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Structure of solar wind velocity along the HCS and related geomagnetic field variations*

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Azimuthal variation of solar wind velocity in the range 300-450 km s^{-1} has been found to exist along the current sheet during 1972-1977. The possibility of using the A_p index (when the earth goes through an IMF sector boundary crossing) to study the azimuthal structure of solar wind has been analysed. The longitudinal variation of the A_p index in terms of Carrington longitude is found to be similar to that of the solar wind velocity variation.

1 Introduction

The interplanetary magnetic field (IMF) exhibits a sector structure near the earth's orbit as pointed out first by Wilcox and Ness[1]. The features and evolution of the sector pattern with the phase of the solar activity cycle have been the topic of interest for the past several years[2-8]. In each sector, the dominant polarity of the magnetic field is either away from or towards the sun. The region separating the adjacent sectors of opposite magnetic polarities is known as the sector boundary[7]. The sector boundary is currently understood as points on heliospheric current sheet (HCS), a huge, warped sheet that separates the entire heliosphere into two hemispheres of opposite dominant magnetic polarity. At the sector boundaries, the solar wind veocity is lower ($\sim$ 400 km s^{-1}) than that inside the sectors[7] ($\sim$600 km s^{-1}).

The heliospheric current sheet maps back to the neutral line, separating the photospheric magnetic structures of opposite polarities. Since this neutral line does not exactly follow the solar equator (i.e. the plane perpendicular to the axis of solar rotation), the HCS is not strictly planar. The curves on the neutral line introduce warps of large heliolatitudinal extensions ($\pm 20°$) in the HCS. As the current sheet rotates along with the sun, the earth observes a sequence of alternating northern or southern magnetic polarities as sectors. The number of sectors observed in a solar rotation depends on the phase of the solar cycle[8].

Using satellite data and IPS measurements, it has been shown that the solar wind veocity in the heliosphere tends to be a minimum on the HCS and increases with the angular distance (heliomagnetic latitude) from the HCS (Refs 9-14). Along the current sheet itself, the solar wind velocity varies with solar longitude[15,16]. Using near-earth satellite data and IPS measurements of solar wind velocity, it has been shown that there exists an azimuthal variation of solar wind velocity on the current sheet[17,18].

Statistical results show a strong correlation between solar wind speed and geomagnetic activities represented by various indices[19-24]. For example, the A_p index and solar wind speed have been shown to have a correlation >0.8 (Refs 19 and 22). For long-term averages (say, months), the A_p index is found to correlate best with the square of the solar wind velocity with a correlation coefficient greater than 0.8 (Ref. 21). On shorter time scales (minutes to hours), the correlation between the two parameters is much poorer[25] because of the controlling influence of the magnitude and direction of the IMF on the level of geomagnetic activity. However, the IMF is poorly correlated (correlation coefficient is ~ 0.3) with geomagnetic activity over long-time scales[19].

In the present work, an attempt has been made to obtain the relation between the solar wind velocity on the HCS and the corresponding geomagnetic activity represented by A_p index. It is found that the A_p values corresponding to points on the HCS varied in a similar manner as that of the corresponding solar wind velocity obtained in an earlier analysis[17].

2 Data and procedure

The period of study (1972-1977) is the declin-

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ing phase of solar cycle 20 and the early ascending phase of the next cycle. During such periods, transient events like solar flares are less in number and the solar wind is stable for considerably long periods. Therefore, this period is ideal for studying long period structures in the solar wind. The planetary activity index A_p has an approximate linear relation with the global variations of the earth's magnetic field[26], and has a linear relation with the solar wind velocity[19-24]. Hence, this index can be used for studying average structures in the geomagnetic field variations, and the corresponding solar wind velocity.

For the present study, we have made use of the near-earth satellite data of interplanetary parameters[27,28]. Near-earth satellites can probe only a narrow region of about $\pm 7.25°$ near the ecliptic. The current sheet, as the sun rotates, crosses the earth two or four times in one rotation, depending on the number of warps in it. These crossings are identified from sharp changes in the azimuthal angle of IMF as the IMF sector boundaries at 1 AU, marked as A and B [Fig. 1(a)], and the solar wind velocity corresponding to this point is considered as that on the HCS. Since other points on the HCS are not easily identified, we have to restrict our analysis to the sector boundary crossings

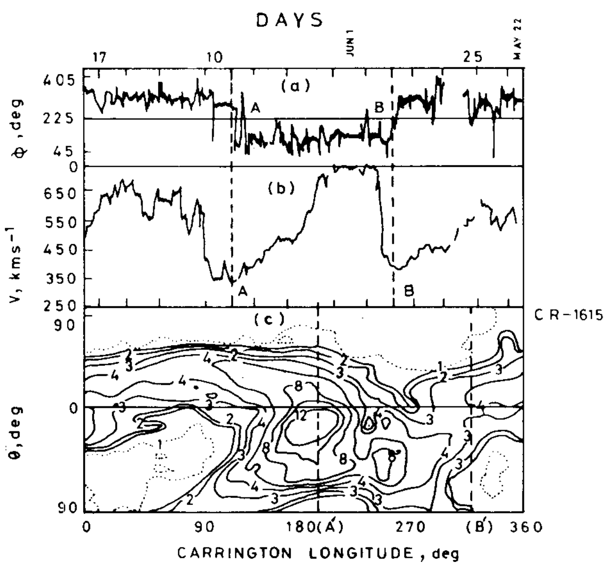

Fig. 1—(a) Longitude ϕ of the IMF in GSE coordinate system for the period 22 May-18 June. (The points A and B are identified as the sector boundary crossings at 1 AU); (b) Bulk velocity of the solar wind for the same period (The velocities at A and B are taken as the velocity on the HCS.); and (c) K-corona contour map for the same period, measured at the east limb of the sun at a height 1.5 $R_\odot$ (The Carrington longitudes of the points A′ and B′ are taken to represent the longitudes of points A and B.)

to study the azimuthal variation of velocity on HCS using A_p index.

Figure 1(a) depicts the variation of the longitude (ϕ) of IMF in GSE coordinate system (above and below $\phi = 225°$, the IMF has opposite polarities), during the period 22 May-18 June[27] depicted at the top of the diagram. The points A and B are identified as the IMF sector boundary crossings[29]. Figure 1(b) gives the bulk velocity of the solar wind during the same period[27]. The solar wind velocity corresponding to the points A and B are noted. Figure 1(c) is the contour map of the K-corona brightness measured on the source surface at a distance of 1.5 $R_\odot$ for the same period[30]. Points A′ and B′ in Fig. 1(c) are the sector boundaries A and B projected back to the corona, taking an average transit time of 5 days for the solar wind to traverse the sun-earth distance. The longitudes corresponding to A′ and B′ are taken to be the Carrington longitudes of the points A and B shown in Fig. 1(a).

The A_p indices corresponding to all the IMF sector boundary crossings during 1972-1977 are taken from the *Solar Geophysical Data*[31]. The A_p index is then re-arranged corresponding to Carrington longitudes of width 30° and the average value ($\bar{A}_p$) in each bin is calculated. The value of $\bar{A}_p$ is then plotted against the Carrington longitudes to see its azimuthal variation (Fig. 2). This is compared with the variation in the corresponding solar wind velocity ($\bar{V}_{sw}$) obtained earlier for the same period[17] and both the $\bar{A}_p$ in Fig. 2 and $\bar{V}_{sw}$ are depicted in Fig. 3. In both the Figs 2 and 3, the upper limit of each longitude bin of 30° is marked on the X-axis.

While projecting the IMF sector boundaries back to the solar corona, we have taken an average

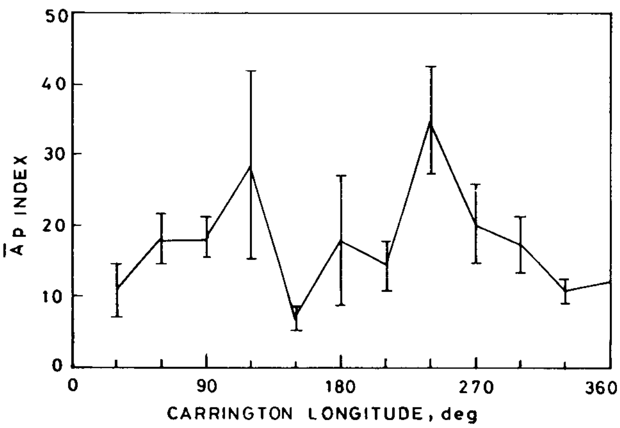

Fig. 2—Variation of $\bar{A}_p$ index along HCS during 1972-1977 (The vertical bar on each point is the standard error of the mean. On the X-axis, the upper limit of the Carrington longitude intervals of 30° is marked.)

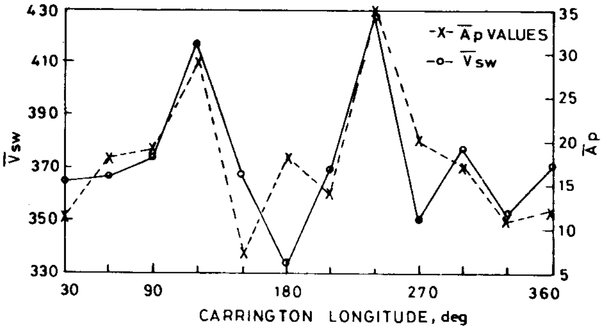

Fig. 3—Comparison of the longitudinal variation of $\bar{A}_p$ index (dashed line) with the solar wind velocity (solid line) along the HCS during 1972-1977

transit time of 5 days since the occurrence of high-speed streams at the sector boundaries are rare[7]. The transit time for a high speed wind (~ 600 km s^{-1}) is about 3 days, while a slow wind (~ 300 km s^{-1}) takes about 5 days to reach the earth. This difference in transit time introduces some uncertainty in defining the exact longitude of the origin of sector boundary on the solar surface. In order to avoid any discrepancy resulting from the shift in longitude due to a fast stream overtaking a slow one, the data are averaged over 30° which is greater than the difference in transit times of the slow and fast solar wind streams.

As mentioned earlier, there are only two or four sector boundary crossings per rotation and they tend to occur at certain Bartels days[7,8]. As a result, the number of data points available in one solar rotation does not cover the entire longitude. Therefore, it is not possible to study the variation of solar wind velocity on the HCS and the corresponding A_p index per solar rotation. Even the yearly averaged data of these two parameters showed considerable gaps in them. Hence, we had to put all the data during the period 1972-1977 together and only an average picture could be obtained. Since a very quiet period of the solar cycle has been selected for the study, we assumed that the evolution of the solar wind velocity structure is negligible compared to the longitudinal variation of the velocity on HCS.

3 Results and discussion

From the analyses of the solar wind velocity using the IPS as well as near-earth satellite data[17,18], it is found that there exists a clear azimuthal structure of the solar wind velocity on the HCS during the period of study; the velocity varied between 300 and 450 km s^{-1}. Also, the K-corona brightness variation at the sector boundary crossings during 1972-1977 showed an inverse correlation with that of solar wind velocity. The present analysis is an attempt to obtain the relation between the solar wind velocity V_{sw} and the $\bar{A}_p$ index during 1972-1977 using the satellite data[27,28] of interplanetary parameters.

From Fig. 2, it is evident that the $\bar{A}_p$ values at the IMF sector boundary crossings do not remain constant at all longitudes, but vary between 7 and 35 during the period of study. The vertical bar on each point is the standard error of the mean. The distribution shows two peaks—one at 90-120° longitude region and the the other at 210-240° longitude, separated by 120°. This pattern of variation of $\bar{A}_p$ values is found to be similar to that of the solar wind velocity variation obtained earlier[17], where the two peaks in $\bar{V}_{sw}$ coincide with the corresponding peak values of $\bar{A}_p$ (Fig. 3). Here, the two curves are identical except at 150-180° and at 270-300° longitude regions. At these longitude strips, the variations of the two parameters are opposite to each other. At both these longitude regions, $\bar{V}_{sw}$ (solid line) is minimum. On the other hand, the $\bar{A}_p$ value (dashed line) in the first case showed a slightly higher value than the minimum which occurred in the previous longitude region 120-150°. In the second case (240-270° longitude region), the $\bar{A}_p$ value is much higher than its second minimum which occurred in the longitude region 300-330°. However, the two parameters showed a linear relation between them with a correlation coefficient 0.73. The regression equation obtained is:

$$\bar{V}_{sw} = 2.38\ \bar{A}_p + 330.45 \text{ km s}^{-1}$$

Though the 30° averaged $\bar{A}_p$ index and the solar wind velocity (Fig. 3) showed good correlation, no one-to-one correspondence between them was observed during the period of study. The correlation coefficient between the two parameters using the individual values was only 0.24.

4 Summary and conclusion

The solar wind velocity tends to be a minimum along the HCS and increases with the heliomagnetic latitude[9-14]. Suess *et al.* [16] have shown that there exists a solar wind velocity gradient along a short portion of the HCS near the ecliptic. Since the current sheet has large warps in it extending up to 20° in both the hemispheres, it is difficult to study the velocity distribution on it using near-earth satellite data. However, identifying the sector boundary crosssings as the in-ecliptic HCS (as mentioned in Sec. 2), the satellite data of solar wind velocity have been used to obtain a long-time scale structure of the solar wind velocity on the

HCS[17]. We found that the velocity varied between 300 and 450 km s^{-1} (Fig. 3). A shorter time scale (yearly) picture of the azimuthal variation of the solar wind velocity on the HCS has been obtained using IPS measurements of solar wind velocity, and it was found that this pattern of variation has a solar cycle dependence[18].

In this analysis, we have obtained a linear relation between $\bar{V}_{sw}$ and the geomagnetic activity index $\bar{A}_p$ during 1972-1977. However, there is no one-to-one correspondence between the two parameters when taken individually; the correlation coefficient was only 0.24. Earlier, we found that the average solar wind velocity and the K-corona brightness corresponding to the sector boundary crossings during the same period showed good anti-correlation between them. This suggests that the A_p index can be used to study the coronal features which are long lived and only on a long-time scale[32].

From the present study as well as earlier studies of the structure of solar wind velocity on the HCS[17,18], we obtained only a long-time average picture. To see the exact nature of the variation of solar wind velocity on the HCS and its evolution with the phase of the solar cycle, it is necessary to study the variation per solar rotation for a complete solar cycle. For studying the azimuthal variation of the solar wind velocity on the HCS in each rotation[33] one has to utilize the IPS measurements[34].

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