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Dynamics of polar plumes observed during the total solar eclipse of August 1, 2008

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Abstract. We study dynamics of polar plumes observed during the 2008 eclipse from three ground-based sites and the Hinode satellite. The speed of apparent upward propagation, as inferred from the changes of brightness within each plume, is found to lie in the range from 30 to 100 km s^{-1}. Some white-light plumes located in polar coronal holes were identified with their X-ray counterparts observed by the Hinode satellite, which showed almost the same speed.

Key words: Sun – polar plumes – dynamics

1. Introduction

Total solar eclipses provide an excellent opportunity for getting insights into the nature of a variety of coronal structures as seen in the white-light, e. g. helmet streamers, coronal holes, polar plumes, etc., and for indirect inferring of distributions of magnetic fields on the solar surface that give rise to these coronal structures, which could, for example, shed further light on the origin and acceleration mechanism of the high-speed solar wind (see, e. g., DeForest et al. (2001)). An interesting class of objects of the white-light corona are polar plumes, observed in coronal holes near the poles around cycle minima. Polar plumes are thin, dense, straight or slightly curved, magnetically-open structures that penetrate coronal holes. Their existence is supposed to be connected with the high-speed solar wind that has its origin in polar coronal holes, e. g. Gabriel et al. (2003), McIntosh et al. (2010). Although polar plumes have been observed during total solar eclipses for more than one-hundred years, their dynamics is still poorly understood (e. g. DeForest et al. (1997)), especially in the inner corona, very close to the solar surface, which cannot be observed by the SOHO or STEREO spacecrafts. Some years ago, a new term "polar rays" was introduced and, frequently, interchangeably used on par with polar plumes. Yet, some studies, e. g. Jing Li et al. (2000) and DeForest et al. (2001; and references therein), seem to indicate that physical properties of polar rays are distinct from those of polar plumes; polar rays are mostly connected with observations in EUV and X-rays made from space, being usually linked with active regions located in mid heliographic latitudes.

One of many questions connected with the existence of polar plumes is their lifetime and dynamics. Waldmeier (1955) found that the lifetime of polar plumes amounts to about 15 hours; it must, however, be stressed that this value was derived from monochromatic observations of the red corona (Fe X, 637.4 nm) by a coronagraph outside a total eclipse. It is, therefore, rather questionable to assume that Waldmeier's polar plumes are identical with classical white-light polar plumes. DeForest et al. (2001) concluded that plumes' lifetime vary from 1 day to 2 weeks. The question of lifetime is closely connected with the very nature of plumes, as proposed by Saito (1965) or Wang (1998), and also discussed by DeForest et al. (2001) using EUV observations of plumes. Even though the total solar eclipse at a particular place takes only a few minutes, coordinated observations along the whole eclipse track provide us with the possibility of measuring changes in coronal structures, e. g. Zirker et al. (1992), Bělík et al. (2000, 2002). Employing a new method of image processing (Druckmüller et al., 2006, Druckmüller, 2009) allowed us to visualize very faint structures and enabled us to find real short-term changes not only of an overall shape of the white-light corona (Bělík et al., 2003), but also in polar plumes. For example, during the 2006 total solar eclipse, observed from different observation places from Niger to Turkey, very significant dynamics in a polar plume was observed (Pasachoff et al., 2008). A careful inspection of a very pronounced polar ray, obtained on a very long observational basis, yielded its radial speed to be about 75 km s^{-1}. A similar observation was also reported during the total solar eclipse on August 1, 2008 (Pasachoff et al., 2009). For the 1998 eclipse polar plume, simultaneously observed aboard SOHO at 195$\AA$, Lites et al. (1999) detected upward propagation speed of 200 km s^{-1} during the eclipse time of 202 s, a landmark observation of this kind. On the other hand, Yang et al. (2011), analyzing eclipse observations of polar plumes during the 2009 eclipse, concluded that "none of them disappears and no new one is created" over 73s. Their observations were carried out with a high speed cadence – 0.65 s.

In this paper, we study dynamical features of several polar plumes observed during the 2008 eclipse from three distinct sites and infer speeds of upward propagation of bright points within each of them.

2. Observing sites

The total solar eclipse on August 1, 2008, was observed by the members of the "Shadow Tracking Expedition" from several sites in Russia and Mongolia. The first observing site was located in the town of Novosibirsk (E 83° 05' 44", N 54° 50' 31", 2nd contact at 10:44:28 UT), the next one near the village of Klyuchi (E 83° 14.204', N 54° 50.397', 2nd contact at 10:44:31 UT) and the last site was in Bor Udzuur (Mongolia, N 45° 43.251', E 92° 06.837', 2nd contact at 11:03:35

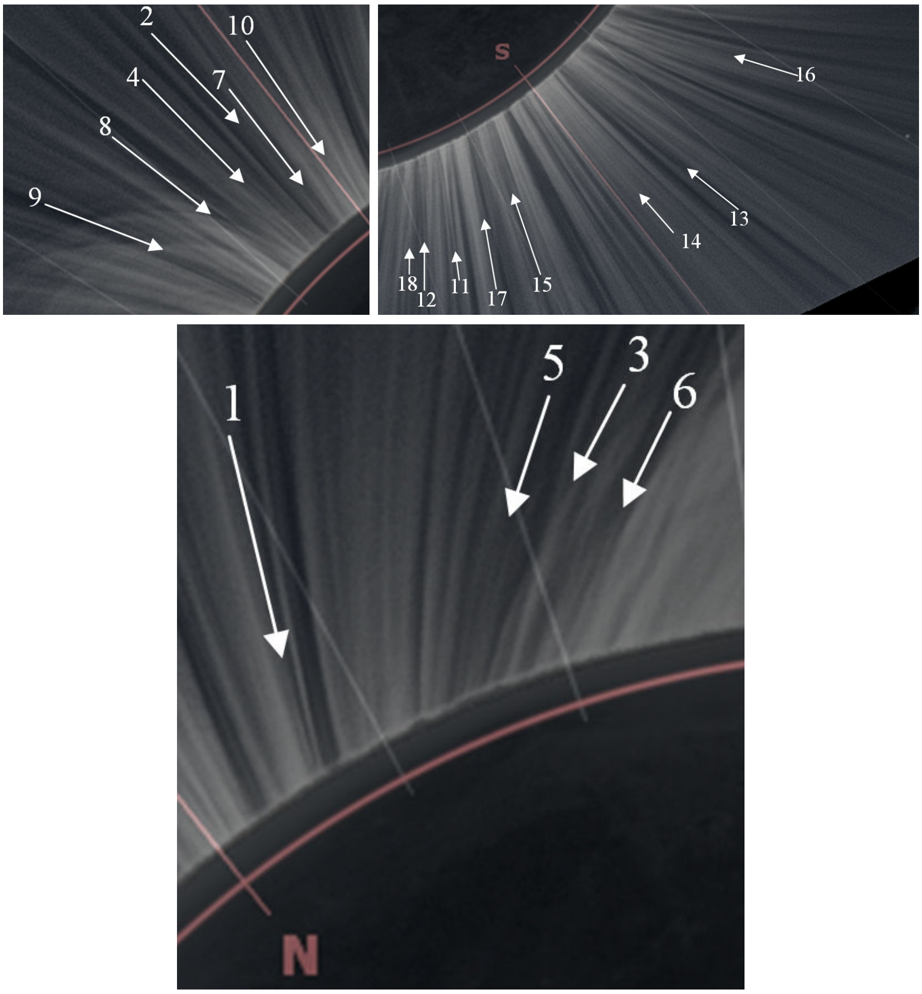

Figure 1. Locations of polar plumes (numbered from 1 to 18) selected for the analysis: Top left and top right – north-eastern and southern regions, bottom – western ones. Images by M. Druckmüller, P. Aniol and V. Rušin (Mongolia) and M. Bělík, H. Druckmüllerová, E. Marková and L. Křivský (Russia).

UT). The time difference between the 2nd contacts in Novosibirsk and Klyuchi was about 3 seconds, whereas that between Klyuchi and Bor Udzuur was as much as 1147 seconds. The weather conditions for solar corona observations were excellent and the time shift around 19.1 minutes was sufficient for spotting any short-term brightness variability in polar plumes.

3. Data analysis

The first task of our study was a very precise comparison of all corona's pictures obtained at the three observing sites. We identified eighteen polar plumes above both the northern and southern polar coronal holes that exhibited some structural (brightness) changes (see Figure 1); ten of them are located in the northern, very pronounced coronal hole, eight in the southern one, all denoted by arrows. The position of the brightest point in each studied plume was carefully measured (we repeated fifty measurements for every single point). By comparison of measurements from all sites we calculated a change of the position of these points between the Russia's and Mongolia's sites eclipse time. For such measurements, it was necessary to find an exact conversion value between the real distances on the Sun and those on the pictures. By using the value of the solar radius $R_\odot$ = 695.99 ±0.07 Mm (Castellani et al., 1998) and our value of the solar radius on white-light eclipse pictures $R_\odot$ = 328.03 ± 0,59 px (obtained from 20 measurements), the conversion value amounts to 2121.69 ± 4.05 km px^{-1}. Based on these data, we calculated the speed of motion of brightest points in each plume. The results are shown in Table 1 and Figure 2.

Table 1. Calculated speeds in the eighteen studied plumes.

Plume number	Speed (km s^{-1})
1	66.6 ± 3.4
2	64.7 ± 7.4
3	62.9 ± 6.1
4	60.5 ± 7.7
5	51.8 ± 12.6
6	33.4 ± 2.0
7	40.6 ± 2.4
8	74.3 ± 5.0
9	75.7 ± 4.3
10	40.7 ± 5.8
11	90.0 ± 26.6
12	68.8 ± 5.4
13	66.7 ± 8.3
14	77.1 ± 7.6
15	75.4 ± 7.0
16	64.8 ± 8.5
17	87.4 ± 10.7
18	57.0 ± 11.0

We have found that the speeds of bright points in all studied plumes lie within the range from 33 km s^{-1} to 90 km s^{-1}. Obtained results are in very good agreement with the speed of 75 km s^{-1} in a polar plume observed during the

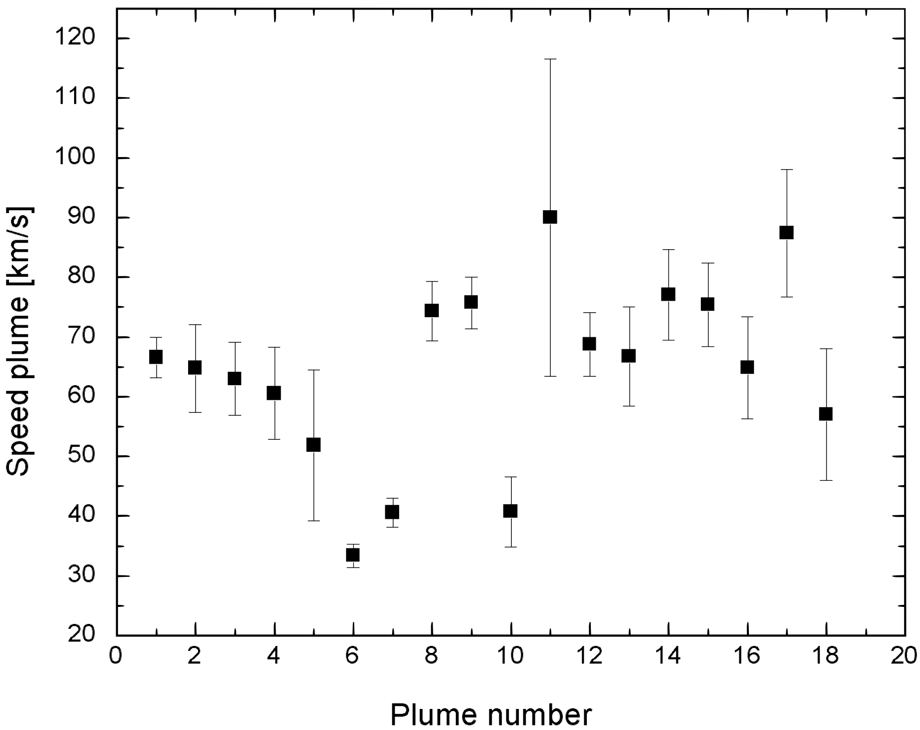

Figure 2. A diagrammatical illustration of the results from Table 1.

total solar eclipse 2006 by Pasachoff et al. (2008). On the other hand, Pasachoff et al. (2009), for the same eclipse, announced birth of a new polar plume, for which the radial speed was estimated to be of 600 km s^{-1}.

4. Hinode and eclipse comparison

Relations between the X-ray/EUV rays and white-light plumes have been studied very rarely. In this section we shall try to fill this gap. To this end, we made an analysis of corresponding X-ray coronal images from Hinode/XRT (available at `http://solarb.msfc.nasa.gov/`).

We employed the images from August 1, 2008, taken at 10:46:35 and 11:04:35 (the time difference is 1080 seconds, or 18 minutes), one of them being shown in Figure 3. The solar radius measurement on the XRT images was made by using the software DS9 and Brooks "Solar Position Calculator" (available at `http://www.pages.drexel.edu/~brooksdr/DRB_web_page/Aerosols/sol_calc.htm`) and it was determined to be $R_{\odot}^{\mathrm{XRT}}$ = 934.63±1.45 arcsec. There were found four X-ray plumes, which could uniquely be identified with some of the plumes visible on white-light pictures – see Figure 5. The speeds of dynamical features in these 4 plumes was calculated by the same method as for the white-light ones and they are listed in Table 2; one sees that the values are very close to those for the four associated white-lights.

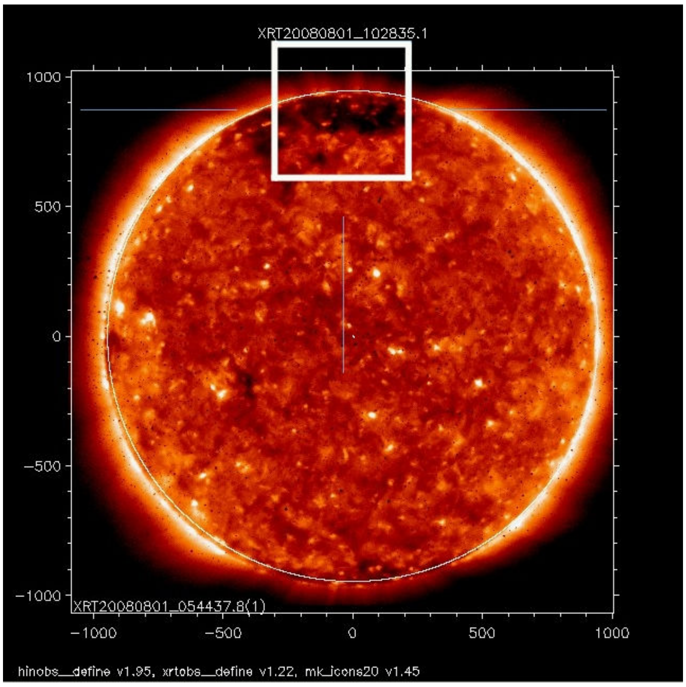

Figure 3. An X-ray image from Hinode. A small rectangle around the north pole shows the analyzed area, depicted in the next figure. Courtesy: Hinode — a Japanese mission developed, launched and operated by ISAS/JAXA, in partnership with NAOJ, NASA and STFC (UK).

Table 2. Comparison of the speeds (in km s^{-1}) in the associated plumes in X-ray and white-light (W-L).

X-ray	W-L	Hinode plume speed	W-L plume speed
A	4	68.3 ±6.6	60.5 ±7.7
B	9	57.4 ±7.4	75.7 ±4.3
C	1	58.6 ±7.8	66.6 ±3.4
D	10	55.8 ±6.3	40.7 ±5.8

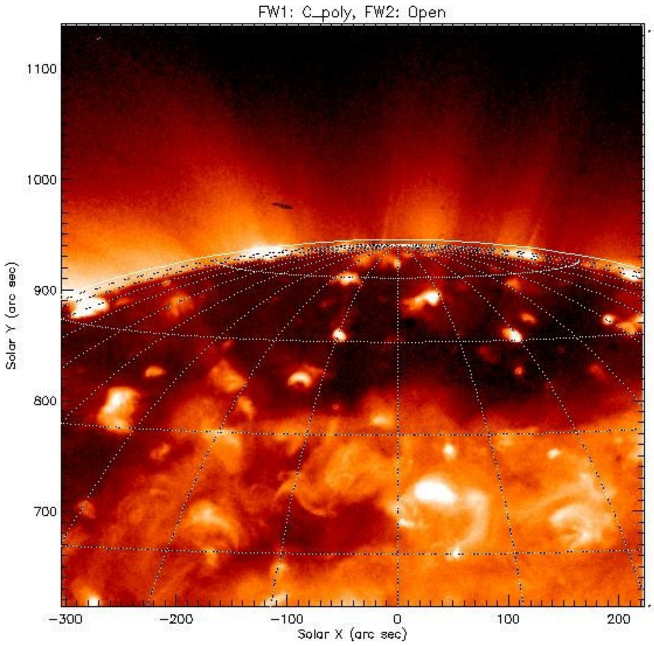

Figure 4. A detailed view of the studied area on the X-ray image shown in the previous figure. Courtesy: Hinode — a Japanese mission developed, launched and operated by ISAS/JAXA, in partnership with NAOJ, NASA and STFC (UK).

5. Discussion and conclusion

We have studied dynamics of a number of polar plumes based on images of the white-light corona observed during the total solar eclipse of August 1, 2008, at two observational sites in Russia and one in Mongolia, 1147 seconds apart. It is found that brightness enhancements in 18 polar plumes, in the radial direction, reached speeds in the range from 33 to 90 km s^{-1}. A similar eclipse polar plume's speed was observed during the March 29, 2006 eclipse (Pasachoff et al., 2008). On the other hand, Lites et al. (1999), from the February 28, 1999 eclipse, concluded that "disturbances appear to propagate radially away from the Sun at speeds of about 200 km s^{-1};" it needs, however, to be mentioned that their EUV jet was embedded in a polar plume and the velocity in question was observed in both structures. Pasachoff et al. (2009), for one of the south polar plumes in the 2008 eclipse, announced a speed of 600 km s^{-1}. Contrary to these results, Yang et al. (2011), using high cadence observations (every 0.65 s) for the 2009 eclipse plumes during 73s, claimed that "no plume disappeared or

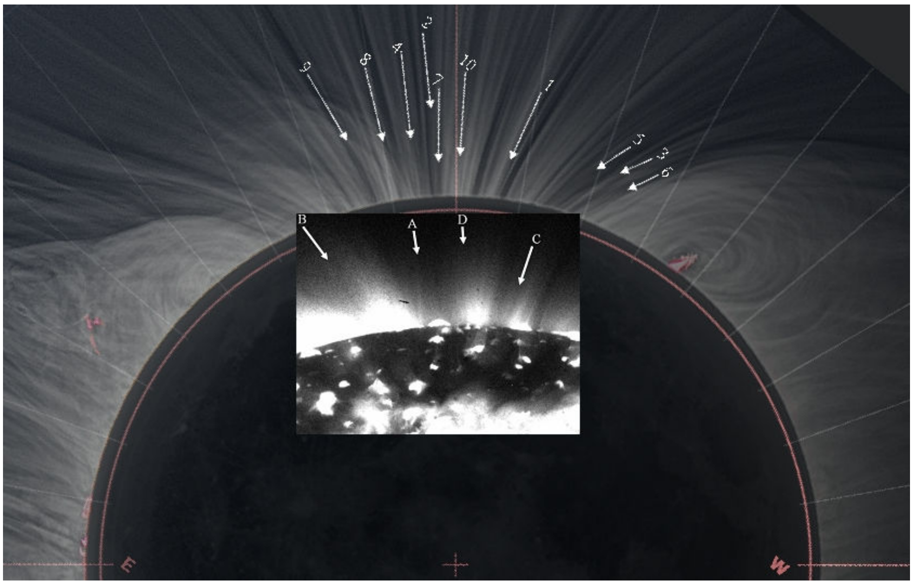

Figure 5. An overlay of the white-light and X-ray images of the solar corona with marked plumes used in this study (see Table 2).

was created." On the other hand, Lites et al. (1999) detected in the 1998 polar plume during 202 s an apparent upward propagation speed of 200 km s^{-1} at the base of the corona.

We have also studied X-ray images from the Hinode satellite. There were found four X-ray plumes (denoted above as A, B, C and D), which could uniquely be identified with some of the plumes visible in the white-light pictures (4, 1, 9 and 10, respectively). The inferred speed for these X-ray plumes lies in the range from 56 to 68 km s^{-1} and from 41 to 76 km s^{-1}, respectively. In this connection it is worth mentioning that upward propagating disturbances in AIA plume-like structures observed by the Solar Dynamic Observatory (Tian et al., 2011) moved with an average velocity of 120 km s^{-1} and these were located not only in polar coronal holes, but also elsewhere above the solar limb.

While the observational speeds for these "common" plumes are close to each other, there is a big difference in the temperature. Observations of plumes in X-rays from Hinode indicate a rather high temperature, log T $\approx$ 7, which is in contrast with a much lower temperature of polar plumes, log T $\approx$ 6 (Golub et al., 2007; Ahmad and Withbroe, 1977). Despite this big discrepancy in the temperature, we think the two kinds of plumes to be intimately connected via magnetic fields and have a common origin.

According to our analysis and some earlier studies as well, we could conclude that polar plumes should be divided into three groups: (a) stable or quiescent,

i. e. those that exhibit no changes, within the limits of measurements, of their brightness in an interval of about 20 minutes and whose lifetime is very long; (b) dynamic, in which an apparent upward propagation speed is in the range from 30 to 100 km s^{-1}, and (c) eruptive with a speed exceeding 200 km s^{-1} close to the solar limb; this kind of polar plumes should be connected with explosive events in the EUV as discussed by Innes et al. (1997) and they should last only a few hours. It is worth mentioning that mechanisms responsible for the observed changes in plumes' brightness (which is proportional to the square of electron density) is still unknown, see, for example, Nakariakov (2006). It is also obvious that some white-light polar plumes are fairly dynamical phenomena whose contribution to feeding solar wind may not be negligible.

We hope that improved methods of observing and analyzing the eclipse white-light corona, when complemented with its space-borne observations, will lead to a deeper understanding of the relation between white-light and X-ray polar plumes and will also shed some light on the source of their activity, as recently discussed by Raouafi et al. (2008).

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