A. Biesecker, J. B. Gurman, *Astrophys. J.* **565**, 621 (2002).
13. K. P. Dere, J.-D. F. Bartoe, G. E. Brueckner, *Astrophys. J.* **267**, L65 (1983).
14. B. Schmieder, M. A. Raadu, P. Démoulin, K. P. Dere, *Astron. Astrophys.* **213**, 402 (1989).

15. Hinode is a Japanese mission developed and launched by ISAS/JAXA with NAOJ as a domestic partner and with NASA and the Science and Technology Facilities Council (UK) as international partners. The mission is operated by these agencies in cooperation with the European Space Agency and the Norwegian Space Centre. U.S. members of the XRT team are supported by NASA contract NNM07AA02C to the Smithsonian Astrophysical Observatory.

Supporting Online Material

www.sciencemag.org/cgi/content/full/318/5856/1580/DC1
SOM Text
References
Movies S1 and S2

26 June 2007; accepted 7 November 2007
10.1126/science.1147050

REPORT

Fine Thermal Structure of a Coronal Active Region

Fabio Reale,[1,2]* Susanna Parenti,[3] Kathy K. Reeves,[4] Mark Weber,[4] Monica G. Bobra,[4] Marco Barbera,[1,2] Ryouhei Kano,[5] Noriyuki Narukage,[6] Masumi Shimojo,[7] Taro Sakao,[6] Giovanni Peres,[1,2] Leon Golub[4]

The determination of the fine thermal structure of the solar corona is fundamental to constraining the coronal heating mechanisms. The Hinode X-ray Telescope collected images of the solar corona in different passbands, thus providing temperature diagnostics through energy ratios. By combining different filters to optimize the signal-to-noise ratio, we observed a coronal active region in five filters, revealing a highly thermally structured corona: very fine structures in the core of the region and on a larger scale further away. We observed continuous thermal distribution along the coronal loops, as well as entangled structures, and variations of thermal structuring along the line of sight.

The solar corona is highly structured by the solar magnetic field and is extremely hot (≥10^6 K). It is widely accepted that the origin of the heating of the hot plasma confined in the closed coronal structures (named loops) lies in the magnetic field (*1*). The determination of the fine thermal structure of the corona is crucial to solving the origin of the