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CHARACTERISTICS OF THE SOLAR WIND AT 1 a.u. IN RELATION TO HALE SECTOR BOUNDARIES

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Abstract—A study is made of the solar wind characteristics at 1 a.u. in the vicinity of Hale and anti-Hale sector boundaries (SBs), after isolating the SBs with solar activity related temporal flows and/or transient interplanetary structures (magnetic clouds) around them. It is found that, on average, the profile of the solar wind flow speed prior to SB passage and the minimum in flow speed at the SB do not differ for the two types of SBs. The flow speed 1–2 days after the passage of anti-Hale SB is found, however, to be significantly higher compared to Hale SB. The results indicate that the polarity configurations of the solar sectorial magnetic field structures with reference to the zonal (activity) structures influence the characteristics of coronal sources of high-speed streams, that accompany SB crossings at 1 a.u.

The sector structure of the interplanetary magnetic field (IMF) has been extensively studied since its discovery just over two decades ago (Ness and Wilcox, 1964), not only to assess its characteristics and comprehend its origin, but also to help understand the apparently complex solar–terrestrial relationships. The IMF sector structure is currently discussed in terms of a global sector boundary surface enveloping the sun and separating two solar hemispheres of opposite magnetic polarity (current or null sheet), and the sector boundary, according to these conceptual models, is an ecliptic plane intersection of the global boundary surface (e.g. Schulz, 1973; Svalgaard and Wilcox, 1976a; Alfven, 1977; Smith *et al.*, 1978). Since the present study is based on the solar wind data obtained in the ecliptic plane near the earth, the term sector boundary (SB) is used in this paper.

Svalgaard and Wilcox (1976b) introduced the terminology of Hale SBs on the sun, by defining the Hale (anti-Hale) boundary as that half of a SB (northern or southern hemisphere) where the change in magnetic polarity across the boundary is the same as (opposite to) that from a preceding to a following sunspot. Using this classification, they have shown that the brightness of the green corona and the strength of the photospheric magnetic field are a maximum (minimum) above Hale (anti-Hale) boundaries. Evidence for a preferential occurrence of solar flares around Hale SBs (in the northern hemisphere) has been documented earlier by Dittmer (1975). As regards terrestrial effects, Nayar (1979) inferred the existence of a significant difference in the response of geomagnetic activity to Hale and anti-Hale SBs, the geomagnetic activity undergoing a sharper and significant increase after the passage of Hale SB compared to anti-Hale SB. The subsequent study of Lundstedt *et al.* (1981) showed, however, that the increase in geomagnetic activity after Hale SB does not always occur (as in odd sunspot cycles), and when it does (as in even sunspot cycles) it can be interpreted in terms of the combined effect of a southward component (in GSM coordinates) of IMF and a high-speed stream in the solar wind which usually follows a SB. This work, which is in accordance with the current views on the origin of geomagnetic activity in relation to solar wind characteristics (e.g. Burlaga and Lepping, 1977; Akasofu, 1981), indicated that the results of Nayar (1979) can be understood even without the concept of Hale SBs.

Recently, Nayar and Revathy (1982) reported that the properties of the solar wind flow near the earth differ around Hale and anti-Hale SBs in that the Hale SB seems to constitute a favourable condition for encountering a high-speed solar wind stream after its passage compared to the anti-Hale SB. They have not taken into consideration, however, the plausible distortion of the profiles of solar wind plasma parameters around SBs, due to the presence of solar activity associated transient flows (e.g. Hundhausen, 1972; Barouch, 1977) and/or transient interplanetary features such as magnetic clouds of different types (Klein and Burlaga, 1982). This, in our opinion, is a major omission in the analysis of Nayar and Revathy because, as already mentioned, solar flares are found to preferentially occur around Hale SBs. The necessity and importance of removing time-dependent flows in studies aimed at assessing relationships between the solar wind characteristics at 1 a.u. and coronal structure can be gauged from the very recent study of Suess *et al.* (1984), which revealed a significant correlation between the flow speed at 1 a.u. (around SBs) and the magnetic field strength on the source surface at 2.6 $R_{\odot}$ (computed from photospheric magnetic field measurements using the potential field models for the corona), but only after the transients are eliminated. In view of these considerations, it is felt worthwhile and necessary to reexamine the solar wind properties at 1 a.u. around Hale and anti-Hale SBs, and in this paper we present the results of such an effort.

As in the earlier studies (Nayar, 1979; Lundstedt *et al.*, 1981; Nayar and Revathy, 1982), the dependence of the solar wind characteristics on the type of SB is assessed by confining the analysis to SBs that occurred during the two equinoctial periods (Vernal equinox: 5 Feb.–5 May; autumnal equinox: 7 Aug.–6 Nov.), when the solar wind variations near the earth correspond predominantly either to the southern or nothern solar hemisphere. Further details of the procedure of classification of SBs into Hale and anti-Hale types can be found in the above cited papers. Data on SB passages at the earth over the period January 1965 through May 1979 are compiled from the listings of Wilcox (1975), Svalgaard (1976) and the interplanetary medium data books of King (1977, 1979, 1983). Only well-defined SBs where the reversal in the IMF polarity is sharp and is preceded as well as followed by 4–5 days of constant magnetic polarity are selected using the plots of King and cross checking between the data sources. This selection procedure is adopted to discard other polarity reversals such as those associated with "flapping" of the heliospheric current sheet due to solar activity related disturbances in the solar wind (Fry and Akasofu, 1985). For some of the selected SBs, the solar wind data (number density and flow speed) were either not available or too scanty. Some SBs had activity-related transient flows (characterized by simultaneous increases in the flow speed, number density, IMF magnitude and proton temperature, and where a high number density and IMF magnitude tend to persist throughout the period of speed enchancement; see Hundhausen, 1972; Barouch, 1977), and/or transient interplanetary features termed "magnetic clouds" (regions with a high IMF strength in which the field direction changes appreciably by means of rotation of one component of the field parallel to a plane; these occur primarily in association with shocks, stream interfaces and "cold magnetic enhancements" at 1 a.u. and are believed to be interplanetary signatures of coronal transients; see Klein and Burlaga, 1982; Wilson and Hildner, 1984) around them. Elimination of all such events led to a final data sample of 24 Hale and 24 anti-Hale SBs over the period mentioned above and the plasma parameters (number density and flow speed), data pertaining to which are subjected to conventional superposed epoch analysis with the times of SB passages as key times. The data sample of SBs used here is such that there is no apparent bias of SBs to any particular phase of the sunspot cycle, as may be seen from the data presented in Table 1. The present study is essentially similar to the one by Nayar and Revathy (1982) except that due to the rather short SB data sample that became available, the Hale (or anti-Hale) SBs in the two equinoctial periods are grouped together for the superposed epoch analysis.

Figure 1 shows the variations of the number density and flow speed of the solar wind at 1 a.u. from −90 h through +90 h of the crossings of Hale and anti-Hale SBs at the earth. Also shown in the figure are the standard errors in the data. The following features are quite evident from Fig. 1: (1) the prominent increase in the proton number density at the SB (which is the outcome of a convolution of true coronal signals with those from dynamical processes associated with stream steepening in interplanetary space, see Borrini *et al.*, 1981) and the number density profile around SBs are not markedly different for the Hale and anti-Hale SBs; (2) the minimum in the flow speed at the SB (which is a genuine coronal signal associated with the SB; see Borrini *et al.*, 1981) and the flow speed profile prior to SB are not dependent on the type of SB, and (3) the flow speed 1–2 days after the passage of anti-Hale SB, in contrast, is significantly higher compared to that after Hale SB.

The present study revealed a distinctive difference in the pattern of solar wind flow at 1 a.u. around Hale and anti-Hale SB crossings at the earth. The flow speeds are significantly enhanced 1–2 days after the

TABLE 1. YEARLY DISTRIBUTION OF SECTOR BOUNDARIES (SB) OVER THE PERIOD JAN. 1965–MAY 1979 (EQUINOCTIAL MONTHS) USED IN THE PRESENT STUDY

	Year													
SB	1965	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Hale	2	3	3	1	1	1	2	1	2	1	2	2	1	2
Anti-Hale	2	3	—	4	1	—	1	3	4	2	—	3	—	1

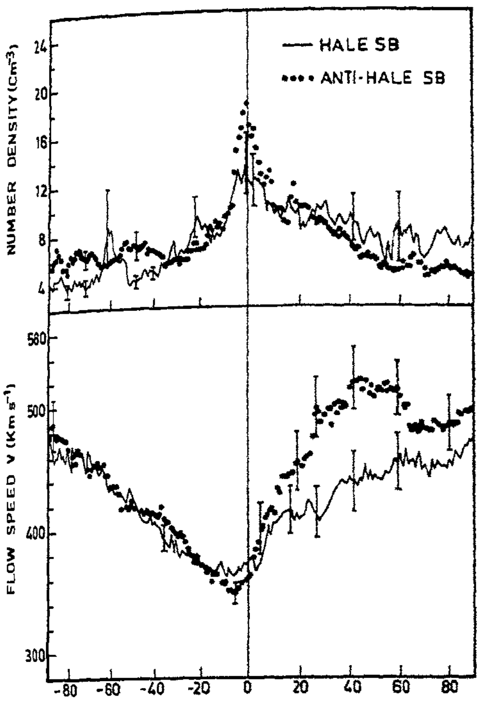

FIG. 1. VARIATION OF THE NUMBER DENSITY AND FLOW SPEED OF THE SOLAR WIND AT 1 a.u. IN THE VICINITY OF HALE AND ANTI-HALE SECTOR BOUNDARIES (24 EACH).

The average pattern is derived from a superposed epoch analysis of the hourly averages of the plasma parameters, using the sector boundary passage at the earth as zero epoch. The vertical bars represent the standard errors in the data. Note the larger amplitude of the high-speed solar wind stream after anti-Hale boundary, compared to Hale boundary.

passage of anti-Hale SB compared to those that accompany Hale SB. The SB passages at the earth generally signal encounter with high-speed solar wind streams (e.g. Hundhausen, 1977). Polar cap coronal holes and their equatorward extensions or diverging unipolar field regions in the corona are the principal sources of wind streams observed in the ecliptic plane near the earth (e.g. Krieger *et al.*, 1973; Bell and Noci, 1976; Hundhausen, 1977; Sheeley and Harvey, 1981). Comparative studies of the synoptic K-coronameter measurements with solar wind speed and IMF polarity variations showed that the displacement of the neutral line (that is drawn around the sun over the belt of bright corona, demarcating the polar cap holes and "connected" holes in such a way as to be consistent with the observed or inferred IMF polarity near the earth, and which corresponds to the heliospheric current sheet of the conceptual models of Schultz, 1973; Saito, 1975 and many others mentioned earlier) from the ecliptic influences the solar wind speed in the ecliptic (Hundhausen, 1977). For example, over the period 1972–76, a neutral line shift (at the distance of 1.5 $R_{\odot}$) of $\sim 25°$ was found to lead to fast wind streams (speed >650 km s^{-1}) in the ecliptic. Recent studies further showed that the placement of the heliospheric sector boundary surface with respect to the solar equator and its extent in heliolatitude vary with the phase of the sunspot cycle (Tritakis, 1984; Hoeksema *et al.*, 1982, 1983). The difference in the solar wind flow speed pattern at 1 a.u. after the passage of Hale and anti-Hale SBs could therefore result from a clustering of SBs (in the selected data sample) of any one type to a particular phase of the sunspot cycle. This possibility is, however, to be discounted because as mentioned earlier, no such clear cut bias is present in our SB data sample (Table 1). It is suggested that differences in the characteristics (spatial extent/field strength/geometrical divergence) of solar wind stream sources in the inner corona are primarily responsible for the difference in the profiles of solar wind flow speed after the passage of Hale and anti-Hale SBs reported here. This is because: (1) the peak amplitude of the high-speed streams at 1 a.u. shows a positive dependence on the size of the associated coronal holes (Nolte *et al.*, 1976), and (2) coronal holes are always located in regions where the field strength is high, and the flow speed at 1 a.u. (around SBs) is positively correlated with the field strength on the solar source surface (Suess *et al.*, 1984 and the results of Wilcox quoted therein). Further work is required not only to assess the validity of the inference reached here, but also to address the fundamental question as to how a match or mismatch of the polarity configurations of the solar sectorial and zonal (activity) magnetic field structures leads to changes in the characteristics of the coronal sources of high-speed streams at 1 a.u.

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