WHITE-LIGHT POLAR PLUMES FROM THREE "MINIMUM-LIKE" SOLAR ECLIPSES

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ABSTRACT

Morphology of the white-light polar plumes seen during last three solar eclipses (1994, 1995, 1997) is described. Analysis of these observations is completed and discussed in connection with the calculated magnetic field topology at the source surface level. Structure of the magnetic field lines of force and position of the neutral line during these eclipses indicate surprisingly steady poloidal magnetic field during at least three years. It is shown that the polar plumes are well visible also within the near-maximum corona (however, in this case, over the heliomagnetic poles instead of the heliographic poles) supposing orientation of the global solar magnetic field with respect to the observer is favourable. Such a case took place, for example, during July 11, 1991 eclipse. Considering inclinations of the observed polar plumes, the lengths of a hypothetical bar magnet were derived for different eclipses. We are of opinion that an older idea on regular changes of such lengths with the solar cycle phase should be rejected or, at least, modified due to the recent findings on the long-term evolution of the large-scale coronal magnetic field.

Key words: solar eclipse corona; polar plumes; global magnetic field; solar cycle.

1. INTRODUCTION

Polar plumes ("p.p." in the next) were intensively studied throughout three decades after 1950 as a phenomenon best seen on the images of the solar corona taken during solar eclipses in the periods of the solar cycle minima (Waldmeier, Saito, Tsubaki, Nesmyanovich, Dzubenko, Nikolskiy, Newkirk and Koutchmy were the principal observers). At that time, morphology of the p.p. was extensively described. Except of that, statistical association of the p.p. with the chromospheric network was found and, in this connection, it was declared that the plumes represent tubes of elevated coronal density constrained by the magnetic field (Newkirk & Harvey, 1969). Presently, a certain renaissance of the p.p. investigation is connected with implications that the p.p. are, in fact, dynamical jet-like features, possibly responsible for coronal heating and the high-speed solar wind acceleration (see the latest YOHKOH and SOHO results).

Principle items of our contribution are: (1) Description of the white-light p.p. observed during the last three solar eclipses (1994, 1995, 1997); (2) A new view on the relation between the p.p. visibility and evolution of the large-scale solar magnetic field, and (3) Comment on variations of the hypothetical bar magnet with the phase of the solar cycle.

2. POLAR PLUMES AT MINIMUM OF THE 22ND SOLAR CYCLE

Three eclipses (November 3, 1994, October 24, 1995 and March 9, 1997) took place near to the minimum phase of the 22nd solar cycle. Detailed descriptions of the coronal structures and relative photometry of them are given in Sýkora et al. (1995, 1998) and in Pintér et al. (1997). A short description of the first two eclipses and namely the statistics of the observed p.p. appeared in Hiei et al. (1997). In the present paper, the corresponding drawings of the eclipse coronal structures are shown in the first column of Figure 2. These drawings were obtained by considering both the photographic and computer processing of the images. The computer processing of the digitized images consisted from successive using of the two-dimensional fast Fourier transformation, digital filtration and application of the numerical unsharp masking method. Examples of the computer-processed images are shown in Figure 1. Similarity of the three global coronal forms (Figure 2) is rather surprising. The p.p. are very well visible directly over the poles, implying presence of a relatively steady poloidal magnetic field on the Sun over this almost three-year period. Considering also the best spatial resolution of the processed images, as visible on the screen of the computer monitor, we are able to bring (Table 1) the following statistics of the p.p. seen at the moments of the three eclipses. Generally, the detected p.p. are situated over the polar coronal holes as seen on the YOHKOH images.


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Table 1. Numbers of the polar plumes and the occupied regions.

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<tr>
<td>North</td>
<td>12</td>
<td>43° (E25-W18)</td>
<td>14 (+4 ?)</td>
<td>90° (E60°-W30)</td>
<td>11</td>
<td>52° (E17-W35)</td>
</tr>
<tr>
<td>South</td>
<td>15 (17)</td>
<td>85° (E60-W25)</td>
<td>16</td>
<td>65° (E30-W35)</td>
<td>13</td>
<td>58° (E28-W30)</td>
</tr>
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Total 27 (29) 128° 30 (34) 155° 24 110°

taken at the eclipse days. Partial inconsistency of this statement is, most likely, due to comparing 2-D projections on both the eclipse and YOHKO images instead of the 3-D reality.

3. POLAR PLUMES AND THE LARGE-SCALE MAGNETIC FIELD TOPOLOGY AT MINIMA OF THE SOLAR CYCLES

It is true that almost all the preceding authors pronounced an idea about relationship of the p.p. distribution with the magnetic field flux tubes and topology of the poloidal magnetic field lines of force (Saito, 1965 and the references therein; Kopecký & Suda, 1966; Newkirk & Harvey, 1968). The prevailing idea was that the magnetic field in the polar region of the corona can be approximated by a field produced by a fictitious bar magnet with its direction parallel to the Sun’s rotation axis and with middle point placed at the sun’s center" (Saito, 1965). That time, of course, very little was known about a long-term evolution of the large-scale solar magnetic field. Such an evolution was clearly demonstrated considerably later by Hoeksema (1993). Taking into account Hoeksema’s results, we would like to point out a close relationship of the p.p. visibility with the real magnetic field topology throughout the 22-year solar magnetic cycle.

We confirm that the p.p. are best seen during the solar cycle minima. In two last columns of Figure 2 the open and closed coronal magnetic fields calculated for the last three solar eclipses are demonstrated. These were typically minimum-like eclipses with the heliographic and heliomagnetic equators practically identical. This identity is distinctly seen in the last column of Figure 3 where distribution of the global magnetic field at distance r = 4.0 R⊙ is shown (the curves represent positions of the solar limb at the eclipse days). The calculated magnetic field lines of force (Figure 2) well copy the observed coronal structures, including the systems of the p.p. It seems noticeable that during almost three years (1994-1997) the minimum-like topology of the solar corona is considerably steady and similar, not being substantially sensitive even to the solar rotation (see Figure 3, where the calculated fields four days after eclipses are presented in the second column). Such a behaviour of the coronal forms and magnetic field topology could be connected with the findings of Cliver et al. (1996) about more rapid evolution of the tilt angle of the heliospheric current sheet (HCS in the next) in the cycle No.22 in comparison with the cycle No.21 and about a certain probability of the prolonged and flat minimum phases of all the even cycles (Hale 22-year solar magnetic cycle pairing consists of an even 11-year cycle followed by an odd 11-year cycle - see also Storini and Šykora (1997)).

4. POLAR PLUMES AND THE LARGE-SCALE MAGNETIC FIELD TOPOLOGY AT MAXIMA OF THE SOLAR CYCLES

We are now of opinion that a real presence of the p.p. is not so much dependent on the phase of the solar cycle as it was believed earlier. In fact, the p.p. are, most probably, permanently present on the Sun, including the periods of the solar cycle maxima. Their visibility depends solely on orientation of the solar magnetic equator and, of course, the HCS relatively to the Earth (to the observer) at the moment of the given eclipse. Clarification of our statement is demonstrated in Figures 4-6 related to the near-maximum eclipses in 1980 and 1991.

In the case of the "favourably oriented" 1991 solar eclipse corona the solar magnetic equator is seen "from the edge" (see lower part of Figure 4), flattening of this corona is similar to those characteristic for the minima of the cycles (see also Figure 1) and the p.p. are well visible as well (Figure 5). However, in this case, over the solar magnetic poles. This, of course, is not so much surprising, having in the mind the revealed relation of the p.p. and general magnetic field.

Situation with the 1991 corona would be drastically different already after 4 days (Figure 6), in contrast to 4-day shifting in the case of minimum-like eclipses shown in Figure 3. Very probably, no p.p. would be visible if the solar eclipse, hypothetically, took place, for example, on July 15, 1991. On this day, topology of the magnetic field would be similar to that of February 16, 1980 when the solar magnetic axis is oriented directly to the observer and the regions near to the both solar poles, including the p.p., cannot be visible. It should be said that, statistically, orientation of the general magnetic field similar to that of July 15, 1991 or February 16, 1980 are considerably more frequent than the specific situation observed on
July 11, 1991. That is why, the p.p. were rarely seen in the past on coronal images taken during periods of the solar cycle maxima.

5. COMMENT ON PRESENCE OF A HYPOTHETICAL BAR MAGNET IN THE SUN

Analysing the 1954 eclipse corona, Waldmeier (1956) has found a linear dependence between position angle ($\phi$) measured from the heliographic pole and the angle ($\alpha$) created by radial directions and tangential lines to the p.p. at the points where the p.p. cross the sphere $t = 1.0$ and $t = 0.0$ (see the scheme in the left upper part of Figure 7). Later, Saito (1965), analysing a number of eclipses, emphasized and supported an idea on possibility to simulate the observed minimim-like corona by existence of a hypothetical bar magnet parallel with the Sun's rotation axis. At the same time he found that "the lengths of the bar magnet vary distinctly with the solar activity cycle". Subsequently, Kopecký and Suda (1966), using data of many authors, reported results somewhat different from those of Saito. For the first time they attributed the found inconsistency in orientation of the bar magnet to the differing structure of the magnetic field above the solar poles during different eclipses".

Using method of Saito (1965) we have analysed solar eclipses observed in 1973, 1991 and the three minimum-like eclipses dealing with in this paper. Corresponding inclinations $k$ of the linear $\alpha/\phi$ dependence were found (Figure 7). Applying theoretical calculations between inclinations $k$ (from equation (1) and the length of the hypothetical bar magnet $d$ (Rušín & Rybánský, 1976) we have obtained the quantity $d$ for the last three eclipses. These values (together with that determined for the 1973 eclipse) were plotted into the original Saito's figure (see the upper right part of our Figure 7 in which, understandably, the 1991 value is due to the actual solar cycle phase 0.76 out of the scale).

Discussing Saito's dependence of the length of the hypothetical bar magnet on the phase of the solar cycle it should be noticed that:
- All the points in Figure 7 are within 0.3 of the full solar cycle length only (the scale for the full cycle is from 1 to 2 on the abscissa) and, except of that, the points in the diagram are remarkably dispersed (the point related to the near-maximum 1991 eclipse is, of course, well outside this figure). Therefore, to draw the dependence of $d$ on the cycle phase seems very questionable under these conditions.
- Moreover, we have realized a computer processing of the white-light corona taken during the near-maximum 1991 solar eclipse. Without any doubts, a lot of the p.p.-like structures have been detected over the solar magnetic poles. It is evident that the hypothetical bar magnet is, in the case of this eclipse, far from to be parallel or identical with the rotational axis of the Sun. The case of the 1991 eclipse imply that the p.p. are, very probably, always present on the Sun. Their visibility near to the solar cycle maxima depends on the real spatial distribution of the large-scale solar magnetic field and the real orientation of the HCS.

- Taking into account both above objections we are inclined to reject idea on possible existence of the hypothetical bar magnet in the Sun.

6. CONCLUSIONS

(1) Polar plumes are numerous and best visible in the periods of solar activity minima when the heliographic and helimagnetic equators are more or less identical.

(2) Number of the polar plumes visible on the white-light eclipse corona images taken with the $D = 10-13$ cm, $f = 100-200$ cm telescopes is about 11-16 over each of the solar poles.

(3) The polar plumes seem to be strongly related and well copy the large-scale solar magnetic field topology.

(4) Polar plumes are, most probably, permanently present on the Sun. Their visibility outside of the solar cycle minima is, however, strongly influenced by the actual geometry of the HCS relatively to the observer.

(5) Original idea about a quasi-rigid hypothetical bar magnet inside the Sun should be rejected in confrontation with the dominant role of the global magnetic field evolution throughout the 22-year solar magnetic cycle. From this follows that the variability of the length of the hypothetical bar magnet with the solar cycle phase represents to large extent illusion only.

(6) Preceding point is directly connected with previously published criticism of the Ludendorff's definition of the solar corona flattening an with a concept of the permanently "flat solar corona (Gulyaev, 1992; Sykora & Badalyan, 1992; Sykora & Ambrož, 1997). We are convinced that the LASCO 3C at SOHO will reveal the flattened corona in a number of days during coming solar cycle maximum always when the orientation of the HCS is well seen from the edge".

ACKNOWLEDGMENTS

This work was supported by the VEGA grants 2/5007/98 and 2/5017/98 of the Slovak Academy of Sciences and partially by the grant GA/AVČR No. A3003806, the Key Project AVČR No. K1-003-061 and by the grant No. 96-02-17054 of the Russian Foundation for Basic Research.

REFERENCES

Figure 1. Examples of the computer-processed eclipse corona images. Due to "favourable" conditions (described in the text) the near-maximum 1991 corona is rather similar in form to the three near-minimum coronae. Substantial difference is in inclination of the flattened 1991 form to the shown heliographic orientation in comparison with other three eclipses.
Figure 2. Drawings of the eclipse coronal structures (in the first column), together with the calculated open and closed coronal magnetic fields in the second and third columns, respectively.

Figure 3. Calculated open magnetic fields for the eclipse days and four days after eclipses. Corresponding synoptic maps of the large-scale magnetic field distribution at the source surface level $r = 4.0 \, R_\odot$ are shown in the last column.
Figure 4. Very different forms of these two near-maximum coronae are due to the specific positions of the neutral magnetic field lines in both cases.

Figure 5. Polar plumes were well visible over the heliomagnetic poles at the near-maximum July 11, 1991 eclipse.

Figure 6. Structure of the 1991 corona would be drastically different after four days, similar to that of February 16, 1980.
Figure 7. Upper row: The scheme to understand geometry of the $\alpha/\varphi$ dependence of the p.p. at different eclipses and the Saito's diagram of the bar magnet length $d$ dependence on the solar cycle phase. Middle row: The really measured p.p. from the slopes of which the $\alpha/\varphi$ relations presented in the lowest row were obtained.