GIANT CHROMOSPHERIC ANEMONE JET OBSERVED WITH HINODE AND COMPARISON WITH MAGNETOHYDRODYNAMIC SIMULATIONS: EVIDENCE OF PROPAGATING ALFVEN WAVES AND MAGNETIC RECONNECTION

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1. INTRODUCTION

The solar chromosphere has been known to be very dynamic (e.g., Bray & 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; Curtain et al. 2007) (see also special issue, Initial Results from Hinode, 2007, PASJ, Vol. 59, No. SP3). It has long been observed that Hz jets called surges often occur in the chromosphere (see, e.g., Rust 1968; Kurokawa & Kawai 1993). Surges are believed to be produced by magnetic reconnection (Heyvaerts et al. 1977; Yokoyama & Shibata 1995, 1996; Isobe et al. 2005), which is an energy conversion mechanism from magnetic energy into thermal and kinetic energies of plasma when two antiparallel magnetic fields encounter and reconnect with each other. New chromospheric observations with the calcium ii H-line broadband filter of the Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board Hinode revealed that jets are ubiquitous in the chromosphere and some of the jets show evidence of magnetic reconnection (Shibata et al. 2007; Katsukawa et al. 2007).

There have been several multiwavelength observations of jets (e.g., X-ray and Hz [Schmieder et al. 1995; Canfield et al. 1996], Hz and EUV [Chae et al. 1999; Jiang et al. 2007], and EUV and X-ray [Alexander & Fletcher 1999]). These have shown that hot jets (X-ray or EUV jets) and cool jets (Hz surge or dark EUV jet) are almost cospatial and cotemporal, and that they are dynamically connected to each other. Yokoyama & Shibata (1995, 1996) explained such a relation between hot and cool jets qualitatively by performing a resistive MHD simulation of an emerging flux model. However, their model was not fully realistic because of various computational difficulties; it was not possible to reproduce both emerging flux and jets self-consistently in one model, so they assumed an unrealistic initial temperature (∼2.5 × 10⁴ K) and density (10¹⁵ cm⁻³ corona) for the corona. Because of this, the coronal Alfven speed in their model was lower than the actual value, so the jet velocity was also lower than the observed velocity of the Hz surge/jet. In this Letter, we succeed in modeling for the first time both the emerging flux and jet self-consistently with realistic coronal temperatures (∼10⁶ K) and densities and attempt to compare simulation results and observations quantitatively.

2. THE 2007 FEBRUARY 9 GIANT Ca JET EVENT

The solar jet studied here occurred on the west limb of the Sun around NOAA active region 10940 on 2007 February 9 at 13:20 UT, which was associated with a weak soft X-ray brightening observed in GOES. The maximum height of the jet was ∼1,400 km and its width ∼600 km. Figures la–lc show Ca ii H-line broadband filter snapshot images taken with SOT on board Hinode, which provide a high spatial resolution (0.2″ or 150 km on the solar surface) and stable observation of the photosphere and chromosphere. The cold plasma jet, which we call the Ca jet, began to be ejected upward with an inclination angle of 45° at 13:18 UT. The jet grew up to a cuspo- or inverted-Y-shaped structure, whose morphology was similar to that of coronal anemone jets (Shibata et al. 1994). The maximum upward velocity occurred 10 minutes later at 13:30 UT (also see Fig. 2a). The jet was accelerated to ∼100 km s⁻¹ along the field line. The cool plasma subsequently fell down with a decelerated free-fall motion.

Yohkoh observations have 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 & Shibata 1995, 1996; Isobe et al. 2005). By extending previous simulations the new simulations consider...
Fig. 1.—Comparison between the Ca jet and simulated jets based on the reconnection model. (a–c) Ca II H broadband filter images of the Ca jet on 2007 February 9, taken with Hinode SOT. (d–f) Two-dimensional distributions of density (log$_{10}$n$_p$; color map) in units of $10^{-7}$ g cm$^{-3}$ in the simulated jets, whose times correspond to those of the observed jets in the top panels. The length is in units of 200 km and the times are in units of 20 s. (g–i) Two-dimensional distribution in density (log$_{10}$n$_p$; color map) in units of $10^{-7}$ g cm$^{-3}$ and temperature (log$_{10}$T; color map) in units of 10$^6$ K of magnetic fields (B; lines) and velocity vectors (v; arrows) in the simulated jets.

a more realistic initial condition, which allow a comparison with observations. Our initial condition of the simulations is basically similar to that of Yokoyama & Shibata (1995), with the only difference being in coronal temperature and density; they were assumed to be 2.5 × 10$^6$ K and 10$^{12}$ cm$^{-3}$ in the Yokoyama-Shibata model, but 10$^6$ K and 10$^{10}$ cm$^{-3}$ in our model. Note that our coronal parameters are much more realistic than theirs.

As a result of our new two-dimensional MHD simulation, we found that a simulated jet is amazingly similar to the observed jet. The comparison among them is shown in Figure 1 (panels d–f are simulation results). These simulations are performed by solving the two-dimensional resistive MHD equations with uniform gravitational field and without thermal conduction and radiative cooling effects. We note that a jet is magnetically driven, not gas pressure driven, so the dynamics of the jet cannot be influenced by thermal conduction and radiative cooling effects even if the temperature is not fully realistic. We also note that evaporation effects due to thermal conduction and radiative cooling are not included in our model, so the evaporation-driven X-ray jets (Shimojo et al. 2001; Miyagoshi & Yokoyama 2004) cannot be modeled in the Letter. As an initial state, we set the hydrostatic plasma in the inner corona and a uniform oblique magnetic field outside the flux sheet in the whole region. This flux sheet is unstable for the magnetic buoyancy instability (the Parker instability; Shibata et al. 1989; Matsumoto et al. 1993), so the perturbed flux sheet is excited and emerges into the
corona. While we performed a two-dimensional simulation, the emerging process of magnetic flux would actually become much more complex in three dimensions (see, e.g., Fan et al. 2003; Isobe et al. 2005). In two dimensions, once reconnection occurs between the emerging flux and preexisting field, the field lines with a polarity opposite to that of the ambient field become connected to the ambient polarity regions, forming an inverted-Y shape or anemone jet. Because the time and spatial scales are arranged almost in the same way as in Figures 1a–1c, the simulation model turns out to be able to explain observational facts very well. Reconnection creates multiple islands which confine cool, dense, chromospheric plasma in the current sheet, which are ejected at the Alfven speed $v_a \sim 10^5$ km s$^{-1}$ ($B/20$ G)$^{1/2} \sim 50–150$ km s$^{-1}$ if we assume coronal field $B \sim 20$ G and density $n \sim 10^{11}–10^{12}$ cm$^{-3}$ in the upper chromosphere, in agreement with the observations (shown in Fig. 2a). These facts support a magnetic reconnection model. Note that if reconnection occurs below the lower chromosphere, shocks are formed in front of a jet due to rapid decrease of plasma density (e.g., Shibata et al. 1982; Tarbell et al. 1999), 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, because not only cool jets but also hot jets are observed simultaneously (see § 3).

Figure 2b shows the distance-time diagram of the position of the Ca jet (as represented by Ca intensity distribution), which revealed the oscillation of the jet with amplitude of 5–15 km s$^{-1}$ and period of 200 s. From the oscillation pattern at three different heights, we find that the oscillation propagates along the jet at 100–200 km s$^{-1}$. Since the jet is believed to be along the magnetic field, the propagation of the oscillation is the evidence of the propagating Alfven waves. The simulation model reproduced also the generation and propagation of Alfven waves (see plus symbols in Fig. 2b). Hinode observations revealed the existence of Alfven waves or Alfven-like oscillation (Okamoto et al. 2007; De Pontieu et al. 2007), but propagating Alfven waves have not been observed until now. Hence our observations are the first observational evidence suggesting the presence of propagating Alfven waves.

3. COMPARISON BETWEEN HOT/COOL COMPONENTS OF THE JET AND MHD SIMULATION

Our simulation shows that both hot and cool jets can be accelerated simultaneously by magnetic reconnection driven by emerging flux, as in Yokoyama & Shibata (1995). The plasma in the corona is heated to temperatures 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. According to the model, X-ray or EUV jets are seen as hot jets that are accelerated by the magnetic tension force of the reconnected field lines, and Hα surges or Ca jets are seen as cool jets that are accelerated by the slingshot effect due to the reconnection, which produces a whiplike motion. Furthermore, if a large amount of energy is injected into the upper chromosphere, the cold plasma above the energy injection point is heated up and evolves into evaporation (Shimojo et al. 2001), although we cannot reproduce it because of the lack of thermal conduction in the energy equation. Such a coexistence of hot and cool jets is indeed confirmed by observations with the comparisons between associated X-ray or EUV jets and Hα surges (Schmieder et al. 1995; Canfield et al. 1996; Chae et al. 1999; Alexander & Fletcher 1999; Ko et al. 2005; Jiang et al. 2007).

Figures 3a–3o show the time evolution images of the jet with multiwavelength observations taken with the SOT and X-Ray Telescope (XRT; Golub et al. 2007) aboard Hinode, and the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) 195 Å filter. An X-ray image before ejection shows a loop structure over the limb, at the footpoint of which a jetlike feature appeared at 13:09 UT, preceding other wavelengths. X-ray emission gradually increased its intensity and, just after 13:16 UT, an X-ray jet started to be ejected, and a cusp- or inverted-Y-shaped structure was formed. An EUV jet was ejected from a looplike bright emission patch at the moment when the patch reached its maximum intensity. The cold plasma ejection, such as the Ca jet and a dark EUV jet in absorption ($\sim10^4$ K), was delayed by 1–2 minutes relative to the X-ray and EUV brightening. The maximum upward velocity of the cool jets occurred about 10 minutes later than the X-ray spike (also see Fig. 2a). As a result of spatial co-alignment, the EUV jet was identified.
with the X-ray jet, whereas the dark EUV jet appeared to be a counterpart to the Ca jet. The X-ray jet and the Ca jet were ejected side by side with each other, which is the same feature as shown in the simulation results of Figure 1l. These observational facts indicate the following three features: (1) The X-ray jet \( (5 \times 10^4 \, \text{K}) \) and the EUV jet \( (\sim 10^6 \, \text{K}) \) are likely to have the same physical origin, and the Ca jet \( (10^4 \, \text{K}) \) and the dark EUV jets (unknown temperature, \( \sim 10^6 \, \text{K} \)) also have the same origin. (2) The X-ray and the Ca jets are different kinds of plasma ejection, implying dynamically connected hot and cool plasma ejections along different field lines. (3) The X-ray jet precedes the Ca jet by 1–2 minutes compared with their maximum intensity time, and some hot structure was also observed with X-ray emission 10 minutes earlier than jet ejection.

We note that the delay of the cool jet may not be due to a cooling effect, because the delay time is much shorter than the cooling time. Furthermore, our simulation without a cooling term reproduces both hot and cool jet very well. According to the simulation, the current sheet is formed between the corona (hot and thin plasma) and the emerging flux with chromospheric density and temperature (cool and dense plasma). Hence the reconnection is very asymmetric (Petschek & Thorne 1967).

In such a case, the low-density part becomes a hot and fast jet, whereas the high-density part forms a cool and slow jet, because the local Alfven speed is high (low) in the low (high) density part. This is why a hot jet preceded a cool jet; i.e., the hot jet reaches higher altitude earlier than the cool jet.

4. SUMMARY AND DISCUSSION

MHD simulation results (Figs. 1d–1l) reproduce remarkably well the dynamics and structure of cool and hot jets and their relative timings. The only structure that the simulations cannot explain is the existence of an X-ray bright point (probably an unresolved loop) in Figures 3m–3o. However, MHD simulations in Figure 1 are two-dimensional, and hence discrepancy between observations and simulations may be explained by three-dimensional effects. In fact, the reconnection model (Yokoyama & Shibata 1995, 1996; Shibata et al. 1992, 1994; Shimojo et al. 1996) predicts the formation of not only jets but also loops in a separated place, which can explain many X-ray observations showing that bright points (loops) are situated separately from jets (Shibata et al. 1992, 1994; Shimojo et al. 1996). In our case, such bright loops may be situated just in front of jets because of three-dimensional projection effects.

On the other hand, detailed comparison between simulations and observations suggests that the current sheet structure in Figure 1e may be visible as one of 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.

We note here that an X-ray brightening at the footpoint cannot be seen in EUV emission but in absorption. This may be interpreted as either the three-dimensional effect that the EUV emission from the X-ray source is covered by cool plasma ejection or the temperature effect such that the temperature in the X-ray source is too high to emit enough EUV emission. (Note that usually X-ray loops cannot be seen in EUV images.)

We also note that both observations and simulations show the generation of Alfven waves when magnetic reconnection occurs: the jet undergoes apparent motion perpendicular to the jet direction at amplitudes of \( 5–15 \, \text{km s}^{-1} \) (see Fig. 2b). This velocity is also comparable to that observed for polar X-ray jets (Cirtain et al. 2007). These Alfven waves are generated by reconnection (Yokoyama 1998; Takeuchi & Shibata 2001), and may contribute to the heating and acceleration of solar wind when the magnetic field is open (Parker 1988; Suzuki & Inutsuka 2005).

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