Evidence for Alfvén Waves in Solar Polar Jets

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

[1] Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
[2]Nobeyama Solar Radio Observatory, Nobeyama, Nagano, 384-1305
[3]National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588
[4]ISAS, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 229-8510

Data collected on X-ray jets during a polar coronal hole observation campaign has revealed that some events have two distinct velocity components, one near the Alfvén speed ($\sim$ 800 km sec^{-1}) and the other near the sound speed (200 km sec^{-1}). Previous reports indicate the incidence of jet formation to be only a few per day, with average radial speeds of 200 km sec^{-1}. With the X-Ray Telescope (XRT) we detect an average of 10 events per hour. These jets are approximately $2 \times 10^3 - 2 \times 10^4$ km wide and than 1×10^5 km long. The jet lifetimes range from 100 - 2500 secs. A large percentage of these jets are associated with small footpoint flares *(1)*. The large number of events, coupled with the high velocities of the apparent outflows, indicate that these jets may contribute significantly to the high-speed solar wind from coronal holes. These observations provide unique and important evidence for the generation of Alfvén waves during reconnection and are possibly the first evidence of Alfvén wave observations driving the high speed solar wind.

Introduction

Ubiquitous throughout the universe, plasmas are often hot, magnetized and highly dynamic. It has proven quite difficult to simulate these environments, either in the laboratory or numerically, so we must rely on observations to guide theory in understanding this state of matter. Only two astronomical cases exist close enough to earth to permit observations with sufficient detail to provide a stringent test of theories. The earth's magnetosphere can be measured with in-situ instruments capable of determining density, temperature, particle velocity, magnetic field properties, etc. The solar atmosphere can be observed from space via remote sensing, and we find that it differs markedly from the earth's magnetosphere. In particular, the plasma is hot, and the magnetic field is predominantly multi-polar and variable, with magnetic field constantly being generated from within the solar convective envelope and emerging to the solar surface.

The solar corona provides a rare opportunity to study the interactions of high temperature plasmas and a dynamic magnetic field. The constant emergence and cancellation of magnetic fields creates a multitude of energetic changes in magnetic topology that can inject enormous amounts of energy into the plasma. It is fairly well-accepted that magnetic reconnection is involved in the subsequent energy release processes which produce solar flares and coronal mass ejections. X-ray jets are thought to be small-scale versions of these phenonmena. An X-ray jet is a burst of hot plasma that is ejected from the sun along (presumably) open magnetic field lines.

After the launch of the Yohkoh satellite, x-ray jets were identified using images collected by the Soft X-ray Telescope (SXT; *2*) on Yohkoh (Solar-A; *3*). Many articles have reported the occurance of jets in polar coronal holes, quiet sun and from within active regions (*1*, *4*, *5*). In particular, Shibata et al. (*6*) found that the jets were a transient x-ray source with essentially collimated motion radially outward from the initiation site. The observed outfow velocity reported in these studies was typically 200 - 600 km sec-1. These jets were reported to have lengths of 1 - 10 $\times 10^5$ km and collimated widths of 10^4 km.

Hinode (formerly Solar-B, *7*) was successfully launched on 23 September 2006 from the JAXA Uchinora Space Center. It was positioned into a polar orbit, following the day-night terminator thus providing nearly continuous observations of the sun. The X-Ray Telescope (XRT; *8*, *9*) is one of the three instruments on Hinode, and is a next generation version of the SXT. With 2" on-axis resolution (1" pixels) and a 33' field of view, the XRT is capable of taking a full sun full-resolution image every 12 seconds (4 Mpixels/image). There are ten focal plane filters, nine x-ray and a 430.5 nm passband.

Here we report the first XRT observations of polar coronal hole jets. Although this is not a new observation in its own right, the increased capabilities of XRT have revealed that these jets occur in far greater number than previously known and that they 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 at speeds of 600-1000 km sec^{-1}, depending on the local plasma density. We have observed several such outflow (radial) velocities for some large jets. The energy released by the reconnection will subsequently produce hot plasma which flows into the corona at the sound speed. We have observed this component of the process and can clearly differentiate it from the high-speed component.

Observations of Coronal Jets and Alfvén Waves

SOHO campaign 7197, entitled Polar Coronal Hole Study, ran from 8-21 January, 2007. Particpating instruments included the Transition Region and Coronal Explorer (TRACE; *10*, *11*); the Large Angle Spectrometric Coronagraph (LASCO), the Coronal Diagnostic Spectrometer (CDS) on SoHO, the UltraViolet Coronograph Spectrometer (UVCS) and the Extreme Ultraviolet Imaging Telescope (EIT) all of which are on the Solar and Heliospheric Observatory (SoHO; *12*); the X-Ray Telescope, the Extreme-Ultraviolet Imaging Spectrometer (EIS) and the Solar Optical Telescope (SOT) on the Hinode satellite.

Campaign 7197 was designed to collect 6-8 hours of continuous observations of a polar coronal hole. Both north and south polar coronal holes were studied. XRT images were primarily 1024 x 512 arcseconds with one image every 30 seconds. We used both a combination of multiple focal plane filters to provide temperature information, and a single filter to study dynamics and geometry. The focal plane filters are used to isolate the energy of transmitted solar x-ray emission to a known energy range. This limitation on the x-ray energy can be used to estimate the temperature of the radiating plasma. In the present study we have only focused on the spatio-temporal variations and not temperature diagnostics nor do we incorporate the many valuable observations by other instruments in this research effort.

The X-Ray Telescope (XRT) on the *Hinode* spacecraft has observed the formation of jets from polar coronal holes. The observed jets are typically $2 \times 10^3 - 2 \times 10^4$ km wide and greater than 1×10^5 km long. We also note that the frequency of jet formation is at least an order of magnitude greater than has been previously reported. An example of an XRT observation is shown in Figure 1 while we show a enlarged image of a particular jet during three stages of the jet's evolution in Figure 2.

The radial velocity of polar coronal hole jets has been measured by forming a plot of the intensity variations as a function of distance and time. To create this plot, the intensity for a single column of pixels along the axis of the jet is determined which will form a 1-D strip in a full image. With an average lifetime of several minutes, there are generally 30 or more images for each event. A column of pixels along the axis of the jet from each image is compiled to form a plot of X-ray intensity as a function of time and position along the jet. The slope of the intensity in the plot is then the velocity of the jet. An example of this technique is shown in

Figure 3.

Using this technique we have examined four jets in detail. We find that there are multiple velocity components for each of the jets. Shimojo et al. (*1*) reported that the spatio-temporal average velocity was ~ 200 km sec^{-1}. We find that one component of the jet velocity is consistent with this velocity. However, a much higher velocity is also observed, roughly ~ 800 km sec^{-1} at the start of each event. We interpret tis as evidence for material being ejected at the Alfvén speed during the relaxation of the the magnetic field following a reconnection event. We have also found that this high speed mass flow occurs multiple times per event, presumably there is a Alfvén wave generated for every field line that reconnections and relaxes. THis would explain the multiple Alfvénic components we observe for each of the jets studied.

We have also studied the numbers of events per hour, and estimated of the mass for each event. This allow us to define the average mass per event and a total mass loss per second. We have found that each event has a proton mass loss of 10^{37}. For both data collected from north and south polar coronal holes, the average number of events per hour is 10. Previous reports of jet observations indicated that there were only a few of these observed *per day*.

Discussion

Two types of outflows are possible during the post magnetic reconnection phase of a jet. (1) An outflow at the local sound speed resulting from an energy deposition into the dense chromosphere plasma. (2) A faster outflow at the Alfvén speed produced during the relaxation of the magnetic field to a more potential (less curved) geometry. In case (1) the plasma is rapidly heated and expands into the overlying low pressure corona via evaporation. This process is governed by the equation

$$v_c = 2\kappa T^{5/2}/3knL_T \quad . \tag{1}$$

Here κ is the Spitzer conductive coefficient, T is the temperature at the location of energy deposition, k is the Boltzmann constant, n is the density of the loop before evaporation is initiated and L_T is the temperature scale length. The average temperature of jets and the related footpoint flares are 6 MK (*13,14*). They also show that the loop density in the coronal hole before the jet is 1×10^8 cm^{-3}. In hydrostatic equilibrium, the temperature scale length is 5×10^4 km, and so the initial velocity of the conduction front would be 200 km s^{-1}.

The other possible velocity is due to case (2). Plasma is accelerated by the formation of an Alfvén wave during the relaxation of the magnetic field. The velocities of Alfvén waves are given by

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

Assuming that the magnetic field is of order 10 Gauss, the Alfvén velocity in the loop prior to evaporation is $\sim$ 700 km s^{-1}.

In addition to the observed high-speed radial velocities, we have also observed transverse oscillations of a jet (see http://xrt.cfa.harvard.edu/resources/stash/17jan2007.html). These oscillations have a period of about 200 secs, and a peak-to-peak magnitude of 8000 km. These observations of transverse oscillations are the first we know to have been reported.

As a small flux region undergoes reconnection, multiple field lines are driven into a current sheet, the field line topology is changed, and the shape of the field distorted. This distortion will create a Alfvén wave as the field line attemps to straigten. Subsequent field lines will go throught the same process and also create Alfvén waves. Accordingly, it is not suprising that in all of the events we have thus far studied which show evidence of Alfvén waves, multiple such high speed outflows are observed during each eruptive phase for these four events. We show an example of a potential field configuration that would produce this resul in Figure 4.

Observations of polar coronal jets have been markedly improved due to the increase in spatial and temporal resolution of XRT. Data collected from Campaign 7197 have shown that these events occur with higher frequency than previously expected. Indirect measurement of changes in flux connectivity, as evidenced by observations of loop geometric variations, has been obtained with SOT in Ca II (K) and with XRT in multiple filters. XRT has shown there is a similarity between these small-scale eruptive events (jets) and the flares/CMEs from active regions in the sense that both phenomena involve topological changes to the coronal magnetic field. This correspondance between events with 3 - 4 order of magnitude range of energies may serve as a prototype for the formation of other astrophysical jets with energy scale many orders of magnitude greater still.

Not only do these observations of coronal jets provide useful insight into the formation of hot, collimated, high-velocity outflows, but it is also a likely large-scale contributor to the mass-loading of the fast solar wind. Parker *15* and Chapman *16* first provided a model for the existence fo the solar wind. Recent work has suggested that Alfvén waves may play an important role in driving the fast solar wind. However, these waves have not been directly observed in the extended corona. These jets may, in fact, be the first observational evidence for Alfvénic wave driving of the fast solar wind. The fast solar wind is known to have velocities of the order 100 km sec^{-1} and is generally observed to originate from coronal holes. Our XRT observations of polar coronal jets havw collected data on several hundred jets events to date. The velocities measured for the evaporative component of the x-ray jets and the estimates of mass loss for these events within coronal holes suggest that the jets may in fact be a source of mass loading for the solar wind. Each event observed has an average proton mass loss of order 10^{37} and there are 10 or more of these events *observed* per hour with an average duration of 10 minutes. This expansion produces a net flux of 10^{12} protons m^{-2} sec^{-1} at 1 AU. Current estimates of the average solar wind flux are only a factor of 10 more than this jet mass loss contribution.

XRT has observed an order of magnitude more x-ray jets in coronal holes per hour than previously done in a day. Our detailed study of four of these events has revealed that there are velocity components that are consistent with both Alfvén wave formation and evaporation outflows. The mass loss for jets could form a sizable fraction of the mass of the fast solar wind. It is also possible that these small-scale events could serve as a model for larger energetic jets which occur throught the universe.

References and Notes

1. Shimojo, M., Hashimoto,S., Shibata, K., Hirayama, T., Hudson, H. S., & Acton, L. W., *PASJ*, **48**, 123 (1996).

2. Tsuneta, S., Acton, L. W., Bruner, M., Lemen, J., Brown, W., Caravalho, R., Catura, R., Freeland, S., et al., *Solar Physics*, **136**, 37 (1991).

3. Ogawara, Y., Takano, T., Kato, T., Kosugi, T., Tsuneta, S., Watanabe, T., Kondo, I., Uchida, Y., *Solar Physics*, **136**, 1 (1991).

4. Wood, B. E., Karovska, M., Cook, J. W., Howard, R. A., Brueckner, G. E., *ApJ*, **523**, 444 (1999).

5. Dobrzycka, D., Cranmer, S. R., Raymond, J. C., Biesecker, D. A., Gurman, J. B., *ApJ*, **565**, 621 (2002).

6. Shibata, K., et al. , *PASJ*, **44**, L173 (1992).

7. Kosugi, T.,et al. , *Solar Physics*, in press

8. Golub, L., et al. , *Solar Physics*, submitted

9. Kano, R., et al. , *Solar Physics*, in press

10. Handy, B. N. et al. , *Solar Physics*, **187**, 229 (1999).

11. Golub, L., et al. , Physics of Plasmas, **6**, 2205 (1999).

12. Domingo, V., Fleck, B., & Poland, A. I., *Solar Physics*, **162**, 1 (1995)

13. Shimojo, M., PhD thesis (The Graduate University of Advanced Studies, Japan, 1999)

14. Shimojo, M., & Shibata, K., *ApJ*, 542, 1100 (2000).

15. Parker, E. N., *ApJ*, **128**, 664 (1958).

16. Chapman,S., *Smithsonian Contr. Astrophysics*, **2**, 1 (1957).

1. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). US members of the XRT team are supported by NASA contract NNM07AA02C to SAO.

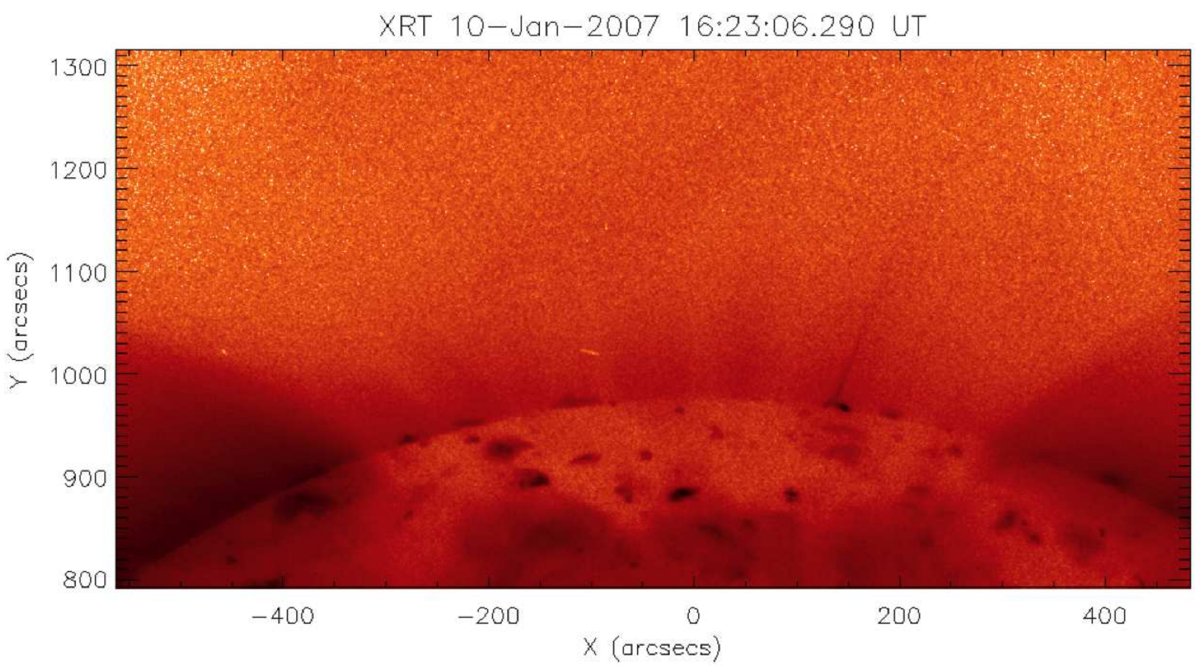

Figure 1: An XRT image of th north polar coronal hole. A typical jet is seen in the center right of this image.

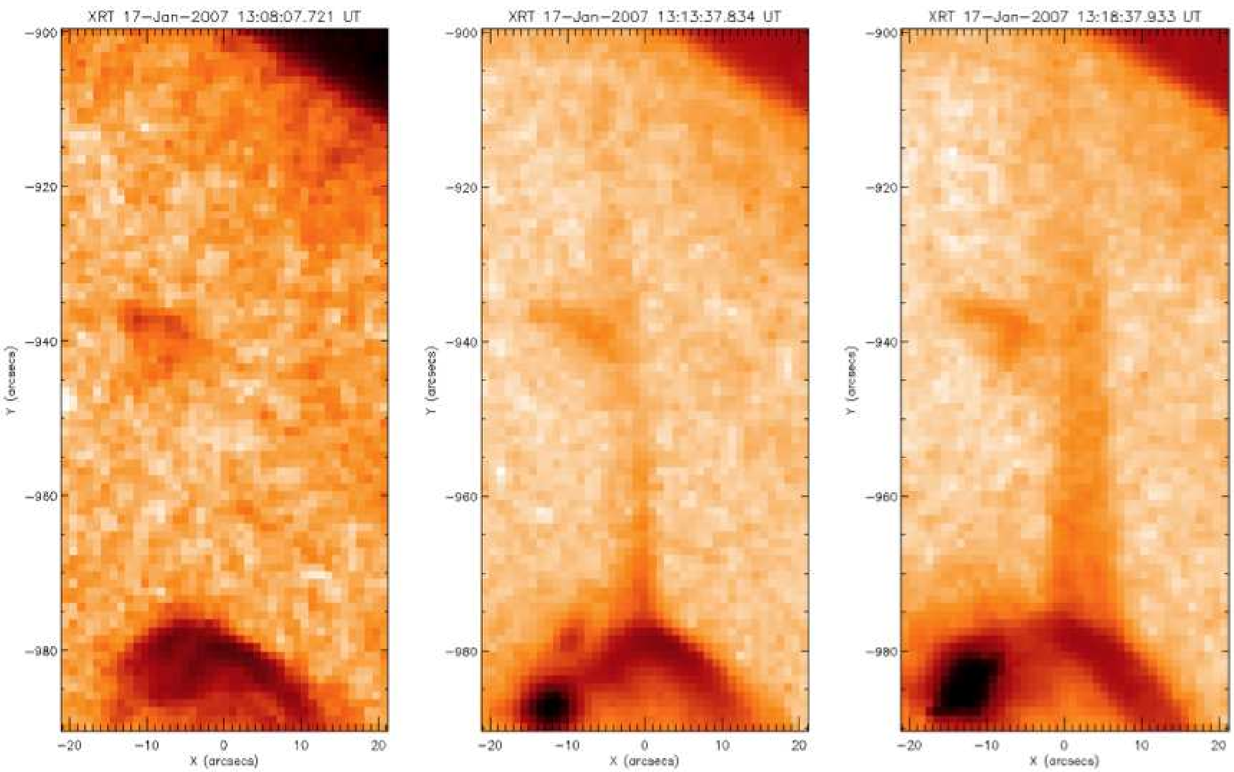

Figure 2: XRT images of three stages in the jet evolution.

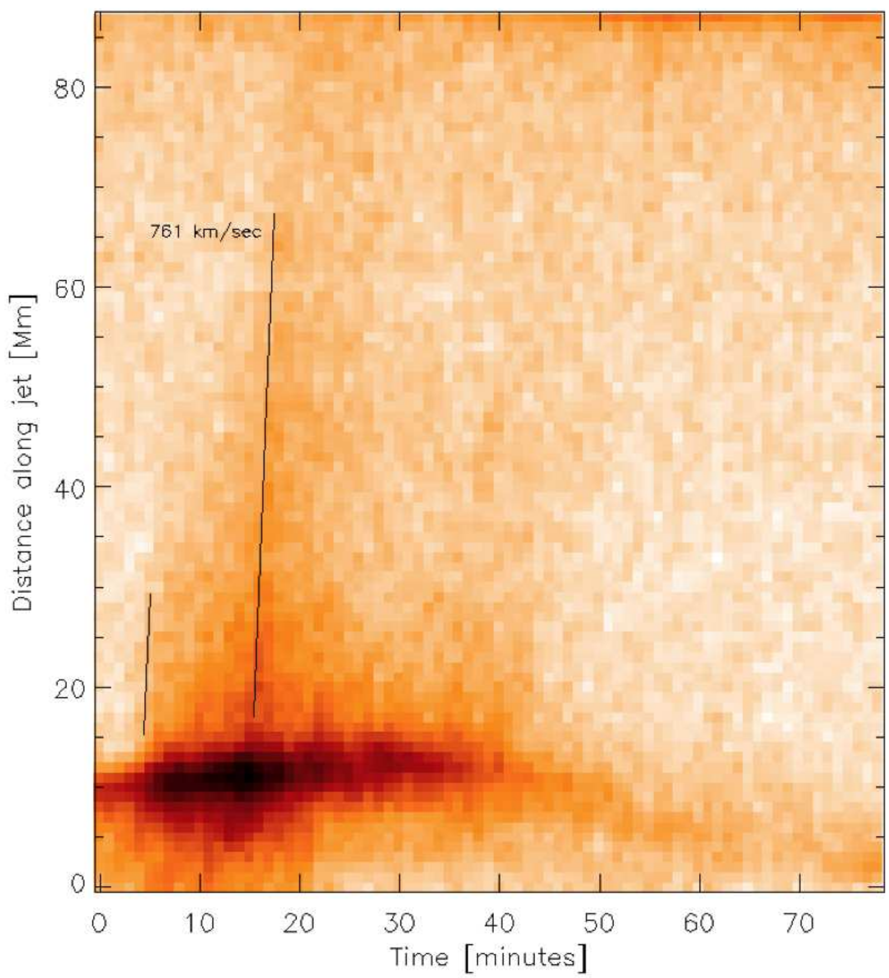

Figure 3: This time-distace plot for the 17 January event at 13:08 UT is used to determine the velocity.The slope in the intensity as a function of distance and time is used for this measurement.

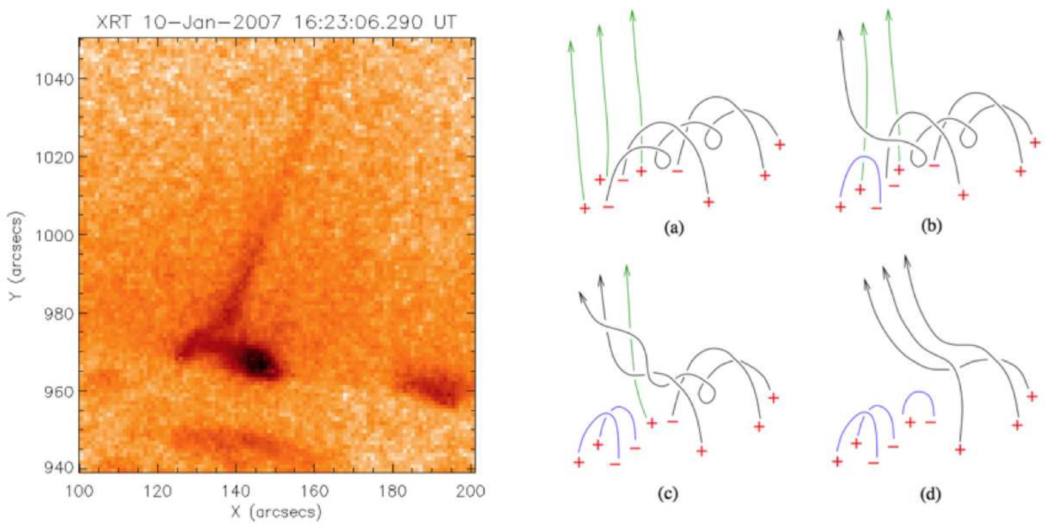

Figure 4: As the magnetic field of a small multipolar region reconnects, the pre-existing field topology can incite multiple reconnection events. A suggested example of a topological evolution is shown above.

Movie 1 (supporting online material): Movie illustrating the frequency and distribution of jets in Figure 1 as imaged by Hinode/XRT with the Al-poly filter. http://xrt.cfa.harvard.edu/resources/stash/17jan

Movie 2 (supporting online material): Movie illustrating the temporal evolution of jets shown in the three panels of Figure 2 as imaged by Hinode/XRT with the Al-poly filter. The jet clearly is seen to oscillate back and forth providing further evidence of the existance of an Alfvén wave. http://xrt.cfa.harvard.edu/resources/stash/17jan2007.html