Bi-directional plasma jets produced by magnetic reconnection on the Sun

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Magnetic reconnection, the process by which magnetic lines of force break and rejoin into a lower-energy configuration, is considered to be the fundamental process by which magnetic energy is converted into plasma kinetic energy[1]. The Sun has a large reservoir of magnetic energy, and the energy released by magnetic reconnection has been invoked to explain both large-scale events, such as solar flares[2,3] and coronal mass ejections[4], and small-scale phenomena, such as the coronal and chromospheric microflares that probably heat and accelerate the solar wind[5,6]. But the observational evidence for reconnection is largely indirect, resting on observations of variations in solar X-ray morphology and sudden changes in the magnetic topology[7,8], and on the apparent association between some small-scale dynamic events and magnetic bipoles[9,10]. Here we report ultraviolet observations of explosive events in the solar chromosophere that reveal the presence of bi-directional plasma jets ejected from small sites above the solar surface. The structure of these jets evolves in the manner predicted by theoretical models of magnetic reconnection[11,12], thereby lending strong support to the view that reconnection is the fundamental process for accelerating plasma on the Sun.

The solar network is the pattern of supergranulation cells seen over the entire surface of the Sun. The cell boundaries, along which the magnetic flux concentrates, is in a state of continuous variability and violent activity. Sudden small-scale plasma jets, microflares[9,13] and explosive events[14–16] are examples of this activity. Explosive events, the subject of this Letter, were first seen in the ultraviolet spectra of the Naval Research Laboratory's high-resolution telescope and spectrograph (HRTS) flown on several rocket flights and on Spacelab 2[14,17]. They were found to be short-lived (60 s), small-scale (1,500 km), high-velocity (± 150 km s^{-1}) flows that occur very frequently over the entire solar surface[16]. There are estimated to be over 30,000 events at any one time on the Sun. The energy involved, however, suggests that they are not the major source of mass or energy in either the chromosophere or corona[15,16]. Their importance lies in the fact that they probably represent the high-energy tail of a spectrum of network events that occur on scales unobservable with current techniques. Dere *et al.*[18] noted that explosive events are associated with freshly emerged magnetic field and that their Doppler velocities are roughly equal to the Alfvén speed in the chromosophere. They concluded that the events result from magnetic reconnection. They also speculated on the possible bi-directional nature of the flows; however the structure of the flows could not be resolved due to limited time and space coverage. The ultraviolet spectrometer SUMER[19–21] (the Solar Ultraviolet Measurements of Emitted Radiation instrument) on the spacecraft SOHO (the Solar and Heliospheric Observatory) has recently made it possible to observe the chromosopheric network continuously over an extended period and to discern the spatial structure of the flows associated with these explosive events. Here we show three examples of explosive events in which the bi-directional nature of the jets is clearly seen. In all cases (1) the Doppler shifts change from red to blue within a few arcseconds, (2) the emission is brightest at the position where the shifts change sign, and (3) the two wings of the emission move away from the site of brightest emission across the Sun's surface.

SUMER is a high-resolution telescope and spectrometer designed to obtain line profiles with a wavelength resolution of $\sim$40 mÅ over the wavelength range 456–1,610 Å and with a spatial resolution of $\sim$1 arcsec (715 km on the Sun) along the entrance slit which is aligned north–south. Explosive events are so frequent that even with the smallest SUMER spectrometer slit, which only covers $\sim 10^{-5}$ of the solar surface, at least one event every five minutes is almost certain to be seen. Events have been detected in several spectral lines from ions of singly to seven-times-ionized species. They therefore cover a wide range of temperatures, but appear to be most prominent in the Si IV 1,393, 1,402 Å line pair formed at $\sim 10^5$ K.

Figure 1 shows sequences of the Si IV 1,393 Å profile obtained during two 90-min observing periods on the 21 and 23 June 1996. The rasters consisted of consecutive 5-s exposures at six or eight scan positions separated by 1.1 arcsec in the east–west direction. In each scanning sequence, first the even scan positions were measured, then the odd positions. During the time of a complete scan, the intensity at the same position changes smoothly enough to justify temporal intensity interpolation at the missing scan position. With the instrument slit orientated north–south, an area of $\sim 9'' \times 120''$ ($\sim 10^{-4}$ of the solar surface) was surveyed with a resolution of about 1 arcsec in both directions and a repetition rate of about 3 per minute.

The first example (Fig. 1a) is from a sequence of rasters taken at solar latitude $\sim 60°$, near the central meridian. Hence the observed line-of-sight velocities are inclined with an angle of 60° to the Sun's surface normal. We see an explosive event lasting about 4 minutes. In the first 60 s, broad profiles with a distinct blue asymmetry are seen at just three scan positions. After 90 s the Doppler shifts have reached a maximum and the event size has almost doubled in the east–west direction. Now the profiles change from predominantly red shifts on the left to predominantly blue shifts on the right. Over the final 90 s the event seems to fade uniformly along its extent. Throughout the whole event, its centre, as identified from the sign change in the Doppler shift, moves less than 1 arcsec. This central position is also the brightest in this emission line.

The observed emission-line asymmetries are those expected from a bi-directional jet whose flow axis is directed at some angle to the line of sight, as sketched in Fig. 2a. As the slit is moved across the jet, the line profiles change from an asymmetric red-shifted profile on the left to a symmetric profile at the centre of the jet and finally to an asymmetric profile with a blue shift on the right. The centre of the jet may be identified with the source of the jet as it is also the position where we see the event first and it stays the brightest throughout the growth phase.

During the initial 30–90 s of the event its size increases by 1.1 arcsec to the left and right. If we assume that this is caused by the heads of the jet propagating out from its source then it is possible to obtain a rough estimate of the true length of the jet. The apparent motion of the heads of the jets during the initial phase corresponds to a transverse velocity of 15–30 km s^{-1}. If the true velocity of the jet head is of the order of the Doppler shift, 100 km s^{-1}, then the inclination angle must be $\sim 10°$. From the apparent length (4×10^3 km), we can conclude that the true jet length is $(1.2–2.4) \times 10^4$ km. The jet probably covers much of the chromosphere and even reaches out into the lower corona. Its final length is comparable to that obtained for macrospicules seen in the ultraviolet on the limb[22]. The lifetime, however, is a little short for a macrospicule although one macrospicule with a lifetime of 3 min has been reported[22]. The event lasts for about two or three minutes after its initial growth phase and it does not continue to spread in size beyond about 6 arcsec. Also, the centre of the jet seems to stay very localized compared to the high gas velocities that it produces.

The second example (Fig. 1b) is from a sequence of rasters taken at disk centre. The observed line-of-sight velocities are therefore normal to the solar surface. This event lasts for $\sim$4.5 min. After the jet has evolved, the blue stream of the jet is far more extended than the red stream. Again we see a spatial spreading of the event during the intial two minutes. During its decay, the velocities remain large as long as the event is bright enough to be seen. In this case, the intensity at the centre of the jet disappears earlier than the intensity in the blue stream of the jet. During this 4.5-min period and within the same 9″ × 40″ area we see the blue stream of a second jet (some distance along the slit) that flared up and faded during the evolution of the first jet. This illustrates how very frequently these jets occur.

The third example (Fig. 1c), also observed at disk centre, shows a jet that is orientated with the asymmetric blue profiles on the left and the red-shifted profiles on the right. The two streams of the jet

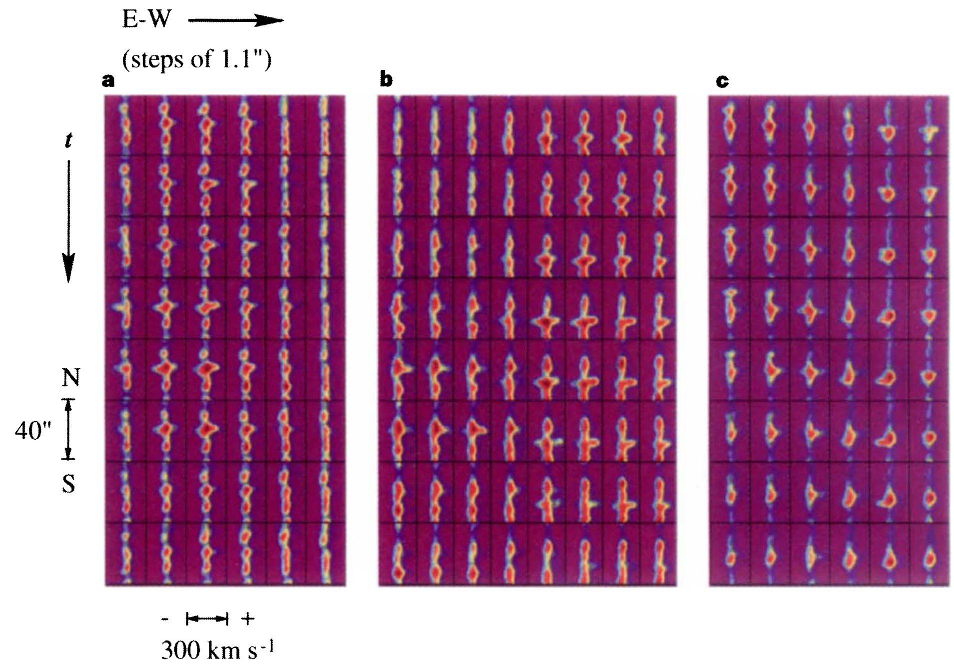

Figure 1 The jets' evolution seen in the Si IV 1,393-Å line profiles obtained with the high-resolution spectrometer SUMER on board SOHO. Each unit in the figures shows a 40-arcsec section of a spectrum along the slit for Doppler velocities from $-150\,\mathrm{km\,s^{-1}}$ (red) to $+150\,\mathrm{km\,s^{-1}}$ (blue). Red shifts are to the left and blue shifts are to the right. Each row shows a single spatial raster with a step size corresponding to a 1.1-arcsec displacement of the slit in the east-west direction. Time increases from top to bottom. **a**, The time between rows is 30 s. The event starts, and is centred at, column 3. The jet has propagated ~1 arcsec to the left and right in the 30 s between taking rasters in rows 2 and 3. The shift from red to blue line asymmetry is clearly visible in rows 4 and 5. **b**, The time between rows is 40 s. The main event is centred in column 5. There is a second event centred in column 1 that is first noticeable in row 4 and lasts ~2 min. In the main event, the blue stream extends over at least three positions and red stream over only one position. We note that the emission from the jet source (column 5) fades before that from the head of the blue stream (columns 7 and 8). **c**, The interval between rows is 20 s. The event is centred in column 4 and reaches its full extent by row 3. This jet is orientated so that the blue stream is encountered before the red stream. Both streams are offset from each other by ~8 arcsec along the slit.

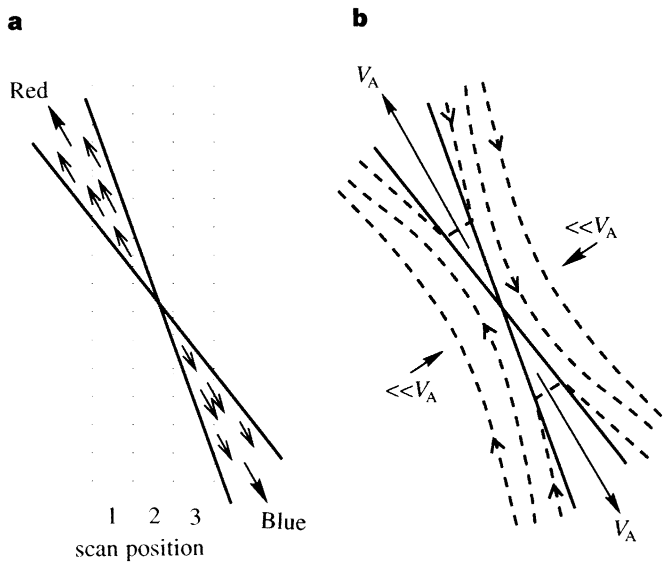

Figure 2 A schematic sketch of a bi-directional jet. **a**, The expected Doppler shifts change as the spectrometer scans across the jet structure. The vertical lines indicate the line of sight at three arbitrary scan positions of the spectrometer slit during east-west raster. **b**, The magnetic field lines (dashed) and the plasma flow (solid arrows) for a reconnection model. The jet speed is of the order of the Alfvén speed, V_A, upstream of the current sheet. The inflow speed is much less than V_A.

are clearly displaced from each other by several arcseconds along the slit. This displacement is seen both at the jet source and at the positions on either side. In terms of the model sketched in Fig. 2a, the reversed blue and red shifts would be due to a reversal of the jet's east–west orientation with respect to the line of sight and the displacement along the slit corresponds to a marked tilt of the projected jet axis with respect to the north-south direction. Again the blue stream, indicating material flowing out of the solar surface, extends to almost 3.3 arcsec away from the source whereas the red stream, although brighter, is only seen 1.1 arcsec from the centre.

The observation that explosive events are bi-directional jets provides new evidence that they result from magnetic reconnection above the solar surface. From simultaneous magnetic field and ultraviolet measurements Dere *et al.*[18] note that explosive events are often found on the chromospheric network boundary and seem to be associated with the cancellation of photospheric magnetic fields. The network consists of curtains of very strong magnetic flux tubes. All flux tubes are anchored by their footpoints to the photosphere. The continual motions in the photosphere mean that field lines of opposite polarity are naturally drawn together. If flux tubes with opposite-polarity field lines are pushed together a current sheet forms. In a finite-resistivity plasma, a small region near the neutral line may collapse and create a thin reconnection region. From this region, plasma is ejected in both directions along the field lines with a velocity of the order of the Alfvén speed[11,12] (Fig. 2b). If there is an obstacle blocking one side, the situation is not as idealized in Fig. 2, and the flow may be uni-directional. For example, jets directed out of the Sun may stream freely up to coronal heights whereas the downward flow could quickly be slowed down by the increasing density of the chromosphere. This would in a simple manner explain the larger spatial extent of the blue-shifted wing in our observations.

The observations presented here seem to establish the association between bi-directional jets and reconnection. Since the launch of SUMER, a vast collection of data on explosive events has been accumulated. We expect that similar bi-directional jets are to be seen at and above active regions wherever reconnection occurs. The present and future observations of this kind will lead to a better understanding of how the Sun's magnetic energy feeds its hot corona and the solar wind. □

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An X-ray-induced insulator–metal transition in a magnetoresistive manganite

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Manganese oxides of the general formula $A_{1-x}B_xMnO_3$ (where A and B are trivalent and divalent cations, respectively) have recently attracted considerable attention by virtue of their unusual magnetic and electronic properties[1–9]. For example, in some of these materials magnetic fields can drive insulator-to-metal transitions where both the conductivity and magnetization change dramatically—an effect termed 'colossal magnetoresistance'[1–3]—raising hopes for application of these materials in the magnetic recording industry[1–9]. Here we show that in one such compound, $Pr_{0.7}Ca_{0.3}MnO_3$, a transition from the insulating antiferromagnetic state to the metallic ferromagnetic state can be driven by illumination with X-rays at low temperatures (<40 K). This transition is accompanied by significant changes in the lattice structure, and can be reversed by thermal cycling. This effect, undoubtedly a manifestation of the strong electron–lattice interactions believed to be responsible for the magnetoresistive properties of these materials[6–9], provides insights into the physical mechanisms of persistent photoconductivity, and may also find applications in X-ray detection and X-ray lithographic patterning of ferromagnetic nanostructures.

The $x = 0$ and $x = 1$ end-members of the $Pr_{1-x}Ca_xMnO_3$ family are insulating antiferromagnets with the manganese ion in the Mn^{3+} and Mn^{4+} valence states, respectively[10]. For intermediate *x*, the average Mn valence is non-integer and the material is generally semiconducting or metallic at high temperatures. At low temperatures, the charge carriers localize in a variety of structural and magnetic ordering patterns with mixed valences of the manganese ions[10]. The charge ordering is associated with lattice distortions which can be revealed by X-ray and neutron diffraction. In $Pr_{0.7}Ca_{0.3}MnO_3$ this metal–insulator transition occurs at temperature $T \approx 200$ K (ref. 3), and the low-temperature charge-ordering pattern[4,10] is sketched in the inset of Fig. 1. Note that this pattern (doubling of the unit cell in one lattice direction) is commensurate with the underlying nearly-cubic lattice despite the incommensurate average Mn valence. The low-temperature magnetic structure is antiferromagnetic with a weak uncompensated moment due to spin canting[4]. The material can be driven back into the metallic state by applying a critical magnetic field H_c; $H_c \approx 4T$ at low temperatures[3,4]. The metallic state is ferromagnetic due to double exchange[4]. This field-induced transition is associated with large hysteresis; the material in fact remains metallic after the field is reduced to zero, but reverts to the charge-ordered state on subse-