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AN INTERPLANETARY DISTURBANCE RELEVANT TO THE TALL-TURNING OF COMET BRADFIELD(1979 L) ON 1980 FEBRUARY 6

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Abstract

Solar wind data obtained with spacecraft and IPS (interplanetary scintillation) observations in early February 1980 are examined in order to determine large-scale propagation properties of a proposed interplanetary disturbance relevant to a very rapid 10^{o} turning of the plasma tail axis of comet Bradfield (1979l) on 6 February 1980. It is shown that a solar-flare-associated interplanetary disturbance having an oblate configuration was responsible for the tail event.

1. Introduction

Some optical characteristics of comets could be used to study the solar wind (e.g., Mendis and Ip, 1977; Brandt and Chapman, 1982; Mendis and Houpis, 1982; Ip, 1985). Fluctuations in the brightness of the heads of comets might be related to properties of the solar wind

(Miller, 1976). Dryer et al. (1976),for example, suggested that the interaction of interplanetary shock waves with cometary atmosphere may be a principal factor responsible for cometary brightness fluctuations. At present, however, the responses of individual comets to solar-interplanetary events are not well-calibrated enough to be used for study of the solar wind. The disconnection of the plasma tail from the cometary head could be related to a passage of a sector boundary of interplanetary magnetic field through the magnetic-line reconnection process (Niedner and Brandt, 1978, 1979; Niedner et al., 1981; Niedner, 1982). On the other hand, Ip and Mendis (1978) and Ip (1980) proposed that dynamic effects of a high-speed solar wind stream could equally cause large-scale perturbation in the cometary ionosphere and plasma tail. The outward motion of knots and kinks in plasma tails seems to be related to solar wind properties (e.g., Jockers, 1981). A secondary tail evolution in comet Bennett (1970 II) observed on 31 March 1970 has been correlated with a solar-flare-associated interplanetary shock wave (Jockers and Lüst, 1973).

Although the above-mentioned optical characteristics of comets have the potential to be used to study the solar wind, the physics involved remains unclear at present. On the other hand, the spatial orientation of the plasma tail of a comet could be used as an indicator of the solar wind velocity because the physical process involved seems to be simple. According to the wind-sock theory of the cometary plasma tail (Brandt et al., 1972; Brandt and Rothe, 1976), the direction of the tail $\mathbf{T}$ is given by $\mathbf{T} = \mathbf{w} - \mathbf{V}$, where $\mathbf{w}$ is the solar wind velocity, and $\mathbf{V}$ is the orbital velocity of the comet. It is easily understood that an encounter with rapidly changing solar wind conditions (change in the magnitude of the flow speed and/or the flow orientation) causes a rapid change in the position angle of the plasma tail axis. For example, if the comet encountered a high-speed stream, a turning or a kink of the plasma tail should be resulted. The tail turning could be produced also by a transient variation in the flow direction. The tail event of comet Kohouteck on 20 January 1974 has been attributed to a large, rapid change in the polar component of the solar wind velocity which was observed on the forward edge of the compression region of a high-speed solar wind stream (Niedner et al., 1978). Jockers and Lüst (1973) proposed that the transient tail turning of comet Bennett (1970 II) on 5 April 1970 took place when the comet would have had an encounter with a high-speed solar wind stream whose existence was inferred from solar wind observations with OGO 5 and HEOS 1 (Jockers and Lüst, 1973). On the other hand, Burlaga et al. (1973) showed that there was no solar wind stream in the ecliptic plane which was responsible for the large kink of the same comet observed on 4 April 1970 and that a high-speed solar wind stream preceded by a shock wave in the ecliptic plane on 27 March 1970 produced no appreciable perturbation in the comet tail. However, since the comet was situated about 40° above the ecliptic plane during the interval from late March to early April 1970, it is necessary to take into account latitudinal variation in solar wind parameters as shown by IPS observations (e.g., Watanabe et al., 1974; Kojima and Kakinuma, 1986). Thus, it is necessary to study individual tail events on the basis of much more complete data sets to establish causal relationship between solar-interplanetary phenomena and cometary tail events.

In this paper, we discuss solar wind properties relevant to a tail event of comet Bradfield 1979l (a very rapid 10° turning of the plasma tail axis) which took place on 6 February 1980 (Brandt et al., 1980; Jockers, 1981; Le Borgne, 1982; Le Borgne, 1983; Niedner et al., 1983) to see which kind of solar-interplanetary phenomenon was responsible for the tail event. The data sources of the solar wind parameters are spacecraft observations and IPS (interplanetary scintillation) observations. Since IPS observations provide us with solar wind data in the region above and below the ecliptic plane, we determine three-dimensional properties of the solar wind relating to the tail event. First, we briefly review photographic observations of the tail event and spacecraft observations of solar wind plasma, then analyze IPS observations to obtain an empirical model of the solar wind structure which produced the tail event.

2. Tail event of comet Bradfield(1979l) on 1980 February 6

Observation of the very rapid turning of the plasma tail axis of comet Bradfield (1979l) on 6 February 1980 has been reported by Brandt et al. (1980). The Joint Observatory for Cometary Research (JOCR) provided several photographs of comet Bradfield 1979l which were taken by the 14" f/2 Schmidt comet camera during the tail event on 6

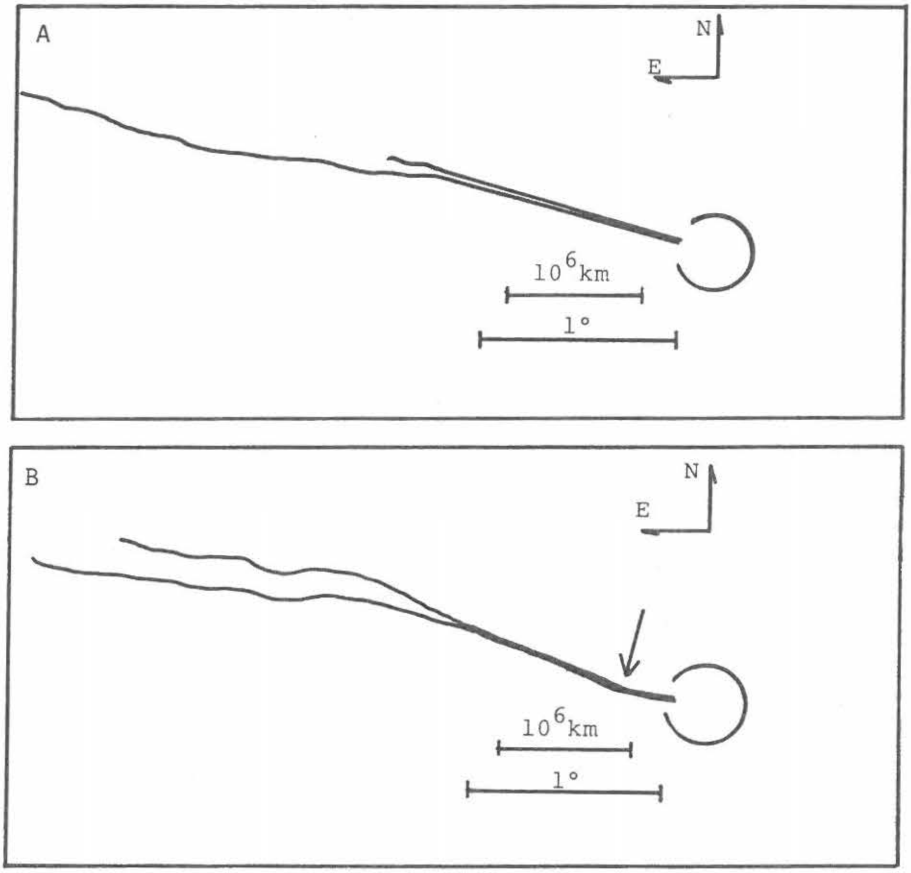

Fig. 1. Schematic drawings of comet Bradfield 1979l taken at (a) 1980 February 6, $2^h32^m.5$ UT, and at (b) $3^h00^m.0$ UT (mid-exposures) after photographs in Brandt et al. (1980).

February 1980. At that time, the comet was situated at 1.13 AU from the Sun and about 25^o to the east of the Sun-Earth line. Two sketches of photographs showing the tail event are given in Figs. 1a and 1b after Figs. 2a and 2c in Brandt et al. (1980). The times of mid-exposure were $2^h32^m.5$ and $3^h00^m.0$ UT, and the exposures were 15 and 10 minutes respectively. The orientation of the innermost plasma tail

(<1.5 X 10^6 km from the coma center) shown in Fig. 1a exhibits the presence of a 30 km/s northward component of the solar wind velocity. In Fig. 1b, the tail shows a sharp bend (arrow) at about 6 X 10^5 km from the coma center, instead of straight configuration of the inner tail seen in Fig. 1a. The increment of the orientation of the inner tail is 10° between Fig. 1a and Fig. 1b. Since the outer tail does not show the bend observed in the inner tail, Brandt et al. (1980) concluded that all or most of the change in the plasma tail between Fig. 1a and Fig. 1b took place in the inner tail region. These authors showed that the position angle of the tail of comet Bradfield on 6 February 1980 was very sensitive to the polar component of the solar wind velocity, and that it was extremely insensitive to the radial and the azimuthal components. They have proposed that a 50 km/s change in the polar component of the solar wind velocity, from about 30 km/s northward to about 20 km/s southward, is necessary to produce the tail event.

3. Solar wind observations

The solar wind was monitored by several spacecraft and by IPS observations of 3C48 and 3C144 in early February 1980. The locations of the spacecraft, Helios 1, Helios 2, Pioneer XII (Pioneer-Venus-Orbiter, PVO), and ISEE-3, and the lines of sight of 3C48 and 3C144 on 6 February 1980 are shown in Fig. 2 as a projection on to the ecliptic plane. The peak of the scattering weighting function of the line-of-sight of each radio source is indicated by an asterisk together with the latitude relative to the ecliptic for each line-of-sight. The location of comet Bradfield 1979l is also shown. It is noted in this figure that Helios 2 was especially well situated relative to the comet, 0.15 AU upstream of the comet on approximately the same solar radial. The spacecraft ISEE-3 was located at $24^{\circ}.7$ to the west of the comet. Solar wind parameters obtained at Helios 2 (flow speed, proton number density, proton temperature, azimuthal flow angle, and polar flow angle) are shown in Fig. 3 after Le Borgne (1982, 1983). The solar wind flow speeds obtained by the IPS observations of 3C48 are also plotted in this figure for comparison. The solar wind parameters (flow speed, proton number density, and proton temperature) at ISEE-3

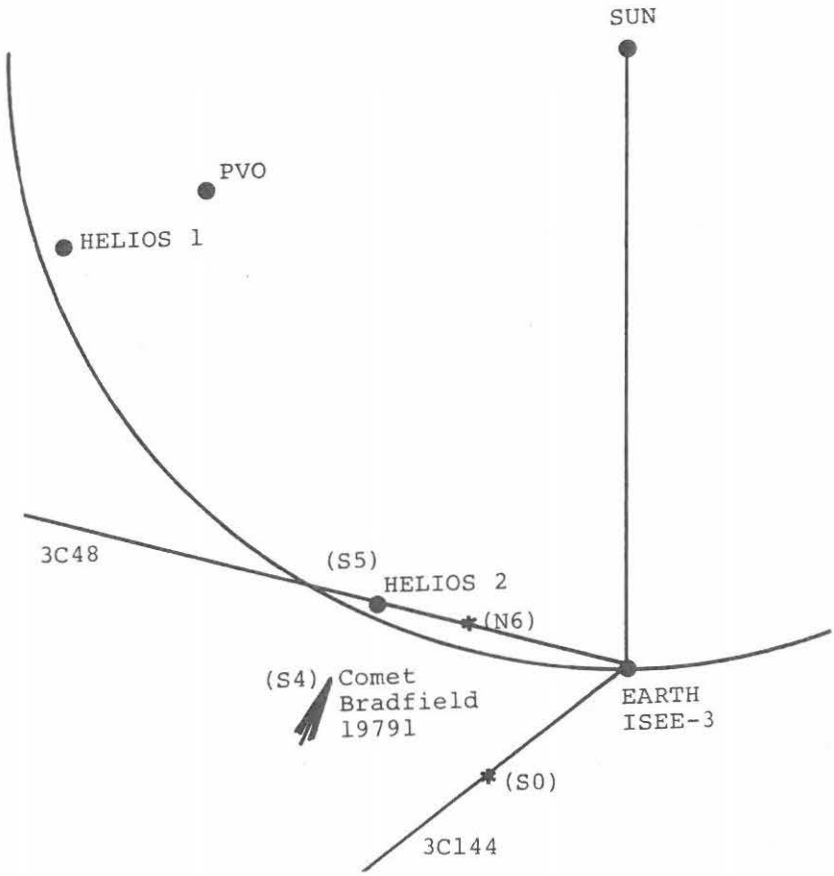

Fig. 2. Geometry of observation points and comet Bradfield 1979l on 6 February 1980 as a projection on to the ecliptic-plane (viewed from the north). The lines of sight of 3C48 and 3C144 are also shown. The asterisk on each line-of-sight represents the position of the peak of the scattering weighting function. The heliocentric latitudes of important observation points are given.

(1-hour averages) are given in Fig. 4 after King (1983). The solar wind flow speeds obtained by the IPS observations of 3C48 are also plotted in this figure. Detailed discussion on the IPS observations will be given in the next section.

As seen in Fig. 3, the solar wind velocity increased rapidly from about 350 km/s to about 880 km/s in less than 2 hours at Helios 2 at about $16^h 30^m$ UT, 5 February 1980, about 12 hours before the tail event. Although this rapid increase in the flow speed suggests the presence of an interplanetary shock wave, the proton number density plotted in Fig. 3 did not show a density spike or compression region accompanying the increase in flow speed (Le Borgne, 1982, 1983; Niedner et al., 1983). Le Borgne (1982, 1983) suggested that very low value of the proton number density ($N_p < 1/cm^3$) of the ambient solar wind was responsible for such a peculiar situation. This solar wind feature should be checked by a much more complete data set. The north-south direction of the solar wind flow vector showed a 20^o turning immediately following the velocity increase. Le Borgne (1982, 1983) and Niedner et al. (1983) have attributed the 10^o turning of the plasma tail axis of comet Bradfield 1979l on 6 February, 1980 to the turning of the flow vector of the solar wind.

For solar wind data obtained at ISEE-3 (Fig. 4), the solar wind flow speed showed an increase from about 320 km/s to about 450 km/s in the data gap between 3^h and 7^h UT on 6 February, 1980. The proton number density also showed an increase from about $7/cm^3$ to $12/cm^3$. This solar wind condition suggests the presence of an interplanetary shock wave disturbance near the Earth, in spite of the data gap. An SSC of geomagnetic storm took place at 03^h21^m of 6 February, 1980 (Solar-Geophysical Data, No. 428 Part I, 138, April 1980, U. S. Department of Commerce, Boulder, Colorado, 30803, U.S.A.). Le Borgne (1982, 1983) and Niedner et al. (1983) suggested that the solar wind feature seen at ISEE-3 is the same structure as was observed at Helios 2 (the sharp velocity increase) on 5 February 1980, about 12 hours earlier than the detection at ISEE-3. Since the 12-hour time delay is incompatible with the expected corotation delay between Helios 2 and ISEE-3 (about 2 days), the presence of a quasi-spherical interplanetary disturbance is suggested by these authors. They also proposed that the solar source of the interplanetary disturbance was a 1B solar flare, accompanied by Type IV radio bursts, which took place at S15E15 at about 13^h28^m UT, 3 February 1980 (Solar-Geophysical Data, No. 447 Part II, 44-73, Nov. 1981). The interplanetary disturbance should have made an anisotropic expansion between the radial directions of Helios 2 and ISEE-3 because the mean transit speed of the interplanetary disturbance between the Sun and Helios 2 was 815 km/s while the mean speed between the Sun and ISEE-3 was 662 km/s (Niedner et al., 1983). The anisotropic nature of the disturbance is also suggested by the difference between the enhanced flow speeds; 880 km/s at Helios 2, while 450 km/s at ISEE-3.

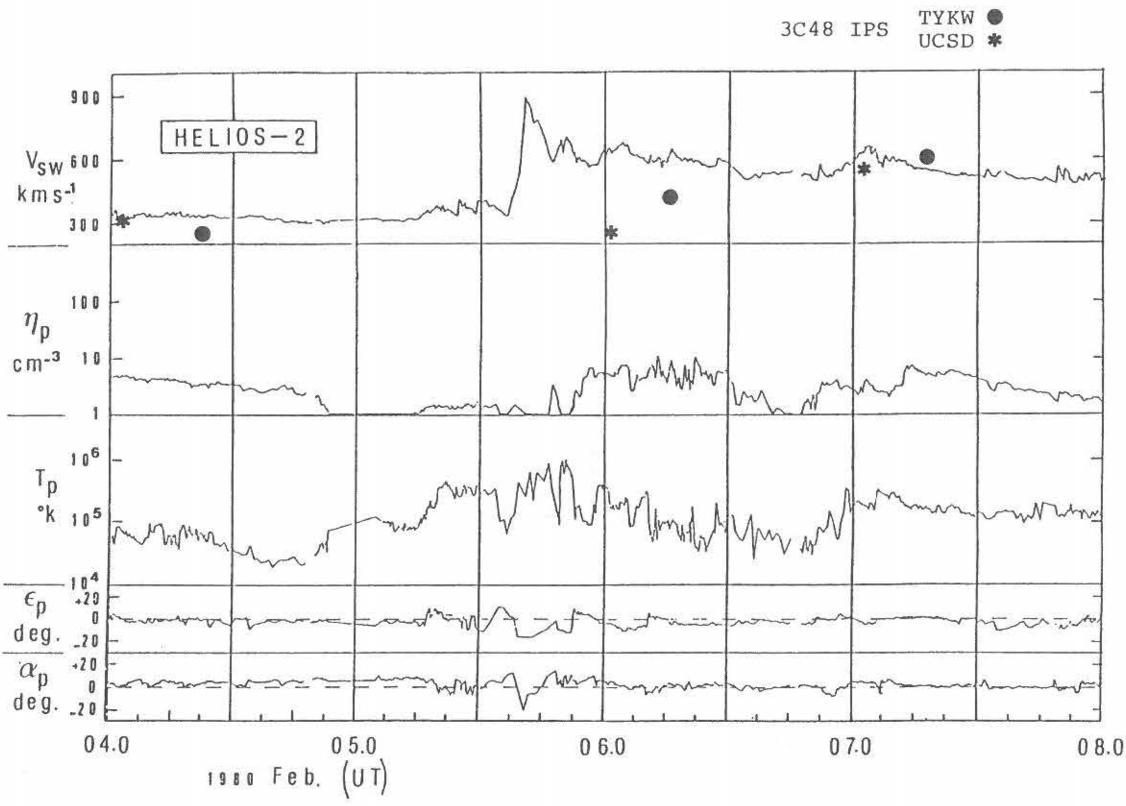

Fig. 3. Solar wind data obtained at Helios 2 in early February 1980 (Le Borgne, 1982): solar wind flow speed (V_{sw}), proton number density (N_p), azimuthal flow angle (ε_p), and polar flow angle (α_p). Solar wind speeds obtained by IPS observations of 3C48 at the University of California, San Diego (UCSD; Solar-Geophysical Data, No. 427 Part I, 35, March 1980) and at Toyokawa (TYKW) are also plotted. The data point for IPS observation at UCSD is the average of the peak velocity and the mean velocity (Solar-Geophysical Data, No. 489 Supplement, 13-14, May 1985). The plot of Helios 2 data are reproduced from Le Borgne (1982) under the author's permission.

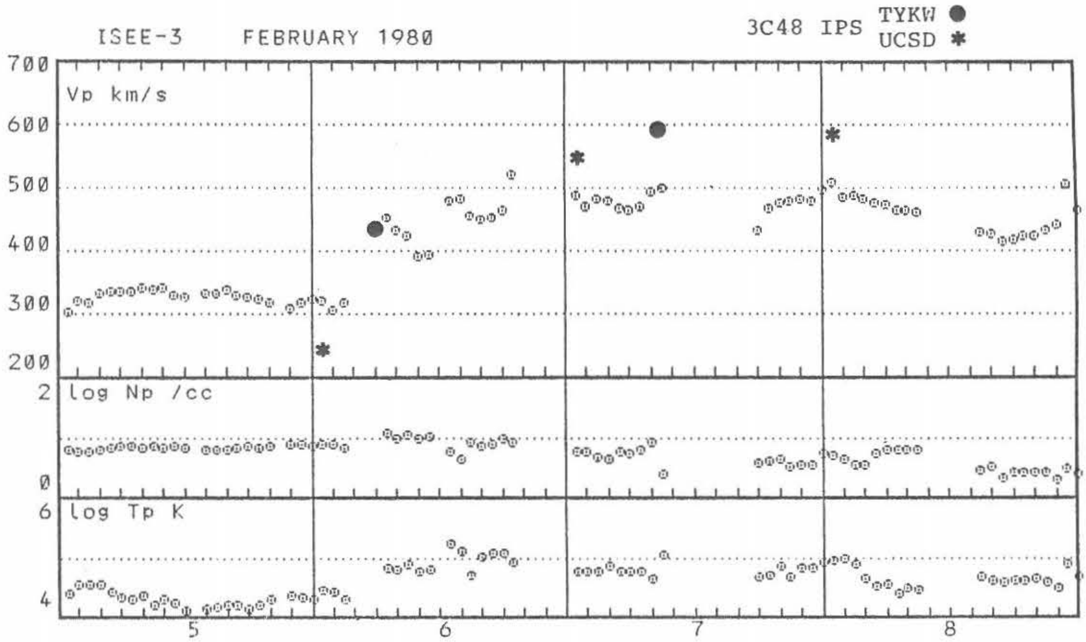

Fig. 4. Same as Fig. 3 but for solar wind data obtained at ISEE-3 (one-hour averages) during 5-8 February 1980 (King, 1983): solar wind speed (V_p), proton number density (N_p) and proton temperature (T_p). Solar wind speeds obtained with IPS observations of 3C48 at the University of California, San Diego (UCSD; Solar-Geophysical Data, No. 427 Part I, 35, March 1980) and at Toyokwa (TYKW) are also plotted.

4. IPS observations

Above-mentioned spacecraft observations of the solar wind plasma suggest the presence of a quasi-spherical interplanetary disturbance which caused the tail event of comet Bradfield 1979l on 6 February

1980. In this section we see how the interplanetary disturbance was observed by IPS observations. The three-station IPS observation provides us with the solar wind speed and the scintillation level, a measure of the turbulent state of the solar wind plasma. In early February 1980, three-station IPS observations were performed by two groups at the University of California, San Diego (UCSD; Armstrong and Coles, 1972) and at Toyokawa (TYKW). The observing frequencies were 74 MHz and 69 MHz respectively. The flow speeds obtained by the UCSD group have been published in Solar-Geophysical Data (No. 427 Part I, 35, March 1980). The solar wind flow speeds obtained by IPS observations of 3C48 in early February 1980 are plotted in Fig. 3 and also in Fig. 4 with spacecraft observations.

Many previous works concerning IPS observations of interplanetary disturbances have showed that an interplanetary disturbance associated with a solar flare or a disappearing solar filament may be identified by the enhanced flow speed and high level scintillation (e.g., Kakinuma and Watanabe, 1976; Watanabe and Kakinuma, 1984). As seen in Fig. 3 (and also in Fig. 4), IPS observations of 3C48 at UCSD at about 01^h UT, 6 February 1980 showed the presence of the slow speed solar wind of less than 300 km/s on the line-of-sight of 3C48. On the other hand, the IPS observation of the same radio source at TYKW, which was performed about five hours after the UCSD observation, at about 06^h UT, 6 February 1980 showed that the solar wind speed increased by about 190 km/s to 427 km/s. The observed level of scintillation at TYKW was high on the date. This suggests that an interplanetary disturbance arrived at the line-of-sight of 3C48 between 1^h UT and 6^h UT on 6 February 1980. Since Helios 2 and ISEE-3 observations suggest the presence of a quasi-spherical interplanetary disturbance near 1 AU during 5-6 February 1980, it is reasonable to conclude that the solar wind feature observed by IPS of 3C48 on 6 is the same solar wind structure (the interplanetary disturbance) as was observed at Helios 2 (5 February) and at ISEE-3 (6 February). The flow speed obtained by IPS observation of 3C48 at TYKW on 6 February 1980 was smaller than the speeds observed at Helios 2 (Fig. 3) but close to those observed at ISEE-3 on the same date (Fig. 4). As shown in Fig. 2, the line-of-sight of 3C48 was located in the region to the north of the ecliptic plane, while Helios 2 was located about 4° to the south of the ecliptic plane. It is conceivable that the IPS data reflect the anisotropic nature of the interplanetary disturbance in question.

5. Empirical modeling of interplanetary disturbance relevant to tail event of comet Bradfield on 1980 February 6

We have seen in the previous section that the solar wind flow speed obtained by the IPS observation of 3C48 on 6 February 1980 suggests the anisotropic expansion of the interplanetary disturbance relating to the tail turning event. Since the flow speed obtained with the IPS technique is the weighted average of transverse components of flow vectors crossing the line-of-sight of the observed radio source, it is necessary to take into account the integration effect in interpretation of IPS data. In this section we try to find an empirical model of the interplanetary disturbance which was responsible for the tail event on 6 February 1980 by adjusting the modeled angular and radial distribution of solar wind parameters (flow speed and level of density fluctuation) obtained with IPS and spacecraft observations.

The method of predicting the flow speed and the level of scintillation is similar to that employed by Harmon (1978) to determine the response in the observed flow speed when a corotating high-speed stream of the solar wind is crossing a line-of-sight. This method assumes an extended weak scattering medium, power-law electron density fluctuations, inverse-square fall off of the level of electron density fluctuations with the heliocentric distance, and Gaussian brightness distribution of the observing radio source. First, we assume suitable spatial distribution of the flow speed and the magnitude of electron density fluctuations, then calculate the cross-spectrum assuming a 100 km baseline of two antennas. The flow speed is estimated from the cross-correlation function which is obtained through the Fourier transformation of the cross spectrum. The level of scintillation is also estimated.

We define a directional coefficient D(L,B) which is a function of the heliocentric longitude L (measured from the Sun-Earth line) and the latitude B (measured from the ecliptic plane);

$$D(L,B) = \cos a(L-L_0) \cos b(B-B_0), \qquad (1)$$

where (L_0,B_0) are the heliocentric coordinates of the highest-velocity point of the disturbance. In this equation, "a" and "b" are multiplication factors. The sign of L (B) is chosen to be negative in the region to the east (south) of the Sun-Earth line (ecliptic plane). The directional distribution of the solar wind speed (radial flow is assumed) is represented by

$$V(L,B) = V_n(L,B) + D(L,B)V_{max} \qquad (2)$$

where $V_n(L,B)$ is the directional distribution of the ambient flow speed, and V_{max} is the maximum flow speed of the disturbance. We also apply the same directional coefficient to the angular distribution of the radial thickness of the turbulent shell and the level of electron density fluctuations. In the modeling procedure we ignore the presence of a sharp peak of the solar wind flow speed up to 850 km/s observed at Helios 2 on 5 February 1980 for about three hours (Fig. 3) for the following reason. According to previous works (e.g., Kakinuma and Watanabe, 1976; Chao, 1984; Hewish et al., 1985), IPS is sensitive to the high density portion of an interplanetary disturbance where the level of electron density fluctuations will be also high. Since the solar wind data obtained at Helios 2 (Fig. 3) suggest that the density of the high-speed portion, which appeared at Helios 2 on 5 February 1980 at the leading edge of the interplanetary disturbance in question, was low and that the radial thickness of the portion was thin, its contribution to observed IPS would not have been important. Thus, we assume that the leading edge of the shell of the turbulent solar wind in the Sun-Helios 2 direction corresponds to the leading edge of the relatively high-density solar wind ($N_p \sim 10/cm^3$) which appeared at about 21^h UT, 5 February 1980 at Helios 2 (Fig. 3). The proton temperature showed a decrease after the appearance of the density enhancement. This seems to be an indication of the driver gas (Zwickl et al., 1983). An enhancement in the He/H ratio will be another indication of the driver gas (e.g., Borrini et al., 1982). The He/H ratio observed at ISEE-3 (Niedner et al., 1983) showed a small increase after the first detection of velocity enhancement at about 7^h UT, 6 February 1980. Although the solar wind data is not fully available at present, the above-mentioned spacecraft observations suggest that the density enhancement corresponds to the driver gas of the interplanetary disturbance. Thus, the empirical model obtained in this section is for the probable shock driver of the interplanetary disturbance relevant to the tail event of comet Bradfield on 6 February 1980.

The spacecraft and IPS observations on 5-6 February 1980 are well reproduced when we assume that the directional distribution of the solar wind speed is

$$V(L,B) = 330 + 440 \cos 2(L+30^{\circ}) \cos 3(B+10^{\circ}) \quad km/s. \qquad (3)$$

The highest-velocity point is located in the radial direction of (L_o=-30°, B_o=-10°). In this modeling, we assume that the maximum thickness of the turbulent shell is 0.4 AU and that the rms electron density fluctuations is 4 times as high as the ambient level. The directional diagram of V(L,B) is shown in Figs. 5a-5b. It is seen that the highest-speed portion of the disturbance is located in the region to the east of the Sun-Earth line and to the south of the ecliptic plane. The latitudinal gradient of the predicted flow speed is larger than the longitudinal gradient. Thus an approximate configuration of the disturbance may be represented by an oblate sphere having a characteristic axial ratio of 1.4. This model is also consistent with the flow speed (470 km/s) which was observed by IPS of 3C144 at about 1.2 AU from the Sun and 13° to the east of the Sun-Earth line on 7 February 1980.

6. Concluding remarks

We have seen that the interplanetary disturbance relevant to the tail turning of comet Bradfield (1979l) on 6 February 1980 was detected by IPS and spacecraft observations. Three-dimensional propagation properties of the interplanetary disturbance near 1 AU has been determined through the model-fitting procedure. The large-scale configuration of the interplanetary disturbance may be approximated by an oblate sphere having an axial ratio of 1.4, as seen for some other events (Watanabe and Kakinuma, 1984). The model predicts rather narrow extent both in the longitudinal and the latitudinal directions. On the longitudinal direction, this model is consistent with the conclusion given by Le Borgne (1982, 1983); the disturbance was not recorded at Helios 1 and at Pioneer XII (PVO) which were located in the eastern, relatively weaker skirt of the modeled interplanetary disturbance (see Fig. 2 and Fig. 5a).

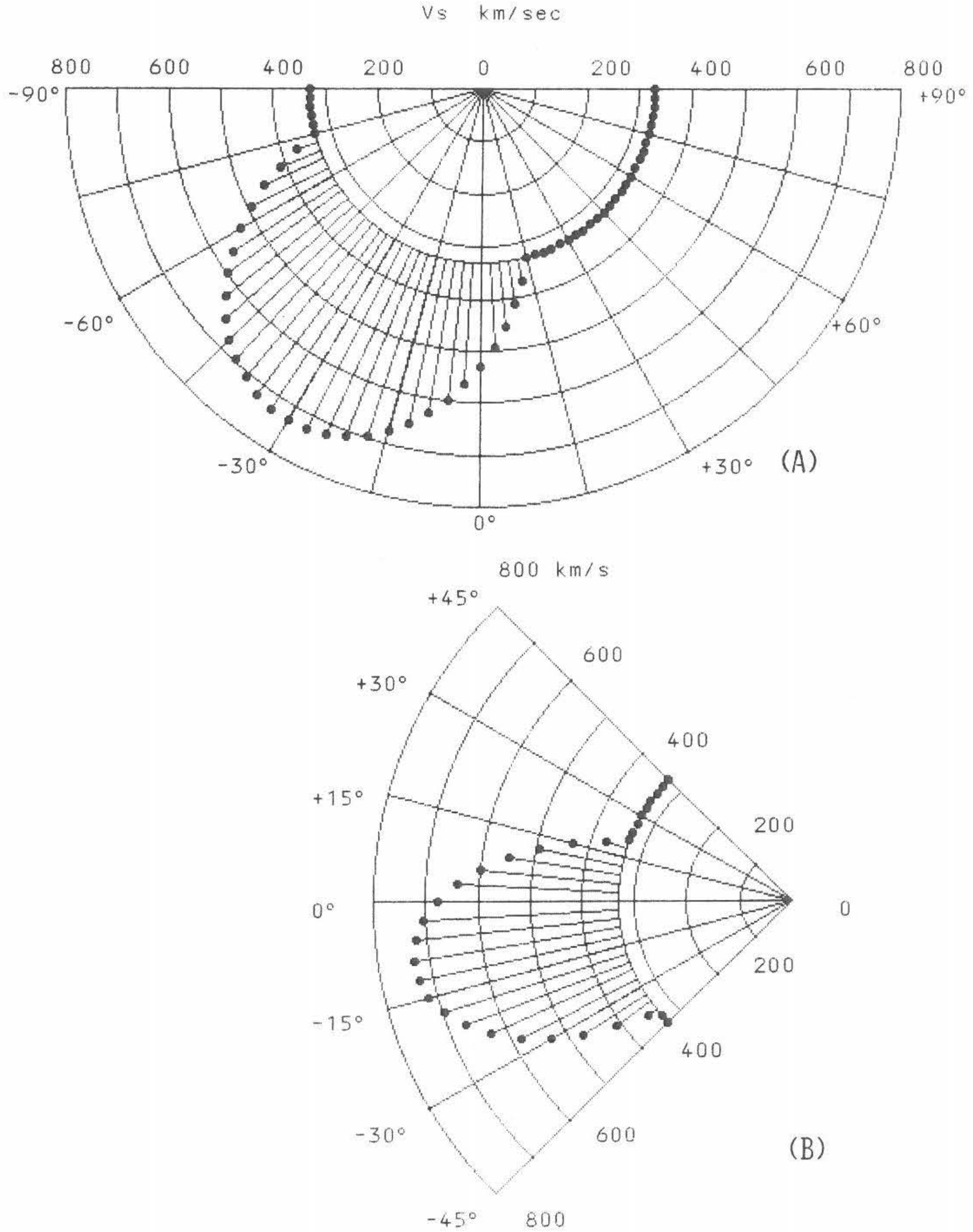

Fig. 5. A directional distribution of the solar wind flow speed representing the modeled interplanetary disturbance relevant to the tail event of comet Bradfield 1979l on 6 February 1980: (a) in the longitudinal direction, and (b) in the latitudinal direction. The speed of the ambient solar wind is assumed to be 330 km/s.

The highest-velocity portion of interplanetary disturbances appeared frequently in the direction around the flare normal (Pintér, 1982). Since the highest-velocity portion of the disturbance was located in the region to the east of the Sun-Earth line and to the south of the ecliptic plane, the solar source of the disturbance would have been to the east of the central meridian and in the southern hemisphere of the solar disk (the heliographic latitude of the sub-Earth point (B_o) was about -6^o in early February 1980). The most plausible candidate for the solar source is a 1B solar flare, the same flare as that proposed by Le Borgne (1982, 1983) and Niedner et al. (1980); $\sim 13^h 28^m$ UT, 3 February 1980, S15E15 with associated Type IV radio bursts.

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