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INTERPLANETETALY MANIFESTATION OF THE "HALO" CORONAL MASS EJECTION OF NOVEMBER 27, 1979

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Abstract

This paper presents a case study of a solar wind disturbance associated with the "halo" coronal mass ejection (CME) of November 27, 1979, which was a 360° coronal density enhancement encircling the occulting disk (Howard et al., 1982). The principal sources of solar wind data are spacecraft observations and IPS observations. The interplanetary manifestation of the CME was a quasi-spherical solar wind disturbance. The total angular spread was greater than 70° at 1 AU heliocentric distance in the longitudinal direction.

I. Introduction

A dense cloud of plasma propagating within the solar corona is termed a "coronal mass ejection" (CME) or a "coronal transient". Observational and theoretical efforts have been focused on understanding the CME phenomenon since many CME events were recorded by

Skylab in 1973 (Hildner, 1979; Dryer, 1980; Wagner, 1984). The study of the CME event is particularly important for solar-interplanetary physics because the mass injected into the solar wind by a CME sometimes exceeds 10^{16} g, and the total energy can be greater than 10^{32} erg (Howard et al., 1985). These values are comparable to those of a solar wind disturbance associated with a major solar flare.

Since CMEs have been observed in projection on the plane of the sky, the three-dimensional characteristics of the CMEs are not fully understood. Trottet and MacQueen (1980) showed that loop-like CMEs are strongly correlated with filament regions where the filament axis was oriented north-south. They proposed that CMEs have a planar structure of small extent in the line-of-sight direction. Mouschovias and Poland (1978) presented a model based on the assumption that a CME is a large loop. On the other hand, Crifo et al. (1983) proposed that, on the basis of the polarization analysis, a seemingly loop-like CME observed by Skylab on 10 August 1973 actually had a bubble-shaped structure. A numerical model of the CME phenomenon also suggests a bubble-like configuration (Dryer et al., 1979; Wu et al., 1983). Thus it is important to distinguish between these two geometrical interpretations by observation. One approach to the question is to observe the interplanetary manifestation of CMEs by a network of observation points which are distributed in a wide range of interplanetary space. The IPS technique is one of the promising means by which to study the three-dimensional properties of CMEs in interplanetary space.

An "edge-on" CME, whose solar source is situated near the solar limb, is somewhat difficult to observe using the IPS technique because the principal portion of the CME in interplanetary space crosses the line-of-sight of a radio source at a position beyond the principal scattering zone (Watanabe and Kakinuma, 1985a). On the other hand, a "halo" CME, which shows a region of excess brightness in the solar corona nearly surrounding the occulting disk (Howard et al., 1985), is suitable for a coordinative study between the white-light coronal observations and the IPS observations. The halo CME is usually associated with a solar phenomenon occurring near the center of the solar disk, thus the expansion toward the Earth is unavoidable. A good example of the halo-type CME was obtained during 0822-0958 UT on November 27, 1979 by the Naval Research Laboratory's white-light coronagraph, Solwind, on satellite P78-1 (Howard et al., 1982). This CME was also observed by the zodiacal light photometers on Helios B at

0.5 AU (Jackson, 1984). A solar wind shock wave disturbance was detected by the ISEE spacecrafts (Ogilvie et al., 1982; Russell et al., 1983) and an SSC (storm sudden commencement) associated with the disturbance was observed at 0738 UT on November 30, 1979 (Solar Geophysical Data, 1979). Howard et al. (1982) proposed that this shock wave was the interplanetary manifestation of the CME. In this paper, the three-dimensional propagation properties of the solar wind disturbance associated with the halo CME of November 27, 1979 are discussed on the basis of IPS and spacecraft observations.

II. Solar/Interplanetary Observations

The halo CME in question was detected by the Solwind coronagraph at 0822 UT on Nov. 27, 1979, and continuously traced for about 4 hours (Howard et al., 1982). The outward speed of the leading edge was 600 ± 50 km s^{-1}, and the speed was approximately constant throughout its propagation in the range from 4 to 8 $R_\odot$ for all position angles. The frontal speed is estimated to have been about 1160 km s^{-1} by the authors, assuming that the speed was constant in the solar corona and that the boundary of emission formed a cone with a constant cone angle of 27° centered at the solar disk center. Several photospheric phenomena were observed immediately before the detection of the CME. According to the H_α patrol at Culgoora with a passband of 0.5 Å (quoted by Howard et al., 1982) a large solar filament situated around N05W03 disappeared between 0540 and 0703 UT on Nov. 27, 1979. The H_α patrol at Tokyo Astronomical Observatory, Mitaka with a passband of 0.75 Å (Fig. 1) also showed that the filament was fading when the picture of 0605 UT was taken, and that the principal portion of the filament disappeared by 0645 UT. A 1N class solar flare was recorded in a nearby active region, Hale plage region No. 16448 (N14E05), at 0647 UT (Solar Geophysical Data, 1981) during the disappearance of the solar filament. No type II radio bursts were detected for the solar flare by ground-based radio observations. Howard et al. (1982) proposed that the disappearing filament as well as the 1N flare were the solar sources of the halo CME. They estimated the total mass of the CME to be 2 X 10^{16} g. This was one of the most massive events observed with the Solwind coronagraph during 1979-1981 (Howard et al., 1985).

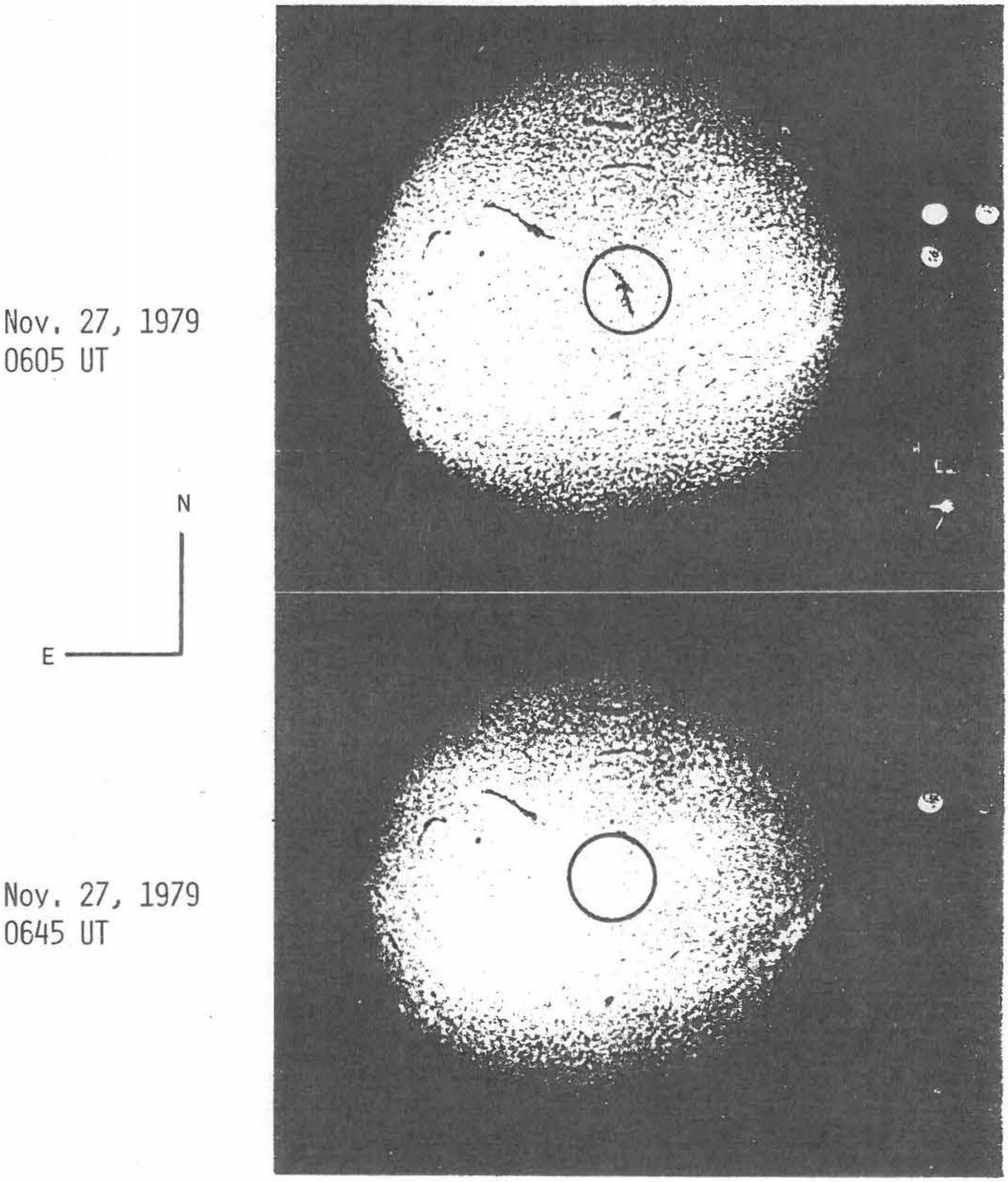

Fig. 1. The H_α filtergrams of the disappearing solar filament of Nov. 27, 1979 taken at Tokyo Astronomical Observatory, Mitaka (through the courtesy of Prof. M. Moriyama).

The northern portion of the CME of Nov. 27, 1979 was clearly observed by the Helios B spacecraft zodiacal light photometers at 30^{o} east of the Sun-Earth line at 0.5 AU heliocentric distance (Jackson, 1984). The brightest portion of the CME showed an approximate outward speed of 500 km s^{-1} at about 0.4 AU from the Sun. The southern portion of the CME was observed by the Helios A photometers at 120^{o} east of the Sun-Earth line at 0.35 AU from the Sun. These observations suggest that the principal portion of the CME was collimated along the Sun-Earth line (Jackson, 1984).

A slight density increase accompanied by an enhancement in the solar wind flow speed was detected at Helios B (E30, 0.5 AU) at 1600 UT on Nov. 28, 1979. Jackson (1979) suggested that this was the interplanetary manifestation of the CME of Nov. 27, 1979. A solar wind shock wave disturbance, whose solar source was attributed to the the halo CME of Nov. 27, 1979 by Howard et al. (1982), was detected at ISEE-1, -2, and -3 on Nov. 30, 1979 (Russell et al., 1983). The best fit shock velocity measured in the observer's frame was 404 km s^{-1} taking account of the angle of the shock normal which was determined by the three-spacecraft observations. The mean shock speed between the Sun and the ISEE-3 spacecraft was about 560 km s^{-1}. Thus the solar wind disturbance decelerated in the region between the Sun and 1 AU heliocentric distance.

The solar wind disturbance in question was also detected by three-station IPS observations. The IPS data (flow speeds) obtained at University of California, San Diego, come from Solar Geophysical Data (1979), and the data obtained at Nagoya University, Toyokawa, are taken from "Solar Wind Flow Speed From IPS Measurements; Jan. - Dec. 1979". Details of the IPS observations were given by Armstrong and Coles (1978) and Kojima (1980) respectively. The geometry of the lines-of-sight of 8 radio sources in late November 1979 is shown in Fig. 2 as a projection on the solar-ecliptic plane (viewed from the north). The daily flow speeds which were obtained by IPS observations of three representative radio sources (3C298, 3C273, and 3C48) are shown in Fig. 3. The IPS index which is rms of intensity fluctuations normalized with respect to the galactic background noise level is also shown for each radio source by shadings on the basis of IPS observations at Toyokawa (arbitrary unit). The solar wind data (flow speed and proton number density) obtained at ISEE-3 and IMP-8 (King, 1983) are also shown in Fig. 3. The identification of a solar wind disturbance in the IPS data can be made in such a way that simultaneous increases in the IPS level as well as in the flow speed due to the turbulent and high-speed post-shock plasma are found (Kakinuma and Watanabe, 1977).

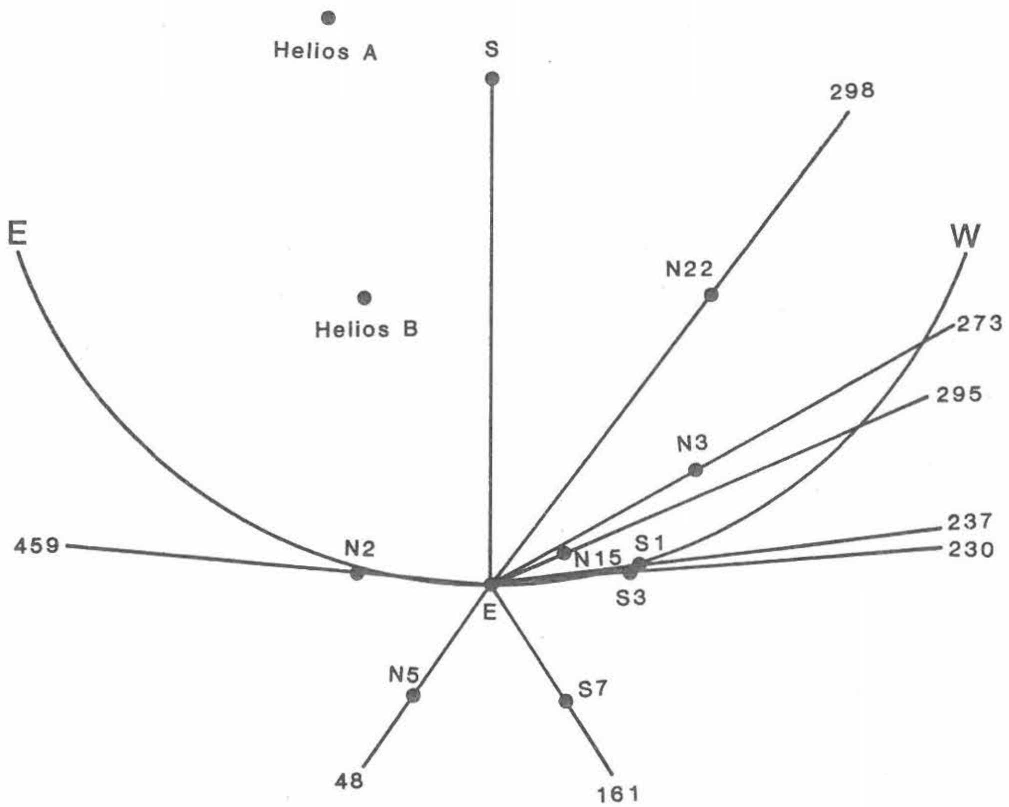

Fig. 2. Geometry of IPS observations in late November 1979. The line-of-sight of each radio source (3C numbers are given) is projected to the ecliptic plane (viewed from the north). The heliocentric latitude of the point of closest approach to the Sun (or the peak of the scattering weighting function) on each line-of-sight is given. The approximate locations of Helios A and Helios B are also shown.

A transient increase in the flow speed as well as the IPS level was observed on Nov. 29 by the IPS observation of 3C298 at Toyokawa. The radio source 3C298 was observed three times a day around the central meridian passage of the radio source. When the first observation was made at 2340 UT on Nov. 28, 1979, a moderately turbulent low speed solar wind of about 290 km s^{-1} was observed. When the second observation was made at 0040 UT on Nov. 29, 1979, the flow speed had increased to 339 km s^{-1}, and a high level IPS was observed.

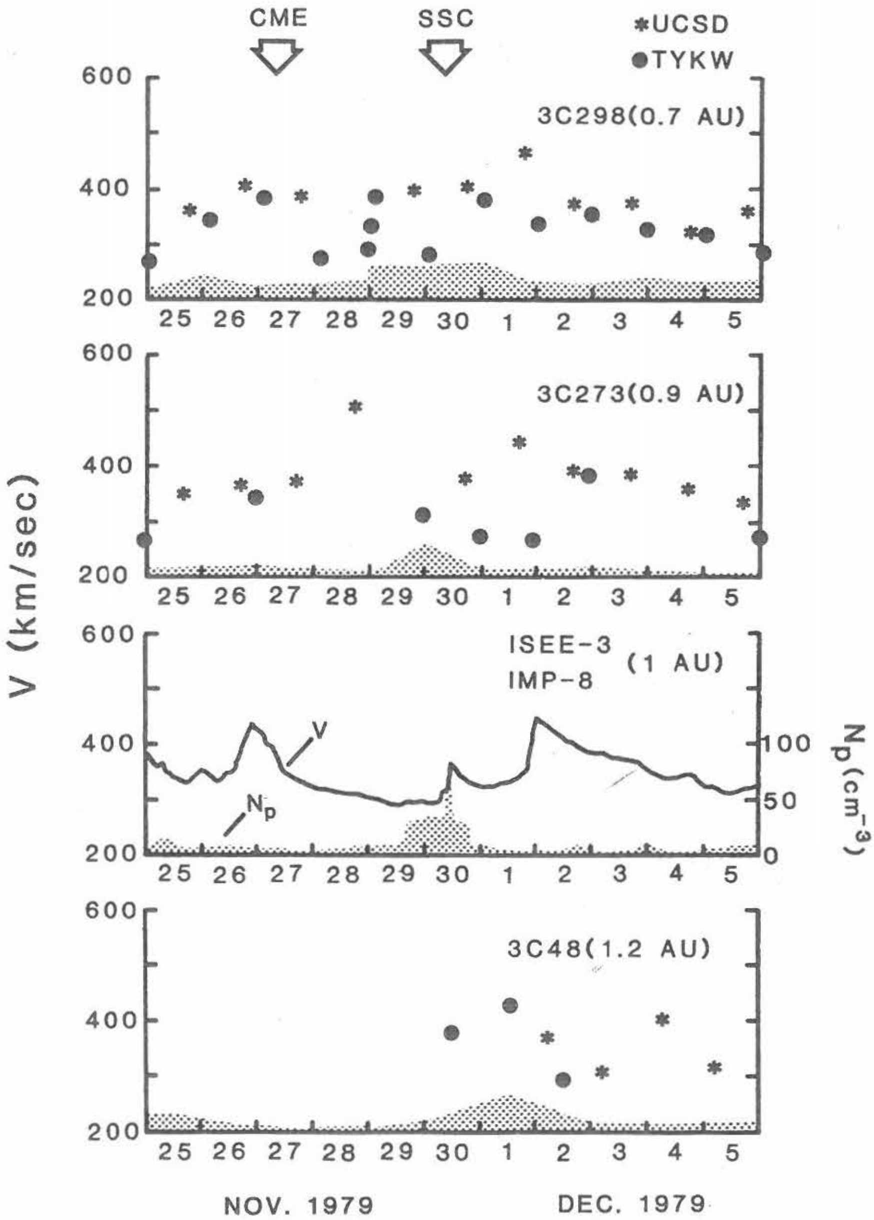

Fig. 3. Daily solar wind flow speeds obtained by three-station IPS observations of 3C298, 3C273 and 3C48 at University of California, San Diego (UCSD) and at Nagoya University, Toyokawa (TYKW). The daily IPS levels obtained at TYKW are shown by shadings in arbitrary units. For the ISEE-3 and IMP-8 solar wind data (King, 1983), proton number density (N_p) is shown by shading.

The high speed and turbulent flow of 390 km s^{-1} was also observed when the third observation was made at 0140 UT. This is one of the rare cases in which a solar wind disturbance crossing the line-of-sight is actually observed. Thus an accurate arrival time of the solar wind disturbance in question at the line-of-sight of 3C298 (about 0040 UT on Nov. 29, 1979) can be determined without the ambiguity (up to 24 hours) caused by the poor time coverage of current IPS observations. The turbulent solar wind with similar speed was also detected by the IPS observations of 3C161, 3C230, 3C237, 3C273, 3C295, and 3C459 on Nov. 30, 1979, and of 3C48 on Dec. 1, 1979. These observations indicate the existence of a "broad-front" solar wind disturbance in the interplanetary region near 1 AU heliocentric distance during Nov. 29 - 30, 1979. The association between the solar wind disturbance and the halo CME as proposed by Howard et al. (1982) is highly plausible because the portion with the highest flow speed appeared around the longitude of the center of the eruption (the normal of the disappearing solar filament of Nov. 27, 1979 at W03).

III. Dynamical Evolution

In this section, the deceleration characteristics of the solar wind disturbance associated with the halo CME of Nov. 27, 1979 are determined on the basis of the IPS and the spacecraft observations. We use the mean shock speed between the Sun and an observation point in interplanetary space and the local shock speed at the observation point. We assume that the dynamical evolution of a solar wind disturbance is expressed by a simple formula;

$$dR/dt = V_o \, (R/R_o)^{-n} \tag{1}$$

where R is the heliocentric distance, and V_o is the initial shock speed at $R = R_o$. Since the transit time, T_i, in which the shock wave travels from R_o to R_i, is obtained through the integration of (1) as follows;

$$T_i = R_i^{n+1} \, / \, (n + 1)V_o R_o^{\,n}. \tag{2}$$

As an approximation, we assume the condition of $R_i \gg R_o$. The mean shock speed, $\bar{v}_i$, in the region between R_o and R_i is

$$\bar{v}_i = (R_i - R_o) / T_i = (n + 1)V_o(R_i/R_o)^{-n}. \quad (3)$$

It is apparent that the power-law deceleration coefficient can be estimated from (4) using the mean shock speed and the local shock speed (Gosling et al., 1975). The heliocentric distance, R', where the mean shock speed is equal to the local shock speed at this distance, is given by the formula;

$$R' / R_i = (n + 1)^{-1/n}. \quad (4)$$

This function has values of 0.4 - 0.5 for n = 0.1 - 1.0. Thus, as a first approximation, each mean speed is plotted at half of the heliocentric distance of the observation point (Pinter, 1982).

For the IPS observations, excepting 3C298, the constraints of the mean shock speed between the Sun and the line-of-sight of each radio source are calculated in the following manner; the upper limit to the mean shock speed is estimated using the heliocentric distance of the point of closest approach to the Sun on the line-of-sight (or the peak of the scattering weighting function along the line-of-sight when the angular distance between the Sun and the radio source was greater than about 70^o) and the time interval between the onset of the relevant solar phenomenon and the time of the IPS observation of the radio source which was made immediately before the first detection of the disturbance. On the other hand, the lower limit to the mean shock speed is estimated using the time of the first detection of the disturbance. We tentatively assume that the onset of the solar wind disturbance was the time of occurrence of the 1N solar flare of 0647 UT, Nov. 27, 1979 which took place while the disappearing-filament phenomenon was in progress near the solar disk center. As a measure of the local shock speed in the observer's frame, the "inferred shock speed" which is the speed taken to be 1.2 times higher than the observed flow speed of the post-shock plasma (Watanabe and Kakinuma, 1984) is calculated for the IPS observations. All of these speeds are plotted in Fig. 4 on a log-log diagram of the shock speed versus heliocentric distance. The local shock speed near the Earth, which is determined by the ISEE spacecraft observations (Russell et al., 1983) and the mean shock speed between the Sun and the Earth are also plotted.

The estimated frontal speed of the halo CME was 1160 km s^{-1}, and

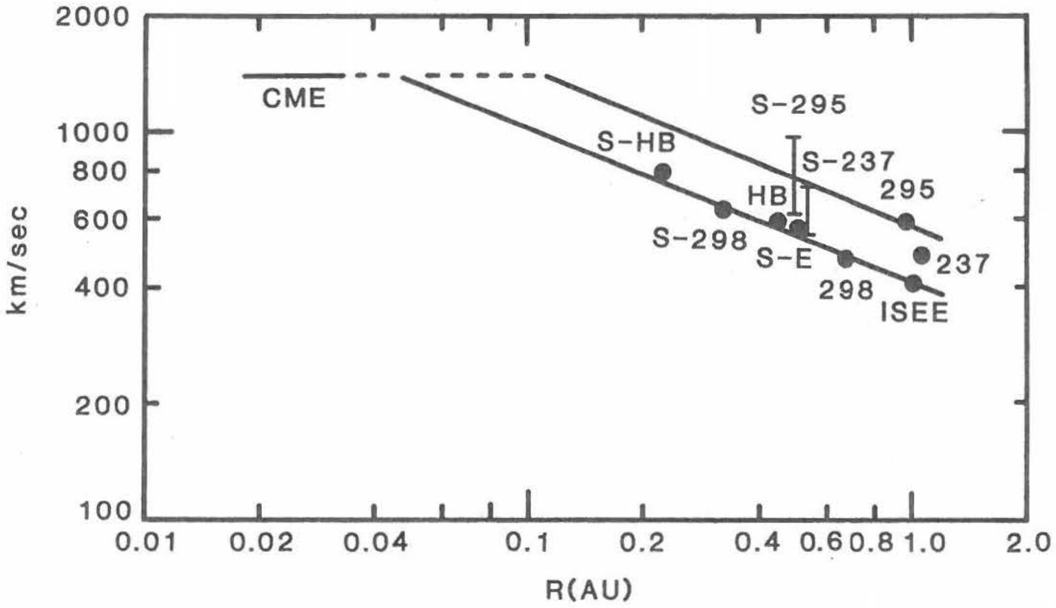

Fig. 4. The shock speed of the solar wind disturbance associated with the halo CME of Nov. 27, 1979 as a function of heliocentric distance, R in AU (see text). The mean shock speed between the Sun and the specific point is indicated in such a way that, e.g., S-E (the mean shock speed between the Sun and the Earth). The shock speed which is inferred from the observations at Helios B (Jackson, 1984) is designated "HB". Since the disturbance showed anisotropic characteristics, the empirical models are given for two representative directions; the Sun-Earth direction and the Sun-3C295 direction (N15).

the speed was nearly constant over the range from 4 $R_\odot$ to 8 $R_\odot$ (Howard et al., 1982). Maxwell and Dryer (1981) suggested that the leading edge of a high-speed white-light CME with a speed of the order 750 to 1000 km s^{-1} is closely related to the contact surface (the front of the piston). Thus the shock speed will be somewhat faster than the speed of the leading edge of the CME, and the authors proposed that the multiplication factor to obtain the shock speed from the outward speed of the CME is 1/0.8 = 1.25. Gergeley (1984) adopted a somewhat larger multiplication factor of 1/0.6 = 1.7 through comparison between the average speeds of the type II bursts and the CMEs. In this paper we adopt a factor of 1.2 following Watanabe and Kakinuma (1984), which is consistent with that proposed by Maxwell and Dryer (1981). Accordingly, the shock speed in the solar corona (4 - 8 $R_\odot$) is estimated to have been about 1390 km s^{-1} for the halo CME of Nov. 27, 1979, as shown in Fig. 4. For the Helios B observations of the CME (Jackson, 1984), the approximate outward speed of the brightest portion of the CME was 500 km s^{-1} at 0.4 - 0.5 AU heliocentric distances. Thus the inferred shock speed is about 600 km s^{-1} at 0.45 AU. The mean propagation speed of the CME between the Sun and the heliocentric distance of 0.45 AU was about 800 km s^{-1} (Jackson, 1984). These speeds are also plotted in Fig. 4.

Because of the probable anisotropic nature of the solar wind disturbance associated with the halo CME of Nov. 27, 1979, not all the plotted data can be expalained by a simple model. In the Sun-Earth direction (and also in the Sun-3C298 direction), the dynamical evolution of the disturbance can be approximated by a power-law relationship, $V_S = 1390\ (R/0.04)^{-0.38}$ km s^{-1} where R is the heliocentric distance in AU ($R \geq 0.04$ AU). This empirical model is consistent with the shock speed at 0.45 AU on the Sun-Earth line which is estimated from the Helios B observations of the CME (Jackson, 1984). In the region apart from the ecliptic plane (N15) near the Sun-Earth line (Sun-3C295 direction), the deceleration coefficient was the same as that in the Sun-Earth direction, but the CME propagated with approximately constant speed out to 0.1 AU. On average, the power-law deceleration coefficient of the disturbance was about 0.4 for 0.1 AU $\leq R \leq$ 1 AU. The dynamical evolution given in Fig. 4 is consistent with that employed by Smart et al. (1983) who used the concept of a constant velocity piston-driven phase followed by a blast wave deceleration.

Ⅳ. Three-Dimensional Directivity of Propagation Speed

The longitudinal and the latitudinal directional diagrams of the shock speed of the solar wind disturbance associated with the halo CME of Nov. 27, 1979 are shown in Figs. 5a and 5b respectively. Each local shock speed at R_i AU heliocentric distance, V_{Si}, is reduced to that at

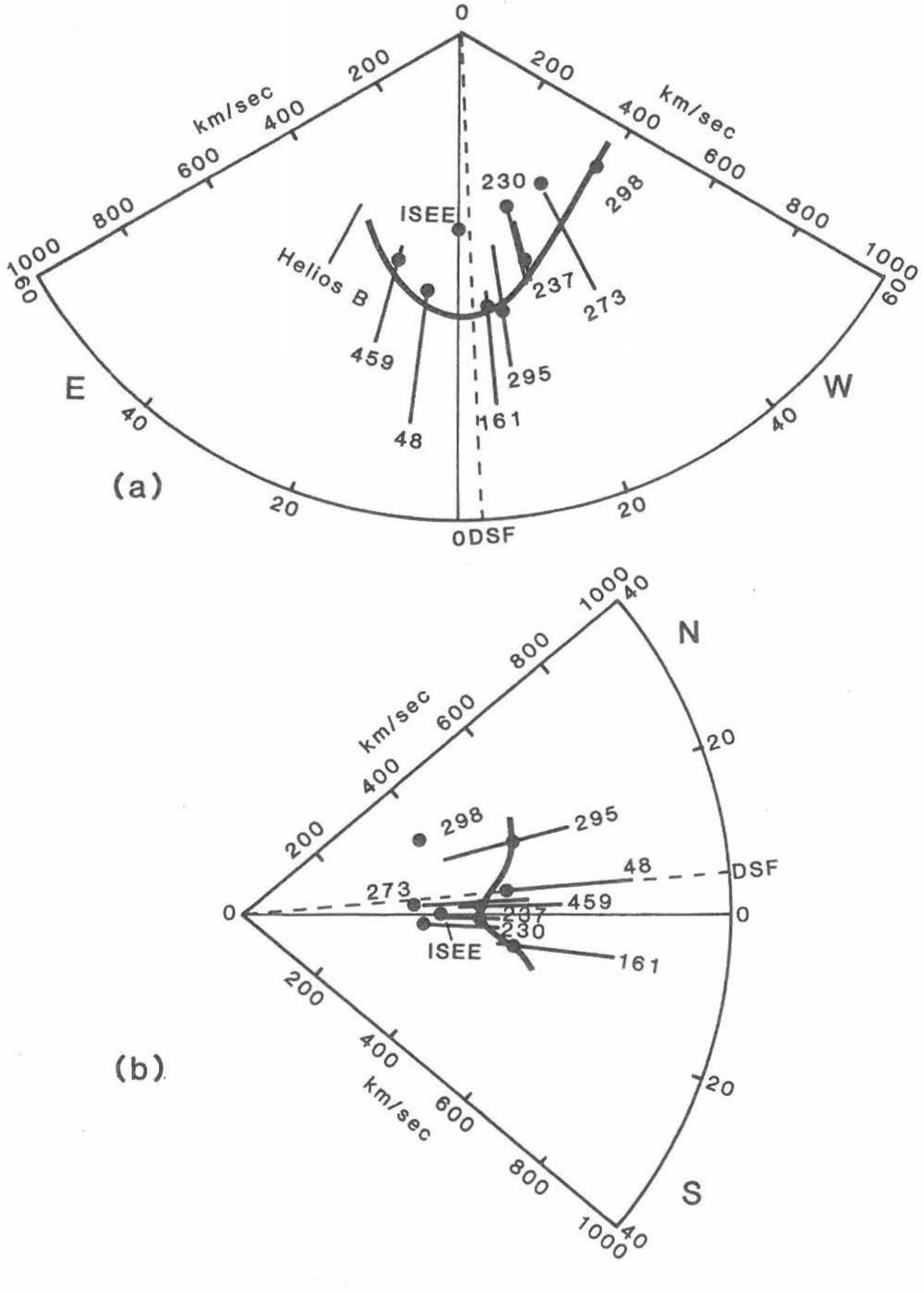

Fig. 5. Longitudinal(a) and latitudinal (b) distribution of the shock speed of the solar wind disturbance associated with the halo CME of Nov. 27, 1979. The constraints for the mean shock speeds are shown by the radial lines. The inferred shock speeds are represented by dots. The local shock speed obtained by the ISEE spacecrafts observations

(Russell et al., 1983) is also given. All data are reduced to those at 1 AU heliocentric distance assuming the power-law deceleration coefficient of 0.4. The constraints for the Helios B data (Jackson, 1984) are discussed in text. The normal of the center of the disappearing solar filament of Nov. 27, 1979 is shown by a broken line in each flame (DSF).

1 AU heliocentric distance using (1) as follows;

$$V_s \text{ (at 1 AU)} = V_{si} R_i^n. \qquad (5)$$

For the upper and lower limits to the mean shock speed between the Sun and an observation point on the line-of-sight to a radio source, the limits are reduced to those at 1 AU heliocentric distance by the following consideration. For the initial distance, R_o in (1), we adopt the distance R_m where the upper limit to the mean shock speed equals the local shock speed at the distance, which can be estimated using (4). Then the upper limit, $\bar{v}_{max}$, is reduced to that at 1 AU by the relationship;

$$\bar{v}_{max} \text{ (at 1 AU)} = \bar{v}_{max} R_m^n. \qquad (6)$$

The lower limit can be also reduced to that at 1 AU in the same manner. We use 0.4 for the value of n in all directions following the discussion given in the previous section. The directional uncertainty for the inferred shock speed is represented by a half angular width of the scattering weighting function of the line-of-sight which is estimated on the basis of the model proposed by Coles and Rickett (1975), and the typical angular width seen from the Sun is 50^o. To avoid unnecessary complexity, the directional uncertainty is not shown in these figures.

The local shock speed near the Earth which was estimated from the ISEE spacecrafts observations (Russell et al., 1983) is given in Fig. 4. For the Helios B data, the existence of the shock front is uncertain (Jackson, 1984). We adopt the mean propagation speed of the density enhancement observed at 1600 UT on Nov. 28, 1979 between the Sun and the spacecraft as the upper limit to the propagation speed at 1 AU. The lower limit is the mean speed reduced to that at 1 AU heliocentric distance assuming the deceleration coefficient of 0.4.

V. Discussion

It is seen in Figs. 5a and 5b that the interplanetary manifestation of the halo CME of Nov. 27, 1979 was a quasi-spherical solar wind disturbance collimated along the Sun-Earth line or the normal of the disappearing filament of Nov. 27, 1979 (N05W03). The total angular spread was greater than 70° in the longitudinal direction at 1 AU. The latitudinal angular spread was greater than 30°. The directional diagrams of the shock speed at 1 AU show an anisotropic nature while the speed of the leading edge of the CME was approximately the same at all position angles (Howard et al., 1982). In the longitudinal direction, somewhat high shock speeds are obtained in the region immediately east of the Sun Earth line. A probable explanation is that the high shock speeds resulted from the propagation of the disturbance within a weak high speed stream of up to 470 km s^{-1} which arrived at the Earth on Dec. 1, 1979. In the latitudinal direction (Fig. 5b), high shock speeds are obtained in the region apart from the ecliptic plane (3C295 and 3C161), and the minimum of the shock speed is seen around the latitude of the center of the disappearing filament (N05).

The longitudinal angular spread of the solar wind disturbance at 1 AU heliocentric distance is estimated to have been greater than 40° in the region to the west of the normal of the eruption. On the other hand, Helios B (E30) detected only a slight enhancement in the solar wind density and the flow speed; there is no evidence that the CME passed east of the spacecraft (Jackson, 1984). This means that the longitudinal angular spread of the solar wind disturbance was about 30° in the region to the east of the normal of the eruption. Thus the total angular spread of the disturbance at 1 AU is estimated to have been larger than 70° while Howard et al. (1982) proposed an acute cone with a total angular spread of $2 \times 27^{\circ} = 54^{\circ}$. If we adopt the angular spread of 40° measured from the center of the cone in the solar corona, the frontal speed becomes about 720 km s^{-1} instead of 1160 km s^{-1} as proposed by Howard et al. (1982). It is presumed that the frontal speed proposed by the authors is the upper limit.

The white-light observations of the halo CME of Nov. 27, 1979 showed no limb-brightening effect (Howard et al., 1982). This fact cannot be explained by a simple spherical-shell model of the CME. Howard et al. (1982) proposed two alternative models; a spherical CME which has no inner cavity, and a hollow and acute conical shell of emitting material, in which the front is significantly dimmer than the side of the cone. According to the solar wind data obtained at ISEE-3 (King, 1983), the high-density post-shock plasma was observed for about 13 hours near the normal of the center of the disappearing filament of Nov. 27, 1979 (E03). The IPS observations of 3C273 show that the highly turbulent, and high density post-shock plasma was observed only on Nov. 30, 1979 at about W26 from the normal (Fig. 3). On the other hand, the turbulent plasma was observed for three days by the IPS observation of 3C298 at about W40 from the normal (Fig. 3). It is therefore concluded that the thickness of the shell of enhanced plasma density, which was formed by the solar wind disturbance, was thinner around the normal of the eruption than in the direction apart from the normal. In the region to the east of the normal of the eruption, a highly turbulent and rather high-speed solar wind of 430 km s^{-1} was observed by the IPS observation of 3C48 at Toyokawa during Nov. 30 - Dec. 1, 1979. The IPS observation of 3C459 (E20) at Toyokawa showed that the turbulent and high-speed plasma was only observed on Nov. 30, 1979. Helios B observed a slight density increase which persisted for $<$12 hours at E33 from the normal on Nov. 28, 1979 (Fig. 3 given by Jackson, 1984). Thus the thick, enhanced-density region was observed in the region to the east of the normal of the eruption (E10). Although the angular distribution of the high-density post-shock plasma seems to have been deformed through interaction with pre-existing solar wind stream structures, the above-mentioned observational results would not be inconsistent with the second geometrical interpretation of the halo CME which was proposed by Howard et al. (1982); the three-dimensional configuration of the CME was a hollow cone with a thin front.

VI. Concluding Remarks

We have seen in this paper that the interplanetary manifestation of the halo CME of November 27, 1979 was a quasi-spherical solar wind disturbance collimated along the Sun-Earth line, as inferred from the Helios observations (Jackson, 1984). Since the disturbance was detected at E30 and at W40 measured from the center of the CME (the disappearing solar filament centered at N05W03), the whole longitudinal angular spread is estimated to have been greater than 70°. The CME propagated with an approximately constant speed of 860 - 1390 km s^{-1} in the region between the solar corona (10 $R_{\odot}$) and 0.1 - 0.3 AU heliocentric distance, then decelerated as a blast-wave like solar wind disturbance with a power-law deceleration coefficient of about 0.4. The general configuration of the disturbance at 1 AU supports the geometrical model; at least high-speed CMEs have bubble-like or cone-like configurations. The total angular spread in the longitudinal direction at 1 AU heliocentric distance was greater than 70° which is somewhat greater than that in the solar corona (54°) proposed by Howard et al. (1982). The low shock speed around the latitude of the normal of eruption has been suggested by Watanabe and Kakinuma (1985b) who made a provisional statistical analysis of solar wind disturbances in 1978-1981.

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