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RESEARCH REPORT

THREE-STATION OBSERVATIONS OF INTERPLANETARY SCINTILLATION AT 327 MHz-II : EVOLUTION OF TWO-DIMENSIONAL SOLAR WIND SPEED STRUCTURE DURING 1983 TO 1985

Masayoshi Kojima and Takakiyo Kakinuma

Abstract

Long-term evolution of the solar wind structure in the heliographic longitude and latitude was studied on the basis of observations of interplanetary scintillation. The evolution from 1983 to 1985 was studied using two-dimensional solar wind maps. These were made with a new mapping method developed to investigate the structure of solar wind in detail. In this period of low solar activity, the low-speed regions are distributed along the wavy neutral sheet made by the magnetic dipole and quadrupole field. The higher-speed regions were more fully developed in the northern hemisphere than in the southern hemisphere. Large latitudinal gradients of speed were developed at the latitude where the high speed region extended. Breadth of the low speed region decreased with subsiding solar activity. Two localized minimum-speed regions appeared on the neutral sheet and their locations coincide with those of the two giant bipolar magnetic regions. These two minimum-speed regions are longitudinally separated almost by 180°.

1. Introduction

Solar wind speed structure has been studied with reference to observations of spacecraft, comets and interplanetary scintillation (IPS) (e.g., reviewed by Dobrowolny and Moreno (1976)). The spacecraft observations provide us with information only in the small latitudinal range from +7.°25 to -7.°25. Though the comets observations can cover a wide latitudinal range, observations are too rare and sporadic to study the solar wind structure in detail. Interplanetary scintillation observations have distinct advantages in that the solar wind can be observed in wide three-dimensional space and observations are available over a long period.

We studied the evolution of solar wind structure on the basis of IPS observations during the three years from 1983 to 1985. These years are in the descending phase and very close to the minimum phase of solar activity. In this period, stable and simple coronal and solar wind structure as well as equatorward extension of the polar coronal holes is expected (Hundhausen et al., 1981). As the high-speed region extends, the low-speed region contracts to a narrow belt (Newkirk and Fisk, 1985). Large latitudinal gradients are often observed over a narrow range in latitude corresponding to the latitude of individual coronal holes (Schwenn et al., 1978).

Solar wind structure has been often studied by taking average over heliographic longitude or heliomagnetic longitude (Newkirk and Fisk (1985) and other references in their paper). Unless the solar wind spatial structure is simple and symmetric about a rotational axis or a dipole axis, it is difficult to infer the solar wind structure from this longitudinal average (Hundhausen, 1978). On the other hand, mapping the solar wind speed structure in the longitude and latitude coordinates can provides us with two-dimensional information without such ambiguities. Sime and Rickett (1978) first introduced the two-dimensional speed map, and these maps have been used for studying the relationship between the solar wind speed and other coronal parameters such as coronal brightness and magnetic field distribution (Sime and Rickett, 1978; Rickett and Coles, 1982; Coles et al., 1980). As resolution of these maps was, however, rather low, only general trends in the large scale structure were studied. Therefore, we have modified their mapping method so that the solar wind structure can be investigated in more detail from IPS observations.

IPS observations and the mapping method are explained in section 2. In sections 3 to 5, the map for each year of 1983 to 1985 is shown and the profile in each map is discussed. In the last section, discussions through the three years are given.

2. Observations and analysis

Regular IPS observations at UHF (327 MHz) have been carried out since 1982. The observatories and the observation system are described by Kojima et al.(1982). From the three-site observations the velocity of a diffraction pattern produced by IPS across the earth is derived with cross-correlation analysis (Kakinuma et al., 1973; Coles and Kaufman, 1978). This IPS pattern velocity can be considered as a weighted average of the transverse component of the solar wind velocity along the line-of-sight. This weighting function consists of a level of micro-turbulence, the Fresnel filtering function and a function of radio source size (Readhead, 1971; Watanabe and Kakinuma, 1972; Harmon, 1975). The weighting functions for our UHF (327MHz) observations are shown in our IPS data book (Kakinuma and Kojima, 1985). These weighting functions have their maximum peaks at the point of closest approach on the line-of-sight to the sun for elongations smaller than about 60°. According to the results of earlier works (Watanabe and Kakinuma, 1972; Harmon, 1975; Coles et al., 1978) comparing in-situ spacecraft measurements and the pattern velocity measured by IPS, we can interpret, for the first approximation, an IPS observation as an estimate of the solar wind speed around the closest point.

The latitudinal and longitudinal structure of the solar wind speed on the source surface has been studied using IPS observations by Sime and Rickett (1978), Coles et al. (1980), Kakinuma et al. (1982), Kakinuma and Kojima (1984), and Hakamada (1984a). We have used a method similar to these earlier works to derive the two-dimensional structure of the solar wind speed. The measured solar wind speed was mapped back along the Archimedian spiral from the subscattering region on to the source surface (at 10 solar radii in our case) and the speed value was assigned to a bin in a two-dimensional grid representing heliographic latitude and longitude. In this mapping-back process we assumed that the solar wind speed was independent of the radial distance from the sun and that there was no interaction between streams. The validity of this first assumption is shown for an outer region of 0.3 AU by Coles and Rickett (1976), Schwenn (1981), and Intriligator and Neugebauer (1975). However, change of speed with radial distance has been observed inside of 0.3 AU (Scott et al., 1983; Kakinuma and

Kojima, 1984; Armstrong et al., 1985). Accordingly, though our IPS observation system at UHF could observe the solar wind at a distance as near as 0.1 AU, we used data obtained outside of 0.3 AU. Since latitudinal and longitudinal coverage is rather sparse for a single solar rotation, we averaged data for periods of some rotations. In this averaging process the earlier investigations (Sime and Rickett, 1978; Coles et al., 1980; Kakinuma and Kojima, 1984) used the following method: latitudinal and longitudinal coordinates were divided into $15^{\circ} \times 15^{\circ}$ grids, corresponding to one day's rotation of the sun in longitude (Sime and Rickett, 1978). All values in each bin were then averaged. Hakamada (1984a) used a different method to derive a smoother map, dividing his map into 8 X 16 bins. After averaging each bin, contour lines with a resolution of $5^{\circ} \times 5^{\circ}$ were drawn using the spline function for interpolation. These two methods have two problems. The first is resolution of the map. The bins are fixed in the longitude and latitude coordinates and all values in the same bin are averaged. This restricts the resolution of the map to that of the grid. The second problem is coverage of the polar region. As each bin is represented by a rectangular grid on the map, the area of a bin at a high latitude on a spherical surface is not equal to that at a low latitude. Therefore, when observations are made at a high latitude, results are assigned only to very narrow area on the sphere. We have improved on these methods, constructing a map with finer resolution and better coverage around the polar region. The map is divided into 48 X 96 cells with a rectangular grid in the longitude and latitude coordinates. The number of cells is arbitrary if cell size is small enough. The speed value is assigned with a weighting factor (reliability) to each cell. The weighting factor w(i,j) for the cell at (i,j) coordinate is determined according to an estimation error of speed Ve and angular distance R(i,j) between center of the cell and the foot point of the Archimedian spiral using the following equation:

$$w(i,j)=Ve/\exp[-[(1-\cos(R(i,j)))/(1-\cos(15/\sqrt{2}))]^2] \quad \text{for } R(i,j) < 15^{\circ},$$

and no values are assigned for $R(i,j) > 15^{\circ}$.

All speed values which fall into the same cell are averaged with weight, and contour lines are drawn through cells of equal speed. The angular distance, for which the factor w(i,j) falls to 1/e, corresponds to a radius of a circle which just encircles a square bin of $15^{\circ} \times 15^{\circ}$ at the equator (we call this circle the bin). The angular distance of 15° used as the outer boundary of w(i,j) is none-too-large compared with the width of the subscattering region along the line-of-sight.

As the bin is not fixed but moves with the foot point of the Archimedian spiral, resolution is no longer restricted by the bin size but determined by the relative distance between the foot points. As our bin size depends on the angular distance, the area of the bin on the sphere is independent of the latitude and the coverage of the map at high latitude is improved.

The map was made kinematically without allowance for stream-stream interaction and the acceleration process, and also was made like superposed-epoch analysis because of rather sparse coverage of the map in one solar rotation. As no corrections like deconvolution (Kakinuma, 1977; Ananthakrishnan et al., 1980; Kakinuma et al., 1982) were made for the integration effect along the line-of-sight, these maps are a first approximation. Therefore the following characteristics of the map must be kept in mind. (1) Small scale and short-term structures may be smeared out in the map. (2) Stream-stream interaction regions, where a slow stream is taken over by a fast stream, could be seen clearly because the Archimedian spirals of both streams never cross each other in this mapping-back process. (3) The latitudinal structure is more reliable than the longitudinal structure because the Archimedian spirals fall on different latitudes and do not cross.

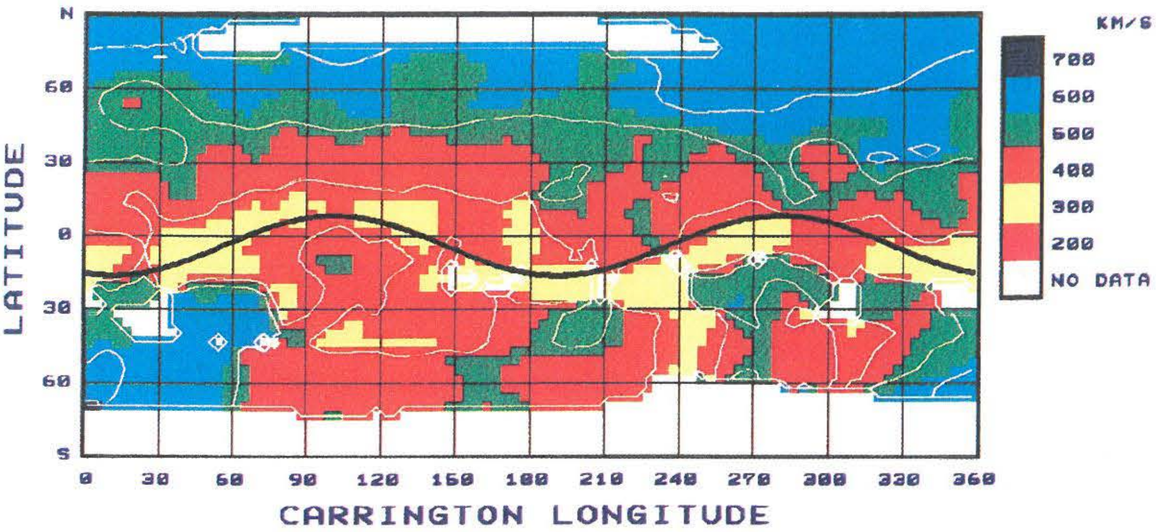
3. Observations for 1983

The solar wind structure in 1983 on the source surface at 10 solar radii was derived and is shown in Figure 1a. Observations during Carrington rotations from 1733 to 1742 were superposed. Speed level is shown with color code and contour lines. Contour lines are given for speeds greater than 400 km/s and drawn at every 100 km/s. The speed level of the color code differs from that of the contour lines by 50 km/s. The coronal structure observed in the white light data with the K-coronameter on Mauna Loa (Rock et al., 1984) was particularly stable in this period. During these rotations, the high-speed (>500 km/s) region extended equatorward uniformly over the entire longitude range from the north pole to $+40^{\circ}$. In the southern hemisphere, the extension of the high-speed region was not uniform, with a local extension of this region to a latitude of -30° at longitudes of 0° to 60°. The distribution of the high-speed regions corresponds to regions of lowest brightness (namely, coronal holes) in the K-coronameter map.

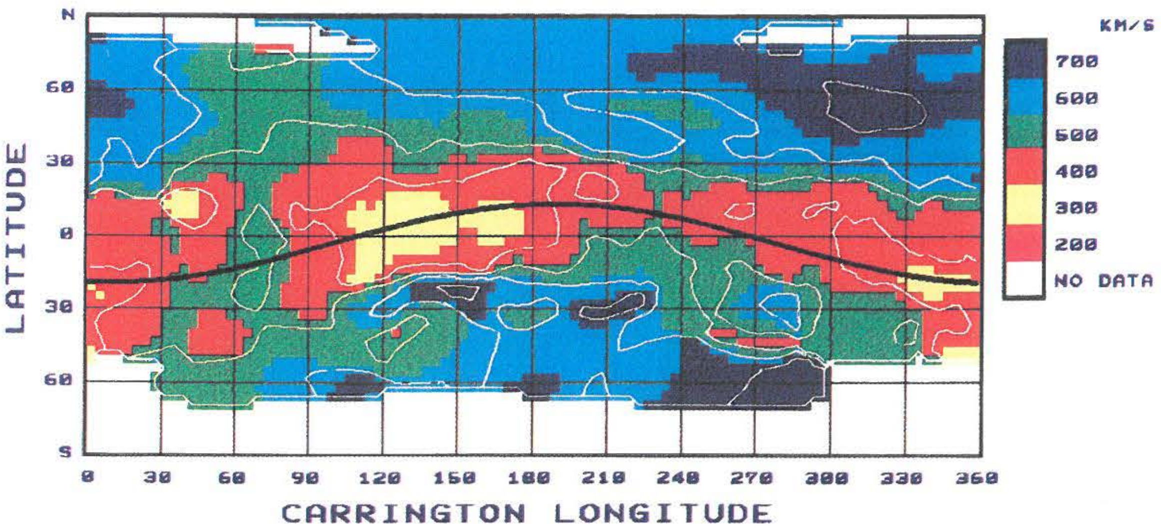
We can find southward and northward warps of the low speed region (colored with yellow) near the equator. Mean solar magnetic polarity observed in 1983 by Stanford Solar Observatory (in 'Solar-Geophysical Data') shows four-sector polarity. As a good agreement was reported between the polarity of the interplanetary magnetic field (IMF) inferred from geomagnetic variations and the polarity of the mean solar magnetic field (SMF) (Severny et al., 1970; Scherrer et al., 1977), we may approximate the mean SMF polarity as equal to the IMF polarity observed on the earth with some time delay. According to this approximation, we can reconstruct the distribution of the magnetic polarity on the source surface using the scanning method introduced by Saito (1975). As we used, for convenience, the same mapping program as that used for the speed map, polarity is mapped over the earth scanning range of $-7^{\circ}.25$ to $7^{\circ}.25$. The distribution was derived in Figure 2a for the same rotations as in Figure 1a. The best-fit sine curve is drawn through the minimum-speed regions in Figure 1a. As this sine curve runs near the neutral regions in the magnetic polarity map (Figure 2a), we can infer the same result in earlier investigations (e.g., Rickett and Coles, 1982; Hakamada and Akasofu, 1981; Zhao and Hundhausen, 1981; Zhao and Hundhausen, 1983; Hakamada and Munakata, 1984b; Suess et al., 1984; Hakamada and Maezawa, 1985), i.e. the slow-speed region distributes along the magnetic neutral sheet.

These maps of speed and magnetic polarity are not always expressed by the tilted dipole field of the sun. Hakamada and Akasofu (1981) showed that distribution of the neutral line could be approximated by a combination of the first and second harmonic terms of a sine function. From their analysis, it is predicted that the first term component will become minimum and the second term will be maximum in

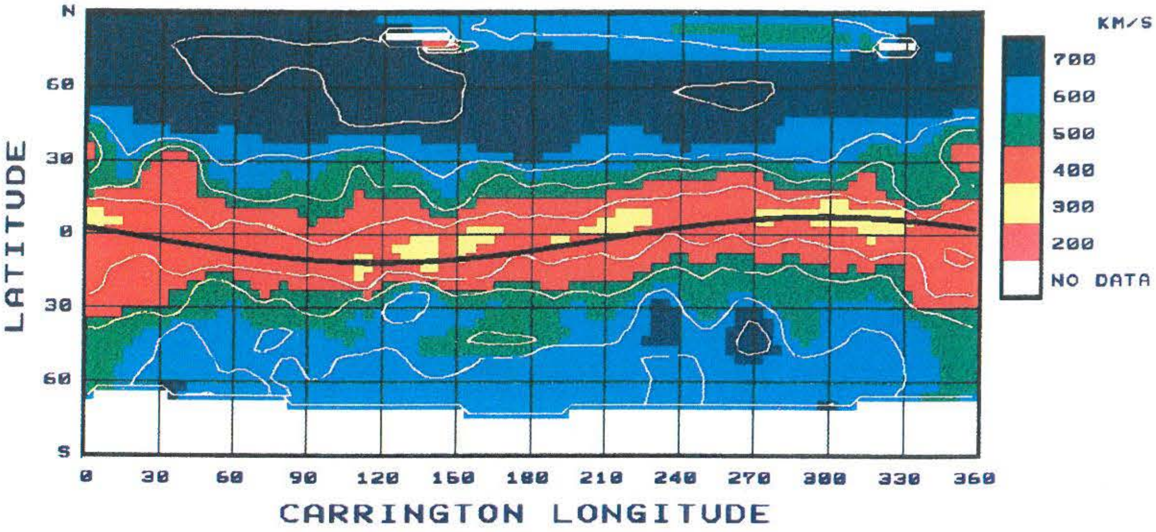
Fig. 1. The solar wind speed synoptic maps in the coordinate of the heliographic latitude and Carrington longitude on the source surface at 10 solar radii. Observations during indicated Carrington rotations were superposed. Speed level is shown with color code and contour lines. Contour lines are given for speeds greater than 400 km/s and drawn at every 100 km/s. The speed level of the color code differs from the contour lines by 50 km/s. Heavy lines are the sine curves drawn through the minimum portion of the speed.



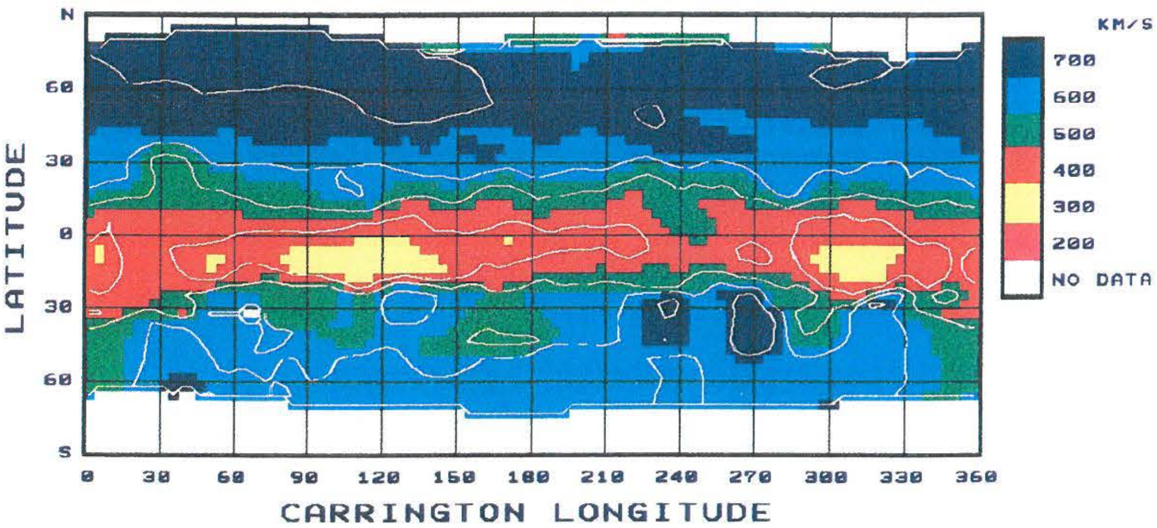
1a. Carrington rotations from 1733 to 1742 in 1983.



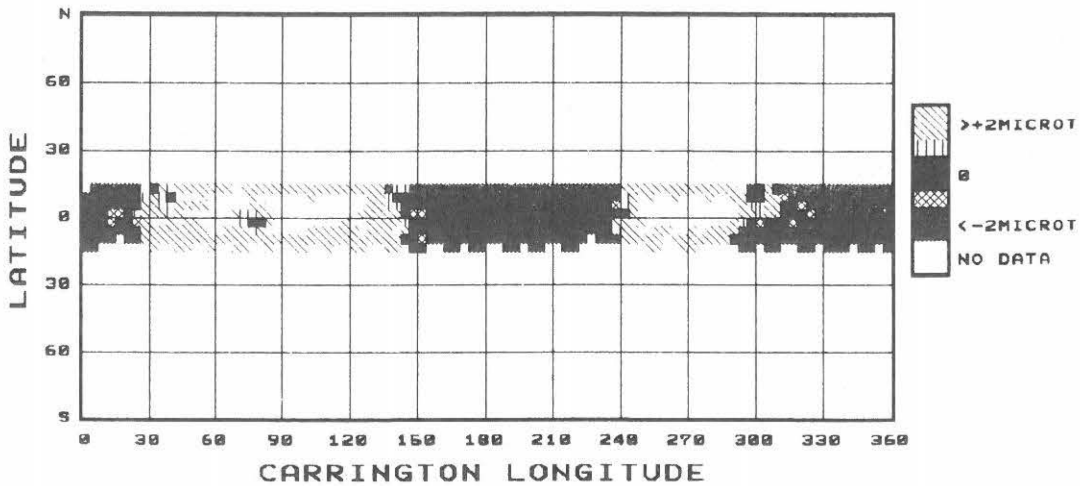
1b. Carrington rotations from 1746 to 1755 in 1984.



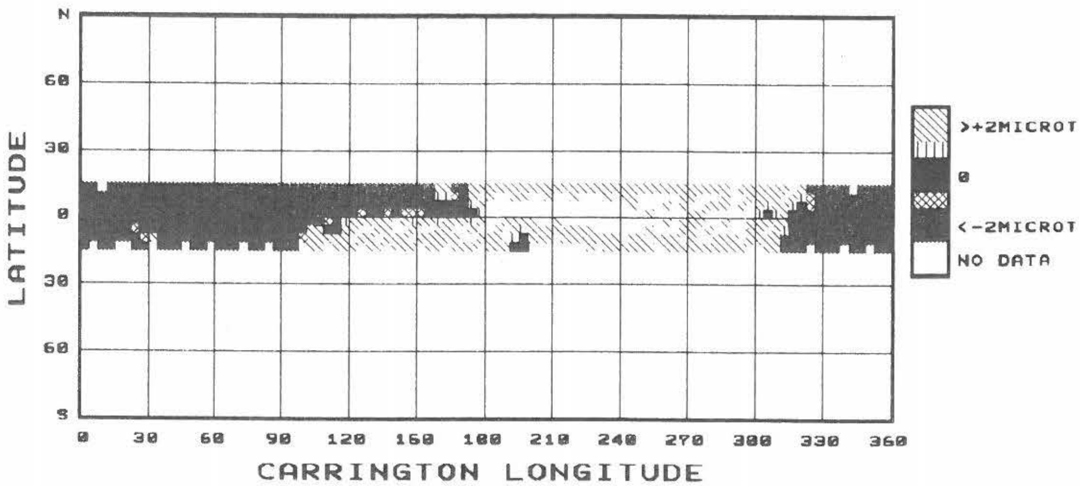
1c. Carrington rotations from 1762 to 1767 in 1985.



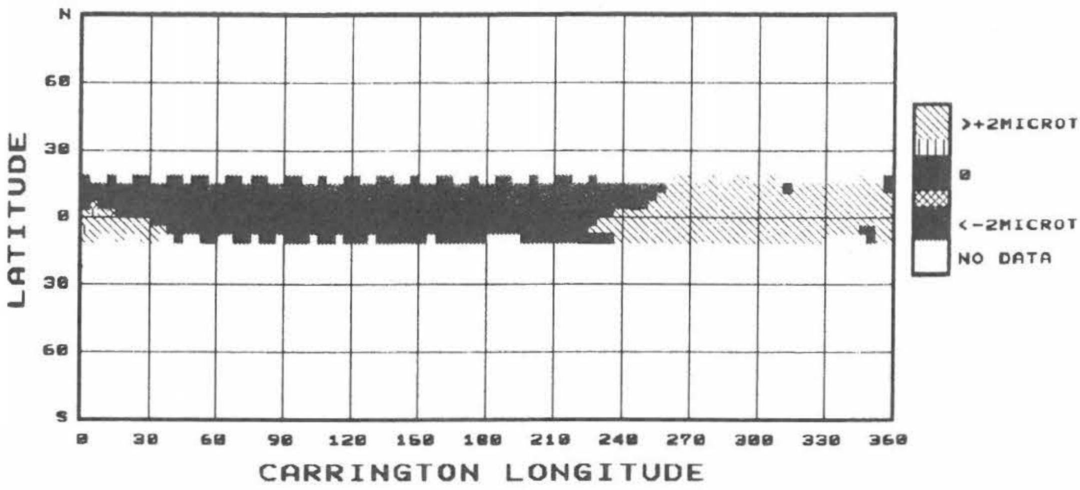
1d. Carrington rotations from 1759 to 1764 in 1985.



2a. Carrington rotations from 1733 to 1742 in 1983.



2b. Carrington rotations from 1746 to 1755 in 1984.



2c. Carrington rotations from 1762 to 1767 in 1985.

Fig. 2. Distribution of the polarity of the mean solar magnetic field. Data obtained during indicated Carrington rotations were superposed, and these rotations are same as those in Figure 1.

1983. Therefore, the neutral sheet in 1983 can be considered the result of a combination of the dipole and quadrupole field.

Another minimum speed region (yellow colored), which does not fit the sine curve, exists at longitude 90° to 140° and latitude -40°. A contour line of 400 km/s extends from the equator at longitude 150° to this slow-speed region. This extended structure often appeared in the K-coronameter map, but was not a stable structure.

4. Observations for 1984

The same kind of speed map is plotted for 1984 in Figure 1b. Superposed Carrington rotations are from 1746 to 1755.

The low-speed region (red- and yellow-colored) shows extension into the northern hemisphere at the center of the map and southern hemisphere at a longitude near 0°. These warps can be approximated with a sine curve, as in Figure 1b. Mean solar magnetic polarity (in 'Solar-Geophysical Data') shows two-sector polarity during this period (Figure 2b). The correspondence of the polarity change to the sine curve is remarkably good at longitudes from 60° to 180°. However, the polarity change at longitude 320° is rather sharp and the correspondence to the sine curve is not good. This simple sine curve is not well-fitted to the minimum-speed region, either, but the distribution of the minimum speed corresponds rather well to the neutral line. However, general trends noticed in the observations in 1984 are growth and stabilization of a tilted dipole.

There are two minimum-speed regions (yellow-colored) located on the sine curve, i.e. on the neutral line, but their distributions are localized rather than elongated along the neutral line, unlike those in 1983. Such localization of the minimum speed region can be found in maps for 1974 made by Hakamada (1984a) and Coles et al. (1980) and also in Figure 1d for 1985. When two localized regions of minimum speed appear on the source surface, their locations are longitudinally separated almost by 180°. Large and strong bipolar magnetic field regions stayed at an almost steady position on the neutral line in 1974 and 1984 (Saito, 1984; T. Saito named this region the "giant bipolar magnetic region" (GBMR)). The position of the localized minimum-speed region exactly corresponds to that of GBMR. The GBMR is a large bundle of magnetic loops which reach up to the source surface, and this is contrasted to the open magnetic field configuration at the coronal hole where the high speed stream emanates.

There are two high-speed regions extending from the northern and southern poles to the equator. The northern one is toward longitude 360° and the southern one is at 180°. Therefore these positions can be considered to be almost symmetric with respect to the tilted dipole axis.

5. Observations for 1985

The speed map for 1985 is shown in Figure 1c and 1d. Superposed Carrington rotation numbers are from 1762 to 1767 and 1759 to 1764 respectively.

The low-speed belt (red-colored) has warps but its amplitude is smaller than that of 1984. Mean solar magnetic polarity shows two-sector polarity during this period (Figure 2c). The best-fit sine curve is drawn through the minimum speed in Figure 1c. This sine curve fits the polarity change in Figure 2c. This can be interpreted as the result of a dipole with a small tilt angle in relation to the solar rotational axis. Figure 1d shows the depression of the low-speed region (the neutral line) to the south of the equator. There are two localized minimum speed regions (yellow-colored) at the longitude of 130° and 310° in Figure 1c and more clearly in Figure 1d. As these longitudes are very close to those in 1984, we believe these longitudinal positions are fairly stable over a year.

Distribution of high speed region was symmetric and uniform about the solar rotational axis in both hemispheres but higher-speed regions above 650 km/s developed asymmetrically between the two hemispheres. The high-speed region (>650 km/s) extended to a latitude of 45° in the northern hemisphere but this high-speed region could not be observed in the southern hemisphere.

The green-colored speed region was contracted into a very narrow belt at the northern and southern boundaries of the low speed region. We find a large latitudinal speed gradient here. Coles et al. (1980) showed from IPS observations from 1976 to 1977 that there was sharp transition from slow to fast speed between a latitude of 15° and 30° and that the gradient of the mean speed is greater than 10 km/s/degree in this narrow latitudinal range. Our map shows a similar trend. Such a large speed gradient can be found in Figure 1a and 1b at a latitude where the high-speed region extends and contacts the low-speed region. Schwenn et al. (1978) reported from spacecraft observations that the gradient is large only over a narrow range in latitude corresponding to the latitudinal boundaries of individual coronal holes. Our observations show his result more clearly in the two-dimensional map.

6. Discussion

Spacecraft observations are limited to a small latitudinal range of $+7^{\circ}.25$ to $-7^{\circ}.25$ and consequently cause some confusion when studying the solar wind structure. Statistical studies, such as taking an average over the longitude or a correlation of speed and the angular distance from the neutral line, smear out fine structures in the solar wind. We have demonstrated the capability of using IPS observations to study the solar wind in more detail with this new mapping method.

The years analyzed, 1983 to 1985, are in the descending phase and very close to the minimum phase of solar activity. The general profiles of solar wind during these years can be summarized as follows: (1) Slow-speed regions were distributed along the magnetic neutral sheet. (2) Extension of the high-speed regions was asymmetric with respect to the heliographic equator and the higher-speed regions was more fully developed in the northern hemisphere than in the southern hemisphere. (3) The boundaries of the polar high-speed regions extended to the lower latitudes and the breadth of the low-speed region decreased with subsiding solar activity. (4) The latitudinal gradient increased as the extension of the high-speed region.

The third profile agrees with the statistical results for the last solar minimum phase deduced by Newkirk and Fisk (1985). In Figure 1d the tilt angle of the magnetic dipole with respect to the rotational axis is small and the speed contour lines run almost parallel to the longitude. Only in such a case, will the statistical study taking the average speed over longitude reflect the real latitudinal speed distribution (Hundhausen, 1978). The map in 1985 shows almost the same latitudinal gradient of about 10 km/s/degree as the results by earlier researchers (e.g., Coles et al., 1980).

There are observations of a much larger gradient of 30 km/s/degree by Schwenn et al. (1978) and 60 km/s/degree by Rhodes and Smith (1981) in a narrow local region. We can also find such large gradients on our maps.

The low-speed regions provided a simple wavy structure: the curve drawn through the minimum portion of the solar wind speed on synoptic maps corresponded to the neutral line estimated from the mean solar magnetic field: the ratio of the dipole field to the quadrupole field was relatively small for the long term structure in 1983 and became large in 1984 and 1985. Many researchers have studied the dependence of solar wind speed on the angular distance from the neutral sheet. Hakamada and Akasofu (1981) showed this dependence by comparing the model with observations at a distance of the earth. Zhao and Hundhausen (1981), Sime and Rickett (1981), Zhao and Hundhausen (1983), Hakamada and Munakata (1984b), Hakamada and Maezawa (1985), and Newkirk and Fisk (1985) studied this dependence statistically by investigating the relation of solar wind speed to angular distance. However, our maps show that though the low-speed regions distribute along the neutral line, the dependence of the solar wind speed on the angular distance is not as simple as their models: the latitudinal gradient is large only at a latitude where the high speed region extends and contacts the low-speed region. Distribution of the high speed region is asymmetric with respect to the heliographic equator and the neutral sheet. Therefore it seems to be more important to investigate the relation of the speed with other coronal parameters such as the magnetic field configuration (Levine et al., 1977, Levine, 1978, Hakamada, 1984), the magnetic field strength (Suess et al.,

1984) and the expansion factor of the coronal hole (Coles, et al., 1980).

As described in section 2, the speed measured by IPS is the weighted average of the transverse component of the solar wind velocity along the line-of-sight, and no corrections for this were made in mapping. Therefore even if there were large transition regions of speed, it might be blurred on the maps. The deconvolution analysis for this line-of-sight integration (developed by Kakinuma (1977) and Kakinuma et al. (1982)) could recover the sharp-transition regions. A deconvolution analysis for 1985 is under way and its results will be reported in another paper. The two-dimensional maps for 1973 through 1985 have been completed and they will also be given in other paper.

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