Study of Chromospheric Jets Using Hinode Observations and MHD Simulations: Evidence of Propagating Alfvén Waves and Reconnection, and Its Implication to the Coronal Heating Problem

Naoto Nishizuka and Kazunari Shibata
Kwasan and Hida Observatories, Kyoto University

Abstract. We discuss the following subjects: 1) the discovery of chromospheric jets by Hinode/SOT and comparison with the reconnection model, 2) the discovery of propagating Alfvén waves associated with a chromospheric jet and the generation of the wave via magnetic reconnection, 3) the energy estimation of the propagating Alfvén wave and its implications for coronal heating.

1. Introduction

The solar chromosphere is known to be very dynamic (e.g., Bray and Loughhead 1974; Zirin 1988). However, recent Hinode observations (Kosugi et al. 2007) revealed that it is even more dynamic than previously thought (Shibata et al. 2007; Katsukawa et al. 2007). Ubiquitous jets and ubiquitous reconnection were discovered in the solar atmosphere as conjectured by Parker (1988): for example, many polar jets (Cirtain et al. 2007), chromospheric (anemone) jets (Shibata et al. 2007; Nishizuka et al. 2008) and penumbral micro-jets (Katsukawa et al. 2007). Hinode observations also revealed ubiquitous Alfvén waves (Okamoto et al. 2007; De Pontieu et al. 2007; Cirtain et al. 2007; Nishizuka et al. 2008), which may be generated by magnetic reconnection.

It has long been observed that Hα jets called surges often occur in the chromosphere (see e.g. Rust 1967; Kurokawa and Kawai 1992). Surges are believed to be produced by magnetic reconnection (Heyvaerts et al. 1977; Yokoyama and Shibata 1995). Yohkoh observations have also led to the interpretation of the anemone-shaped structure as a result of magnetic reconnection between an emerging magnetic bipole and a preexisting coronal uniform field (Shibata et al. 1992, 1994; Shimojo et al. 1996). This interpretation has been supported by magnetohydrodynamic (MHD) simulations of emerging flux (Heyvaerts et al. 1977; Yokoyama and Shibata 1995). Furthermore, MHD simulations show that Alfvén waves are generated by reconnection (Yokoyama 1998; Takeuchi and Shibata 2001; Isobe et al. 2008; Pariat et al. 2009) and that the heating is due to both slow and fast mode MHD shocks which are generated by nonlinear mode coupling with Alfvén waves (Kudoh and Shibata 1999; Moriyasu et al. 2004).

In this paper, we analyzed a giant chromospheric jet with multiwavelength observations by Hinode/SOT, XRT and TRACE 195Å. We also performed 2-dimensional MHD simulations extending the Yokoyama and Shibata model (1995) with more realistic initial parameters. We compared the simulation re-
Figure 1. Comparison of multi-wavelength observations and simulation results: (a-o) Snapshot images of the jets taken with Hinode/SOT, TRACE/195 Å filter and Hinode/XRT. (p-s) Two-dimensional distribution in temperature ($\log_{10} T$; color map) in units of $10^4$ K, magnetic fields ($B$; lines) and velocity vectors ($v$; arrows) in the simulated jet.
Results with the observation and found that they are quite similar. We also found the propagating Alfvén wave associated with the jet in the simulation result is quite similar to the jet observed with Hinode/SOT. We estimated the energy transported by the wave, and discussed its implication to the coronal heating model.

2. The 2007 February 9 Giant Ca Jet Event and Reconnection Model

The solar jet studied here occurred on the west limb of the Sun around the active region NOAA 10940 on 9 February 2007 13:20 UT, which was associated with a very weak subflare in GOES soft X-ray brightening. The maximum height of the jet was $\sim 14,000$ km and its width $\sim 6,000$ km. Figure 1a-1o shows the snapshot images of the jet with multiwavelength observations taken with the Solar Optical Telescope (SOT; Tsuneta et al. 2008) CaII H-line broad-band filter, with the X-Ray Telescope (XRT; Golub et al. 2007) on board Hinode, and with the TRACE 195 Å filter. As a result of spatial co-alignment, the bright EUV jet was identified with the X-ray jet, whereas the dark EUV jet appeared to be a counterpart to the Ca jet (see Fig. 2). The X-ray jet and the Ca jet were ejected side by side, while the X-ray jet precedes the Ca jet by 5 minutes when comparing the times of maximum intensity.
Reconnection and Alfvén Waves in Jets

Figure 3. Distance-time diagram of Ca intensity across the jet, revealing the oscillation of the jet at amplitude of 5-15 km s\(^{-1}\) and period of 200 s, at five locations (heights). It is found that the oscillation propagates from lower altitude at slit 1 position to higher altitude at slit 2, 3, 4 and 5 positions. Since the jet is considered to be parallel to magnetic field lines, this is the evidence of the Alfvén wave propagating at the velocity 100-200 km s\(^{-1}\).

We also performed a 2-dimensional MHD simulation by extending previous simulations and considered a more realistic initial condition, which allow a comparison with observations (see Nishizuka et al. 2008 for detail). Our simulation shows that both hot and cool jets can be accelerated simultaneously by magnetic reconnection driven by emerging flux, as in Yokoyama and Shibata (1995). Because the time and spatial scales are arranged almost in the same way as in Figure 1b–1e, 1g–1j and 1l–1s, the simulation model turns out to be able to explain observational facts very well. The plasma in the corona is heated to temperature ranging from a few million K to about 10 million K. This hot plasma can be observed as microflares and soft X-ray jets. At the same time, cool jets are accelerated if the reconnection occurs in the transition region or in the upper chromosphere, where cool plasma is situated near the reconnection point. Note that, if reconnection occurs below the lower chromosphere, shocks are formed in front of the jet due to the rapid decrease of plasma density (e.g., Shibata et al. 1982), which may eventually accelerate jets along magnetic field lines. However, in such a case, only cool jets are formed. In our case, it seems that reconnection occurred in the transition region or upper chromosphere.

The delay of the cool jet may not be a cooling effect because the delay time is much smaller than cooling time. Furthermore, our simulation was without a cooling term but could reproduce both hot and cool jets very well. According to the reconnection model, thin and hot plasma can be heated before heating occurs in the cool and dense plasma. This is why a separate hot jet precedes a cool jet (Asymmetric reconnection; Petschek and Thorne 1967).

On the other hand, detailed comparison between simulations and observations suggests that the current sheet structure in Figure 1r may be visible as
one of the legs in the inverted-Y shaped structure. It is interesting to see that EUV and X-ray loops seem to be situated along the same leg, i.e., possibly corresponding to the current sheet (Fig. 1i, 1n).

The only structure that the simulations cannot explain is the existence of the X-ray bright point (probably an unresolved loop) in Fig. 1m–1o. It is noted here that the X-ray brightening at the footpoint is seen in absorption in the EUV lines, not in emission. This may be interpreted as either a three dimensional effect where the EUV emission from the X-ray source is covered by the cool plasma ejection, or as a temperature effect such that the temperature in the X-ray source is too high to emit enough EUV emission (see Fig. 2). (Note that usually the X-ray loop cannot be seen in EUV images.) In fact, the reconnection model predicts the formation of not only jets but also loops that form separately, which can explain many X-ray observations showing that bright points (loops) are situated separately from jets (Shibata et al. 1992, 1994; Yokoyama and Shibata 1995; Shimojo et al. 1996). In our case, such bright loops may be situated just in front of jets because of the three-dimensional projection effect.

3. Evidence of Propagating Alfvén Waves and Its Implication for the Coronal Heating Problem

Figure 3 shows the distance-time diagram of the position of the Ca jet (as represented by Ca intensity distribution), which revealed an oscillation of the jet with amplitude of 5–15 km s$^{-1}$ and period of 200 s. From the oscillation pattern at five different heights, we find that the oscillation propagates along the jet at 100–200 km s$^{-1}$. This velocity is also comparable to that observed for polar X-ray jets (Cirtain et al. 2007). Since the jet is believed to be along the magnetic field, the propagation of the oscillation is evidence of the propagating Alfvén waves (exactly speaking, the kink mode of a fast magnetosonic wave along a dense jet, e.g. see Erdélyi and Fedun 2007). The simulation model also reproduced the generation and propagation of Alfvén waves. Hinode observations revealed the existence of Alfvén waves or Alfvén-like oscillations (Okamoto et al. 2007; De Pontieu et al. 2007), but propagating Alfvén waves have not been observed until now. Hence our observations are the first observational evidence suggesting the presence of propagating Alfvén waves.

The poynting flux carried by the waves can be estimated from the following equation: $F_{Alfven} \sim \frac{1}{4\pi} B_{\perp} B_{\parallel} v_{\perp} \sim \rho v_{\perp}^2 v_{A}$, where $B_{\parallel}$ ($B_{\perp}$) is the magnetic field strength parallel to (perpendicular to) the jet direction, and $v_{\perp}$ is the amplitude of the jet oscillation (transverse velocity). If we assume the pressure balance between the inside and the outside of the jet, we can estimate the jet density $\rho \sim 10^{11} \text{ cm}^{-3}$. Therefore we can estimate the energy flux from figure 3 to be $\sim 4 \times 10^6$ erg s$^{-1}$ cm$^{-2}$, which is sufficient to heat the corona. Also in the case of the kink mode, the energy flux estimated from the observational results does not change, except that the estimated Alfvén velocity and the magnetic field become larger by a factor of $\sqrt{2}$ because the group velocity of kink mode is roughly $v_{A}/\sqrt{2}$. Although the estimated Alfvén velocity becomes smaller if we subtract the jet velocity from the propagating wave velocity, in the case of the kink mode it seems that the Alfvén velocity is comparable to the apparent wave velocity.
Figure 4. Various jets phenomena in quiet region of the Sun; X-ray jets/SXR microflares, EUV jets/EUV microflares, and spicules/photospheric nanoflares. All these jet phenomena may be generated by magnetic reconnection. Note also that the reconnection is a source of large amplitude (high frequency) Alfvén waves (Fig. 3 of Shibata et al. 2007).
Ubiquitous jets and ubiquitous reconnection were discovered in the solar atmosphere with *Hinode* observations as conjectured by Parker (1988), not only in the corona but also in the transition region and the chromosphere (see Fig. 4); for example, as many polar jets, chromospheric jets and penumbral micro-jets. *Hinode* observations also revealed ubiquitous Alfvén waves, which may be generated by magnetic reconnection. Such a process has been reproduced by MHD simulations. Furthermore, lots of ubiquitous horizontal fields were discovered in the photosphere with high spatial and steady observations of *Hinode* (Lites et al. 2007; Ishikawa et al. 2008). They may suggest ubiquitous reconnection in the photosphere/low chromosphere and resulting generation of ubiquitous Alfvén waves. It is likely that the chromosphere and corona are heated by Alfvén waves (and slow mode shocks) generated by reconnection in the photosphere and low chromosphere (Kudoh and Shibata 1999; Moriyasu et al. 2004; Antolin et al. 2008), contributing to the heating and acceleration of solar wind when the magnetic field is open (Parker 1988; Suzuki and Inutsuka 2005). These discoveries may suggest a unified model of Alfvén wave-nanoflare mechanisms.

Acknowledgments. We wish to thank B. Lites and A. Hillier for their careful reading and correction of this paper. *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). The numerical computation was performed on Fujitsu VPP5000 at NAOJ.

References

Bray, R. J. and Loughhead, R. E. 1974, The Solar Choromosphere (The international astrophysics series; London Chapman and Hall)
Cirtain, J. W. et al. 2007, Science, 318, 1580
De Pontieu et al. 2007, Science, 318, 1574
Katsukawa, Y. et al. 2007, Science, 318, 1594
Okamoto, T. J. et al. 2007, Science, 318, 1577
Shibata, K. et al. 2007, Science, 318, 1591