DIAGNOSTICS OF THE HELIOSPHERE BY MEANS OF GROUND-BASED ULF OBSERVATION

Takao SAITO, Kiyohumi YUMOTO and Tadayoshi TAMURA

Onagawa Magnetic Observatory and Geophysical Institute, Tohoku University, Sendai 980

Abstract: ULF waves have been utilized for diagnostics of the earth's magnetosphere since the 1960's. Similarly, an attempt is given in the present paper to diagnose the magnetosphere of the sun by utilizing the ULF waves observed at the Onagawa Magnetic Observatory. The diagnostics is based on the observed high correlation among the solar wind speed, amplitude and duration of Pc 3, which is the so-called sensitive anemometer for the solar wind. We selected the two extremes of distinct 27-day recurrence time patterns: the vertical pattern in 1974 and the horizontal pattern in 1954. From the vertical pattern, we diagnose the heliosphere with a tilted neutral sheet, which is the representative feature for the excursion phase of a solar cycle. While, the analysis of the horizontal pattern derives the heliosphere with a less-warped neutral sheet near the equatorial plane. This is the representative configuration of the heliomagnetospheric neutral sheet in the aligned phase. The two representative sheet configurations are discussed in terms of the solar cycle variation of the heliosphere.

1. Introduction

Before 1950, geomagnetic pulsations had been ascribed to some fluctuations of the ionospheric currents (*e.g.*, TERADA, 1917). Soon after KATO and UTASHIRO (1949) started to observe pulsations at the Onagawa Magnetic Observatory in early 1950's, a relation between the pulsations and the hydromagnetic waves in the upper atmosphere was recognized. Based on this relation, scientists began to search the magnetosphere condition by ULF waves. Utilization of HM waves to study remote magnetosphere in space physics is much like the use of sound waves to diagnose internal organs in medical science. Hence, this method became very popular since the 1960's with expressions like "diagnostics of the earth's magnetosphere by means of ground-based ULF observation (*e.g.*, TROITSKAYA and GUL'ELMI, 1967; NISHIDA, 1978)".

Meanwhile, various relations between ULF waves and solar wind parameters were found (SAITO, 1964b; TROITSKAYA, 1967). The first relation discovered was the one between the solar wind speed (V_{SW}) and the geomagnetic activities like Pc 3 and Pc 4; A_{Pc3} (Pc 3 amplitude), A_{Pc4} (Pc 4 amplitude), K and Kp (SAITO, 1964b; see Fig. 1A). Correlation coefficient of the solar wind speed with A_{Pc3}, A_{Pc4}, ΣK and ΣKp showed 0.80, 0.70, 0.69 and 0.61, respectively. Because V_{SW} has the highest correlation coefficient with A_{Pc3}, Pc 3 is called sometimes *a very good anemometer for the solar wind.*

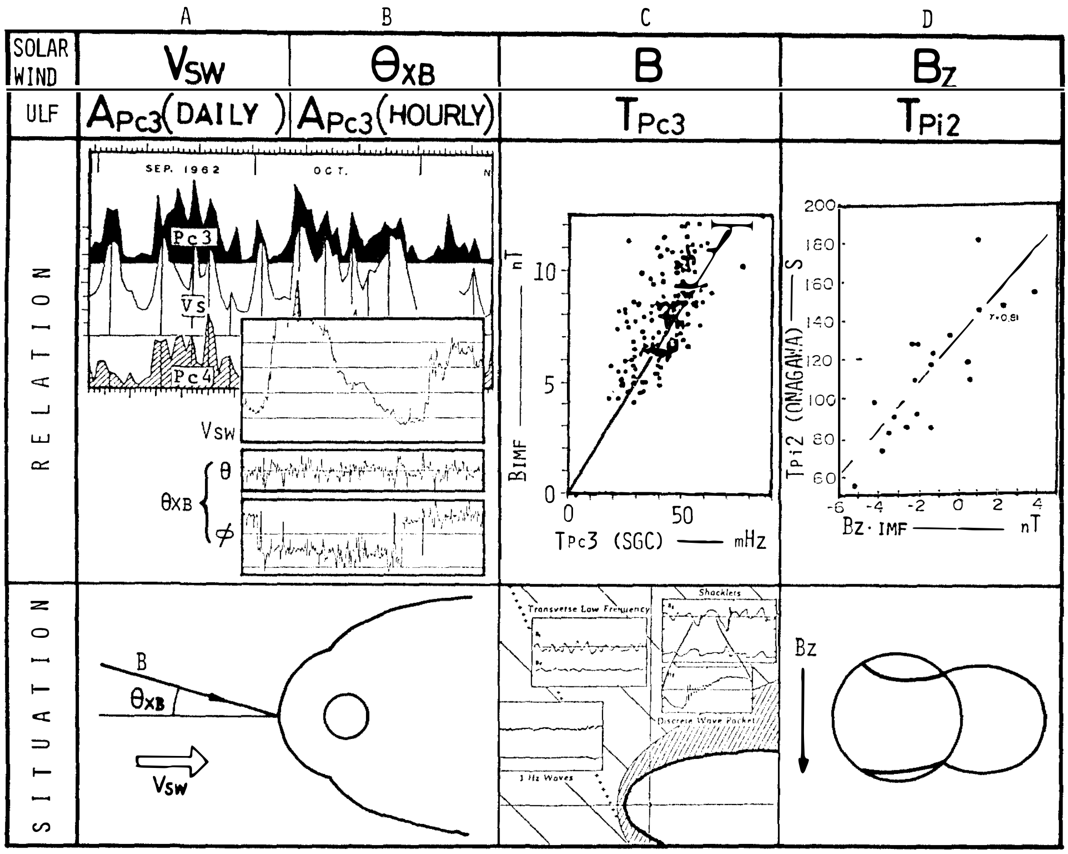

Fig. 1. Observational relations and assumed situation on solar wind parameters and ULF parameters. The relations are; (A) solar wind speed V_{SW} and Pc 3 amplitude A_{Pc3}, (B) cone angle of the solar wind magnetic field θ_{XB} and Pc 3 amplitude A_{Pc3}, (C) solar wind magnetic field intensity B and Pc 3 period T_{Pc3}, and (D) northward component of the solar wind magnetic field B_z and Pi 2 period T_{Pi2}.

The second relation is between the cone angle θ_{XB} of the solar wind magnetic field and A_{Pc3} as displayed in Fig. 1B (TROITSKAYA and GUL'ELMI, 1967). The third of the Pc 3 characteristics is the relation between Pc 3 period T_{Pc3} and intensity B of interplanetary magnetic field (IMF) (YUMOTO *et al.*, 1984, see Fig. 1C). The last is the relation between IMF-B_z and Pi 2 period T_{Pi2} as shown in Fig. 1D (SAITO and MURAKAMI, 1981).

Based on these relations, we can infer the solar wind parameters V_{SW}, θ_{XB}, and B by Pc 3 during daytime, and B_z by Pi 2 during nighttime. The time variation of V_{SW} is rather gradual, while that of θ_{XB} is rapid, as exemplified in Figs. 1A and B. Consequently, we may infer V_{SW} and θ_{XB} separately by daily value and hourly value of A_{Pc3}, respectively. The fact that these solar wind parameters can be inferred from ground-based observations of ULF waves means that we can make "diagnostics of the heliosphere by means of ground-based ULF observation".

The purpose of the present paper is to provide the first example of the diagnostics of the heliosphere by ULF waves.

2. Diagnostics of the Heliosphere in the Sunspot Declining Phase

The daily activity index of Pc 3 amplitude, C3 (SAITO, 1964b), has been provided from 1958 through the present based on the continual observation of ULF waves at Onagawa as shown in Fig. 2. The index has been expressed also in the format of the 27-day recurrence diagram. (For an example of the diagram, see Fig. 61 of SAITO, 1969). It is well known that Pc 3 activity (SAITO, 1964a), as well as other geomagnetic activities, shows a clear 27-day recurrence in the sunspot declining phase. Among the recurrence patterns, a typical case of the most distinct recurrence is exhibited in Fig. 14 of SAITO and SETO (1979). The case of the 1974 index in the figure clearly shows the two *vertical* trends of Pc 3 enhancement.

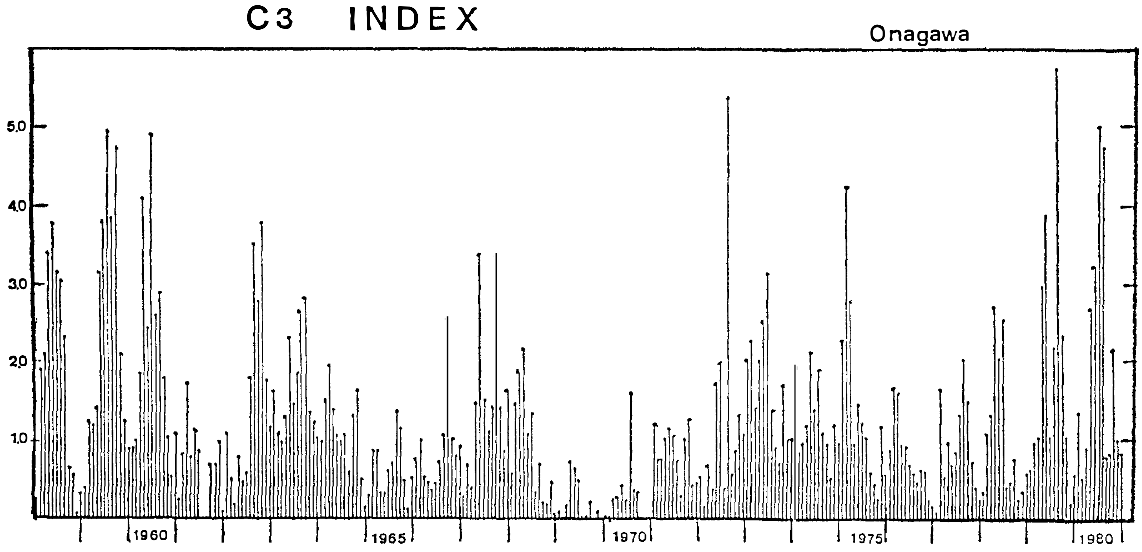

Fig. 2. Pc 3 activity index C3 from 1958 to 1980.

From the first relation betweeen the solar wind parameters and the ULF waves as summarized in Fig. 1, we may derive that the vertical structure of the Pc 3 is due to some vertical structure of the solar wind speed. Hence, the contour line of the C3 index can be read as the contour line of the solar wind speed.

Statistically, V_{SW} is enhanced $1\sim 2$ days after the IMF sector boundary crossings (WILCOX and NESS, 1965). Hence, the enhancement of Pc 3 amplitude, and therefore the enhancement of the solar wind speed, can be used for diagnostics of the sector boundary crossing. From the two vertical structure of C3 and V_{SW}, we can also determine that the solar wind magnetic field must be the 2-sector structure throughout the year of 1974. Then we compare our diagnostics with the observed data in Fig. 3, where 27-day recurrence diagrams of IMF sector polarity, IMF-B_z component, solar wind speed, and geomagnetic C9 index are displayed in the same format. As shown in the figure, V_{SW} exhibits the two vertical stripes and the IMF has the two-sector structure throughout the year.

The C9 index also shows the two vertical stripes, depending on the V_{SW}, but the index is strongly controlled by the Russell-McPherron effect as seen in the B_z-diagram. This control means that Pc 3 is a much better phenomenon to diagnose the solar

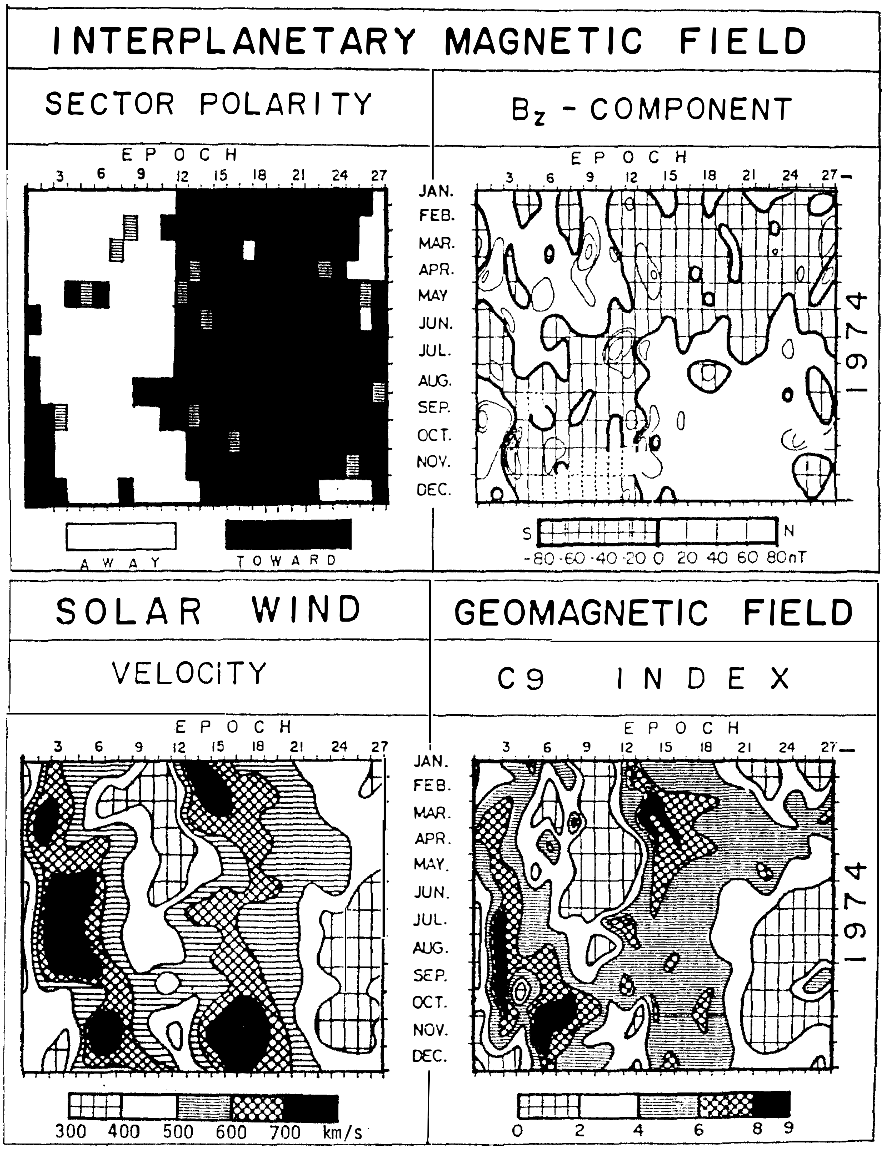

Fig. 3. The 27-day recurrence time patterns of interplanetary sector polarity, IMF-B_z component, solar wind velocity, and geomagnetic C9 index in 1974.

wind than general geomagnetic indices like C9.

By using the scanning method (SAITO *et al.*, 1978), we may diagnose the structure of the heliosphere from the 2-sector structured diagram as shown in Fig. 4. The observed 2-sector structure can be explained by this model with the rotation of the tilted neutral sheet. The two vertical trends of C3 and V_{SW} are also interpreted by the two high-speed streams from the two coronal hole tongues extending from the northern and the southern polar caps, respectively. The exact tilt angle of the neutral sheet cannot be diagnosed from the C3 index alone because of the restriction of the helio-latitudinal range of the scanning method. However, the angle is determined to be between 30° and 50° by comparing *K*-corona data, solar magnetograph, IPS data, etc. (SAITO and SETO, 1979). Such a tilting is identified as the characteristic feature of the heliosphere during the excursion phase in which recurrent storms are frequently

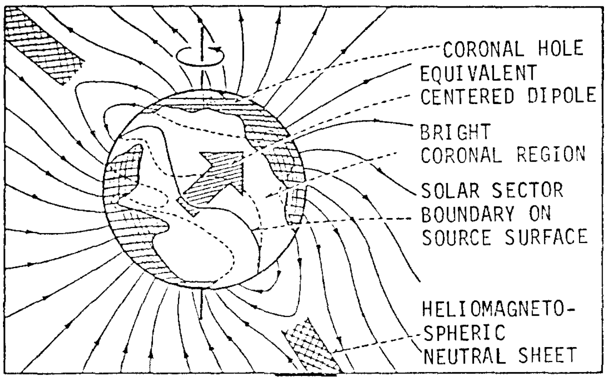

Fig. 4. Assumed situation of the heliomagnetosphere in 1974.

observed (SAITO, 1981).

3. Diagnostics of the Heliosphere in the Sunspot Minimum Phase

In contrast to the two vertical trends as discussed in Section 2, Pc 3 amplitude sometimes shows clear two *horizontal* trends in the 27-day recurrence diagram. The clearest example is displayed in Fig. 5, where no distinct vertical trend is recognized. HOLMBERG (1953) found that amplitude of Pc 3 is proportional to frequency of occurrence of Pc 3. Since his finding, this relation has been supported by many researchers (see the review by SAITO, 1969). Hence, frequency of occurrence of Pc 3 as measured by hourly duration per day is used in Fig. 5 instead of its amplitude.

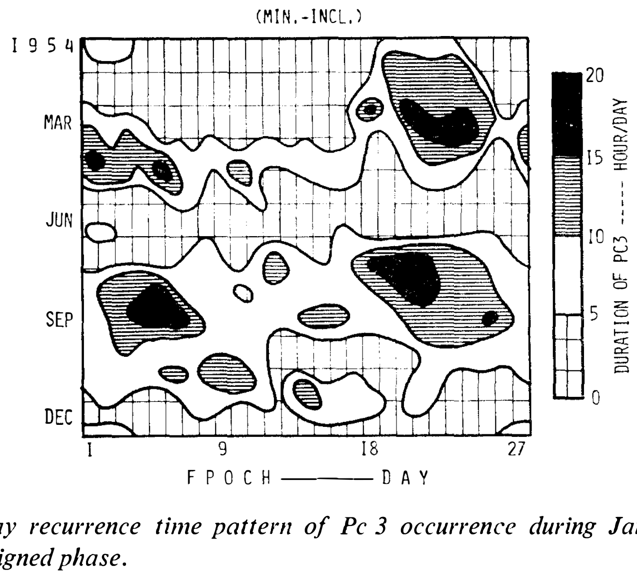

Fig. 5. The 27-day recurrence time pattern of Pc 3 occurrence during January to December, 1954 in aligned phase.

According to the scanning method, the Bartels rotation number can be transferred into heliolatitude, and the epoch into heliolongitude. Consequently, the 27-day recurrence diagram is transformed to the synoptic chart of V_{SW} in Fig. 6B. The source region of the high-speed solar wind is located in relatively higher heliolatitudes within

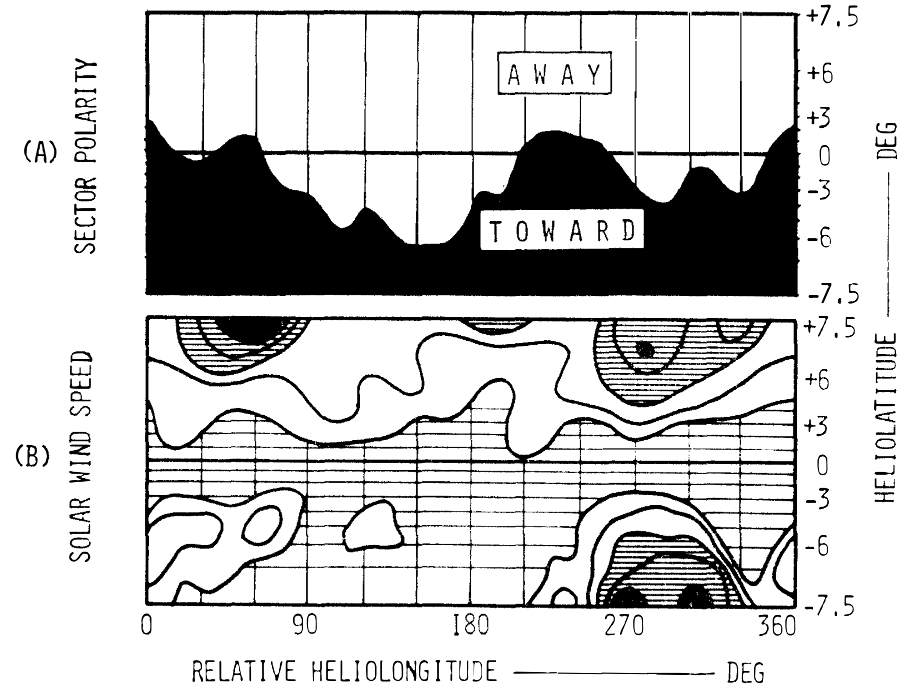

Fig. 6. Synoptic charts of (A) the solar sector polarity and (B) the solar wind speed obtained from the observed IMF and Pc 3 occurrence, respectively. The darker area in (B) means the source region from which the higher speed wind flows out. The contour scale is arbitrary.

the $\pm 7.5°$ latitudinal range. Statistically V_{SW} is smallest on the day of the sector boundary crossings. Hence, the distribution of the smallest V_{SW} near the solar equator in Fig. 6B implies that the neutral sheet or the solar sector boundary must be between the two high-speed regions. Actually this diagnostics is examined by applying the scanning method to the observed IMF sector polarity. (The reader may refer to SAITO (1975) for further explanation on this application.) Figure 6A shows the result on the solar sector boundary on the solar source surface.

A comparison between Figs. 6A and 6B leads to a conclusion that our implication is appropriate. When the neutral sheet is nearly on the heliographic equatorial plane with small warp, the state is called the aligned phase (SAITO and MURAKAMI, 1982). It is because the neutral sheet in this state is expressed by an equivalent centered dipole that is nearly in alignment with the solar rotational axis. The aligned state is a typical configuration of the heliosphere during the sunspot minimum phase (SAITO and MURAKAMI, 1981).

4. Discussion and Conclusion

We picked up the two extreme cases of the 27-day recurrence pattern of Pc 3 amplitudes. One is the two vertical trends of enhancement, and the other is the two horizontal trends. Diagnostics of the heliosphere was carried out on the two cases by using the scanning method. The result indicates that the two vertical patterns imply the tilted neutral sheet of the heliosphere, while the two horizontal patterns suggest

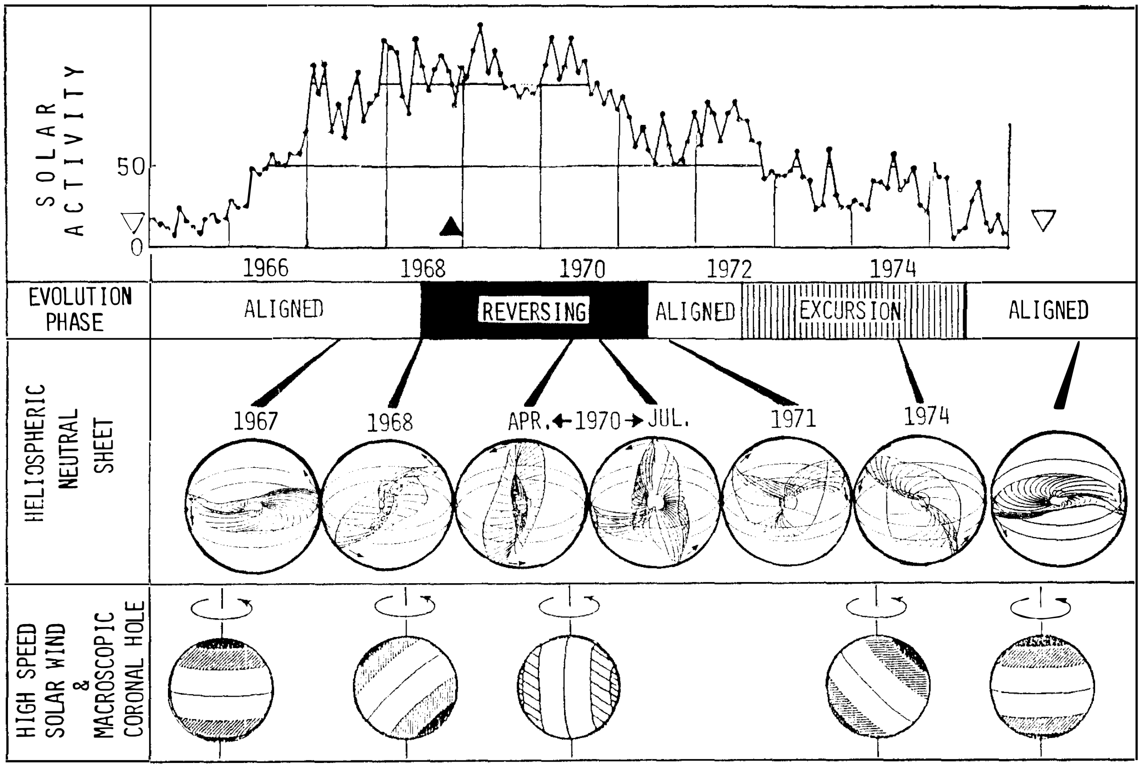

Fig. 7. Solar cycle evolution of the heliosphere as derived from various solar, interplanetary, and terrestrial phenomena. From the viewpoint of the heliomagnetosphere configuration, one solar cycle is divided into cyclic phases from aligned, via reversing, aligned, excursion, and to aligned phases, respectively.

the aligned neutral sheet. These conditions of the neutral sheet are quite standard for the cases of excursion and aligned phases, respectively, during one solar cycle as shown in Fig. 7, where the solar cycle evolution of the heliosphere as derived mainly from the solar magnetic field is displayed.

Since Bartels invented the 27-day recurrence diagram method, the diagram has been used to find some of the recurrent phenomema. In other words, only some vertical patterns have been taken into consideration. The present analysis revealed that the non-vertical pattern also provides a very important information.

Although the aligned structure of the neutral sheet is the characteristic feature during the sunspot minimum phase, the horizontal pattern in 1954 is especially distinct. Therefore, in order to study this peculiarity, the relative sunspot number for the recent half a century is displayed in Fig. 8B, where the number is expressed in logarithmic scale to enlarge the smallest portion. It is evident in the figure that the 1954 sunspot number is the smallest within this half a century. The 1954 eclipse (Fig. 8A) is famous as the typical equatorial type corona. The relation among these facts can be explained in the following way; since there was little sunspot activity in 1954, both of the fundamental equatorial type corona and the purely aligned structure of the heliosphere were not distorted by local sunspot fields.

We analyzed the typical vertical and horizontal patterns to diagnose the heliosphere in this introductory paper. We are entering an age in which the diagnostics

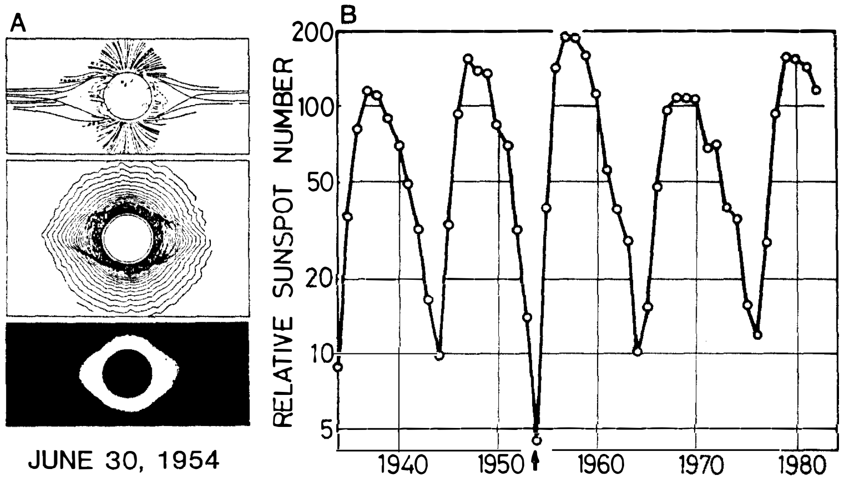

Fig. 8. Typical equatorial type corona observed during the total eclipse on June 30, 1954 (cf. Fig. 5 of Saito, 1975) (A). Relative sunspot number showing the extremely low value in 1954 (B).

of the heliosphere is possible from ULF observation data. The diagnostics is very important for Japanese scientists who had no direct data of observed IMF, and who have to examine the Japanese Halley spacecraft data (Saito and Murakami, 1982) by the diagnosed IMF data. Further study of diagnostics will be carried out in the future by using the C3 index obtained at Onagawa for the past 30 years.

Acknowledgments

The authors wish to express their sincere thanks to Dr. Y. Kato, Emeritus Professor of Tohoku University, and Dr. J. Ossaka, Director of the Sendai Municipal Astronomical Observatory, who took the 1954 ULF data as the director and the observer in charge, respectively, of the Onagawa Magnetic Observatory.

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(Received June 20, 1984; Revised manuscript received February 4, 1985)