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Identification and prediction of prolonged intervals of geomagnetic calm

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RESUMEN

A partir del índice diario Ap de la actividad geomagnética, para el período 1963-1968, son identificadas las secuencias de valores consecutivos de Ap≤ 4 para cuatro días y de Ap≤7, para 8 días. Se establece una característica sistemática de cambio de los días precedentes a la calma geomagnética y los días que siguen. La velocidad y la variabilidad del viento solar alcanzan un mínimo mucho después del inicio de la secuencia calma y con un intervalo más largo.IMFB alcanza su menor valor en el comienzo de los intervalos de calma, y sigue con un valor bajo hasta el fin de la secuencia. Durante los largos intervalos de calma del campo geomagnetico es posible encontrar los valores más pequeños de la densidad que preceden el inicio de la secuencia de calma y de menor variabilidad de todos los parámetros con posibles valores límites de V~ 320 km/sec, B~ 4 nT, Bz>0 (~0.8 nT). Los intervalos de calma del campo geomagnético pueden ser previsibles a partir de los parámetros del viento solar, con un éxito moderado.

PALABRAS CLAVE: Medio interplanetario, actividad geomagnética, calma magnética, viento solar, campo magnético interplanetario.

ABSTRACT

From the daily index Ap of geomagnetic activity, sequences of consecutive occurrence of Ap≤4 for four days and Ap≤7 for 8 days are identified in the period 1963-1998. A superposed epoch analysis is performed with the onset of these sequences and with eight different solar wind and IMF parameters. A systematic pattern of change from days preceding to the days following the quiet intervals is clearly established. Solar wind velocity and its variability attain their lowest values after the onset of the quiet sequence and lengthen the interval. IMF B, on the other hand, attains the lowest value at the onset of the quiet intervals and remains low till the end of the sequence. Possible threshold values of V~320 km/sec, B ~4 nT, Bz > 0 (~0.8 nT), are found for prolonged intervals of geomagnetic calm. Geomagnetic quiet intervals could be predicted from the solar wind parameters with moderate success.

KEY WORDS: Interplanetary medium, geomagnetic activity, geomagnetic calm, solar wind, interplanetary magnetic field.

INTRODUCTION

According to Burlaga and Ogilvie (1970) 'quiet' solar wind is an unusual extreme condition. Neugebauer (1976) identified 14 intervals where speed, proton density and temperature variations were small over periods comparable to the solar wind expansion time. He found that the density varies as the inverse square of the velocity, and the magnitude of B is independent of V and density. Rich and Gussenhoven (1987) suggest that a quiet state of the ionosphere/magnetosphere system occurs when IMF Bz is near zero or northward for an extended period and when solar wind velocity is low. The quiet conditions can be extremely lasting during a solar minimum. They occur on the trailing edge of a well defined stream.

Kern and Gussenhoven (1990) proposed the baseline conditions for near-minimal energy of the solar wind - magnetosphere system.

(i) Solar wind speed less than 390 km/sec

(ii) Magnitude of IMF B less than 6.5 nT and

(iii) The angle $180 - \arctan |By / Bz|$ less than $101°$ when Bz is negative or zero.

(iv) All these conditions should last for at least 5 hours.

In this paper we identify long intervals of geomagnetic calm when Ap≤4 for at least 4 days. We examine the variability in 16 solar wind and IMF parameters over four days on either side of the quiet intervals. We use a supplementary list of key days based on a sequence of 8 consecutive days with daily Ap≤7. As our duration of geomagnetic calm intervals is longer than that used by Kern and Gussenhoven (1990) and the parameter representing geomagnetic activity is the daily Ap index our results may complement the earlier analysis and may yeld an estimate of the conditions prevalent in the interplanetary medium preceding, during and after an interval of prolonged geomagnetic calm.

DATA AND ANALYSIS

We identify prolonged intervals of geomagnetic calm with daily values of Ap≤4 (or Kp = 1o) for four consecutive days between 1963 and July 1998. Spacecraft observations of IMF and solar wind were available from NGDC in the form of OMNI tape, and on anonymous FTP. We also considered the occurrence of Ap ≤ 7 (equivalent Kp ≤ 2 o) consecutively for 8 days.

Between 1963 and July 1998 there were 87 sequences with Ap≤4 and 66 sequences with Ap≤7. The daily averages of corresponding solar wind and 16 IMF parameters (IMF B, velocity (V), density(N), Bx, Bye, Bym, Bze, Bzm, and their variability, denoted by sig.B, sig. V etc.) were extracted from the OMNI tape of NGDC, (see King, 1991). The key day (day 0) corresponds to the beginning of the sequence of quiet intervals.

Individual columns (12 for Ap≤4 and 16 for Ap≤7) were averaged and the standard error of the mean was computed (Figure 1 a, b). The intervals associated with Ap≤4 will be referred to as "very calm" and those with Ap ≤ 7 as "calm". Rangarajan and Iyemori (1997) identified 13 intervals with Kp≤ 1+ for at least 32 consecutive 3–hour intervals (four days) between 1963 and 1998 July. The results of their superposed epoch analysis are shown in Figure 2, for V and B.

RESULTS

Systematic change in almost all 16 parameters, are shown in Figure 1. The error bars are roughly proportional to the mean of each parameter, except for Bz and By components.

Here sig.V is the change in the average standard deviation of V derived from 24 hourly mean values of the day as provided in the OMNI tape, not to be confused with the error bars. The same is true for the other parameters.

Solar wind velocity changes from 400 km/sec prior to the commencement of the calm period, to about 320 km/sec during quiet times; later it systematically rises again almost to the pre-calm level. The error bars suggest that the event-to-event variation in velocity was minimum during a geomagnetic calm on days +2 and +3; this feature is also mimicked in the sig.V plot. Minimum velocity is attained on the last day of the quiet sequence. The same is observed for sequences of quiet days with Ap ≤ 7 over 7 consecutive days.

However, this minimum velocity is marginally higher (around 350 km/sec), because of empirical relationship between Ap and V (Maer and Dessler, 1964).

The density has a well defined maximum on the day following the last day of a sequence (days no. 4 or 8).

The pre-calm epoch, one or two days before a 'very calm' sequence, has a low density. Persistent low density for 48 hours may suggest a precursor for long quiet intervals. When the geomagnetic activity level is marginally increased, as for Ap ≤ 7 (Figure 1 b) the minimum on day 0 is well defined.

The magnitude of IMF (B) has a low ~4 nT throughout the "very calm" epoch, and attains a stable post-quiet interval level at nearly 50 % increase. The variability in B is also marked by a clear minimum at the beginning of the quiet sequence.

The choice of the coordinate system (GSE or GSM) does not appear to be important. The associated error bars are large, so that not all variations may be statistically signficant.

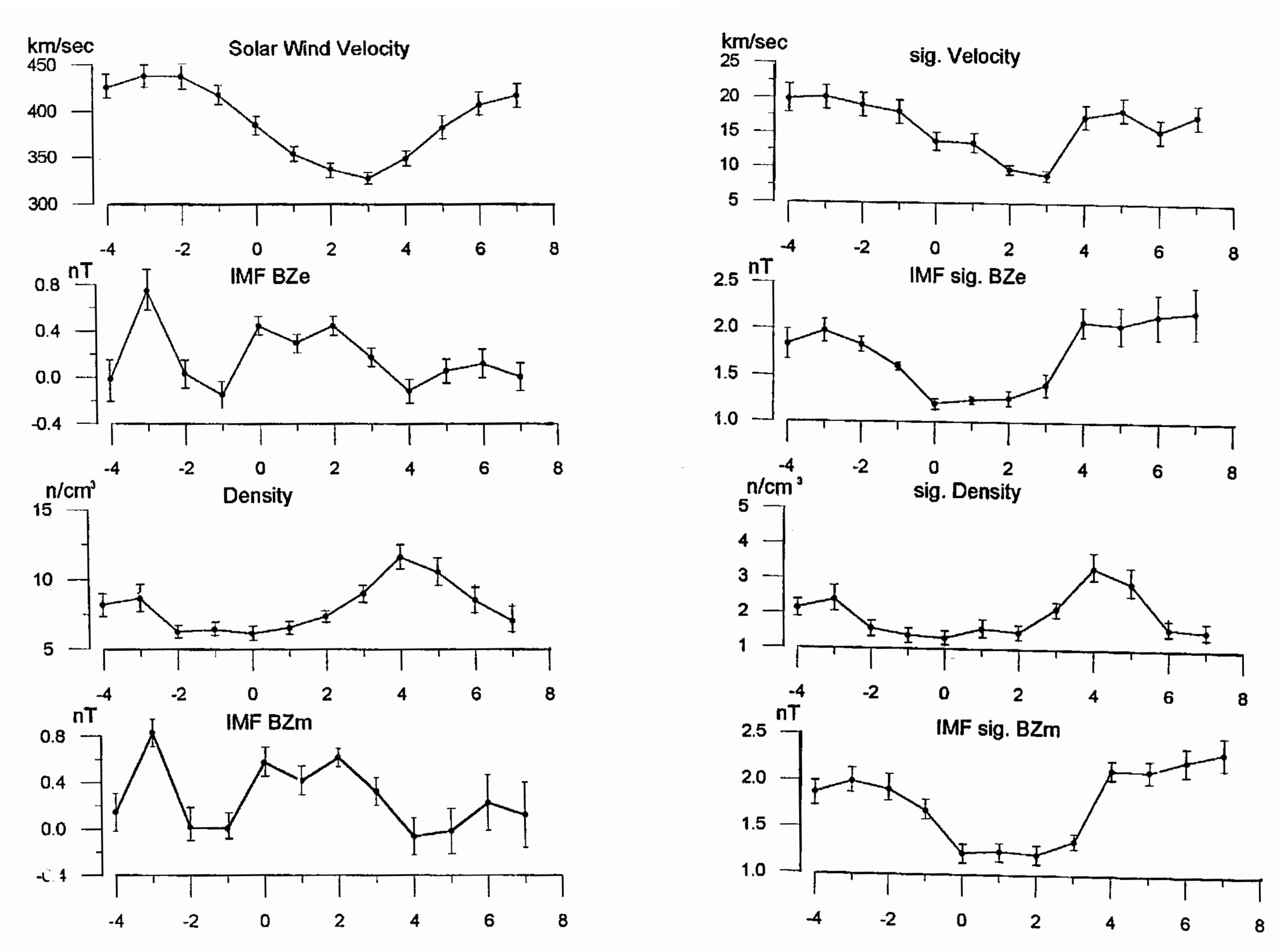
The value of IMF Bz during 'very calm' and 'calm' intervals is less than 1 nT but distinctly positive, as would be expected if the magnetosphere behaves as a half-wave rectifier (Burton *et al.,* 1975; Crooker, 1980).

The variabilities in the parameters Bx, By and Bz show significant differences the quiescent days (0 to +3 day in Figure 1 a and 0 to + 7 day in Figure 1 b), and the preceding and following days.

When the magnetic activity is high and the duration is long, the variability in the components of IMF shows a sharp minimum on day +1 followed by a monotonic increase during the quiet interval. This is not the case for 'very calm' intervals (see Figure 1 a).

The value of Bx for 'very calm' intervals is up to 1 nT, but a systematic fluctuation from positive to negative values may be seen from day 0 to day 7. The change in polarity of IMF occurs near day +2 or +3. Otherwise from day 0 to +4, Bx is practically zero and the swing from positive to negative values is confined to the post-quiet interval (from day +7 to +10).

Figure 2 shows the values of IMF and B from 4 days before the onset of 'very calm' intervals up to four days following the end of quiescence. The 13 key days used here correspond to an uninterrupted sequence of at least 32 3-hour intervals with Kp≤1+. These are not necessarily the same sequences used in the earlier analysis. The patterns described earlier are repeated with a minimum in V occurring on the last day of the sequence and a change in speed from about



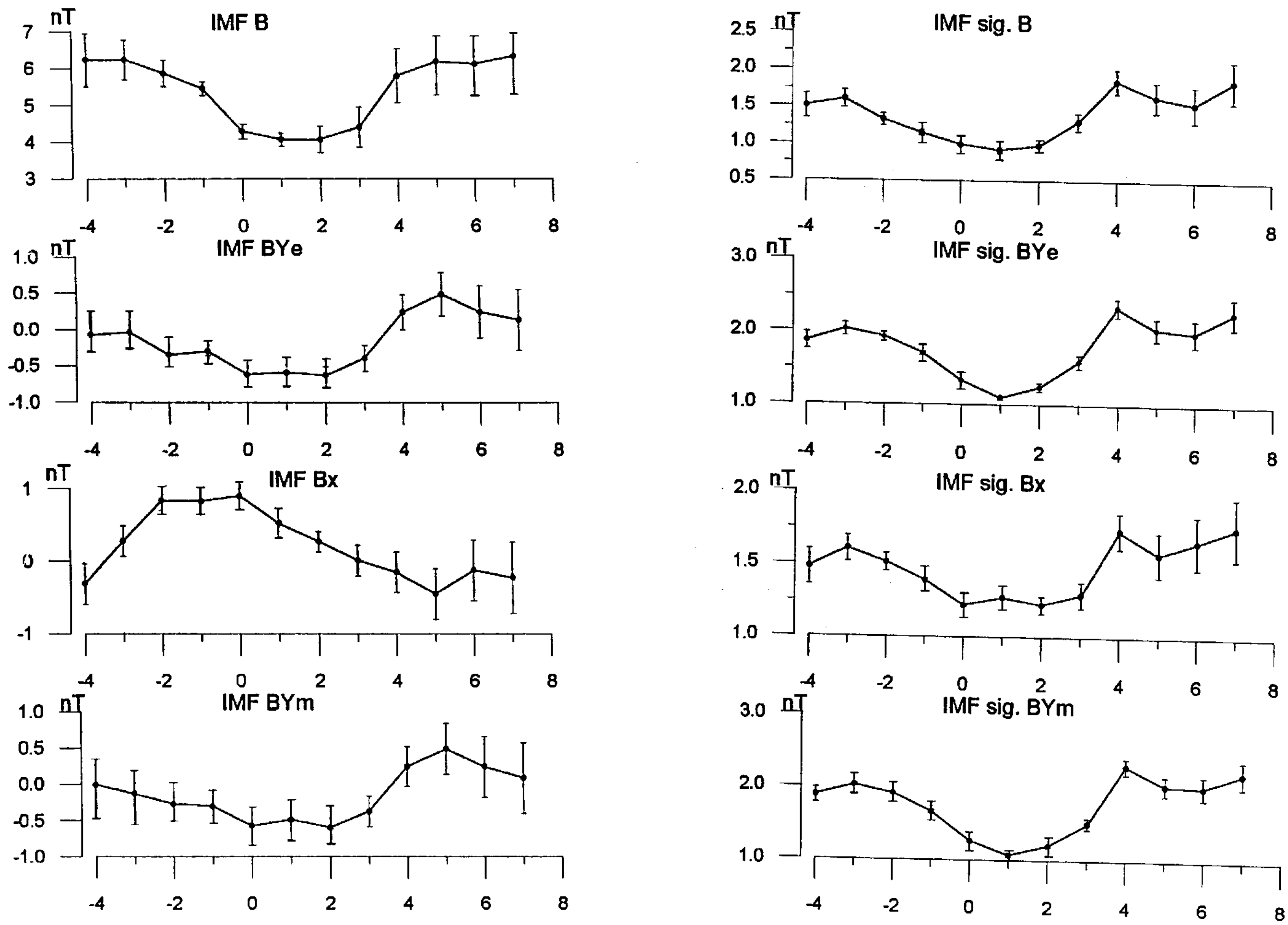
Figs. 1aI and 1aII. Time variations of solar wind and IMF parameters, beginning from four days prior to the key day (day no. 0), which corresponds to the commencement of a sequence of four consecutive quiet days with Ap ≤ 4, and up to four days after the termination of the sequence of quiet intervals. The labels sig. before the variable indicates the hourly variability in the parameter, as reported in the OMNI tape for the period 1963 to July 1998. The units for solar wind velocity and its variability are km/sec, for density it is n/cm^3 and for all other parameters (B, its components and their variability) it is nT.

450 km/sec to around 300 km/sec. The value in B falls from day –3 to day +1. The error bars, though derived from a much smaller sample, undergo significant change from before the key days to day +3 when the minimum velocity is reached. Thus the variability in the solar wind velocity and the value of IMF B is very small when geomagnetic activity is low.

We used the Method of Natural Orthogonal Components (MNOC), to separate a matrix of variables into distinct components (Kendall, 1948 ; Golovkov *et al.,* 1978). If most of the rows in the matrix have nearly the same pattern of change across various columns, the first component is dominant. We examine the variation in the parameters B and V when Bz is marginally northward. Any missing values in B and V were interpolated.

Figure 3 shows the first Principal Component (PC-1) in V and B between days –4 and +7. Nearly the total variance of the system may be accounted for by this component alone (> 90 percent).

If coefficient for a row is 100 percent, the variation in V or B around that key day will be the same as the first principal component, and percentage values different from this value will change the value of the PC1. We noticed that the principal components show the same pattern of change in V and B as seen in Figure 1a. The variability of the coefficient is more pronounced for V than it is for B. Often, the coefficients of PC-1 for B are close to 100. The values for V, on the other hand, show greater fluctuations; thus the changes B are much better ordered with respect to the sequence of



Figs. 1aI and 1aII. Continued.

'very calm' intervals as compared to the speed of the solar wind. Thus B does not depend on V (Neugebauer,1976).

Consider now two restrictions:

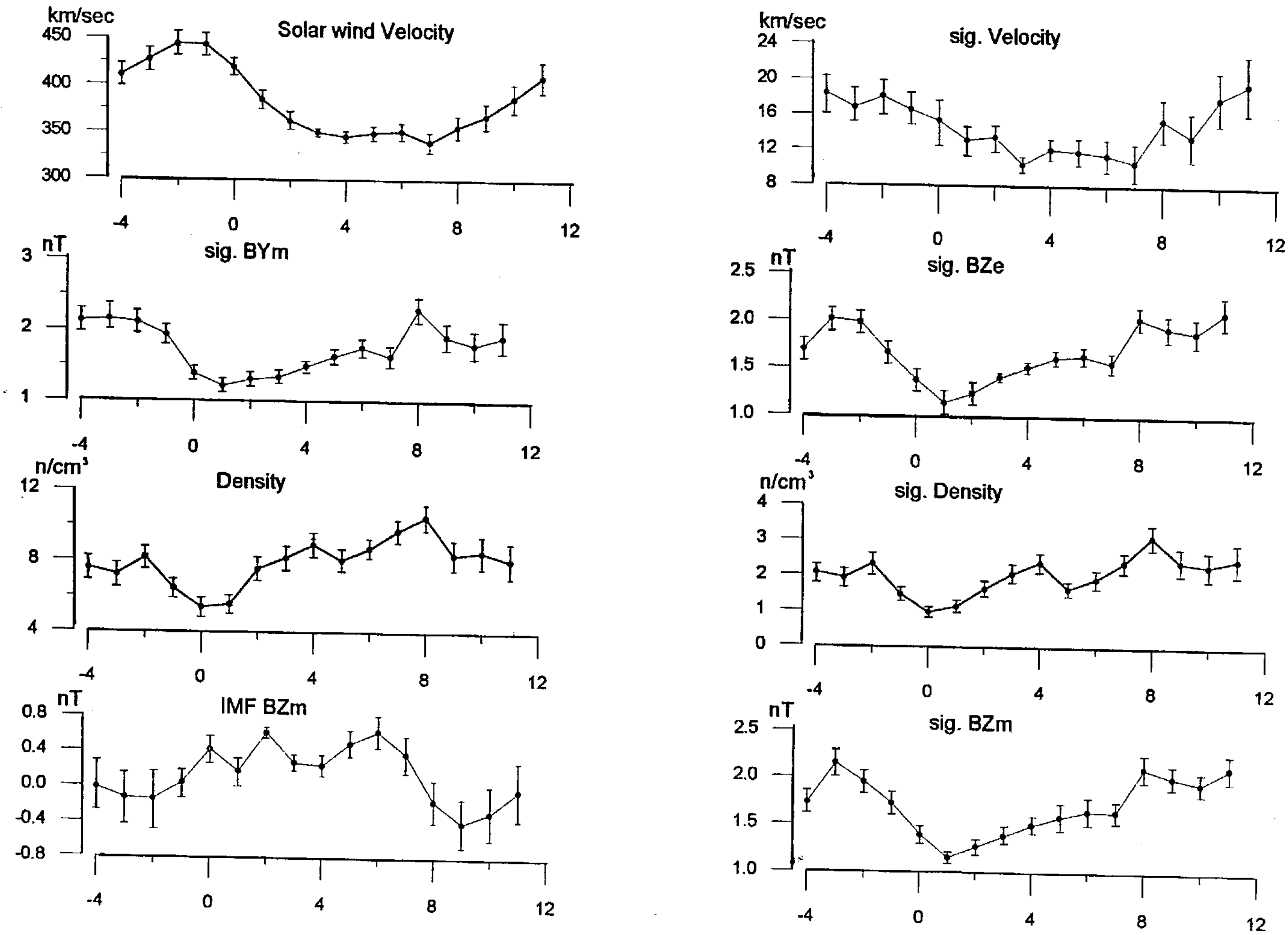
(1) The velocity for four consecutive days is greater than 400 km/sec and decreases monotonically over the next three days;

(2) The value of IMF B is greater than 5 nT for at least three consecutive days, and there is a drop of more than 0.7 nT followed by nearly the same values for the next 3 days.

The mean values of Ap for four consecutive days, beginning one day after the decrease in V and following the change in B, are shown in Figure 4. Ideally, we should expect the original pattern of quiet sequences to be reproduced but that is not the case. However, the predicted mean values of Ap for four days, based on a change in velocity pattern, does provide a good list of days with mean value of about 5. On the other hand, a prediction using B leads to a list of days with average Ap ≥5 with no mayor deviations. Thus the combination of B and V for the above conditions may lead to a reassonable prediction of geomagnetic quiet intervals, except for Ap ≤ 4.

DISCUSSION AND CONCLUSIONS

The two groups of prolonged intervals utilised in the present analysis represent two classes of quiet conditions of the magnetosphere (Gussenhoven, 1988; Bhargava and Rangarajan, 1977). Whether the 'very calm' category of days with Ap≤4 represents 'baseline magnetosphere' is uncertain. Neugebauer (1976) gave a range of N=15 to 67 cm^{-3}, V= 348 to 606 km/sec and B=4 to 7.7 nT. King (1986) estimated a typical value of B in the quiet solar wind of about 5 nT, and Burlaga and Ogilvie (1970) suggested that



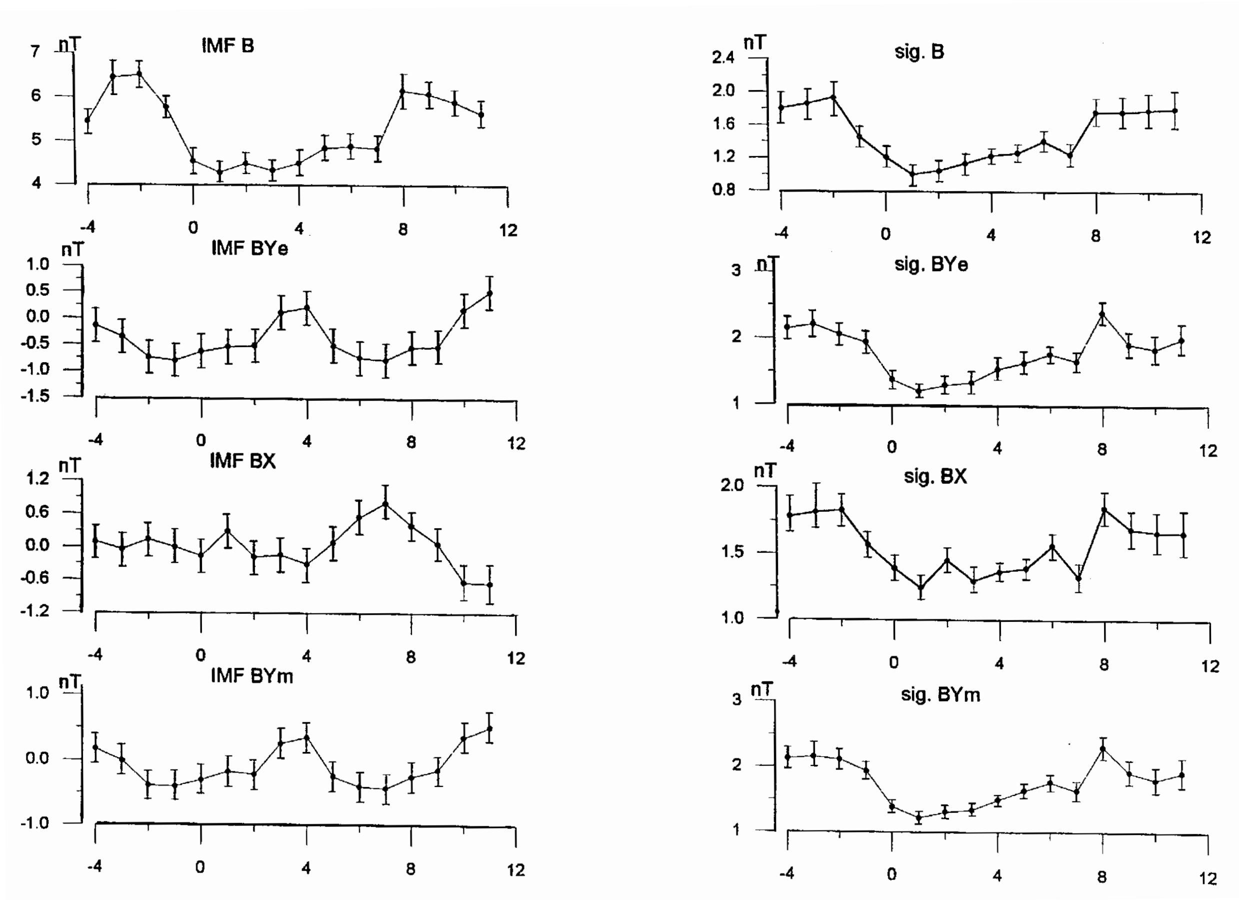
Figs. 1bI and 1bII. Same as Figure 1a except the key day is the beginning of a sequence of eight consecutive quiet days with Ap ≤ 7.

V≤250 km/sec during quiet intervals. Gosling *et al.* (1976) found that the speed of the solar wind reached a value of 250 to 275 km/sec only a few occasions, thus establishing a lower limit for the speed from spacecraft observations. The present analysis suggests IMF values of ~4nT throughout the 'very calm' intervals and in the early part of the 'calm' intervals. The lowest value of the speed is, on the average, about 325 km/sec when Ap is ≤4 and marginally higher (~350 km/sec) when Ap is ≤7. The speed continues to decrease in the quiescent periods and the minimum value is reached on the last day. The velocity change is analogous to the time profile of solar wind speed as a function of the passage of IMF sector boundary past the Earth (Wilcox and Ness, 1965). Quiet intervals of geomagnetic activity tend to follow the trailing part of the IMF structure (Gussenhoven, 1988). Our velocity threshold is consistent with the results of Murayama *et al.* (1980).

According to Yokoyama and Kamide (1997), southward turning of IMF is important in initiating the main phase of a storm and in determining the storm intensity. Thus Bz should be zero or positive when the geomagnetic activity is lowest. The IMF is ordered in the GSE system, but its interaction with the magnetosphere is controlled by the GSM coordinate system (e.g., Russell and McPherron, 1973).

Our Figure 1 indicates that in either coordinate system, the Bz component of IMF is small but positive during the 'very calm' or 'calm' intervals. Unlike Stern (1988), we find that during the conditions of geomagnetic calm Bz is definitely positive for intervals of 4 or 8 days. Rich and Gussenhoven (1997) find that in the quiet magnetosphere, Bz can be northward but the solar wind velocity should also be low. Both conditions are satisfied in the present analysis. Perhaps a distinction between 'baseline magnetosphere' and 'quiet magnetosphere' would lead to two separate thresholds of the IMF and solar wind.

The role of density in solar wind–magnetosphere interaction is not clear. In general, there is an inverse relationship



Figs. 1bI and 1bII. Continued.

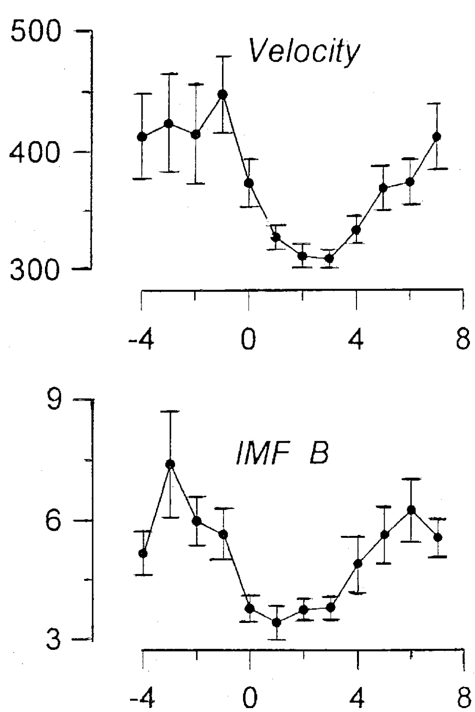


Fig. 2. Same as Figures 1aI and 1aII, except the key day is the beginning of a sequence of at least 32 intervals with Kp ≤ 1+. The superposed epoch analysis is restricted to only solar wind velocity and IMF magnitude, B.

between the wind speed and proton density, but the two are not perfectly anti-correlated. Rosenberg (1982) suggested that an enhancement in density could be a precursor for geomagnetic storms, particularly in association with corotating interaction regions. Ivanov and Mikerina (1987) found an unusual decrease in density associated with a very quiet interval. Superposed epoch analysis of proton density in the vicinity of 'very calm' intervals shows that the density minimum does not coincide with either the velocity minimum or the B minimum (see Figure 1a), but the change in density within the interval itself is anti-correlated with V. A prominent maximum in density at the end of the sequence of very quiet intervals is absent in V. For long calm intervals, from day 0 to the end (day +11), density and velocity are in phase opposition. Again, the maximum in density is found when the sequence of quiet intervals is terminated (on day +8).

According to Gussenhoven (1988) and Kern and Gussenhoven (1990), the value of IMF should be less than 5 nT and the solar wind speed should be less than 390 km/sec. These conditions are met in the present work. Sutcliffe (1998) found that half the number of intervals could not comply with Gussenhoven's (1988) criterion, and half of the rejected part could not pass the criterion of Kern and Gussenhoven.

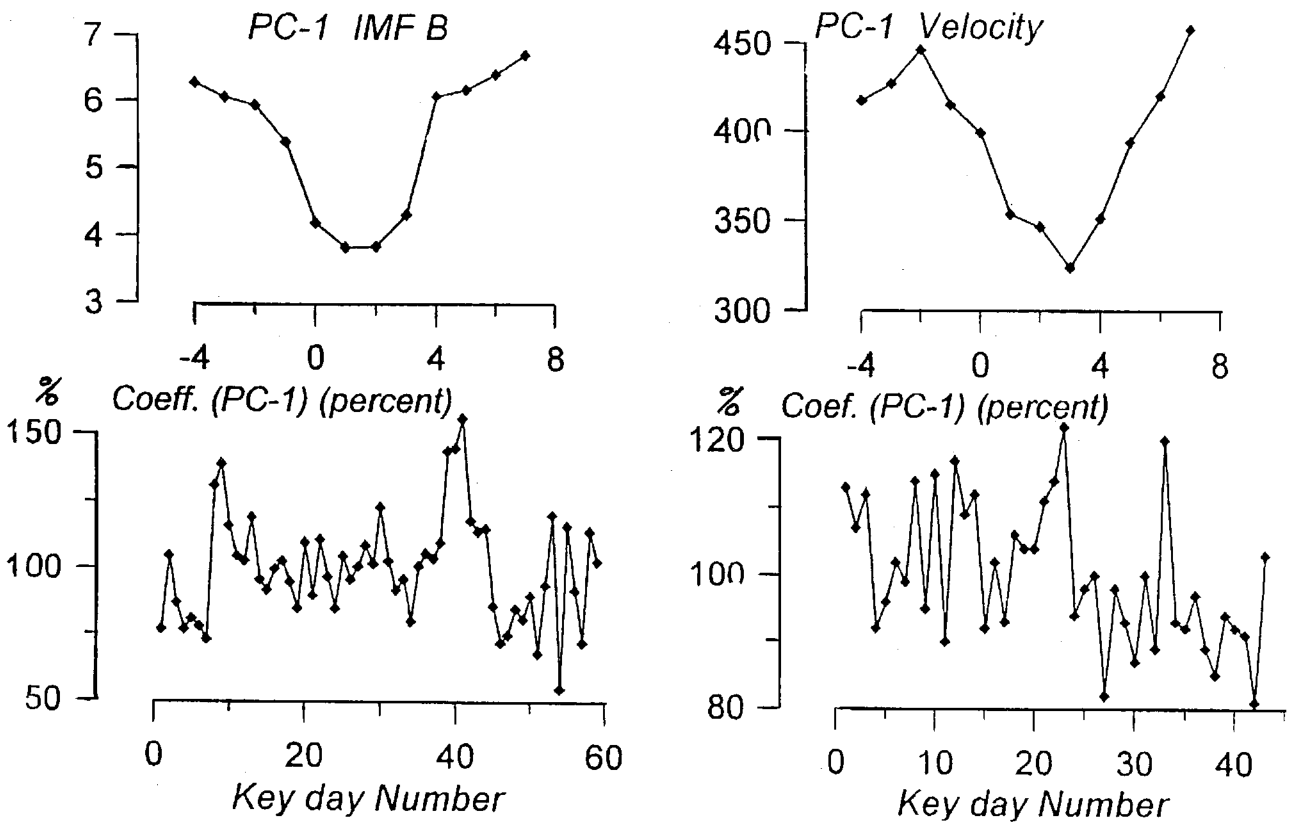


Fig. 3. First principal component of IMF B and solar wind velocity. The component is derived from the data for intervals beginning from four days prior to the commencement of a sequence of four consecutive days with Ap ≤ 4 up to four days after the termination of the sequence of quiet intervals. In the bottom panels are given the coefficients (as percentage) for each row of the data matrix which provides an idea about the magnitude of the contribution of the first component in each case.

In one case the velocity was more than 400 km/sec. This suggests that apart the magnetosphere should also attain a steady state to be qualified as a "baseline magnetosphere". But a 'quiet magnetosphere' might comply with less stringent conditions. Kern and Gussenhoven used only the intervals covered by day -1 and +1 of the present analysis.

They find that IMF B retains almost the same value for 24 hours preceding the key hour and shows only a gradual rise in the 17 following hours. This is consistent with our results. Their values for northward Bz are much larger mean magnitude (1.8 nT) than ours (~0.8 nT), but they are always positive during the quiet intervals of geomagnetic activity. Thus the longer duration for averaging tends to reduce the value of Bz. Unlike Kern and Gussenhoven, we find that the value of Bx changes across the sequence of 'very calm' intervals. In the quiet periods, however, |Bx| is larger than |By|, as they report, but the error bars are quite large. We agree that the significant parameters for determining prolonged periods of magnetic quiet are IMF magnitude and orientation and V. In addition the variability of the components of IMF, solar wind velocity and density may be relevant. 'Very calm' intervals of geomagnetic activity are marked by clear minima in the variability.

In conclusion, we find that all parameters change in an orderly fashion across the quiet intervals. This enables us to predict the values of the parameters that control the solar wind – magnetosphere interactions during quiet times. The relevant values are ~4 nT for B, ~320 km/sec for V and a positive Bz value < 1 nT. The density remains low from days before the very quiet interval and attains a maximum at the of the quiet sequence. The density is mostly anti-correlated with V. The variations in B and V are not very similar as V reaches a minimum much later in the sequence of calm days, whereas B is minimum early in the sequence and remains low through the rest of the sequence.

Principal Component Analysis suggests that the pattern of variation in V and B across the sequence of 'very calm' intervals is preserved in individual events. The variability from one key day to another is less pronounced in B

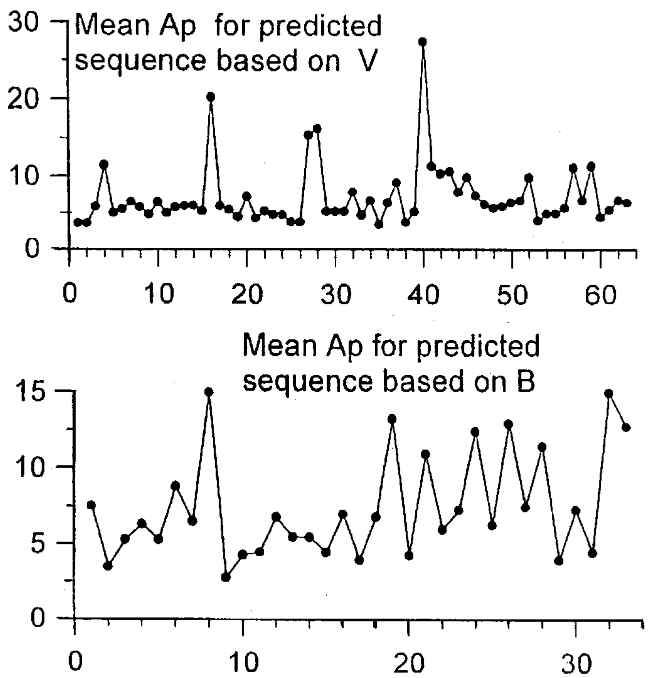


Fig. 4. Mean Ap values for four days predicted as quiet sequence based on the average value of V and IMF B for three days and a subsequent uniform decline over next three days. The predicted sequences were independently derived using V and B.

than it is in V. A prediction of 'very calm' intervals using average conditions in V and B and their rate of change can be reasonably successful, though use of V yields more consistent results.

Definitions of baseline magnetosphere suggest that there may be two different states, one corresponding to the lowest level of energy input of the solar wind into the magnetosphere, and the other corresponding to the lowest levels of geomagnetic activity. These results complement the earlier work by Kern and Gussenhoven (1990). Many features of the time variations show up more clearly when a longer interval is observed.

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