Velocity Structure of Jets in Coronal Hole

Suguru Kamio, Hirohisa Hara, Tetsuya Watanabe
Hinode Science Center, Solar Physics Division, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka
suguru.kamio@nao.ac.jp

Keiichi Matsuzaki
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara,

Kazunari Shibata
Kwasan and Hida Observatories, Graduate School of Science, Kyoto University, Yamashina, Kyoto, 607-8471 Japan

Len Culhane
Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury

Harry Warren
Solar Terrestrial Relationships Branch, Naval Research Laboratory, 4555 Overlook Avenue, SW Washington, DC 20375

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Abstract

Velocity structures of jets in a coronal hole have been derived for the first time. Hinode observations revealed the existence of many bright points in coronal holes. They are loop-shaped and sometimes associated with coronal jets. Spectra obtained with the Extreme ultraviolet Imaging Spectrometer (EIS) on board Hinode are analyzed to infer Doppler velocity of bright loops and jets in a coronal hole of the north polar region. Elongated jets above bright loops are found to be blue-shifted by 30 km s$^{-1}$ at maximum, while foot points of bright loops are red-shifted. Blue-shifts detected in coronal jets are interpreted as upflows produced by magnetic reconnection between emerging flux and the ambient field in the coronal hole.

Key words: Sun: corona – Sun: atmospheric motions – Sun: UV radiation

1. Introduction

Coronal holes are dark regions of the corona seen in soft X-ray or coronal spectral lines. In a coronal hole, there is open magnetic field where solar wind is flowing out, while bright corona of the surrounding area is composed of closed field. It is obvious that magnetic field plays an important role in forming varying structure of corona, but the mechanism responsible for energy and mass supply to the corona remains a mystery. Study of the dynamics in coronal holes is, therefore, crucial for understanding coronal heating and the acceleration of the solar
wind.

Shimojo et al. (1996) and Shimojo & Shibata (2000) derived physical parameters of X-ray jets using the soft X-ray telescope (Tsuneta et al. 1991) on board Yohkoh spacecraft (Ogawara et al. 1991). They claimed that the observed properties of X-ray jets were consistent with the theory, in which jets were produced by evaporation flows due to reconnection heating.

Moses et al. (1997) studied coronal jets in a sequence of 195Å images obtained with EIT on SOHO. They found apparent rising velocity of the jets is 100 – 400 km s$^{-1}$.

But the measurement of Doppler velocity of coronal jets is needed to firmly establish the model, because their analysis is based on the apparent motion of the jets which may differ from the actual plasma motion.

Wang et al. (1998) identified white-light jets in 2 – 6 R$\odot$ range of LASCO images, which corresponds to EUV jets observed with EIT. They were rooted in bright points. The leading edge of white-light jets propagated with speeds of 400 – 1000 km s$^{-1}$.

Coronal plume is a stationary structure extending from coronal holes observed in the EUV and coronagraphs in visible light. Deforest et al. (1997) traced plume structures from the surface to 15 R$\odot$ by combining EIT and coronagraph data. While coronal jets are transient phenomena, plume structures are stable, at least for 24 hours. The study of temporal variation is important to distinguish jets and plumes.

The Extreme ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007) on board Hinode (Kosugi 2007) is capable of obtaining EUV spectra with high resolution and high efficiency. It is designed to derive properties of the solar corona, such as temperature, line-of-sight velocity, and density, through spectroscopic observation. Although features in coronal hole are dark in coronal spectral lines, the high throughput of the EIS allows us to determine Doppler shifts in coronal holes. In the present work, we studied the velocity structure of bright points in a coronal hole in the north polar region. The EIS observations are described in §2. The data reduction procedure and the method of data analysis are shown in §3. Results are presented in §4 and their interpretation is discussed in §5.

2. Observation

A coronal hole in the north polar region was observed by Hinode on 9 January 2007. Figure 1 shows an X-ray image obtained with the X-Ray Telescope (XRT; Golub 2007). Many bright points are found even in a coronal hole. They are loop-shaped and X-ray jets are occasionally formed from bright points.

One raster scan was performed with the EIS from 16:10 – 18:24 UT. The EIS field of view is overlaid on Fig. 1. EIS has two spectral ranges, 170–210Å and 250–290Å, and the spectral windows of Fe X 184Å, Fe VIII 185, Fe XI 188Å, Ca XVII 192Å, Fe XII 195Å, Fe XIII 202Å, He II 256Å, Fe XIV 274Å, and Fe XV 284Å were selected and recorded. The slit of 1” width was selected to determine the Doppler shift of spectral lines. The raster swept a
Fig. 1. X-ray jets in the polar coronal hole observed with XRT. The overlaying box indicates the EIS field of view. The bottom of the EIS field of view is outside that of XRT.

256'' × 256'' area with a 30 sec exposure at each slit position. Since this observation was aimed at studying spatial distribution of coronal hole in a large area, the temporal evolution of coronal features is not analyzed in the present paper.

Figure 2 presents intensity maps in selected lines. The field of view covered a part of the coronal hole and surrounding quiet region in the north polar region. In the Fig. 2, the coronal hole boundary is located at about $Y = 850''$. In this data set, the corona above the limb was also observed near the upper end of the field. In prominent Fe XII 195Å line ($\log T_e = 6.1$), data numbers sufficient for spectrum fitting were obtained in the dark coronal hole, which allowed us to study the Doppler velocity structure over the entire field. XRT obtained a sequence of images at the same time, showing the apparent motion of jets elongating from bright points in the coronal hole.

3. Data Reduction

Basic reduction of the EIS data was carried out by standard procedures provided in Solar Software (SSW). The EIS data consist of series of EUV spectra at each slit position in the raster scan. Dark current subtraction and flat field correction were applied to the raw data. Spikes caused by cosmic-rays and hot pixels were marked as invalid data and ignored in the following process.

Single Gaussian component fitting was performed with calibrated spectra to determine the center position, amplitude, and width of the spectral lines. If the data count was not enough to perform spectral fitting, the pixel was treated as no signal. Because no distinct case of a two
Fig. 2. Intensity maps in selected lines from the EIS data set. The coronal hole boundary is around $Y = 850$, and upper regions correspond to part of the coronal hole in Fe XII 195Å ($\log T_e = 6.1$) and Fe X 184Å ($\log T_e = 6.0$). The coronal hole is not noticeable in Fe VIII 185Å or He II 256Å. The north limb and the corona above the limb are found near the upper end of the field.
component spectral line was found in this data, single component fitting gives reliable results.

In order to derive Doppler shift of the spectrum, a wavelength reference must be defined as the EIS does not have an absolute wavelength reference. Line center positions determined from spectral fitting indicate cyclic modulation, since the EIS instrument experiences temperature variation in sync with the spacecraft orbit. It leads to an orbital variation of the line center position ranging to 70 km s\(^{-1}\) in Doppler velocity in peak-to-peak.

Since this data set covers long range in the slit direction (256” height), local coronal structures are smoothed out by averaging the line center positions along the slit. The orbital variation of the spectrum position can be computed over the raster and subtracted from the line shift to determine true Doppler shift. The result is the velocity with respect to the average over the field. Angle of slit tilt, which results in artificial wavelength shift of the spectrum, is determined by using quiet region observation at disk center at 16:02 UT and 21:43UT, before and after this coronal hole observation. The slit tilt is removed in the Doppler velocity measurement.

The mean velocity is not zero in coronal temperature lines. Sandlin et al. (1977) determined a net blueshift of 6 km s\(^{-1}\) in Fe XII from the Sun. Peter & Judge (1999) found a temperature dependence of Doppler shifts which is consistent with the result from Sandlin et al. (1977). Assuming that non-radial velocities are canceled in the corona, the Doppler shift outside the limb must be zero. In the present work, the off-limb area excluding jets is regarded as the velocity reference. This method may introduce ambiguity in the velocity, but the error must be smaller than the net blueshift of 6 km s\(^{-1}\) found by Sandlin et al. (1977).

The Doppler velocity is only derived for Fe XII line, which has a large data count to perform spectrum fitting for the most of the field. In other spectral lines, spectrum fitting can be done for a limited portion of the data and it is hard to define a reference position in spectra.

4. Results

Figure 2 shows intensity maps in He I, Fe VIII, Fe X, and Fe XII. In the Fe XII panel showing coronal plasma (log \(T_e\) = 6.1), several bright points are found within the dark coronal hole. Some of them show loop-shaped structure with faint threads stretching above the loop. Similar features are found in Fe X, it is degraded because of the low data count. At dark pixels, spectrum fitting was not performed because of low signal to noise ratio. Fe VIII represents lower temperature plasma (log \(T_e\) = 5.6), and the boundary of the coronal hole is not obvious. Comparison with Fe XII indicates that the foot points of bright loops in Fe XII are bright in Fe VIII, implying lower temperature in the foot points. As the Fe VIII mainly represent transition region features, it outlines the lower end of the corona and is seen as a bright layer above the limb. He II shows the lowest temperature available for EIS (log \(T_e\) = 4.7). There are bright features associated with the coronal bright points, but they may be contaminated by a Si X line blended in the red wing of He II spectrum.
**Fig. 3.** Running difference of XRT data obtained at 17:23 UT and 17:35 UT. White indicates intensity increase in the X-ray. The FOV is the same as in Fig. 2.

**Fig. 4.** Doppler velocity inferred from Fe XII spectra. Color scale represents the velocity from -35 km s\(^{-1}\) to +35 km s\(^{-1}\). Positive and negative velocities correspond to red and blue shifts, respectively. Cross and asterisk symbols indicate the location of spectra in Fig. 6.

Figure 3 shows running difference of XRT data indicating an outward propagating jet (X = -180). A sequence of XRT data allow us to find the temporal change of the jet and to distinguish it from stationary plumes. The EIS slit scanned the jet at about 17:40 UT when the jet was growing in XRT.
Doppler velocity derived from Fe XII line is shown in Fig. 4. Comparing with the intensity map in Fig. 2, bright points in coronal hole have noticeable Doppler shifts. In this data, loop foot points of bright loops are red-shifted by 15 km s$^{-1}$. This is larger than the velocity ambiguity of 6 km s$^{-1}$, hence it is real red-shift suggesting downflow in the loop.

The magnitude of red-shift decreases from the bottom of the loop to the top. The velocity becomes zero at the asterisk symbol in Fig. 4. A blue-shifted feature is stretching above the bright point. The maximum velocity of -30 km s$^{-1}$ is attained at the cross symbol in Fig. 4, where a faint thread extends upward in Fig. 2.

There are other bright points showing similar structure, but their Doppler amplitude are smaller. It is interesting to note that the direction of these blue-shifted feature above the bright points are close to the radial direction, taking heliocentric coordinates into account. There are bright points outside the coronal hole, but their velocities are much smaller and no stretching feature is found.

Figure 5 presents the full width at half maximum in Fe XII. Since the instrument width is not compensated, it shows the distribution of relative line width. A significant line broadening is detected in the elongated feature above the bright point. The maximum line width enhancement is about 30 km s$^{-1}$ there. No significant change in line width is found outside the coronal hole.

Raw spectra of Fe XII are presented in Fig. 6. The solid line shows the spectrum at the asterisk symbol in Fig. 4, where no significant line width enhancement is found. The dotted line spectrum obtained at cross symbol in Fig. 4 indicates enhancement in the blue wing. It is clear that the line broadening in Fig. 5 is due to the enhancement in the blue wing.
Fig. 6. Solid and dotted lines present Fe XII spectra at asterisk and cross symbols in Fig. 4.

Fig. 7. The same as Fig. 6 but for He II spectra at the same positions.
Figure 7 shows He II spectra. Although the red wing of the spectra may be contaminated by Si X, enhancement in the blue wing is attributed to He II. Broadenings in Fe XII and He II suggest an explosive nature of the jet.

5. Discussion

The intensity maps from EIS clearly show that bright points in the coronal hole have loop structures at coronal temperature. Some of them are accompanied by faint elongated features stretching higher up into the corona. Doppler velocity measurement revealed blue-shifted features above bright points. Assuming that these features are expanding radially, they imply an uplifting plasma above the bright point. Comparison with XRT images (Figs. 1 and 3) indicates that these features are co-spatial with X-ray jets. Shimojo et al. (1996) and Shimojo & Shibata (2000) determined physical parameters of X-ray jets from Yohkoh SXT observations. Their statistical study shows that the apparent velocities of X-ray jets are $10 - 10^3$ km s$^{-1}$ with an average of 200 km s$^{-1}$. Taking the projection effect into account, the measured velocity of 30 km s$^{-1}$ in line-of-sight direction suggests that the actual velocity of the jets could be one-order of magnitude larger, which would fit into the range of apparent velocities.

The present observation shows that the bright points in the coronal hole are red-shifted in their the foot points. The amount of red-shift decreases and crosses zero-velocity near the top of bright loop. Blue-shifted feature above the bright point can be interpreted as jet, since it is transient (Fig. 3). Spectra broadenings also indicate explosive nature of the jet. (Figs. 6 and 7). Wilhelm et al. (2002) analyzed ultraviolet spectrum of jets and found that the outer wings reached +230 km s$^{-1}$ – -230 km s$^{-1}$ in Ne VIII ($\log T_e = 5.8$) and +210 km s$^{-1}$ – -280 km s$^{-1}$ in C IV ($\log T_e = 5.0$). In the present paper, enhancements in the blue wings of Fe XII and He II are found. They are interpreted as upward motion of the jet in the corona ($\log T_e = 6.1$) and transition region ($\log T_e = 4.7$).

Shibata et al. (1992) suggested a model of X-ray jet formation, in which emerging flux collides and reconnects with pre-existing field. According to his model, a bright loop is formed by reconnected field near the foot point of the jets. The observed loop structures (Fig. 1 and 2) are thought to be the reconnected fields. In addition, upward motion is expected along the ambient field line. Shimojo et al. (2001) simulated the evolution of X-ray jets and suggested that they are evaporation flow produced by magnetic reconnection taking place near the foot points of the loop. The strong blue-shift determined in Fig. 4 is interpreted as line-of-sight component of upward motion of the jet. But the foot points are red-shifted by about 15 km s$^{-1}$, which exceeds the velocity ambiguity of 6 km s$^{-1}$. If they are not red-shifted, then average velocity of quiet region outside coronal hole (region of $Y < 850$” in Fig. 4) must be blue-shifted by 20 km s$^{-1}$ or greater, which is not realistic. The observed red-shifts are not consistent with chromospheric evaporation, since evaporation flow is expected to be an upflow at the coronal temperature of Fe XII. The red-shifts can be reconnected loops moving downward from the
reconnection point, but present observation indicates that all foot points of bright points in coronal hole are red-shifted. A more detailed model is needed to explain the observation.

On the other hand, the bright features in the quiet region outside the coronal hole do not show significant velocity variation. The difference in velocity structure reflects the different field connectivities inside and outside the coronal hole. There are ambient open fields in the coronal hole, which can reconnect with emerging flux to form jets stretching high to the corona, but outside fields are closed and elongated jets are rarely formed.

6. Summary and Conclusions

We studied the properties of jets in a coronal hole by using a raster scan of EIS on board Hinode. The high resolution and sensitivity of EIS allowed us to study the Doppler velocity of coronal jets. Our observation showed that bright points in coronal holes are loop-shaped at coronal temperatures, and have bright foot points at transition region temperatures.

Determination of Doppler shifts in Fe XII line revealed that jets extending from bright points are blue-shifted by $30 \text{ km s}^{-1}$ at maximum. Taking the projection effect into account, the observed velocity is consistent with that of jets expected from chromospheric evaporation flow caused by magnetic reconnection. Bright loops at coronal temperature are explained as loops formed after reconnection between emerging flux and ambient fields in the coronal hole. But observed red-shifts near the foot points of loops are not fully understood in the model.

Collaboration of all three telescopes on board Hinode is important for studying the connection between the photosphere and the corona. XRT is capable of obtaining a sequence of X-ray images with high cadence, which is suitable for studying the temporal variation of the coronal bright points. The spectro-polarimeter of solar optical Telescope (SOT) obtains very high resolution transverse and longitudinal magnetic fields in the photosphere which are needed for a better understanding of the formation of bright points and jets in the corona.

Hinode is a Japanese mission developed and launched by ISAS/JAXA, collaborating with NAOJ as domestic partner, NASA and STFC (UK) as international partners. Scientific operation of the Hinode mission is conducted by the Hinode science team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the post-launch operation is provided by JAXA and NAOJ (Japan), STFC (U.K.), NASA (U.S.A.), ESA, and NSC (Norway).

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