Evolution of the Solar Wind Structure in the Acceleration Region during 1990–1993 (STEP Interval)

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The single-station measurements of interplanetary scintillation (IPS) at 2 and 8 GHz are used to study the radial distribution of solar wind velocity and density fluctuations near the sun. IPS observations in the ecliptic plane reveal the occurrence of the solar wind acceleration in the radial range between 10 and 30 Rs (solar radii), and also reveal the radial decrease of density fluctuations with a power index of approximately -2. Such structure is basically unchanged during the period from 1990 to 1993; i.e. the solar maximum to the declining phase. On the other hand, IPS observations at the high latitude region of the sun demonstrate a significant reduction of the turbulence level as well as a marked development of high speed streams in the low solar activity. This fact is in good agreement with the well-known solar cycle variation of the coronal hole. From the comparison between IPS data at 2 and 8 GHz, it is found that there is a slight but significant difference in the radial slope of the scintillation index variation. This might be attributed to the effect of either source size or spectral index of turbulence.

1. Introduction

The drastic change of the solar wind structure over the 11-year solar activity cycle has been clarified from several long-term studies using either direct or indirect measurements (Schwenn and Marsch, 1990; Kojima and Kakinuma, 1990; Rickett and Coles, 1991; Manoharan, 1993). However, these studies are mostly for the radial range farther than about 30 Rs, and the long-term variation of the near-sun plasma within this distance is much less known to us. Improved knowledge of the solar wind properties near the sun is very critical to the development of an understanding of the processes, which accelerate the coronal plasma outward to form the solar wind.

The interplanetary scintillation (IPS) measurements at GHz frequencies are useful to probe the solar wind acceleration region (Bourgois, 1969; Ekers and Little, 1971; Armstrong and Woo, 1981; Scott *et al.*, 1983b; Lotova *et al.*, 1985; Efimov *et al.*, 1990; Coles *et al.*, 1991; Tokumaru *et al.*, 1991, 1992, 1994; see also the reviews of Coles (1978) and Bird (1982)). This paper presents the results of a study of the solar wind structure from IPS measurements at 2 and 8 GHz, which have been conducted in the period from 1990 to 1993. Our IPS observations cover the radial range from a few to about 80 Rs, and the period analyzed here corresponds to that from the solar maximum to the declining phase of the solar cycle 22. The variation of the radial dependence of the solar wind velocity and the turbulence level near the sun during this period is discussed here.

2. Observations

The simultaneous IPS measurements at 2 and 8 GHz have been carried out since 1990 using a large radio telescope at the Kashima Space Research Center of the Communications Research Laboratory. In

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the previous paper (Tokumaru *et al.*, 1994; Hereafter, Paper I), we reported these IPS observations up to 1992 and the velocity estimation using the co-spectrum technique. As IPS measurements in 1993 were made in the same way as those in 1992, the detailed description about them is not repeated here, but the brief one on our IPS measurements including the scintillation index analysis is presented.

The IPS is observed at 2 and 8 GHz simultaneously for two radio sources; 3C273B and 3C279, in our IPS surveys. The geometry of IPS observations changes slowly by the annual motion of the earth. The line-of-sight for these sources approaches very closely to the sun in the period from late September to early October, taking different trajectories. Figure 1 illustrates the time variation of the IPS geometry for 3C279 and 3C273B. As shown in this figure, the trajectory of the line-of-sight for 3C279 is almost radial, and lies along the ecliptic plane. Such trajectory is quite suitable for studying the radial variation of plasma properties in the equatorial region of the solar wind. The other source 3C273B has more intense radio flux than 3C279, and this results in a better signal-to-noise ratio of IPS data. However, the line-of-sight for 3C273B moves from low to high latitude as the source approaches to the sun (the minimum solar offset is 18 Rs). Therefore, the radial variation of IPS data for 3C273B could be influenced significantly by the latitude variation. In the other sense, IPS observations for 3C273B allow us to study the solar wind structure at high latitude region of the sun.

The solar wind velocity V and the scintillation index m , given by $m = (\text{rms intensity fluctuation}) / (\text{mean source intensity})$, are derived from our IPS data. Here, the co-spectrum method is applied to estimate the solar wind velocity from single-station IPS observations (See Paper I and Scott *et al.* (1983a)). To calculate the m index, the on- and off-source beam data is used (Tokumaru *et al.*, 1991). The m index expresses the strength of IPS, and the square of m is linearly dependent on the integration of the turbulence level along the line-of-sight (Salpeter, 1967). Considering that IPS observed on the ground is usually dominated by the scattering around the closest point to the sun along the line-of-sight (P point), the IPS is well explained by the model of the weak scattering layer with a thickness of L , which is located at the P point ($L \ll$ the distance between the earth and the P point). Therefore, it is assumed that

$$m^2 \sim (\Delta N_e)^2 L \quad (1)$$

where ΔN_e is the average rms level of electron density fluctuations in the scattering layer. Under this hypothesis, the radial variation of m indices derived from IPS observations can be converted directly to that of density fluctuations in the solar wind (Lotova *et al.*, 1985; Manoharan, 1993). That is, $m \sim R^{-X}$, where

Fig. 1. The trajectories of the line-of-sight plotted in terms of the radial distance from the sun and the heliographic latitude for (a) 3C279 and (b) 3C273B. The dotted and dashed lines correspond to turnover distances from weak to strong scattering for 2 and 8 GHz signals, respectively.

R is the radial distance from the sun, yields $\Delta N_e \sim R^{-X-1/2}$, since $L \sim R$. Using this formula, $\Delta N_e(R)$ near the sun is investigated from our IPS data at 2 and 8 GHz.

3. Results and Discussions

3.1 Solar wind velocity

The solar wind velocities derived from IPS observations of 3C279 and 3C273B are shown in Figs. 2 and 3, respectively, being plotted as a function of the radial distance from the sun. IPS data taken in 1990–1993 are included in these figures. In order to reduce the scatter due to short-term variations of the solar wind, averages have been taken over small distance ranges with 2 Rs width.

The IPS data of 3C279 (Fig. 2) indicates clearly that the solar wind gains the speed monotonously with increasing the radial distance; from ~ 150 km/s at 12 Rs to >300 km/s at 30 Rs. Since the line-of-sight for 3C279 follows the radial trajectory, this variation is considered as the intrinsic acceleration of the solar wind. The radial increase of the solar wind velocity is also found in IPS data of 3C273B taken within 30 Rs. However, the 3C273B data (Fig. 3) shows a peak, followed by the decrease at large distance. From the comparison with He1083 nm observations (Preliminary Report and Forecast of Solar Geophysical Data, NOAA), close association between the location of the velocity peak and the coronal hole is demonstrated (Paper I). Therefore, the radial deceleration shown in Fig. 3 is ascribed to the apparent variation caused by the motion of the line-of-sight from the fast wind region linked with the coronal hole to the slower wind region (see Section 2). The radial acceleration found within 30 Rs cannot be explained by this apparent effect, and it is certainly attributed to the intrinsic effect of the solar wind acceleration.

Fig. 2. The solar wind velocities (circles) estimated from IPS data of 3C279 versus the radial distance from the sun for the years 1990–1993. Velocity estimates are averaged over a distance range of 2 Rs width. The vertical bars are 2σ in the mean. The marks without a bar correspond to the case where only one data is available in a given distance range. The shaded area corresponds to the radial range of the strong scattering for 2 GHz. Velocity estimates in this range are not reliable (see Paper I).

Fig. 3. The solar wind velocities estimated from IPS data of 3C273B in the same format as Fig. 2.

The IPS data of 3C273B also shows that there is a significant growth of the high speed wind near the sun; i.e. at a high latitude, during 1990–1993. This suggests that the polar coronal hole develops gradually with decreasing solar activity, and shows good agreement with the solar cycle variation of the coronal hole (Hundhausen *et al.*, 1981). On the other hand, the IPS data of 3C279 is mostly dominated by the low- or moderate-speed, and no long-term variation associated with the solar cycle is found. This implies that the solar wind structure in the ecliptic plane is little influenced by the solar cycle variation.

3.2 Turbulence level

Figures 4 and 5 display the radial dependence of m indices derived from 2/8 GHz IPS observations for 3C279 and 3C273B, respectively. IPS data taken at radial distances of >15 Rs and >4 Rs, where the weak scattering theory is applicable for 2 GHz and 8 GHz signals, respectively, are included in these figures. The frequency dependence of the m index; $m \sim f^{-1}$ is not normalized here. Derived indices are averaged over small distances as is the case of the velocity data (Figs. 2 and 3), while the average is taken on the log-log scale. The solid and dashed lines in each panel of the figures correspond to the power-law function $m \sim R^{-X}$ fitted to indices from IPS data at 2 and 8 GHz, respectively.

The radial variation in m indices is described excellently by the power law function for each case of IPS data shown in these figures. This suggests that the turbulence level ΔN_e in the solar wind also falls off as the power law of index $-X-1/2$, where X is a power index given by the least square fit (Section 2). The power-law radial dependence of m indices for 3C279 and 3C273B agrees with each other in the case of 1990. However, it is shown in Fig. 5 that the radial variation obtained from 3C273B observations flattens systematically as the solar activity decreases. Such systematic variation of the radial slope is not found in 3C279 data (Fig. 4), and the radial variation maintains a steep index during the period. The radial slope obtained from IPS observations for 3C279 is close to -1.5 , and this suggests that density fluctuations in the solar wind decrease nearly as R^{-2} .

This difference of the radial slope between 3C279 and 3C273B data is attributed to the different

Fig. 4. Scintillation indices, m derived from IPS observations for 3C279 at 2 GHz (circles) and 8 GHz (squares), being plotted as a function of the radial distance in the log-log scale. The horizontal and vertical bars are 2σ in the mean. The marks without a bar correspond to the case where only one data is available in a given distance range. The solid and dashed lines indicate the least square fit of the power-law function to IPS data at 2 and 8 GHz, respectively.

trajectories of the line-of-sight for these sources, as is the case of velocity measurements. The flattening of the radial dependence of m indices for 3C273B suggests that the turbulence level at the polar region of the sun reduces in the low solar activity. The reduction ratio of the turbulence level at 20 Rs in 1993 to that in 1990 is about 0.7. The reduced turbulence region is considered to be the coronal hole. A close association between the reduced turbulence and the coronal hole is found from the comparison of our IPS data with He1083 nm observations (Preliminary Report and Forecast of Solar Geophysical Data, NOAA). This result is generally consistent with IPS measurements at Nancy (Bourgois and Coles, 1992) and those at Ooty (Manoharan, 1993). In addition, it is in good agreement with the solar cycle variation of the coronal hole (Hundhausen *et al.*, 1981).

It is also found from Figs. 4 and 5 that the radial slope for 8 GHz indices is usually less steep than that for 2 GHz indices except for the case of IPS data of 3C273B in 1991. While the cause of this difference is not understood fully, effects of either the source size or the spectral index are proposed here as a possible cause. That is, the m index is a function of the source size (Little and Hewish, 1966; Bourgois, 1969) as well as the turbulence level in the solar wind. If the sources have a different source size at 2 and 8 GHz, this may cause the different radial slope of the m index variation for two frequencies. Further, the m index has a dependence on the spectral index of the solar wind turbulence (Armand *et al.*, 1987). It has been reported that the spectral index varies as a function of the radial distance from the sun (Woo and Armstrong, 1979; Armstrong and Woo, 1981; Tyler *et al.*, 1981; Tokumaru *et al.*, 1992). The radial dependence of the spectral index inferred from IPS observations at 2 and 8 GHz may differ from each other, since IPS observations at these frequencies are sensitive to the different range of the spatial scale

Fig. 5. Scintillation indices, m derived from 2/8 GHz IPS observations for 3C273B in the same format as Fig. 4.

of the solar wind turbulence. Therefore, this may result in the difference of the radial slope between 2 and 8 GHz indices.

4. Summary

IPS data taken at 2 and 8 GHz simultaneously have been analyzed to investigate the solar wind structure near the sun and its evolution in the period from 1990 to 1993 (STEP interval). The solar wind velocities estimated from these data show that the solar wind gains the speed significantly in the distance range between 10 and 30 R_s . Here, it should be noted that the solar wind acceleration takes place at radial distances well farther than the source surface of the thermally driven solar wind model (so-called "Parker (1958)'s model"). This fact suggests that the energy addition by the nonthermal process is necessary to account for the solar wind acceleration.

The present study also has revealed that the structure of the near-sun solar wind changes considerably in this 4-yr period, which spans from the solar maximum to the declining phase of the solar cycle 22. The pronounced change of the structure occurs at the polar region of the sun. Namely, high-speed winds and reduced turbulence regions develop there as the solar activity declines. On the other hand, little change is found for the solar wind structure in the equatorial region. From the comparison between our IPS data and He1083 nm observations (Preliminary Report and Forecast of Solar Geophysical Data, NOAA), it is demonstrated that fast winds and reduced turbulence regions are closely associated with the coronal holes (low-density open magnetic field regions of the corona). The polar coronal holes exhibit cyclic growth and decay with the 11-yr period of the solar activity cycle; they shrink in size during the high solar activity, and they develop markedly as the solar activity decreases (Hundhausen *et al.*, 1981). The solar wind

evolution disclosed here is found to be consistent with such long-term variation of the coronal hole.

Thus, the solar wind structure shows a drastic evolution over the solar activity cycle, so that we need a careful consideration for the period, when the observation was taken, in studying about it. The distribution of solar wind properties is expected to deviate largely from the spherical symmetry particularly in the period of the low solar activity. Therefore, it is essential in the future study to distinguish the radial variation from the latitude and longitude variations by observing the solar wind along the same flow tube simultaneously as Coles *et al.* (1991) performed. The result of this study also implies that we must be careful in using m indices at different frequencies simultaneously. Further study of the m index variation from the viewpoints of effects by the source size and the spectral index is needed.

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