Does a polar coronal hole's flux emergence follow a Hale-like law?

A. Savcheva[1], J.W. Cirtain[2], E.E. DeLuca[1], L. Golub[1]

asavcheva@cfa.harvard.edu

ABSTRACT

Recent increases in spatial and temporal resolution for solar telescopes sensitive to EUV and X-ray radiation have revealed the prevalence of transient jet events in polar coronal holes. Using data collected by the X-Ray Telescope on *Hinode*, Savcheva et al. (2007) confirmed the observation, made first by the Soft X-ray Telescope on *Yohkoh*, that some jets exhibit a motion transverse to the jet outflow direction. The velocity of this transverse motion is, on average, 20 $\mathrm{km\,s^{-1}}$. The direction of the transverse motion, in combination with the standard reconnection model for jet production (e.g. Shibata et al. 1992), reflects the magnetic polarity orientation of the ephemeral active region at the base of the jet. From this signature, we find that during the present minimum phase of the solar cycle the jet-base ephemeral active regions in the polar coronal holes had a preferred east-west direction, and that this direction reversed during the cycle's progression through minimum. In late 2006 and early 2007, the preferred direction was that of the active regions of the coming sunspot cycle (Cycle 24), but in late 2008 and early 2009 the preferred direction has been that of the active regions of sunspot cycle 25. These findings are consistent with the results of Wilson et al. (1988) that there is a high latitude expansion of the solar activity cycle.

Subject headings: Sun: corona, Sun: UV radiation, Sun: x-ray jets, Sun: polar coronal hole, Sun: flux emergance

1. Introduction

Recent *Hinode* observations confirmed, in general, the Shibata et al. (1992) topological construct for the evolution of the magnetic field during the formation of a jet. In this

[1]Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Mail Stop 58, Cambridge, MA, 02138

[2]Marshall Space Flight Center NASA,Mail Code: VP62, Marshall Space Flight Center, Al, 35812

model, a small magnetic bipole emerges into a nearly uniform magnetic field, such as the one found in coronal holes. As the magnetic flux of the emerged region pushes against the pre-existing "background" field, a magnetic null is formed and eventually a current sheet through which magnetic field is free to travel and "reconnect". This process, at least in terms of appearances, is now readily observed by the X-Ray Telescope (XRT; Golub et al. 2007) on *Hinode*. These reconnection events are typically associated with small X-ray brightenings and occasionally are large enough to register as an "A" or "B" class flare.

Moreno-Insertis et al. (2008) built a 3D MHD model for the formation of an anemone jet by an emerging twisted flux tube in ambient open field. This model is a generalization of the 2D model by Shibata et al. (1992) to full 3D. A current sheet is formed above the buoyant flux tube in the corona and reconnection takes place across it producing the jet and separating the vault underneath the X-point into two parts, in one of which the reconnection bipole forms. In cross-section their model looks exactly like the Shibata model. Moreover, this model seems to reproduce many of the jet statistical properties reported in Savcheva et al. (2007), such as jet upward and transverse velocities and lifetimes.

Another 3D MHD model of the formation of a jet was presented by Pariat et al. (2009) where the basic driver for the jet is the twisting of the footpoints of the coronal loops. A basic assumption of the model is that the magnetic configuration is axisymmetric, which maintains the stability for enough time for magnetic energy to build up. Quasi-ideal MHD instability finally causes this energy to be released. This model has been invoked to explain helical jets in STEREO data (Patsourakos et al. 2008). However, the model predicts jet outward velocities of the order of the Alfven speed. XRT observations have shown that only a small fraction of the jets move at such speeds (Cirtain et al. 2007).

X-ray jets were often observed by the Soft-X-ray Telescope (SXT) of *Yohkoh* (Tsuneta et al. 1991). Numerous articles have reported on the physical properties of these events (Shibata, Yokoyama, & Shimojo 1994; Aurass, Klein, & Martens 1994; Shimojo et al. 1996; Shimojo, Shibata, & Harvey 1998). These articles all agree that X-ray jets have certain general properties: (1) The length of the jet is much larger than the width; (2) the jet is highly collimated in the direction of eruptive outflow; (3) the average observed outflow velocity is ≈ 200 km s^{-1}. These articles and numerous others report the characteristics of jets formed in coronal holes, quiet sun and within and near active regions. In the current work, we limit the discussion to jets formed within polar coronal holes.

The XRT began regular observations in mid-November 2006. The first observations of the north polar coronal hole were carried out on 23 November 2006 from 12-18 UT. This initial dataset consisted of 1024x256 arcsec Aluminum on polyimide filter images with a cadence of 30 seconds. Cirtain et al. (2007) used data from this and other early polar coronal hole observations to reach several conclusions. One of the more important findings was the observation that jets occur at a rate of at least 7 per hour, many times larger than previously reported. Using simple estimates of the mass-loading to the fast solar wind, Cirtain et al. (2007) estimated that jets could contribute $\approx$ 20% of the mass of the fast component of the solar wind. Savcheva et al. (2007) extended many of these efforts by providing the first statistical study of XRT jets, using XRT data to determine several additional parameters for polar coronal hole jet events. Many jets are also observed to have a "whip-like" motion perpendicular to the direction of elongation with an average velocity of 20 $\mathrm{km\,s^{-1}}$and these jets are observed to occur throughout the polar coronal hole with no apparent preference for latitude or proximity to the coronal hole boundary.

Tsuneta et al. (2008b) used the Solar Optical Telescope of *Hinode* (SOT; Tsuneta et al. 2008a) to map the solar polar coronal hole vector magnetic field. On these maps it is apparent that the magnetic bipoles line up along the East-West direction. This is consistent with the observation we introduce in this paper that a majority of bipoles are oriented east-west in polar coronal holes. As a consequence of this orientation of the underlying bipoles, jet transverse motions are also observed to be oriented E-W (see Section 2).

2. Data and Analysis

To study the jet transverse motions we used datasets from November 2006, January and March 2007, September and October 2008, and January 2009. The images were taken in the Aluminum and Titanium polyamide filters with field of view 1024x256 arcsec, 1024x512 arcsec, and 384x384 arcsec, with cadence 25s, 30s and 1min respectively. The 1 arcsec resolution and the high cadence of the observations allowed a determination of the jet transverse motions with accuracy 1%-15% depending on the event. In Table 1 we have collected the relevant information for the observations, such as field of view, filter, cadence, etc. In Fig. 1 we have also sketched a timeline of the observations showing how many hours were spent observing the South and North poles during the different months.

Based on a careful inspection of each jet in the dataset we determined that about 14% of XRT jets show signs of twisting. This is consistent with the report that about 10% of *Yohkoh* SXT jets were helical (Shimojo et al. 1996). We exclude the helical jets from the sample of jets with reliably determined transverse velocities. Based on these small percentages we conclude that the Moreno-Insertis et al. (2008) model, and in particular the Shibata construct can be used to explain the majority of the XRT jets. In both of these models the production of transverse motion of the jets plays an important role.

The process of reducing the data and determining the transverse velocities is as follows: initially all the data were cleaned of cosmic ray hits and then the xrt_prep routine from SSW was used to remove various sources of noise. The jet events were identified by eye from animated sequences of images following the criteria that the elongation of the jet is much bigger than the width, the jet is collimated and the duration is a few minutes. Separate events were selected spatially and temporally and the frames were rotated so that the jet elongation is vertical and hence the transverse motion is horizontal. A box containing the jet was selected and the image was Gaussian smoothed with σ=3 pixels. The Laplacian of the image was taken and added to the smoothed image to enhance the jet. Finally, contours of equal brightness were plotted on the image and a smooth contour with well defined peak was selected to represent the position of the jet. From the motion of the peak and several points around the peak of the contour we determined the transverse velocity. We also checked that the results are insensitive to the choice of a contour outlining the jet. Some ephemeral regions produce sequential jets and exhibit motion both in the west and the east direction; we determine the direction and transverse velocity for each jet individually.

3. Results and Discussion

We determined the transverse velocities for 97 non-twisting jets out of a total of 157 jets in the South polar coronal hole from January and March 2007 (late cycle 23), and 72 jets out of total 178 in the North polar coronal hole from September and October 2008 (early cycle 24). In addition we found 31 transverse-moving jets out of a total of 70 jets in the South from September - October 2008 and January 2009, and 8 velocities for jets in the North from November 2006. The total number of jets given above refers to all jets, including twisting jets as well as jets without reliably determined velocities, for the given pole and solar cycle. On the histogram on Fig. 2 one can see the distribution of velocities for both poles. The positive velocity is the westward velocity for both poles, and the negative is the eastward. From the figure one can clearly see that there is a preferred direction - westward for the South pole and eastward for the North. We found that 70% of the transverse moving South pole (SP) jets from early 2007 move preferentially to the West and these jets constitute 44% of the total number of SP jets from Cycle 23. 69% of the transverse moving North pole (NP) jets from late 2008 move to the East, or 28% of the total number of NP jets from Cycle 24.

It is important to note here that jet transverse velocities were reliably determined only for the larger jets of the sample, with width more than 8000 km. Thus for a large number of jets in the sample we could not determine the transverse velocities. We think this is the main the reason why so many jets do not display transverse motion, rather than the possibility that the underlying bipolar structure is oriented North-South. Inspection of the jet movies showed no overlapping bipoles at the base of the jet. We cannot exclude some tilt to the East-West direction.

We applied the χ^2 test to check the statistical significance of the result. The probability that this result is derived from a binomial distribution with a 50% chance for both directions occurring for the jets for which transverse velocities could be determined is 3×10^{-5} for the North pole and 6×10^{-5} for the South pole, indicating high statistical significance for the result.

We also separated the sample of jets in the two poles in time, in order to check for differences with the evolution of the solar cycle. It seems that earlier (during Cycle 23) - 23 Nov 2006 - 71% of the transverse moving jets (or 62% of the total number of jets from Cycle 23) at the North pole move westward while the data from September and October 2008 (Cycle 24) show that 69% move to the East. Similarly, for the South pole in early 2007, 70% of the jets with transverse velocities move to the West while in late 2008 and early 2009 84% move to the East (or 37% of the total number of jets). This hints at a dependence of the jet transverse velocity direction on the solar cycle. The information on the number of jets with both directions of transverse velocities for both poles and both cycles is summarized in Table 1. We have proposed a plan for regular South and North pole observations for the extent of the entire *Hinode* mission to further confirm this result.

The basic Shibata jet cartoon shows two underlying bipoles in the ambient open field with the smaller brighter one formed from the interaction of the ambient field and the emerging flux. On Fig. 3 we have sketched the basic process for producing a jet in accordance with that picture. In addition to the velocity determination we checked, by eye, the position (East or West) of the brighter bipole that lightens up at the same time as the emergence of the jet. These observations showed that a majority of bright bipoles were oriented horizontally at the poles and that there is a preferred side for the smaller bright bipole - 62% of the brightenings appear on the West side for the North pole jets, and 68% appear on the East side for the South pole jets. We checked whether there is correlation between the transverse velocity direction and the position of the bright bipole. The result is that 79% of the jets on South pole that move in the preferred westward direction have the bright bipole on the East side, and 76% of the jets that move eastward have the bright bipole on the West side.

From the direction of transverse motion of the jet, along with a knowledge of the dominant polar hole magnetic field direction and the location of the bright point, we can infer the polarity of the emerged flux region. The background field and the emerged flux region interact to form a new bright point, thus signifying the approximate location of the magnetic null point where reconnection is occurring. The transverse motion of the jet is away from the reconnection site (*viz.* Fig 3). From Fig. 3, it is evident that the loop footpoint found below the null point must be of opposite polarity relative to the background flux, and we can therefore determine the polarity distribution for both the emerged flux region and the bright point created by the reconnection event.

From the results shown in Fig. 2 and Table 1, it is clear that there is a statistically significant asymmetry in the emerged flux region polarity orientation. In the case of the south pole results from January and March 2007, the emerged flux regions produced mostly westward propagating jets and so the eastward polarity of the emerging flux regions (EFR) was opposite to that of active regions from the same cycle. From November 2006 and January 2007, north pole transverse velocities tended to move west, and so had eastward (trailing) polarity, opposite to that of the south pole EFR polarity orientation. In early 2007, the north and south background field polarities were *negative* and *positive* respectively. As such, EFRs in the north were oriented negative (leading/westward) and positive (trailing/eastward) while south pole EFRs were positive (leading/westward) and negative (trailing/eastward), or **identical to the polarity of active regions for cycle 24!** Observations of polar jets taken during September 2008 – February 2009 indicate that the polarity of EFRs reversed relative to the orientation observed during the early 2007 observations. The polar background flux is unchanged from those early 2007 observations, leading to the conclusion that the EFRs changed their preferred polarity orientation, becoming that of the active regions of the now-ending Cycle 23 and of Cycle 25, the cycle after the now-starting Cycle 24. The situation is summed up schematically in Fig. 4.

The polarity relationship identified for EFRs in polar coronal holes from November 2006 – March 2007 is similar to that found by Martin & Harvey (1979) and Hagenaar (2001) for EFRs at lower latitude. Prior to the observation of active regions that exhibit a 'new' polarity orientation indicative of the start of a new cycle, this polarity orientation inversion is observed for large EFRs at latitudes higher than typical for active regions.

The results presented herein support that result and extend it to even higher latitude and to within polar coronal holes. In this sense it is consistent with the findings of Wilson et al. (1988) who use the coronal green line as an indicator for small ephemeral regions at polar latitudes. However, the observations of sign reversal in the leading/trailing flux for EFRs so soon into the new cycle (in this case cycle 24) is a new and unexpected result. Wilson et al. (1988) present a result that faster-than-average and slower-than-average differential rotation bands also migrate in latitude depending on the phase of the solar cycle. They report that migration from polar latitudes to the equator may take about 22 years, with the migration starting at polar latitudes with onset of active regions in the current cycle and ending with the minimum of the following solar cycle (Fig.1 from Wilson et al. 1988). This observation may be invoked as supporting evidence that early in Cycle 24 we already see emerging flux at the poles from Cycle 25. We note that the model of Nandy and Choudhouri (2002, Fig. 3) shows a strong toroidal field being generated at high latitudes with opposite sign to that of the toroidal field belt underlying active regions at low latitudes. This high latitude toroidal field subsequently migrates equatorward, advected by meridional circulation in their model, and produces active regions of the next cycle after a certain time lag. We believe that our results are relevant for constraining such solar dynamo simulations and more complete observations in the coming years may help distinguish between competing models.

We have demonstrated the applicability of jet transverse motions and bright point locations as a proxy for determining the EFR polarity relationship to the polar background field. This measurement provides specific and compelling data on the non-random preference for EFR polarity orientation. We expect to extend this result through long-term observations of the solar polar coronal holes to increase the statistical certainty of this result.

Hinode is a Japanese mission developed, launched, and operated by ISAS/JAXA in partnership with NAOJ, NASA, and STFC (UK). Additional operational support is provided by ESA, NSC (Norway). This work was supported by NASA contract NNM07AB07C to SAO. We would like thank Dibyendu Nandi, Piet Martens, Andres Munoz-Jeramillo, and Julie Stern for helpful discussions. We would like to thank the referee for very useful comments and suggestions that greatly helped to make this paper better.

REFERENCES

Cirtain, J.W., et al. 2007, Science, 318, 1580.

Golub, L., et al. 2007, Sol. Phys, 243, 63.

Hagenaar, H.J. 2001, ApJ, 555, 448.

Martin, S.F. and Harvey, K.L. 1979, Sol. Phys, 64, 93.

Nandy, D. and Choudhouri, A.R. 2002. Nature, 296, 1671.

Pariat, E., et al. 2009, ApJ, 691, 61.

Patsourakos, S., et al. 2008, ApJ, 680, L73.

Savcheva, A., et al. 2007, PASJ, 59, 771.

Shibata, K., et al. 1992, PASJ, 44, L173.

Shibata, K., Yokoyama, T., & Shimojo, M. 1994, in New Look at the Sun with Emphasis on Advanced Observations of Coronal Dynamics and Flares, ed. S. Enome & H.S. Hudson, NRO Rep,. 360, 75.

Shimojo, M., et al. 1996, PASJ, 48, 123.

Shimojo, M., Shibata, K., Harvey, K.L. 1998, Sol. Phys., 178, 379.

Tsuneta, S., et al. 1991, Sol. Phys., 136, 37.

Tsuneta, S., et al. 2008a, Sol. Phys., 249, 167.

Tsuneta, S., et al. 2008b, ApJ, 688, 1374.

Wilson, P. R., et al. 1988, Nature, 333, 748.

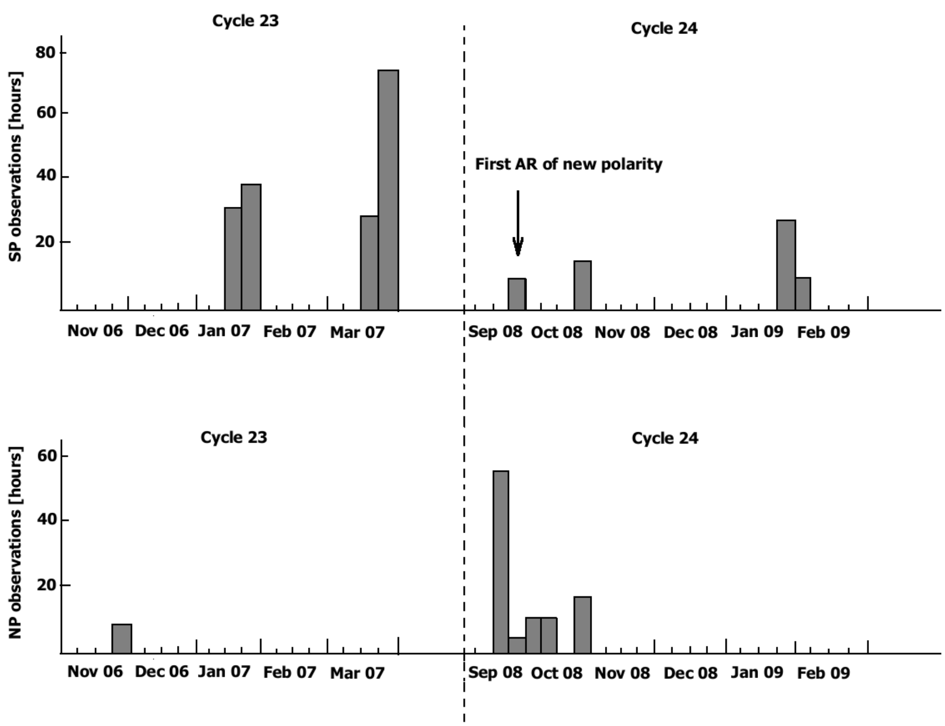

Fig. 1.— Timeline of observations for the South pole (upper pannel) and North pole (lower pannel). The time of the first active region of cycle 24 polarity is marked.

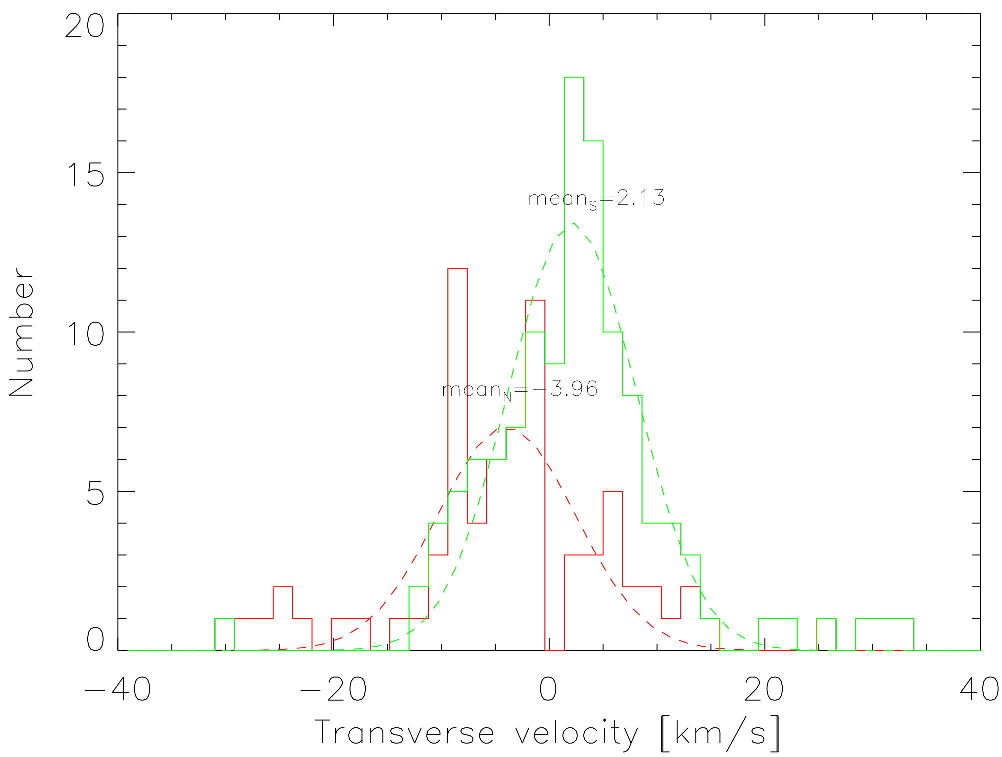

Fig. 2.— Histogram of the jet transverse velocity distribution for both the North (red) and South pole (green). Positive velocity is the westward velocity for both poles. Gaussians are plotted as well and the mean is shown on the plot. The histogram shows velocities only for jets from January and March 2007 and September and October 2008.

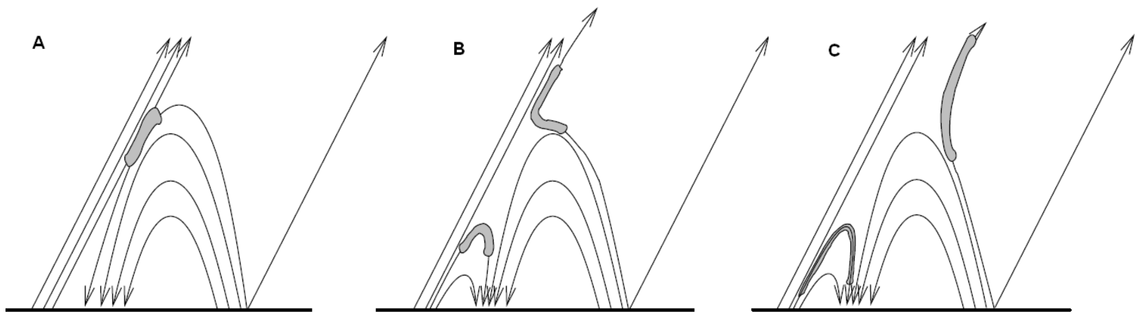

Fig. 3.— A cartoon sketch representing the process of producing a jet via reconnection of emerging flux and ambient field. Part A represents the reconnection between the emerging bipole and the ambient field; part B shows new configuration after a smaller brighter bipole was created from this process; part C demonstrates the jet transverse motion away from the smaller bipole. The shaded patch on the figure represents the reconnection heating of the corona - in part C, it is clear that the heating splits between the jet and the bright bipole.

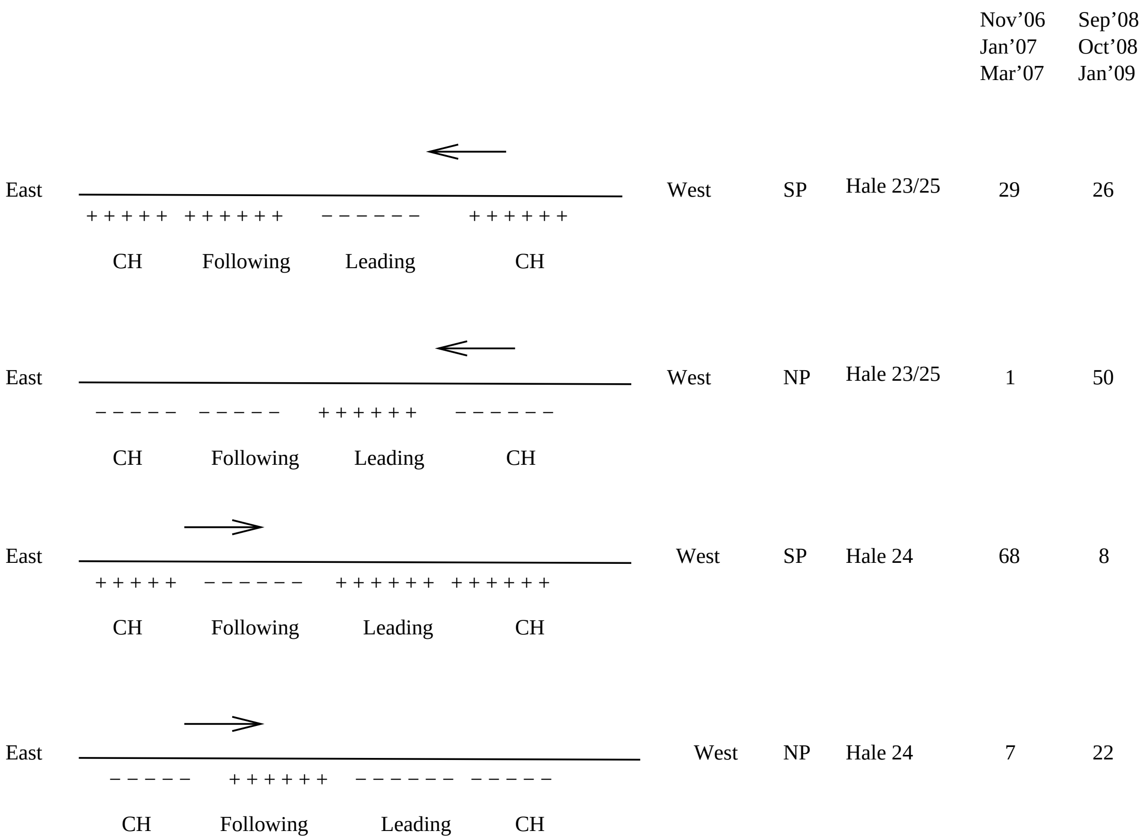

Fig. 4.— A summary of the results for jet transverse velocity. The observables are the polar coronal hole field polarity (indicated by the sign above the text CH), the direction of the transverse motion (indicated by the arrow, above the reconnection site) and the pole being observed (NP, SP). The number of jets with different orientations are shown by the numbers on the right. From the Shibata model of jets we can deduce the orientation of the emerging bi-pole. The signs of the leading and following bi-pole polarities are shown. The four rows cover all of the possible examples of bi-pole emergence into a coronal hole. The total number of jets from the South pole from early 2007 is 259 and from late 2008 and early 2009 - 70. The total number of jets from the North pole from November 2006 is 13, and from late 2008 - 178.

Table 1: Summary of transverse velocities for Cycles 23 and 24. The first column displays the time period of observation, second column gives the total number of hours of observation in these periods, the third column states which pole was observed, the fourth column gives the total number of jets observed for this period, the fifth column gives the number of Eastward moving jets, Westmoving jets,a nd jets with no transverse motion determined from right to left, and the last column give the field of view, filter and cadence of the observations in the given period.

Time	# hours	Pole	# Jets	# East, West, No	FOV/Filter/Cadence
23 Nov 06	7	N	13	1, 7, 5	1024×256/Al_poly/30s
12 Jan 07 – 21 Jan 07	69	S	113	12, 36, 65	1024×512/Al_poly/25s
11 Mar 07 – 13 Mar 07	17	S	29	4, 5, 20	1024×256/Ti_poly/30s
13 Mar 07 – 19 Mar 07	71	S	96	10, 20, 66	1024×512/Ti_poly/30s
19 Mar 07 – 20 Mar 07	14	S	21	3, 7, 11	1024×512/C_poly/30s
20 Sep 08 – 26 Oct 08	105	N	178	50, 22, 106	384×384/Al_poly/60s
25 Sep 08 – 25 Sep 08	8	S	13	3, 0, 10	384×384/Al_poly/60s
25 Oct 08 – 27 Oct 08	20	S	26	3, 2, 18	384×384/Al_poly/60s
27 Jan 09 – 28 Jan 09	20	S	31	17, 6,8	384×384/Al_poly/60s