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SHORT-TERM VARIABILITY OF SOLAR WIND NUMBER DENSITY, SPEED AND DYNAMIC PRESSURE AS A FUNCTION OF THE INTERPLANETARY MAGNETIC FIELD COMPONENTS: A SURVEY OVER TWO SOLAR CYCLES

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Abstract. The variability of hourly values of solar wind number density, number density variation, speed, speed variation and dynamic pressure with IMF B_z and magnitude $|B|$ has been examined for the period 1965-1986. We wish to draw attention to a strong correlation in number density and number density fluctuation with IMF B_z characterised by a symmetric increasing trend in these quantities away from $B_z = 0$ nT. The fluctuation level in solar wind speed is found to be relatively independent of B_z. We infer that number density and number density variability dominate in controlling solar wind dynamic pressure and dynamic pressure variability. It is also found that dynamic pressure is correlated with each component of IMF and that there is evidence of morphological differences between the variation with each component. Finally, we examine the variation of number density, speed, dynamic pressure and fluctuation level in number density and speed with IMF magnitude $|B|$. Again we find that number density variation dominates over solar wind speed in controlling dynamic pressure.

Introduction

The B_z component of the interplanetary magnetic field (IMF), which is parallel to the z-axis in GSM (geocentric-solar-magnetospheric) coordinates, is important as it is often used to assess the likelihood of magnetic reconnection of the IMF with the terrestrial magnetic field. It is believed that reconnection at the subsolar magnetopause is favoured at times when the IMF is directed southward ($B_z < 0$). The dependence of trans-polar voltage on B_z (see reviews by Cowley, 1984; Reiff and Luhmann, 1986) is one primary piece of evidence supporting the belief that magnetic reconnection is the dominant mechanism for driving convective flows in the magnetosphere and ionosphere, as originally proposed by Dungey (1961). Magnetic reconnection is thought to occur in either a "quasi-steady" manner or in transient bursts known as "flux transfer events" (FTEs). These events have been evoked to explain and predict smaller-scale ionospheric flow vortices through coupling of the dayside auroral ionosphere with the magnetopause (eg. Lockwood et al., 1989). However, it has also been noted that FTEs alone are not sufficient to explain all the observed signatures of vortical flow and that some, but not all, events may have been induced by solar wind dynamic pressure changes - even at times of northward IMF (Farrugia et al., 1989; Sibeck et al., 1989). A theoretical explanation of how dynamic pressure changes produce flow signatures in the auroral ionosphere has been provided by Southwood and Kivelson (1990), who show that anti-sunward motion of closed field lines ("viscous-like" momentum transfer across the magnetopause) can be caused by the "buffeting" effect on the magnetosphere of changes in solar wind dynamic pressure, as originally suggested by Dessler (1964). Lockwood et al. (1990) have indicated that solar wind dynamic pressure variability would be expected to be the same for northward and southward IMF. This would appear to limit the contribution that this coupling mechanism can make to the total trans-polar voltage, to below the peak value of ~30 kV observed during northward IMF. This inference is true provided that the magnetosphere does not alter in form in some manner, such that its response to solar wind dynamic pressure changes is greater for southward-directed IMF. This paper examines the relationship between solar wind dynamic pressure and the IMF, and in particular B_z. It also considers the factors that control dynamic pressure and its variability on time-scales of ~0.1 - 1 hour.

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Analysis of the Solar Wind Dataset

The OMNItape version 4 from NSSDC was used as the data source for the analysis. It is recognised that this is an inhomogeneous dataset; containing data from more than 10 spacecraft (eg. IMP-8, ISEE-3, VELA) at a variety of locations, and covering a period of 25 years (1963-87). A total of 60226 hourly values of solar wind ion number density n, standard deviation in number density σ_n, speed v, standard deviation in speed σ_v, and IMF components B_x, B_y and B_z (all three in GSM coordinates), were available in the dataset. The following parameters were also derived from those listed above; dynamic pressure $P_d = m.n.v^2$ (where m was assumed equal to one proton mass), IMF magnitude $|B|$, fractional fluctuation in number density, σ_n/n, and fractional fluctuation in speed, σ_v/v. In order to examine the variation of one parameter, Y, with another, X, the data were sorted by the value of X. Data points which did not fall in the extreme wings of the distribution of X, were then averaged in 118 'inner' bins of 500 data points (X,Y) per bin (≈ 0.83 % of the total dataset per bin). The remaining 1226 data points, representing the wings of the distribution of X, were divided into 2 'outer' bins of 613 data pairs in each (≈ 1.02 % of the total dataset per binned data point). The total number of binned data points (<X>,<Y>) was thus 120. This binning procedure ensures that all displayed data points in the figures are an average of a large (≥500) number of hourly values. The effect of varying the number of data points per bin was investigated for the case of B_z as the X parameter. The general

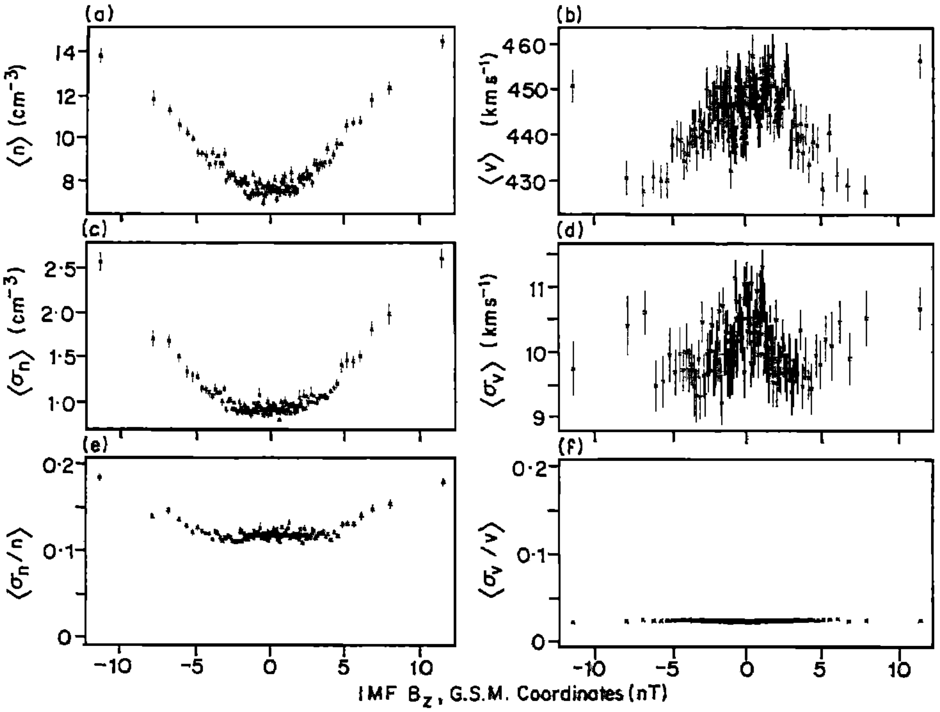

Fig. 1. Means of (a) ion number density $\langle n\rangle$, (b) solar wind speed $\langle v\rangle$, (c) number density variation $\langle\sigma_n\rangle$, (d) speed variation $\langle\sigma_v\rangle$, (e) fractional number density variation $\langle\sigma_n/n\rangle$, and (f) fractional speed variation $\langle\sigma_v/v\rangle$ plotted against IMF B_z.

trends reported here were always observed. The standard errors of the means of X and Y were also calculated, and all error bars shown in the figures represent deviations from the mean of ±1 standard error. The number of samples per hour used in calculating n, v, σ_n and σ_v is very variable (~6 - 120) depending on the spacecraft used as the data-source. To examine the effects of inhomogeneity in the data source (due to different sampling rates and spacecraft location), the analysis was performed for the pairs of years 1968-69 (principally AIMP-1 and -2, IMP-4 and -5 and HEOS-1 and -2) , 1978-79 (approximately half-and-half from IMP-8 and ISEE-3), 1975-76 and 1985-86 (both periods vitually all IMP-8 data). Despite the variation in data source, the same trends were found in the results for these data-subsets as for the whole dataset.

The analysis was also performed for GSE (geocentric-solar-ecliptic) coordinates, and again the same trends in the results were observed. In this paper we have used the components of IMF in the GSM coordinate system because they are more relevant to studies of solar wind-magnetosphere-ionosphere coupling.

Variation of n and v with B_z

Figure 1 shows the results of the analysis for solar wind number density and speed as binned values, sorted on IMF B_z. From figures 1(a), 1(c) and 1(e) it can be seen that there is a systematic symmetric trend in mean number density, $\langle n\rangle$, mean number density variation, $\langle\sigma_n\rangle$, and mean fractional variation, $\langle\sigma_n/n\rangle$; all of which increase with $|B_z|$. The corresponding variations for solar wind speed , v, are shown in figures 1(b), 1(d) and 1(f). Some variation with B_z is evident, in particular for $\langle v\rangle$; however, the standard errors are relatively larger and the variation much smaller than in the corresponding plots relating to number density. Average velocity $\langle v\rangle$, is generally lower at large $|B_z|$ (where $\langle n\rangle$ is higher), except for the two 'outer' bins. The mean velocity variation $\langle\sigma_v\rangle$ shows a weak minimum at B_z = 0 nT. Figure 1(f), when compared with figure 1(e), reveals that the mean fractional variation in number density, $\langle\sigma_n/n\rangle$, is a factor of ≈ 5 greater than that in velocity, $\langle\sigma_v/v\rangle$, at B_z = 0 nT increasing to ≈ 7.5 at $|B_z|$ = 10 nT because of the relatively small trend in $\langle\sigma_v/v\rangle$ with B_z. We also note that $\langle\sigma_n/n\rangle$ is relatively constant for $|B_z|$ < 5nT.

Variation of P_d with IMF Components

Figures 2(a), 2(b) and 2(c) show, respectively, the variation of mean dynamic pressure, $\langle P_d\rangle$, with each component of the IMF, B_x, B_y and B_z. Each plot exhibits a general trend to higher pressure with increasing field (irrespective of sign) though there are differences in the plots with regard to the behaviour of $\langle P_d\rangle$ around 0 nT. The component B_y shows the widest spread in magnetic field value and B_x shows the least. In general, all three plots reflect the fact that B tends to increase with dynamic pressure (at least for larger B - see figure 3(c)) but note that B_z is the only component for which P_d increases almost monotonically with the magnitude of the field component.

Variation of n, v and P_d with |B|

Figures 3(a) through 3(e) show, respectively, the variation of $\langle n\rangle$, $\langle v\rangle$, $\langle P_d\rangle$, $\langle\sigma_n/n\rangle$ and $\langle\sigma_v/v\rangle$

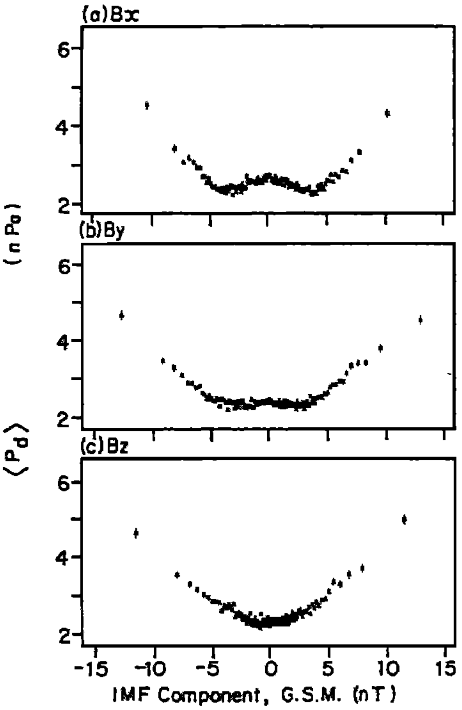

Fig. 2. Mean dynamic pressure $\langle P_d \rangle$ plotted against IMF component (a) B_x, (b) B_y, and (c) B_z.

with IMF magnitude $|B|$. Mean ion number density, $\langle n \rangle$, exhibits a minimum at $|B| \approx 4$ nT where mean speed, $\langle v \rangle$, shows a corresponding maximum; $\langle v \rangle$ also shows a flat minimum at $|B| \approx 9$ nT and its highest values at large $|B|$. The anticorrelation of $\langle n \rangle$ with $|B|$ for $|B| < 4$ nT (corresponding to ~25 % of the dataset) is consistent with the results presented by Burlaga (1968), Vellante and Lazarus (1987), Roberts et al. (1987) and Roberts (1990). An interpretation of the anticorrelation as being due to the presence of nonpropagating structures with internal pressure balance and a characteristic time scale of < 10 hours was put forward by Vellante and Lazarus. Roberts (1990) proposed that the "pseudosound" theory of Montgomery et al. (1987) may be a possible explanation for the presence of these structures in the solar wind. Vellante and Lazarus also noted that there is a change, at larger time scales, to the positive correlation of n with $|B|$ as reported by Burlaga and Ogilvie (1970). We suggest tentatively that this may be responsible for the turnaround in the variation of $\langle n \rangle$ with $|B|$ in figure 3(a). We do not, however, offer these results as evidence of positive correlation of n with $|B|$ at larger time scales. Although the averages are of hourly values, persistently high values of n and $|B|$ over periods of several hours might lead to positive correlation being evident in the mean of hourly values. Indeed, detailed examination of a limited number of high $|B|$, high n cases has shown that such conditions can prevail over time-scales as long as 20 hours. Furthermore, in some cases, these conditions were followed by periods of enhanced solar wind speed. The positive correlation is due largely to the growth (or "piling-up") of the interaction regions of fast solar wind streams (Burlaga and Ogilvie, 1970). This would be consistent with the positive correlation of $\langle n \rangle$ with $|B|$ in figure 3(a), occuring for high $|B|$, and with the associated high mean solar wind speed, $\langle v \rangle$, of figure 3(b). Mean dynamic pressure, $\langle P_d \rangle$, and mean number density fractional variability, $\langle \sigma_n / n \rangle$ show the same general behaviour as $\langle n \rangle$ with a minimum at $|B| = 4$ nT. The fractional variability in speed, $\langle \sigma_v / v \rangle$, is lower than that in number density by a factor ≈ 4 at $|B| = 4$ nT and ≈ 8 at $|B| = 19$ nT. Again this suggests that number density dominates over speed in controlling solar wind dynamic pressure.

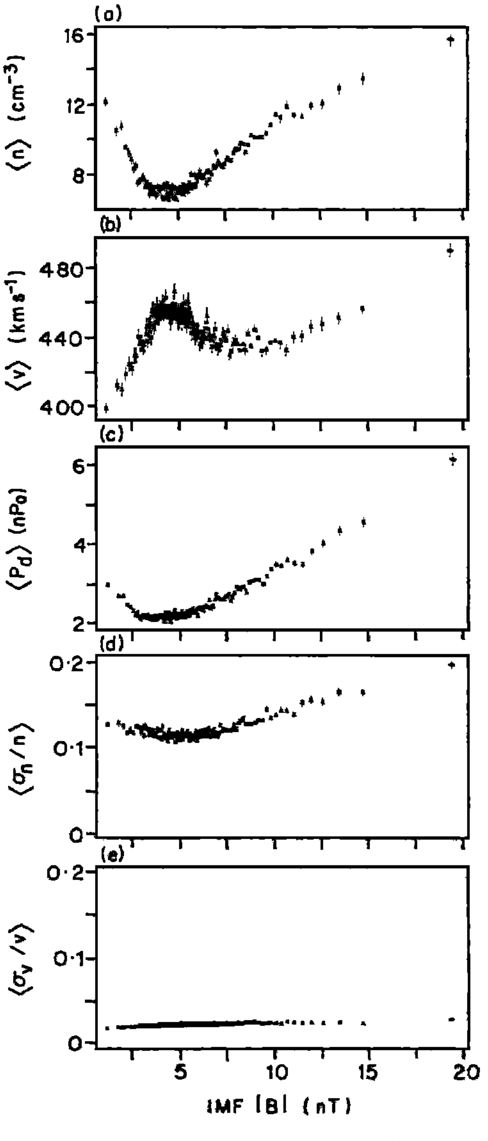

Fig. 3. Means of (a) ion number density $\langle n \rangle$, (b) solar wind speed $\langle v \rangle$, (c) solar wind dynamic pressure $\langle P_d \rangle$, (d) fractional number density variation $\langle \sigma_n / n \rangle$, and (e) fractional speed variation $\langle \sigma_v / v \rangle$ against IMF magnitude $|B|$.

Conclusions

The results presented in this paper are largely of a phenomenological nature - we have not sought here to explain the systematic trends that we have identified, except in general terms. The nature of the analysis is such that short-term (< 1 hour) variability alone has been investigated directly. We speculate that large scale features in the solar wind such as stream interaction regions and perhaps "flux-bubbles" from coronal mass ejections (for example see review by Holzer, 1979) may be responsible for the enhancement in dynamic pressure at larger than average values of IMF and during periods when the IMF has a large out-of-ecliptic component. An analysis of 10 major magnetic storms, which occured during 1978/1979 and which were associated with large southward B_z, led Tsurutani et al. (1990) to attribute nine of the ten to interplanetary shocks and the remaining one to a non-compressional density enhancement. The averages of solar wind number density, number density fluctuation level and dynamic pressure have all been shown to increase systematically with $|B_z|$ and symmetrically about $B_z = 0$ nT; i.e. there is no difference between northward and southward IMF orientation. Because solar wind mean speed and its mean variability are found to be relatively independent of B_z, we infer that the fractional variability or "buffeting level" of dynamic pressure (i.e. $<\sigma_{Pd}/P_d>$), on a time scale of $\sim$0.1 - 1 hour, will increase with $|B_z|$, reflecting the variation in $<\sigma_n/n>$. We conclude that buffeting of the magnetopause by dynamic pressure variability could, in theory, influence the observed anti-correlation of trans-polar voltage with B_z when $B_z < 0$. However, in order to postulate that increased buffeting contributes significantly to the additional transpolar voltage that is observed when the IMF is directed southward (the voltage usually being ascribed to the effects of subsolar magnetic reconnection), some viable explanation must be supplied to account for the fact that this does not occur when the IMF is directed northward.

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