Proceedings of the Research Institute of Atmospherics,
Nagoya University, vol. 34(1987)

RESEARCH REPORT

Solar Wind Structure Observed by Interplanetary Scintillation and Spacecraft in 1985 and 1986

Masayoshi Kojima, Takakiyo Kakinuma, Koh-ichiro Oyama[1],
Toshinori Mukai[1], Takafumi Hirano[2], and Wataru Miyake[3]

1. Institute of Space and Astronautical Science, Meguro, Tokyo 153, Japan
2. NEC Cooperation Space and Laser Communications Development Division, Satellite Transponder Development Department, 4035 Ikebecho, Midoriku, Yokohama 226, Japan
3. Hiraiso Solar Terrestrial Research Center, Radio Research Laboratory, 3601 Isozakicho, Nakaminatoshi, Ibaraki 105, Japan

Abstract

The spatial structure of the solar wind in 1985 and 1986 was studied with observations by interplanetary scintillation and Japanese spacecraft, SAKIGAKE and SUISEI. The solar wind speed maps on the source surface were derived from IPS observations. Superposition of the spacecraft data on the IPS map improved the resolution of the map in the low latitude range. During September and November of 1985, a leading edge of the northern high-speed region, which extended from the pole, had a large latitudinal speed gradient of 40 km/s/degree and inclined at a small angle to longitudinal direction on the source surface. Stream-stream interaction was well developed at this leading edge, traveling a distance of 1 AU. During January and April of 1986, a low-speed belt on the source surface had a nearly flat structure, and high-speed regions extended to low latitudes in wide longitude ranges in both hemispheres. SAKIGAKE observed the southern high-speed stream and the low-speed belt. The leading edge of the southern high-speed region did not have a remarkable speed jump. At the leading

edge, a temperature increase was detected but no density increase was observed.

1. Introduction

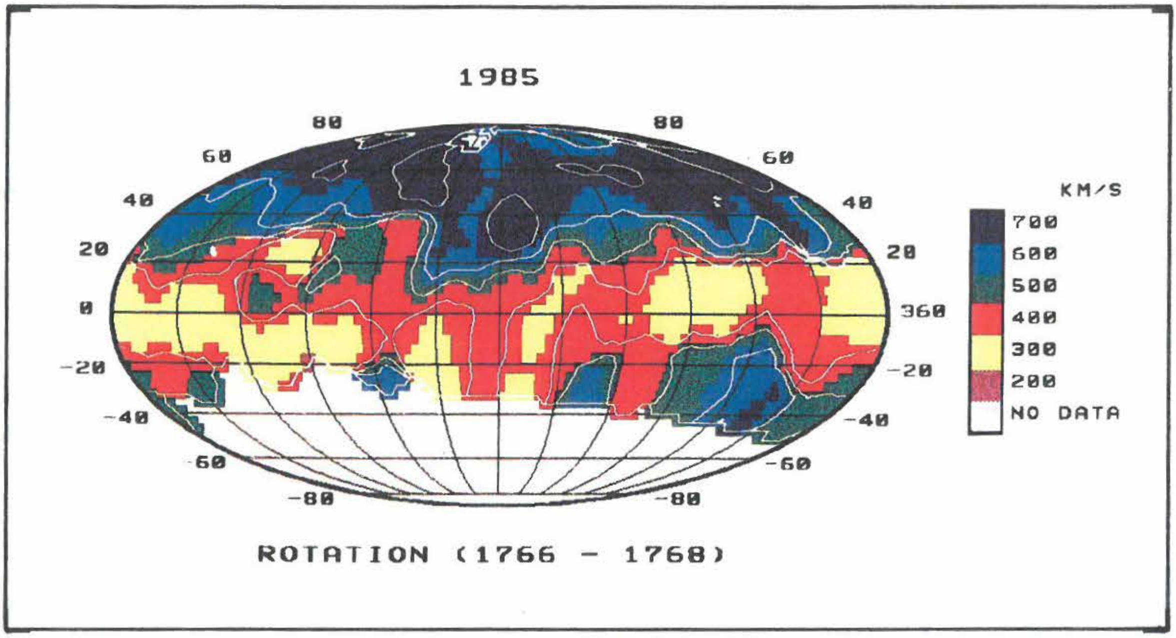
Observations of the solar wind by interplanetary spacecraft have been restricted to a small heliographic latitude range near the solar equator, and the number of spacecraft has not been great enough to understand the large spatial structure of the solar wind in three-dimensions. On the other hand, the method of interplanetary scintillation (IPS) has the advantage of being able to observe the three-dimensional structure of the solar wind using many IPS sources, which are distributed widely in both longitude and latitude coordinates. Solar wind observations by the IPS method at a UHF frequency, which have been carried out at the Research Institute of Atmospherics, Nagoya University, can be made between distances of 0.1 to 1 AU and in a wide latitude range. The spatial resolution of IPS observations is, however, not good enough to study fine structures in the solar wind because of integration of the solar wind parameters along the line of sight (Readhead, 1971; Watanabe and Kakinuma, 1972; Harmon, 1975; Kakinuma and Kojima, 1985). On the other hand, spacecraft observations can detect fine structures. Therefore solar wind observations by the IPS and spacecraft methods could be complementary to each other. If the global structure of the solar wind in three-dimensions is known from the IPS observations, it becomes easy to understand and analyze the spacecraft observations. Likewise, spacecraft observations can improve the resolution of the solar wind speed maps which are derived from the IPS observations.

First we derive solar wind speed maps on the source surface from the IPS observations. Then the data obtained by the spacecraft SAKIGAKE are superposed to improve the resolution of the maps. Using these maps, the observations of the solar wind by SAKIGAKE and SUISEI will be explained.

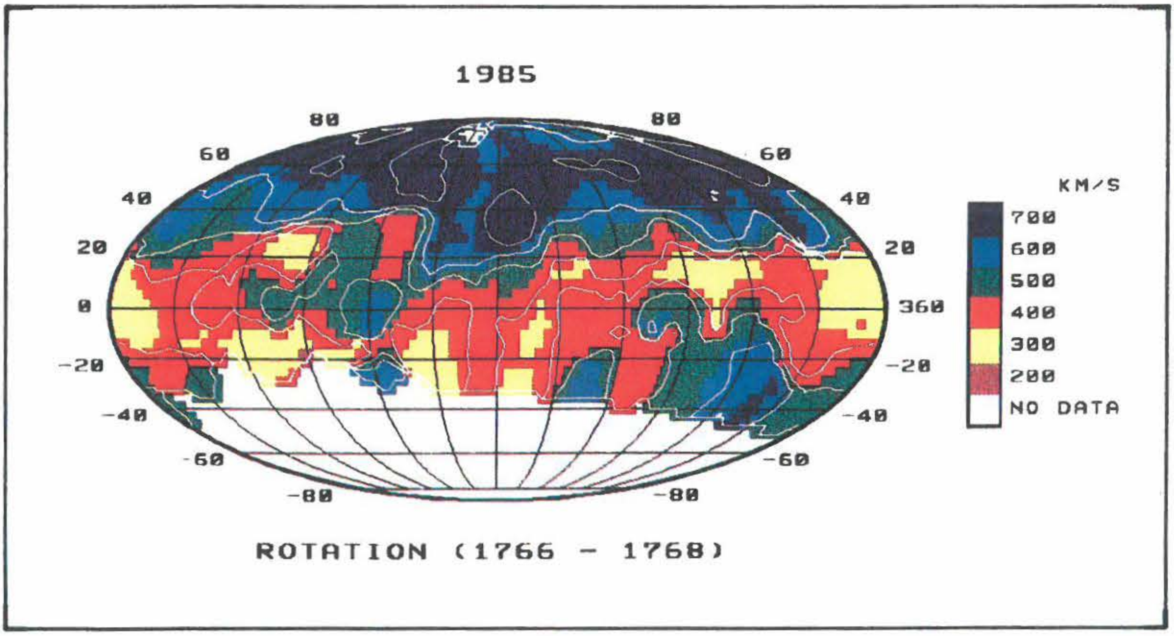
2. Global Structure on the source surface in 1985

Solar activity in 1985 was very close to the minimum, and the year 1985 was in the excursion phase of the two-hemisphere model

(a)


1985
80
80
60
60
40
40
20
20
0
360
-20
-20
-40
-40
-60
-60
-80
-80
KM/S
700
600
500
400
300
200
NO DATA
ROTATION (1766 - 1768)

(b)


1985
80
80
60
60
40
40
20
20
0
360
-20
-20
-40
-40
-60
-60
-80
-80
KM/S
700
600
500
400
300
200
NO DATA
ROTATION (1766 - 1768)

(Saito, 1984). The low-speed belt on the source surface had a fairly flat structure early in 1985 and began to incline again to the solar equator in mid-1985 (Kojima and Kakinuma, 1986, 1987). The solar wind speed maps in Figure 1 were derived from the IPS and spacecraft SAKIGAKE observations during the Carrington rotations (CR) 1766 to 1768. The method of making the two-dimensional speed maps has been given by Kojima and Kakinuma (1986, 1987). Speed levels are shown with a color code and contour lines. Contour lines are given for speeds greater than 400 km/s at intervals of 100 km/s. The contour lines are shifted from the color boundaries by 50 km/s. The global structure in Figure 1a was derived from the IPS observations. In Figure 1b, the SAKIGAKE data have been superposed on the map of Figure 1a to improve its resolution in the low latitude region. Although the global structure in Figure 1b did not change from that of Figure 1a, two compact high-speed regions, which corresponded to coronal holes, were resolved at longitudes 120° and 250°.

The northern high-speed region consisted of two structures: (1)the region between longitudes 150° and 270° was an extension of the polar high-speed region; (2)two compact high speed-regions on the equator at longitudes 120° (blue colored) and 70° (green colored) corresponded to local coronal holes observed by H-alpha (Solar Geophysical Data, 1985). The high-speed region at longitude 120° on the equator seems to have been connected with the high-speed region extending from high latitudes.

There was a low-speed island (red colored) at latitude +30° and longitude 130°. The western edge of this island was bordered closely by the high-speed region. Figures 2 and 3 are data plots of IPS observations of radio sources 3C 286 and 3C 298. Data were mapped back to the source surface along Archimedian spirals under assumptions of constant and radial velocity without any considerations for stream-stream interaction and acceleration. This sharp boundary was observed by these IPS sources around November 16th in CR 1768 between longitudes 120° and 150°.

Fig. 1. (Previous page) A solar wind speed map in the coordinate of the heliographic latitude and Carrington longitude on the source surface. Observations during CR 1766 and 1768 were superposed. Speed contour lines (white color) are given for speeds greater than 400 km/s at intervals of 100 km/s. (a) is derived from the IPS data, and (b) is derived from the observations by IPS and SAKIGAKE.

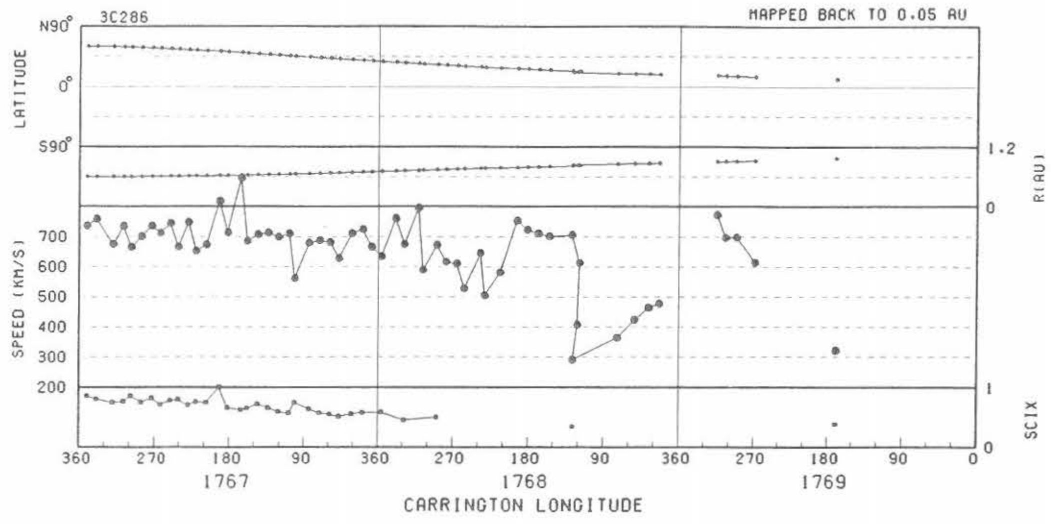


Fig. 2. Solar wind speed observed by a IPS source 3C 286. Data were mapped back to the source surface. An abscissa is shown by Carrington longitude but data are arranged in order of observation time from left to right. Top two frames are trajectories of main scattering region of the IPS of this radio source.

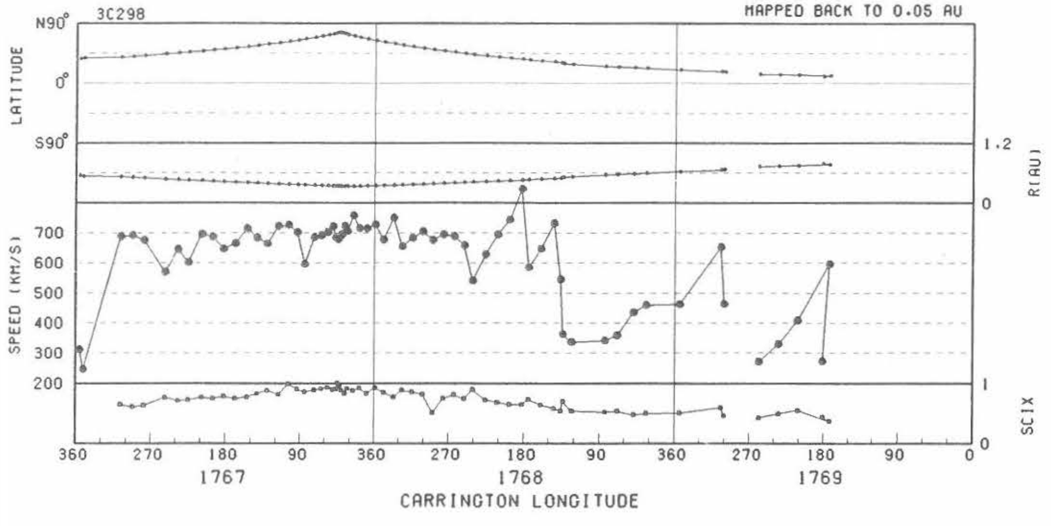
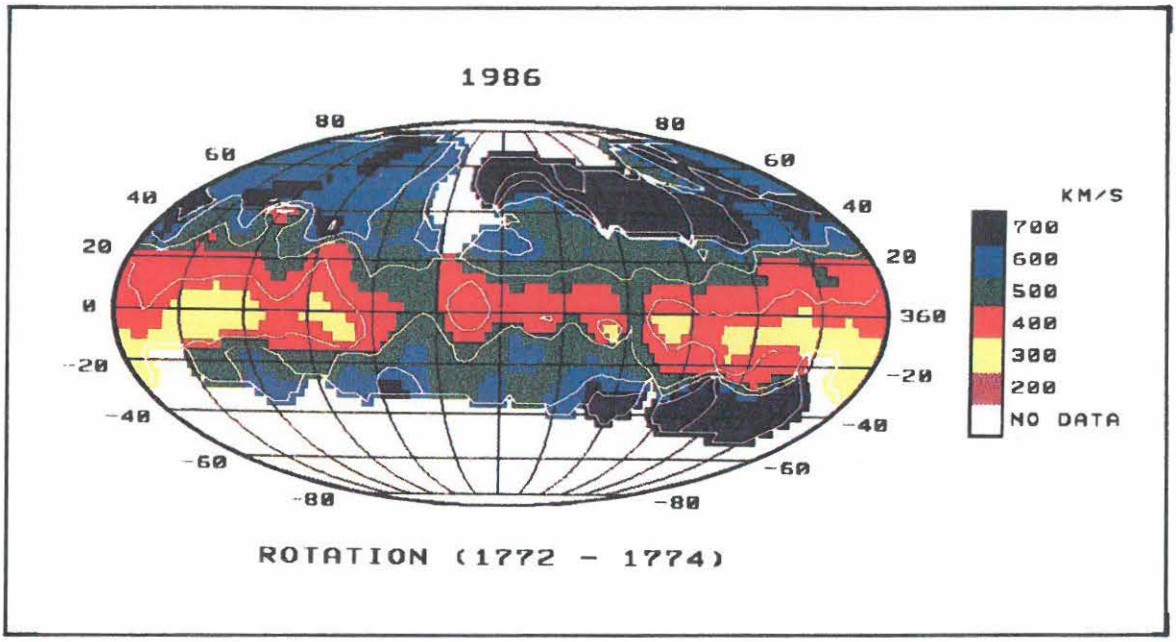
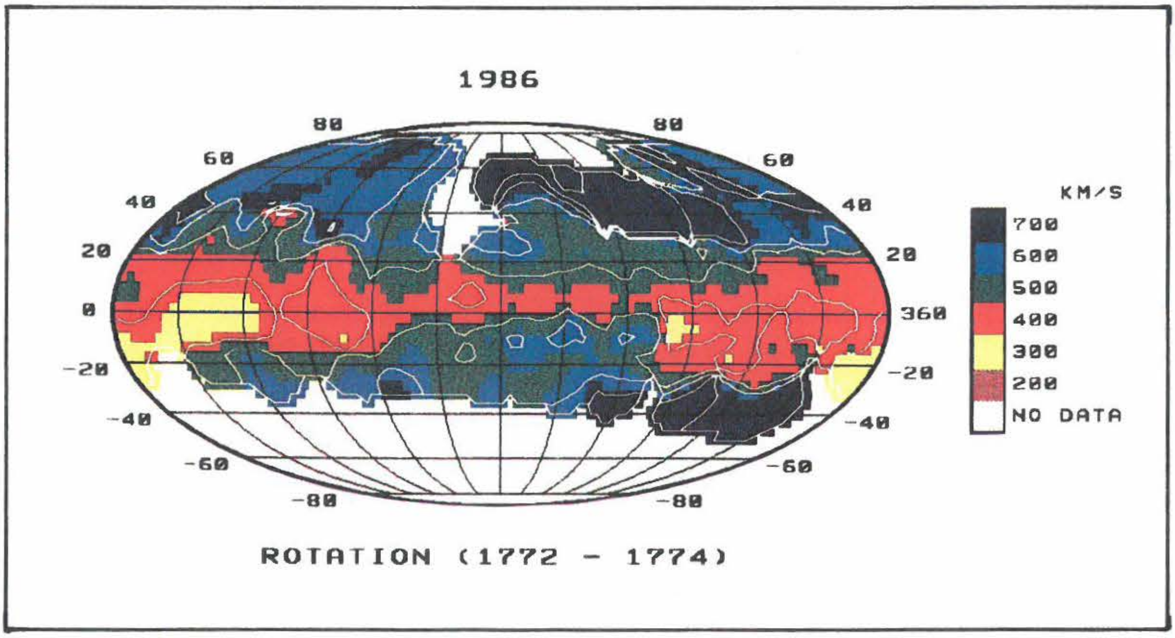


Fig. 3. Solar wind speed observed by a IPS source 3C 298. The Figure is shown with the same method as that used for Figure 2.

(a)


1986
80
80
60
60
40
40
20
20
0
360
-20
-20
-40
-40
-60
-60
-80
-80
KM/S
700
600
500
400
300
200
NO DATA
ROTATION (1772 - 1774)

(b)


1986
80
80
60
60
40
40
20
20
0
360
-20
-20
-40
-40
-60
-60
-80
-80
KM/S
700
600
500
400
300
200
NO DATA
ROTATION (1772 - 1774)

The leading edge of the northern high-speed region had a large latitudinal speed gradient between longitudes 150° and 270°. This edge inclined at a rather small angle to longitudinal direction. The leading edge of the southern high-speed region between longitudes 300° and 330° inclined at a large angle to longitudinal direction.

3. Global Structure on the source surface in 1986

The solar wind speed maps of Figure 4a and b were derived from the IPS and SAKIGAKE observations during CR 1772 - 1774. Figure 4a was derived from IPS observations and Figure 4b is the result of superposition of the SAKIGAKE data on Figure 4a. The width of the low-speed region (red colored) became narrower in Figure 4b than that of 4a between longitudes 120° and 240°. Within the same longitude range, the speed level of the southern high-speed region increased near the low speed region in Figure 4b, and consequently the latitudinal speed gradient became larger. In the central region of the map, southern and northern high-speed regions extended nearly to the equator in a wide longitude range. The low-speed belt (red colored region) was warped a little northward at the center of the map. At both sides of the map there were minimum-speed regions (yellow colored) at latitude -20° and the belt was warped southward. However, in spite of these warps, inclination of the low-speed belt was very small and it can be considered to be nearly flat.

4. Observations of SAKIGAKE and SUISEI in 1985

In order to show characteristic differences between observations by SAKIGAKE and those by SUISEI, data were mapped back to the source surface by the same method as that used in Figures 2 and 3, and the solar wind speed and density observed by SAKIGAKE and SUISEI has been plotted together in Figure 5 as functions of the Carrington longitude. Since data are arranged in order of observation time from left to right, the Carrington longitude goes from right to left. The top frame

Fig. 4. (Facing page) Same as Figure 1. Observations during CR 1772 and 1774 were superposed. (a) is derived from the IPS data, and (b) is derived from the observations by IPS and SAKIGAKE.

indicates heliographic latitudes, and the next frame indicates heliocentric distances of the spacecraft. The bottom frame shows the proton densities observed by SAKIGAKE.

SAKIGAKE observed one high-speed stream centered at longitude 120° in CR 1766. In following the two rotations CR 1767 and 1768, two streams were observed at longitudes 270° and 90°, respectively. SUISEI also observed these two streams in CR 1768. However, it observed only part of the stream centered at longitude 270° in CR 1767 due to observation gaps. Following are the characteristic differences between the observations by the two spacecraft: there was a large velocity difference of about 200 km/s at longitude 180°; a wider stream was observed by SUISEI than by SAKIGAKE between longitudes 0° and 180°; on the other hand, SAKIGAKE observed a wider stream than SUISEI between longitudes 180° and 360°.

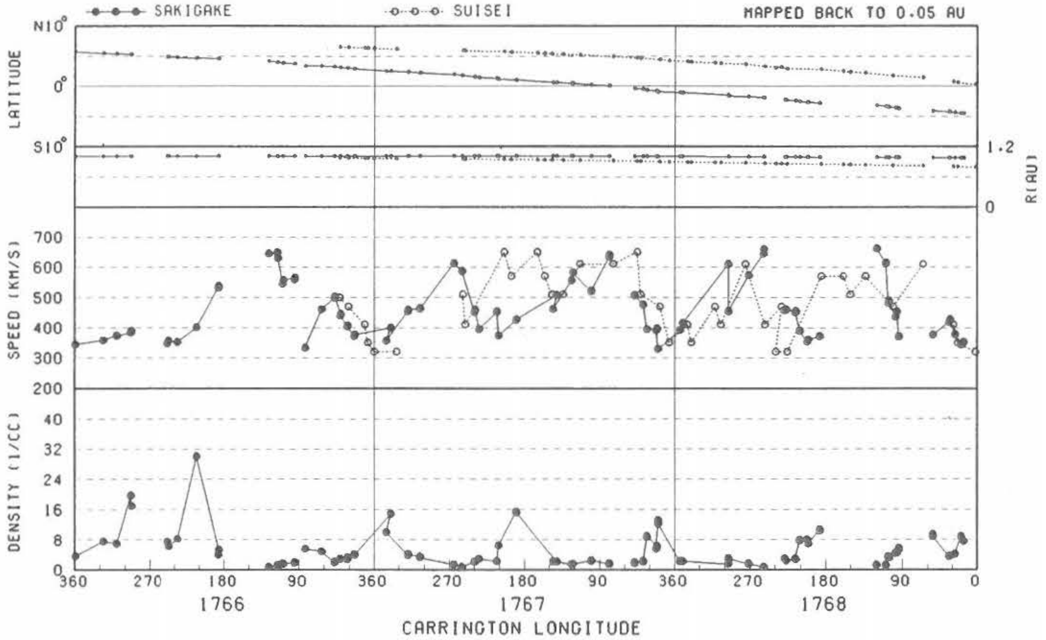


Fig. 5. Solar wind parameters observed by SAKIGAKE and SUISEI. The bottom frame is proton density observed by SAKIGAKE. The Figure is shown with the same method as that for Figure 2.

5. Explanation of Spacecraft Observations in 1985

The two spacecraft trajectories were separated by about 5° in heliographic latitude, and SUISEI was north of SAKIGAKE. Both of the spacecraft were in the northern hemisphere during CR 1766, and SAKIGAKE crossed the equator and entered the southern hemisphere at the end of CR 1767. SUISEI crossed the equator at the beginning of CR 1769. When the spacecraft were far from the equator in the northern hemisphere, only the northern high-speed regions were observed between longitudes 0° and 270°. When they approached the equator and entered the southern hemisphere, they observed not only the northern high-speed regions but also the southern region located between longitudes 180° and 360°.

Since the leading edge of the northern high speed region in CR 1767 had a rather small inclination to longitudinal direction (ie. trajectories of SUISEI and SAKIGAKE) between longitudes 150° and 270°, and SUISEI was 5° north of SAKIGAKE, SUISEI entered this high-speed region at longitude 210° while SAKIGAKE entered at 150°. When they cut the southern high-speed region, the situation was reversed; SAKIGAKE entered the region at 300° while SUISEI entered at 270°. But, Since

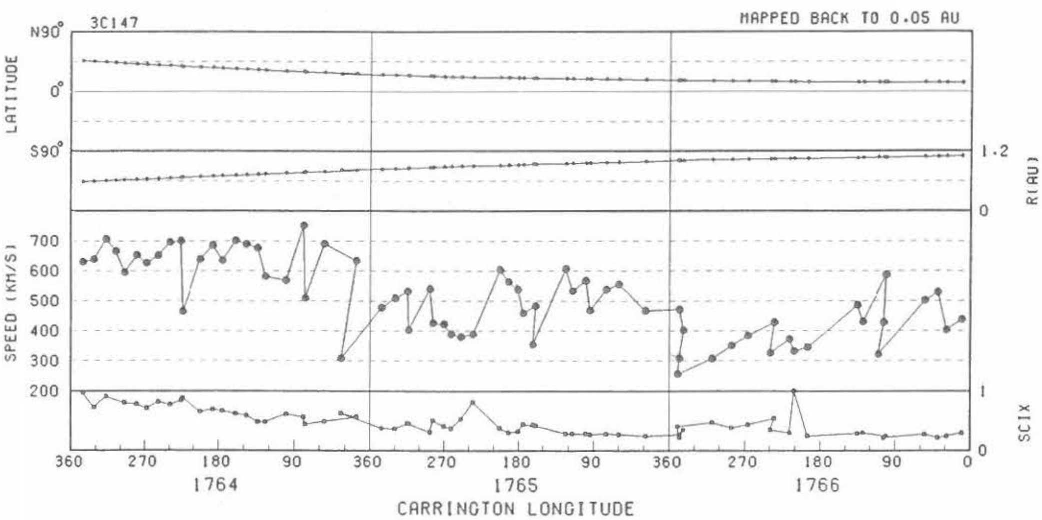


Fig. 6. Solar wind speed observed by a IPS source 3C 147. Bottom frame is scintillation index and unit of its ordinate is arbitrary. The Figure is shown with the same method as that for Figure 2.

the leading edge of the southern high-speed region had a large inclination to longitudinal direction, the longitudes at which the two spacecraft crossed the edge were not as far from each other as was the case in the northern high-speed region. The speed gradient in the latitudinal direction at the boundary of the northern high-speed region is calculated to be as large as about 40 km/s/degree because of the fact that a 200 km/s velocity difference was observed between the two spacecraft, which were separated by only 5°.

SAKIGAKE observed a large density increase of 30/cc at longitude 210° in CR 1766. The density increase at this longitude was observed also in the following two rotations. The region where the density increase was observed corresponded to the leading edge of the northern high-speed region. This means that a stream-stream interaction region was well developed at the leading edge ,traveling a distance of 1 AU. At this leading edge, IPS source 3C147 observed a large scintillation index in CR 1766, as shown in the bottom frame of Figure 6. This IPS had already detected the index increase in CR 1765 at latitude $+20^{\circ}$. These facts indicates that the interaction region was developed in the latitudinal range of between a few degrees south of the equator and 20° north of the equator.

6. Observations of SAKIGAKE in 1986

The trajectories and observations (speed, proton temperature and proton density) of SAKIGAKE from CR 1771 to 1773 are shown in Figure 7. SAKIGAKE was south of the equator during CR 1771 and 1772, and crossed the equator in CR 1773. It observed a high-speed stream between longitudes 150° and 270° in CR 1771. The speed in regions out of the stream did not drop to a low level in CR 1771, but stayed around 500 km/s. Therefore the stream boundaries were not clearly observed in this rotation. In CR 1772, the boundaries of the high-speed stream were clear at longitudes 150° and 270°. At longitude 150° in CR 1772, the speed dropped to a low level of between 300 and 400 km/s and this low-speed observation continued until the end of the next rotation, CR 1773. The velocity jump at the leading edge was not large and the average speed of the pre-stream level between longitudes 270° and 360° in CR 1772 was around 500 km/s. Temperature showed a large increase of more than $400,000^{\circ}K$ at the leading edge in CR 1772. However this leading edge was not accompanied by any great density increase.

7. Explanation of Spacecraft Observations in 1986

In CR 1771 and 1772, SAKIGAKE cut the southern high-speed region between longitudes 150° and 270°. The sharp velocity drop at longitude 150° in CR 1772 implies that SAKIGAKE had crossed the top boundary of the high-speed region and entered the low-speed belt. SAKIGAKE stayed in the low-speed belt throughout the next rotation, CR 1773. Of these three rotations, clear observations of the high-speed stream were made only in CR 1772. Therefore the 27-day recurrence of speed seems

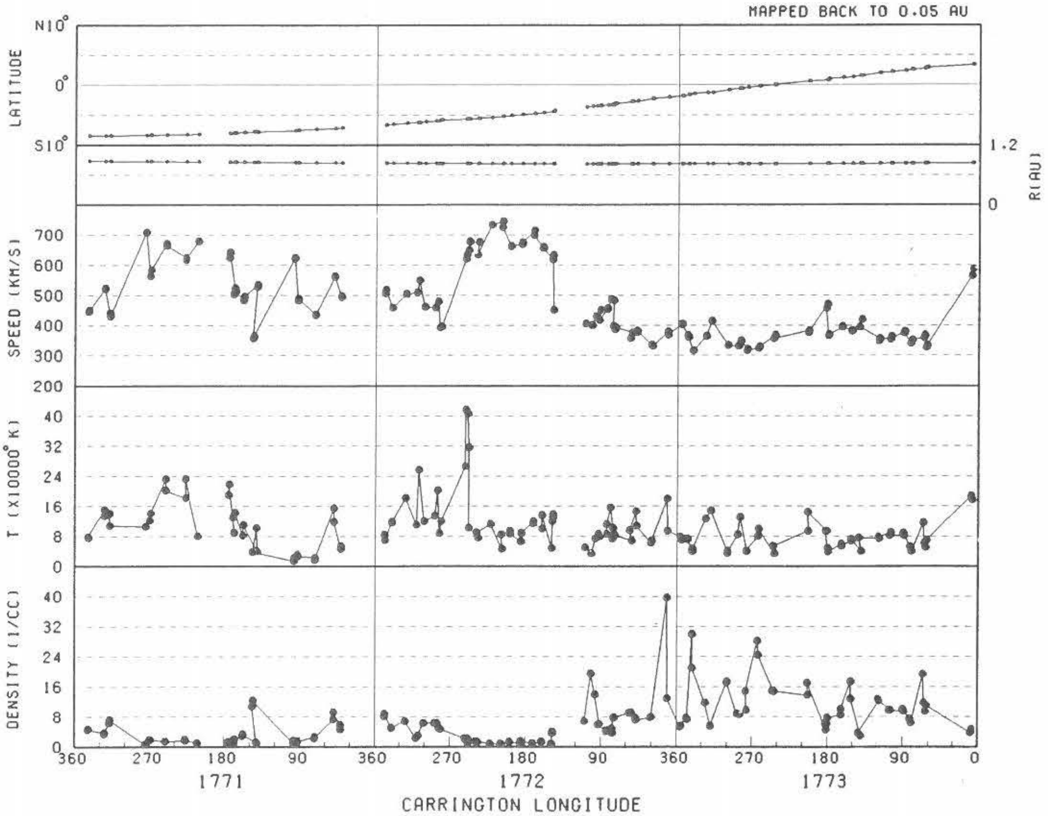


Fig. 7. Solar wind parameters observed by SAKIGAKE. The Figure is shown with the same method as that for Figure 2.

to have disappeared during CR 1771-1773. The leading edge of the southern high-speed region was not clear in CR 1771, and also, average speed before the leading edge in CR 1772 was at a medium level of about 500 km/s. This may be one reason why the density did not increase enough at this edge.

8. Summary

The period from September to November of 1985 was in the excursion phase. In the excursion phase, it is expected from the two-hemisphere model (Saito, 1984) that a neutral sheet is inclined to the solar equator at a small angle. The low-speed belt on the source surface during this period showed a structure similar to the expected structure of the neutral sheet. The high-speed regions in both hemispheres extended to low latitudes and approached this low-speed belt. The leading edge of the northern high-speed region had a large latitudinal speed gradient of about 40 km/s/degree and had a small inclination angle to longitudinal direction. Stream-stream interaction was well developed at this leading edge, traveling a distance of 1 AU, and it was observed as a large density and scintillation index increase. The beginning of the year 1986 was expected to be very close to the aligned phase because the low-speed belt had a nearly flat structure. The southern high-speed region did not have a sharp leading edge; a temperature increase was observed, but a density increase was not.

Acknowledgments

We would like to thank Prof. T. Yoshino and his colleagues for allowing us to make IPS observations at the Sugadaira Radio Wave Observatory, University of Electro-Communications. We would also like to thank Messrs Y. Ishida and K. Maruyama who have helped to continue IPS observations and to improve the observation system. Our thanks also go out to Mrs. M. Yoshida for her assistance in daily data analysis.

The program to draw contour lines, "CTLKTL", developed by Dr. T. Kamiya (Nagoya Univ. Computer Center Numpac Library), was used in making the speed maps.

References

Harmon, J. K.: Scintillation studies of the density microstructure in the solar wind plasma, Ph.D. thesis, Univ. of Calif. at San Diego, La Jolla (1975)

Kakinuma, T., and M. Kojima: 'Solar wind speed from IPS measurements, for Mar.-Dec. 1983', Res. Inst. of Atmospherics, Nagoya Univ., Toyakawa, Japan (1985)

Kojima, M., and T. Kakinuma: Three-station observations of interplanetary scintillation at 327 MHz-II: Evolution of two-dimensional solar wind speed structure during 1983 to 1985, Proc. Res. Inst. of Atmosph., Nagoya Univ., **33**, 1-18 (1986)

Kojima, M., and T. Kakinuma: Solar cycle evolution of solar wind speed structure between 1973 and 1985 observed with the interplanetary scintillation method, J. Geophys. Res., to be published (1987)

Readhead, A. C. S.:Interplanetary scintillation of radio sources at metre wavelengths-II, Mon. Not. Roy. Astron. Soc., **155**, 185-197 (1971)

Saito, T.: Solar cycle change of the structure of the heliosphere, in Extended Abstracts of Joint U.S.-Japan Seminar on Recent Advances in the Understanding of Structure and Dynamics of the Heliomagnetosphere During the Current Maximum and Declining Phase of Solar Activity, Kyoto, Nov. 5-9, 1984

Watanabe, T., and T. Kakinuma: The recurrent solar wind streams observed by interplanetary scintillation of 3C48, Publ. Astron. Soc. Japan., **24**, 459-467 (1972)