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" SPRING COLLEGE ON GEOMAGNETISM AND AERONOMY "

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" Recurrent geomagnetic disturbances "

" Worldwide features of the strength of recurrent geomagnetic activity "

" Long and short term relationships between solar wind velocity and geomagnetic field at low latitudes"

presented by :

G.K. Rangarajan
Indian Institute of Geomagnetism
Dr. Nanabhoy Moos Road
Colaba
Bombay, 400005
India

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Recurrent Geomagnetic Disturbances

G.K. Rangarajan
Indian Institute of Geomagnetism
Colaba, Bombay 400 005
India.

One of the striking features of the Bartels' musical diagram of Kp indices is its ability to pinpoint recurrence tendency in geomagnetic activity (both active and quiet) and its dependence on solar activity.

A plot of Aa indices from 1868 to now and sunspot number (Rz) clearly indicates that apart from enhanced geomagnetic disturbances during high solar activity there is a secondary maximum in the declining phase of the solar cycle. Catalogue of geomagnetic disturbances also clearly shows two distinct types (i) sporadically occurring, severe ones usually marked with a well defined sudden commencement and (ii) Moderate, gradually commencing disturbances recurring with a periodicity of about 27 days. The former is usually associated with the solar plasma emanating from errupting solar flares. No visible evidence on the solar disc was available for the recurrent magnetic disturbances. Bartels called the regions, devoid of visible features on the solar disc as 'M' - regions. These were considered hypothetical solar features only made evident by terrestrial features. Allen suggested that M-regions tend to avoid sunspot areas (cone of avoidance hypothesis). Mustel advocated that M-regions are correlated with active enters possibly young plage regions. Another candidate was 'Unipolar Magnetic Regions' (UMRS). With the availability of 'in-situ' solar wind and IMF measurements, first evidence of corotating structure of the solar plasma/IMF became available (Wilcox and Ness, 1965). It was inferred that enhanced geomagnetic activity occurs whenever IMF orientation in the ecliptic plane changed direction which could lead to a 27-day pattern when the sector structure is well ordered. With the 'skylab' mission, for the first time a new and well-defined solar source called 'CORONAL HOLE' could be identified as responsible for recurrent disturbances and can be related to the M-region.

Though recurrence tendency is most prominent during the declining phase of the solar cycle, such activity could exist even during high solar activity. Extensive information on the 'coronal holes' became available with the skylab missions between 1973 May and Feb. 1974. Skylab offered for the first time an opportunity to study the sun from space. In the pictures of the sun taken in X-ray wavelength coronal holes stand out as dark voids. Continuous coverage established that coronal holes are the source of high speed solar wind streams.

A working definition (BOHLIN 1972) of coronal holes is - "A fairly large scale, cool, low density area at low latitudes in the corona and at polar caps encompassing weak predominantly unipolar magnetic fields which extend away from the sun in diverging open lines of force that give rise to high speed solar wind streams that cause geomagnetic storms".

Individual coronal holes range from 1-5% of the area of the sun and persists upto 10 solar rotations. Holes rotate rigidly (only 3% variation from pole to equator) with a synodic period of 27 days. Long lived recurrent holes and streams are more evident in the declining phase.

"If we can somehow understand the mechanism by which solar wind couples to the magnetosphere, we have a tool of extraordinary power for investigating long-term solar terrestrial influences as we have geomagnetic activity data going back 200 years". Typically a high speed stream has a rapid rise in flow speed followed by a slow decline. A short period of very high densities near the leading edge is followed by long period of low densities. The IMF polarity usually constant within a high speed streams. The duration on the average is about 5 days. The transit time between Sun and earth for the stream is about 4 days.

Altschuler et al. (Sol. Phys. 23, 410, 1972) examined coronal holes during solar eclipse. They suggested that holes geneally occur over quiet chromospheric regions in weak and diverging magnetic field and that a primary characteristic of the coronal hole is a significantly reduced coronal electron density and K-coronal intensity compared to the surrounding areas. Neupert and Pizzo (1974 JGR 79, 3701) mention that all the solar features examined only coronal holes of substantial size lying atleast in part near the sun-earth line at central meridian passage could be associated with recurrent geomagnetic activity.

Relationship of Ap index with bright coronal regions, regions of diminished surface brightness, major sunspot areas and plage areas were all considered. Gulbrandsen (P.S.S. 21, 703, 1973) showed that high density coronal regions, associated with closed magnetic field structures were the origin of enhanced λ5303. Weakened 5303 intensity characterised open magnetic field lines. Gulbrandsen concluded that a great majority of analyses or solar source of high speed streams provide results consistent with the inference that solar M-regions should be identified with the central portion of magnetically open solar regions or coronal holes.

Legrand and Simon (Sol. Phys. 70, 1981, 173) have examined solar and magnetic activity over 110 years (Aa index and Rz) together with 17 years of solar wind data to bring out features of sporadic and recurrent magnetic activity and their solar origin.

A color graphic display of coronal holes, IMF polarity, solar wind velocity and geomagnetic activity for sequence of years can be seen in a series of papers by Sheeley et al. (Sol. Phys. 49, 271, 59, 1978, 70, 241)

The striking similarity leads to the conclusion that the holes are closely related to solar wind streams and associated geomagnetic disturbances. CH are the solar origin of the high speed streams near the ecliptic plane. Most low latitude holes are terrestrially effective. But high latitude holes are geoeffective only when they lie in the same solar hemisphere as the earth.

Some features of the strength of recurrent geomagnetic disturbances (27-day periodic signal)

A 27-day variation associated with solar synodic rotation has been observed in a variety of solar interplanetary and geophysical parameters. Moos (in 1910) showed that when mean daily values of H were arranged in 27-day sequence dominant 27-day and 13.5 day oscillations became very apparent whose amplitude was a function of the phase of the solar cycle. In the spectrum of indices of magnetic activity a broad band peak between 24 and 31 days usually occurs which could be explained in terms of the varying periodicity of solar spots at different latitudes. Banks (Geophys. J. Ras. 1969) computed power spectra showing 27-day line at several phases of solar activity cycle and indicated that the signal is strongest during the declining phase. The current systems responsible for the variations produce a magnetic field at the surface which can be represented by spherical harmonic.

In the mean daily field of H at low latitudes, covering 1932-1954 and 1946-1968 blocks. Bhargava and Rangarajan detected a spectral peak of periodicity 26. 2 days with two sidebands at 30.5 and 22.8 days. They correspond exactly to periods that results from amplitude modulation of the fundamental 26.17 day line by a semiannual periodicity. Similar modulation by annual or 11-yr solar cycle line was absent. Sidebands of same type were observed in Ci index and Ap index too by others.

In the K-index data of low latitudes, it was seen that when solar activity increases the periodicity increase from about 27 to nearly 31 days. Once again the line was sharp and well resolved only during the declining phase.

Diurnal asymmetry of the 27-day signal

The time series of horizontal intensity restricted to 1 hour at a time was spectrally analysed. The power densities at 27-day periodicity as a function of local time showed significant strength just after local noon and a forenoon/evening asymmetry. (Bhargava, 1973) Rangarajan (1984) showed that the wherence between solar wind velocity fluctuations and low latitude field variations was quite significant near 27-day periodicity. The diurnal asymmetry over an extended period covering four solar cycles was examined by Bhargava and Rangarajan (JGG 1975) using hourly values of low latitude H field. They could show the role played by the asymmetric ring current in relation to the peak spectral density as a function of local time. During high solar activity peak power occurs 3-4 hours later than during declining phase and the asymmetry was more complex. This shift was consistent with the progressive change in the phase of the asymmetric ring current with the strength of geomagnetic disturbance.

Using mean daily values of H at equatorial stations during high declining and low solar activity periods, Ehargava and Rao (Planet Sp. Sci. 1970) showed that the power density increased during high solar activity and diminished during low solar activity towards the dip equator. They associated this solar activity dependence with the IMF and solar wind velocity changes and to possible anti-phase relationship between 27-day oscillation of the ring current intensity and Sq dynamo.

Rangarajan and Bhattacharyya (1984 see reprint) carried out an extensive global analysis of the characteristics of the 27-day variation. They choose a period marked by persistent recurrent pattern not vitiated by solar transients. They could show that the equatorial electrojet strength and Sq dynamo currents also exhibit 27-day periodicity atleast for durations devoid of transient and sporadic solar eruptions.

Recurrent activity as an index of the solar maximum of the next cycle

Predicting the sunspot number from the geophysical parameter changes in the preceding cycle has been attempted by several authors.

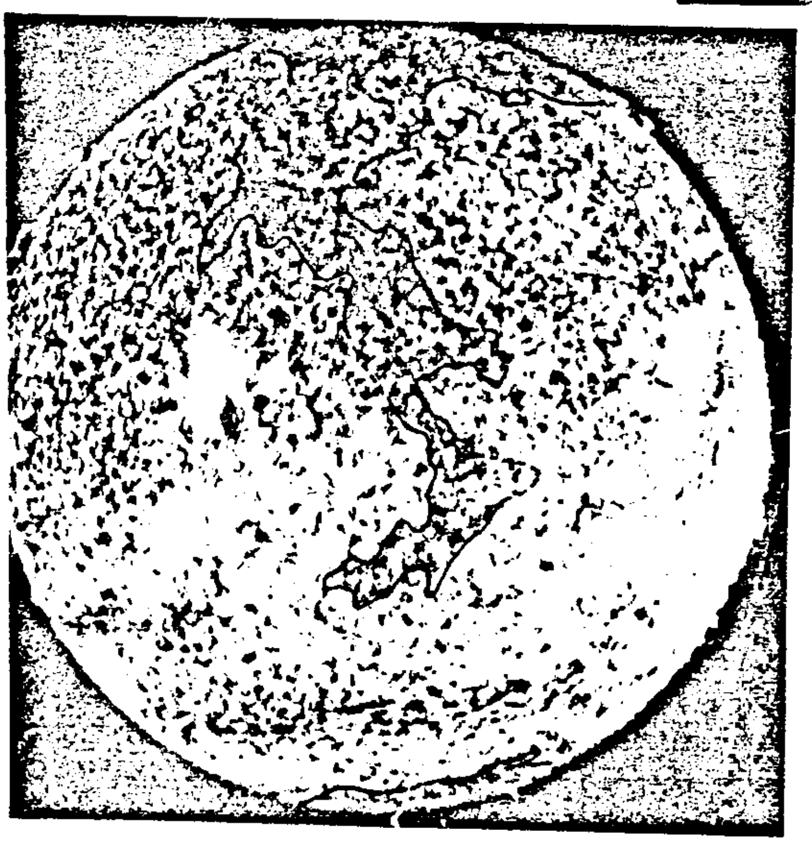
Ol (Geomag. Aeron 1971) showed a close relationship between intensity of recurrent magnetic disturbances and the maximum Rz in the succeeding cycle. This was considered to be a consequence of the unipolar magnetic regions at the end of one solar cycle and development bipolar spot groups in the next cycle. Bhargava and Rangarajan (1975 Sol. Phys. Reprint) computed power densities of 27 and 14-day spectral lines at low latitude station for four declining phases of solar cycle and found a close relationship between magnitude of the recurrent activity (27 and 14 day periods) and of the succeeding cycle. In addition to this relationship they could also find that the rate of decline of the sunspot number of the succeeding cycle is related to the strength of recurrent activity in the preceding cycle.

One of the most interesting parameters used for the prediction, unrelated to the topic under discussion is the occurrence of Abnormal Quiet Days in middle latitudes.

3

HE BOOT OF ITALY HOLE, and others like it, were atched continually by several Skylab telescopes. It is aced out on a picture of the high chromosphere (2) made the ultraviolet one day after the preceding needlepoint ew (1) was made. Coronal holes appear at this lower, oler level of the solar atmosphere as fadings in the iromospheric network.

In an X-ray photograph of the Sun (3), made simultane- usly with (2), the coronal hole has nearly identical form. ; in (2), boundaries of the hole have been outlined for arity.



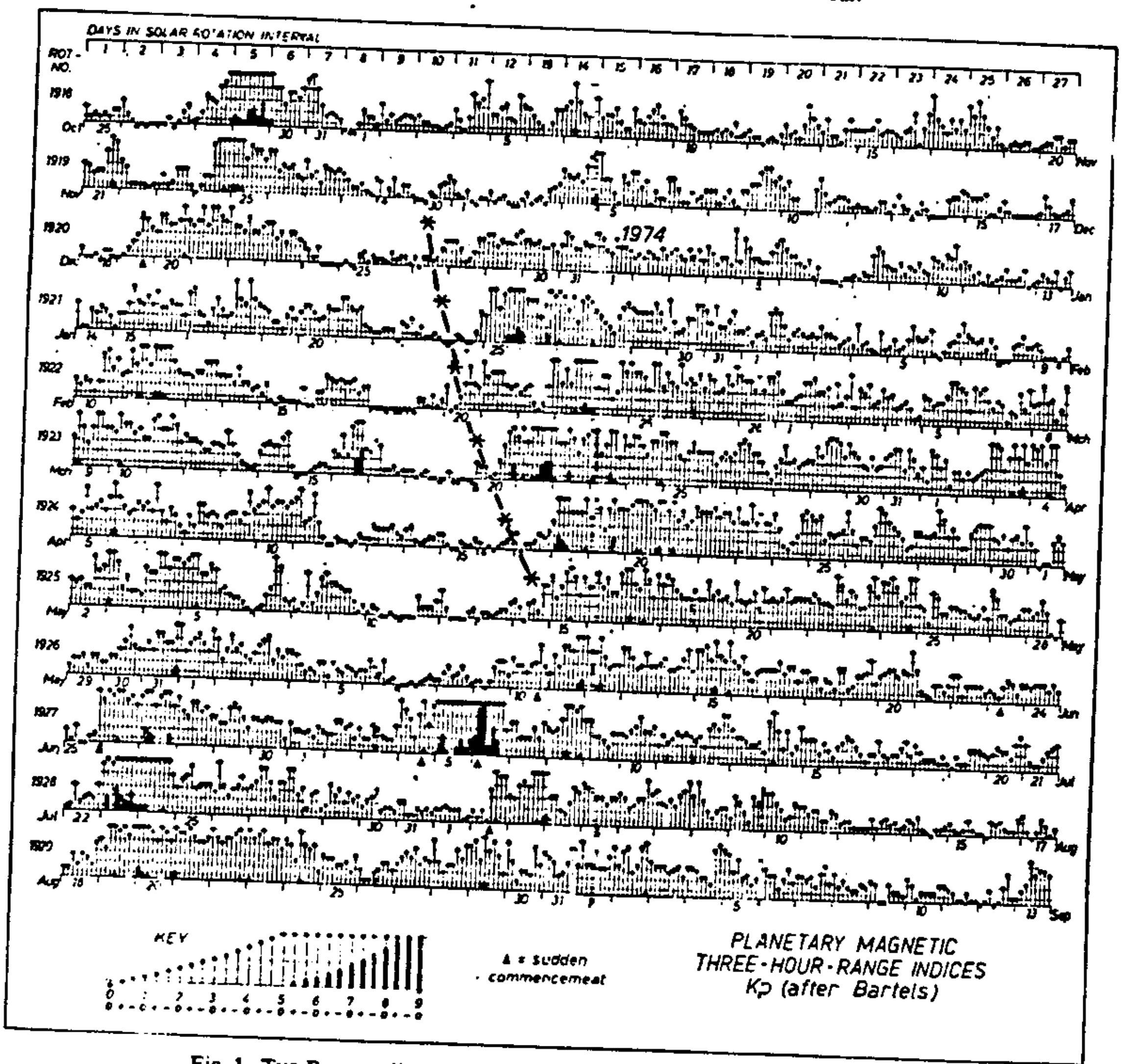


Fig. 1. THE BARTELS "MUSICAL DIAGRAM" OF GEOMAGNETIC INDEX FOR 1974.
Asterisks mark the sequence of recurrent M-region disturbances studied here. The sequence was apparently disrupted by the resurgence of solar activity including major flares and associated sudden commencement geomagnetic storms around 4 July 1974.

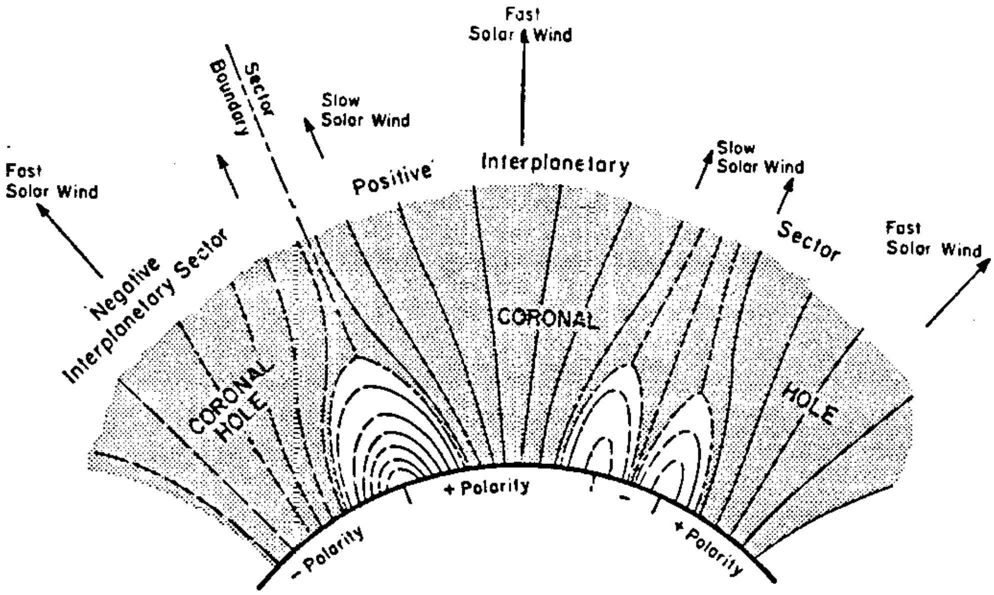


FIGURE 2. A sketch of the magnetic field and density structure of a coronal hole. Coronal holes occur in regions that are magnetically open to interplanetary space. Their low densities make them appear dark in any radiation emitted (X-rays, ultraviolet, or forbidden lines in the visible) or scattered (white light) from the corona.

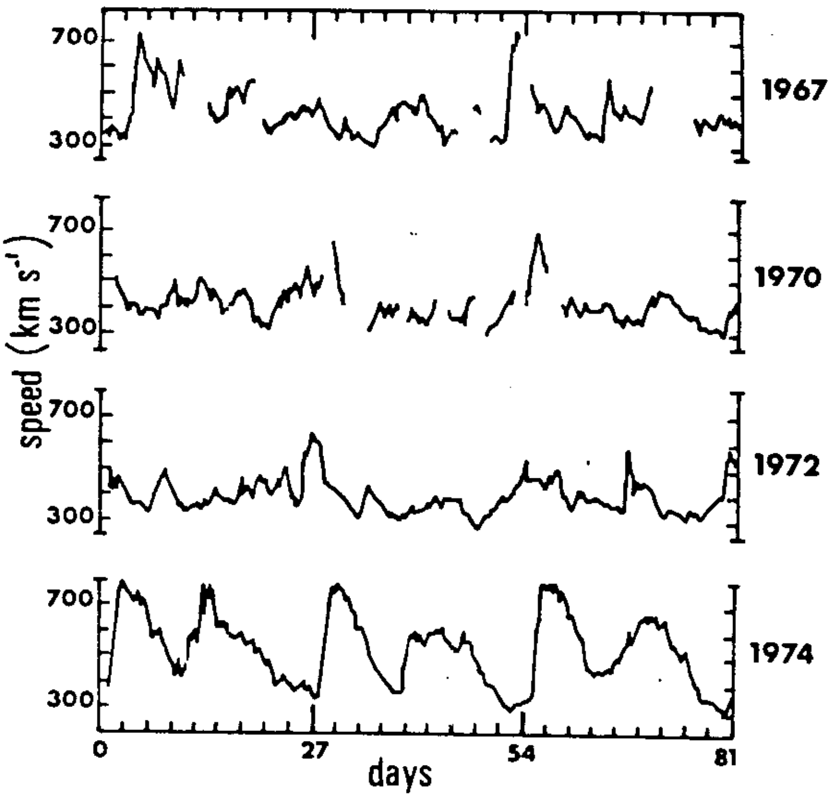


Fig. 3. Examples of the speed structure of solar wind streams at four different epochs of solar cycle 20 (Bame *et al.*, 1976).

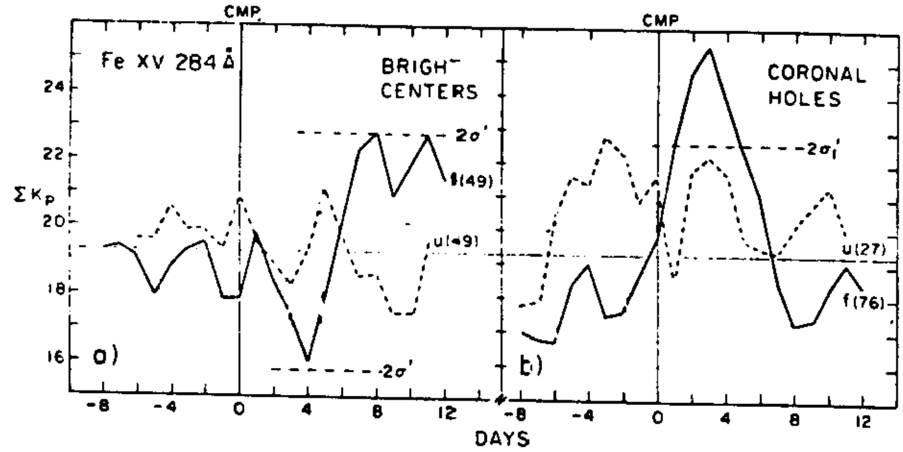


Fig. 2. Superposed epoch curves of the average Kp associated with CMP of (*a*) bright regions and (*b*) coronal holes in the 284-Å emission of Fe XV in the favorable (*f*, solid lines) and unfavorable (*u*, dashed lines) solar hemisphere. Number of CMP days is given in parentheses.

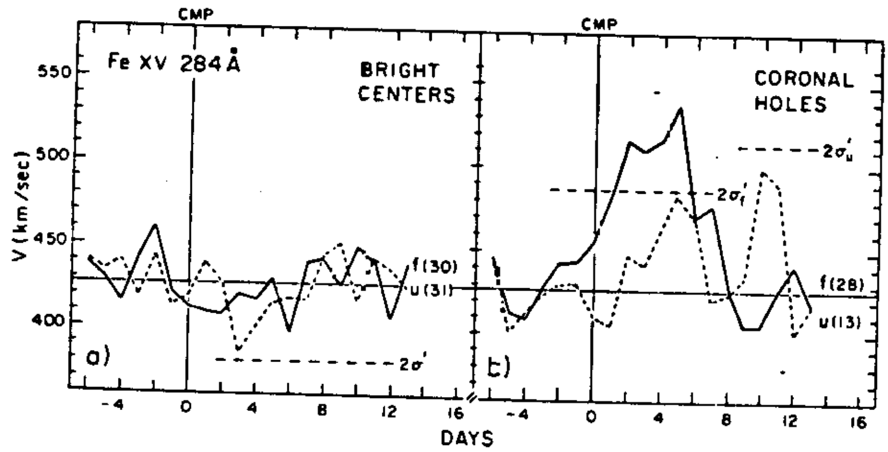


Fig. 3. Superposed epoch curves showing average solar wind bulk velocity (Pioneer 6 and 9 combined) with zero day defined by CMP of (*a*) bright regions and (*b*) coronal holes in the 284-Å emission of Fe XV (solid lines, Pioneer in the favorable hemisphere; dashed lines, Pioneer in the unfavorable hemisphere). Numbers in parentheses indicate the average number of cases.

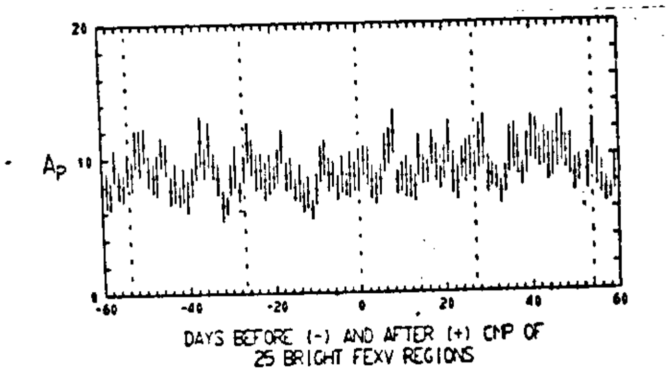


Fig. 4. Superposed epoch analysis using coronal regions having high surface brightness in the emission line of Fe XV at 284 Å. Regions used in Figure 4 had an area equal to or greater than 2.8% of the projected solar disk.

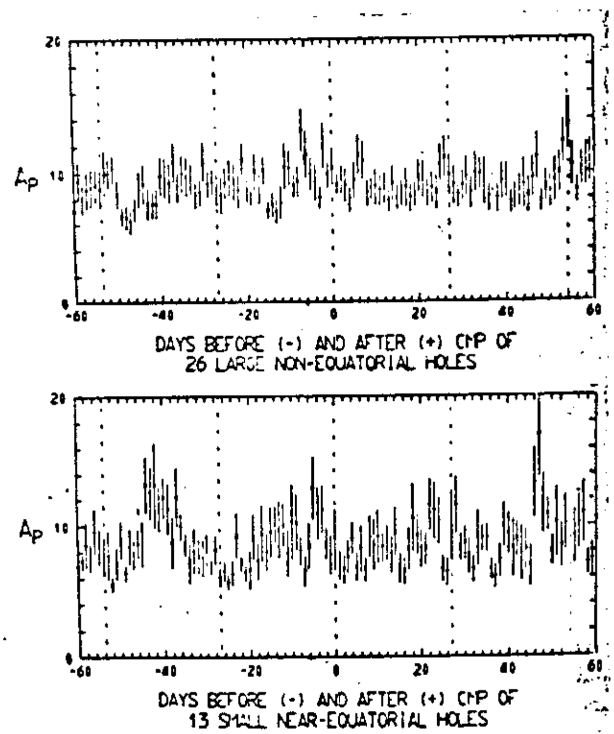


Fig. 6. Superposed epoch analyses using (*a*) 26 large corcnal l not extending to within 5° of the subearth point and (*b*) 13 l extending within 5° of the subearth point but having a total less than 3.5% of the solar disk. In neither case is an enhancer in *Ap* observed after cmp.

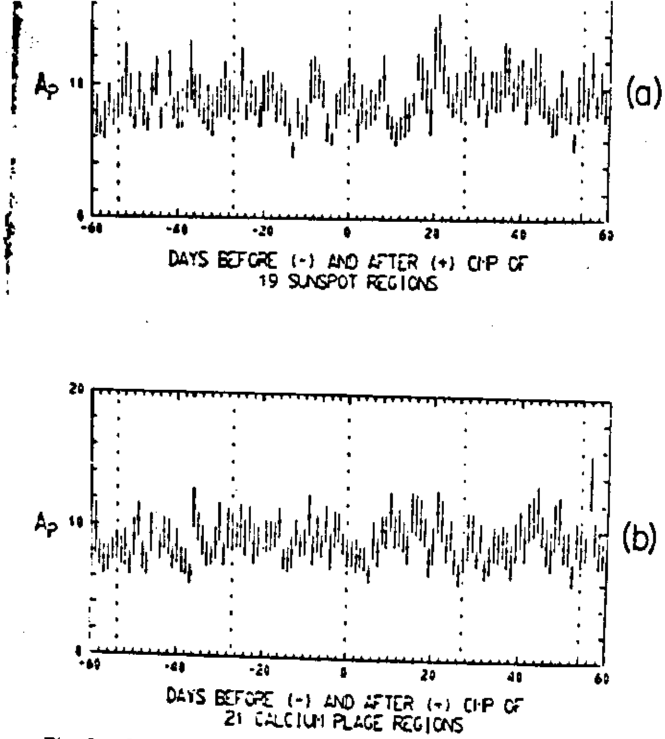


Fig. 3. Superposed epoch analyses using (*a*) the cmp of 19 large sunspot areas and (*b*) the cmp of 21 large calcium plage areas observed between January 1972 and January 1973. See text for the criteria used in selecting these areas.

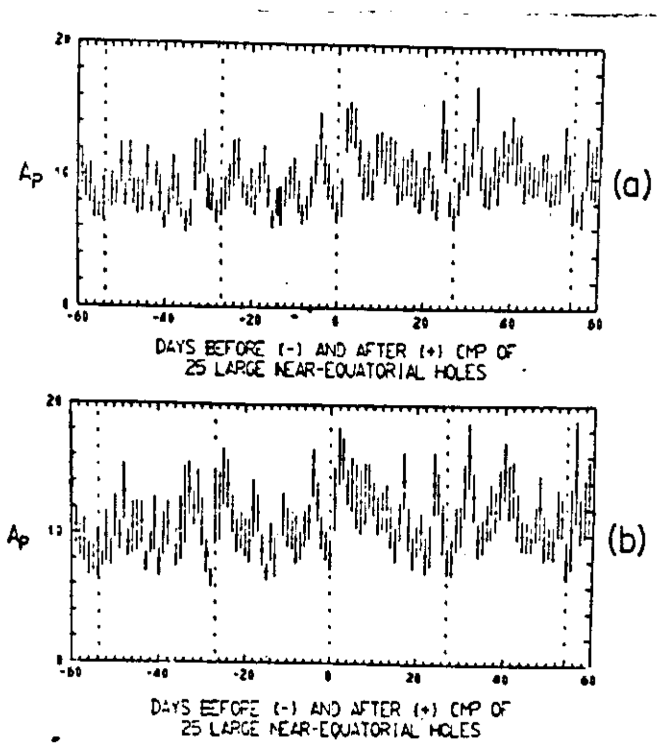


Fig. 5. Superposed epoch analyses using 25 large coronal regions of low surface brightness (coronal holes) extending to within 5° of the solar subearth point at cmp. (*a*) The *Ap* observations recorded during moderately severe sudden commencements have been deleted. (*b*) Only *Ap* observations during times of enhanced high-energy proton fluxes have been deleted. Note the peak in *Ap* after cmp of such coronal holes.

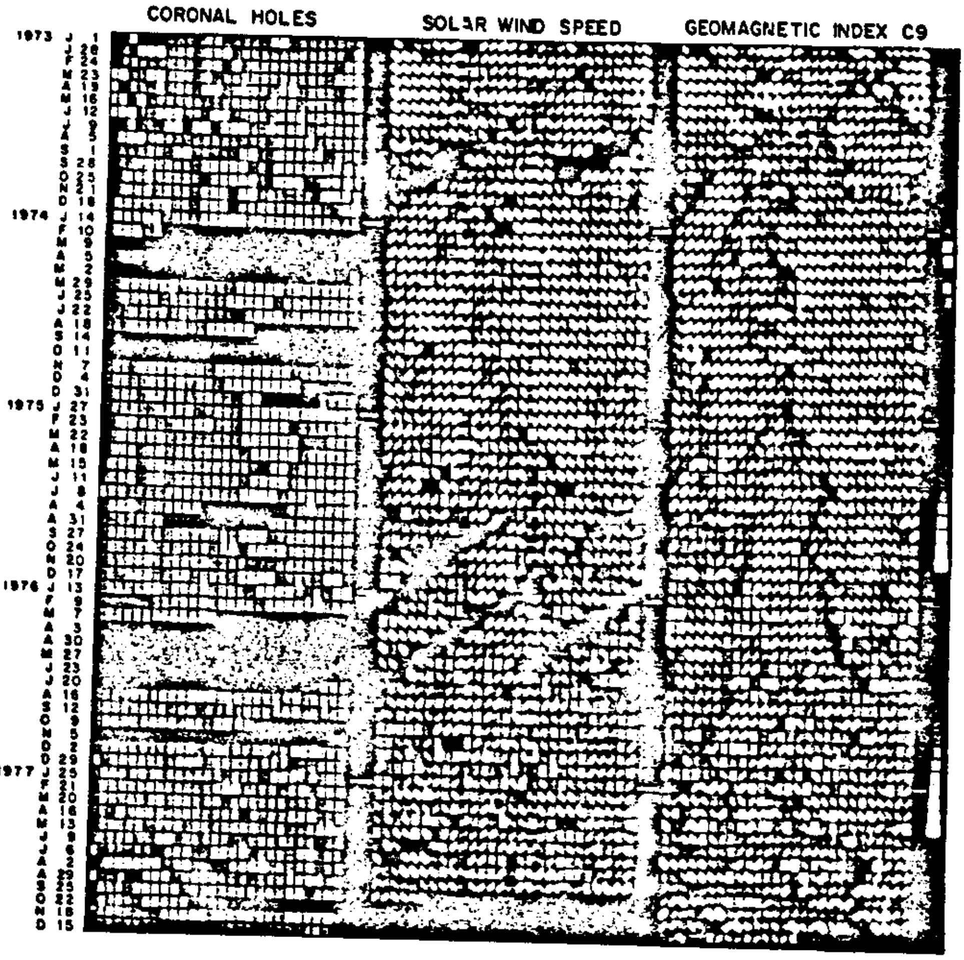


Fig. 7 A Bartels display of coronal hole central-meridian-passage dates (plus 3 days), solar wind speed at Earth, and the C9 geomagnetic disturbance index for the 5-year interval January 1, 1973–January 10, 1978. On the left, *strong* coronal holes within 40° of the solar equator are indicated by orange (+) and light green (−) entries depending on the polarity of their respective photospheric magnetic fields. *Weak* holes are indicated by red (+) and dark green (−) entries. In the center and right sections, the sector polarity of the interplanetary magnetic field is indicated by entries slanted to the upper right (+), upper left (−), or not slanted (mixed or indeterminant polarity). Solar wind speed and the C9 index are indicated by progressively lighter shades of color according to the middle and lower color legends at the extreme right respectively. In all three sections, black areas without entries refer to days for which observations either were not obtained or have not yet been reduced.

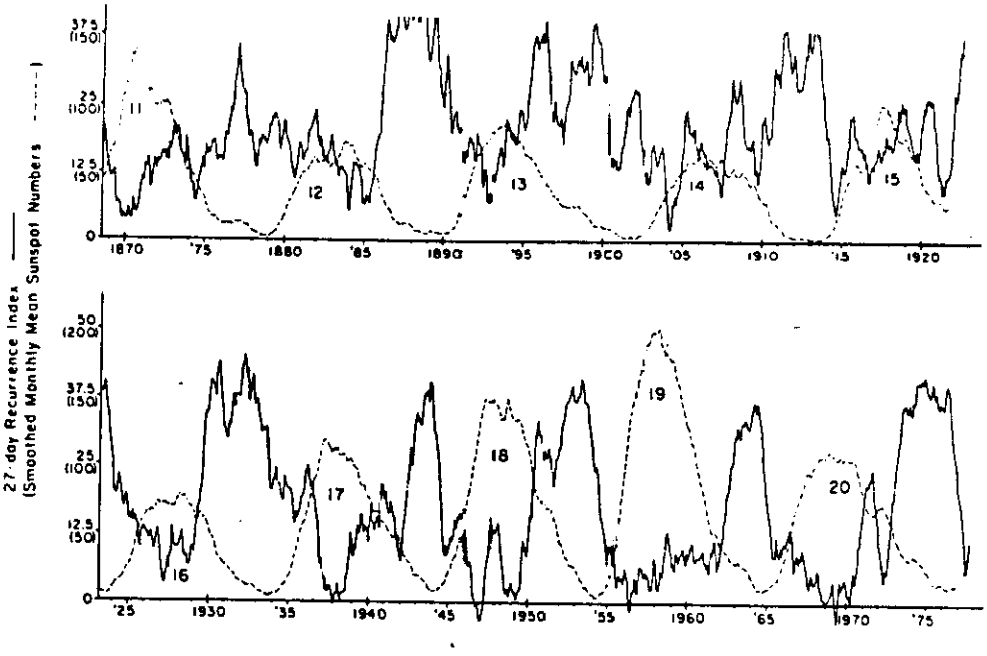


Figure 2. 27-day Recurrence Index and smoothed monthly mean sunspot numbers from 1868 to the present.

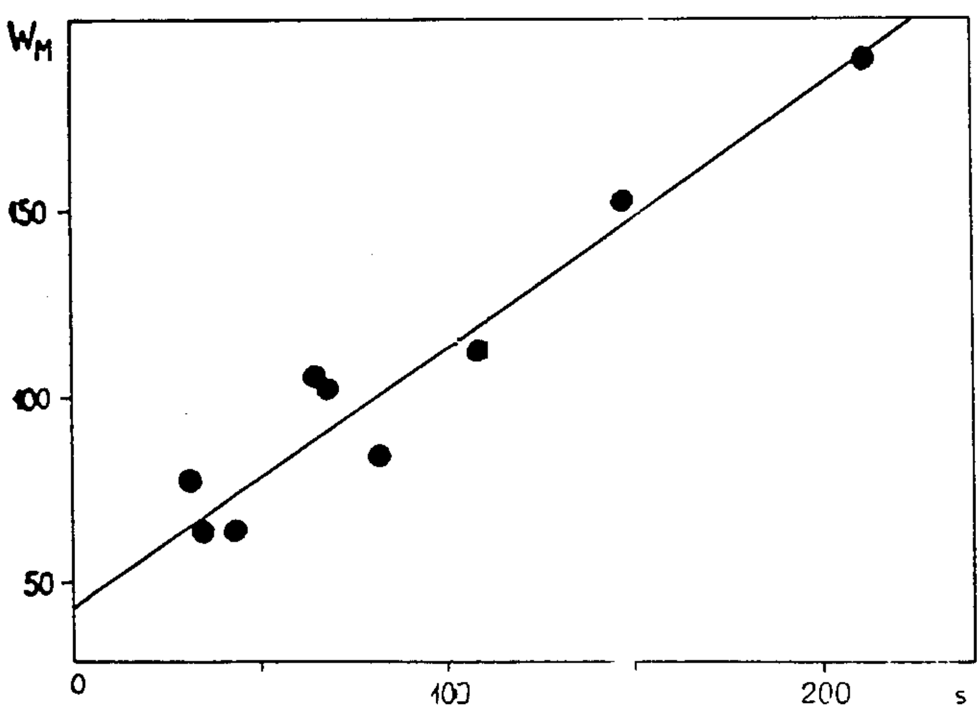


Figure 1. A relation between the indexes of recurrent magnetic disturbances and Wolf's number W_M in the maximum of the next 11-year cycle.

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Worldwide features of the strength of recurrent geomagnetic activity

G K RANGARAJAN and A BHATTACHARYYA
Indian Institute of Geomagnetism, Colaba, Bombay 400 005, India.

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Abstract. Variation of the strength of recurrent geomagnetic activity, which occurs just before a sunspot minimum, with local time is studied for a network of observatories covering different latitude and longitude zones. For this purpose, hourly averages of horizontal intensity(H) for each UT hour for 173 days, which are totally free of disturbances due to solar transients, have been subjected to spectral analysis. Well-defined spectral peaks associated with periodicities of 28, 14 and 9 days were present in almost all the spectra. The pattern of daily variation of the strength of the 27-day signal changes from a diurnal one at low latitudes to a semi-diurnal one near the Sq focus and in this region, the 14-day signal appears to have an independent origin irrespective of the longitude zone. A study of 27-day oscillation in mean daily H field also indicates that apart from ring current modulation, both Sq and electrojet fields also undergo 27-day oscillations during the declining phase of a solar cycle possibly through the ionospheric wind system.

Keywords. Worldwide features; geomagnetic activity; sunspot minimum; ring current; tidal winds.

1. Introduction

The strength of recurrent geomagnetic activity, as measured by the amplitude of 27-day oscillation in the mean daily values of horizontal magnetic field has been studied in the equatorial region for different phases of solar activity (Bhargava and Rao 1970). Recurrent activity before sunspot minimum is now known to have features quite distinct from activity during other phases of the solar cycle (Legrand and Simon 1981). Bhargava (1973) and Bhargava and Rangarajan (1975) have studied the evening forenoon asymmetry in the amplitude of the 27-day oscillations of horizontal magnetic field at Alibag (dipole lat. 9.5N) both during the declining phase of solar cycle just before minimum and during high solar activity. The asymmetry in signal strength was attributed to the corresponding diurnal asymmetry in the equatorial ring current intensity.

In order to study noise-free 27-day signal of recurrent activity it is essential to pick an interval free of disturbances from other solar transients. One such interval has been identified by Hansen *et al* (1976), who found that the period extending from mid-December 1973 to mid-June 1974 shows a highly persistent pattern of geomagnetic activity without any SSCs; flares and other transient activities were totally absent. Van Hollebeke *et al* (1981) recently studied in detail the relationship between energetic particle events and high speed solar wind for the period November 1973 to August 1974, during which two well-defined recurring high speed streams were seen to persist for nearly 10 solar rotations.

Studies on the low latitude field signals of the 27-day oscillation referred to earlier utilised data over longer time spans of 2–3 years during which period solar transients could also have contributed to geomagnetic activity. As pointed out by Hansen *et al* (1976) such geomagnetic activity would be positively correlated with solar features which tend to reverse or destroy the signal of recurrent activity as this type of activity is found to be inversely related to the intensity of coronal structures.

In this paper we carry out a systematic search for the local-time and latitude dependance of the 27-day geomagnetic signal due mainly to recurrent solar features using horizontal intensity observations for the period 20 December 1973 to 10 June 1974 (Bartels rotation No. 1920 to 1926) of a carefully selected network of observatories. The coordinates of the stations chosen are given in table 1. In the Indian zone, the stations cover the region between the equatorial electrojet belt to just above the northern Sq focus. Inclusion of Nurmijarvi-dipole conjugate of Kerguelen—in the analysis was necessitated to establish the anomalous nature of the 27-day oscillation at Kerguelen, an island in the southern hemisphere.

2. Data analysis

Hourly averages of horizontal intensity (H) for each UT hour for the period 20 December 1973 to 10 June 1974 (173 days) were used in spectral analysis using a version of FFT described in detail in Rangarajan and Bhargava (1974), adopting 0.002 as bandwidth for each spectral estimate. Some sample power spectra at two stations—Trivandrum and Alibag—are shown in figure 1. For each station, two spectra are depicted, one for that particular hour when the strength of the 27-day signal is close to a minimum and another for the hour when the power spectral density associated with the 27-day signal is maximum. In almost all the spectra there were well-defined spectral peaks, above the continuum, corresponding to the periodicities of 28, 14 and 9 days. Power densities associated with these periodicities, representing the solar synodic rotation periodicity and its first harmonic, for each hour are noted. These are depicted in figures 2 to 6.

Table 1. Geographic and dipole coordinates of observatories used in the analysis.

Station Name	Code	Geographic		Dipole	
		Latitude	Longitude	Latitude	Longitude
Trivandrum	TRD	8° 29′N	76° 57′E	1.1° S	146.4°
Alibag	ABG	18° 38′N	72° 52′E	9.5° N	143.6°
Sabhawala	SAB	30° 20′N	77° 48′E	20.5° N	149.7°
Tashkent	TKT	41° 20′N	69° 37′E	32.3° N	144.0°
Lunping	LNP	25° 00′N	121° 10′E	13.8° N	189.5°
Simosato	SSO	33° 34′N	135° 56′E	23.0° N	202.4°
Memambetsu	MMB	43° 55′N	144° 12′E	34.0° N	208.4°
Teoloyucan	TEO	19° 45′N	99° 11′W	29.6° N	327.0°
Hartebeesthoek	HBT	25° 53′S	27° 42′E	26.9° S	87.8°
Hermanus	HER	34° 25′S	19° 14′E	33.7° S	81.7°
Kerguelen	KGL	49° 21′S	70° 12′E	56.5° S	127.8°
Nurmijarvi	NUR	60° 30′N	24° 39′E	57.8° N	112.6°

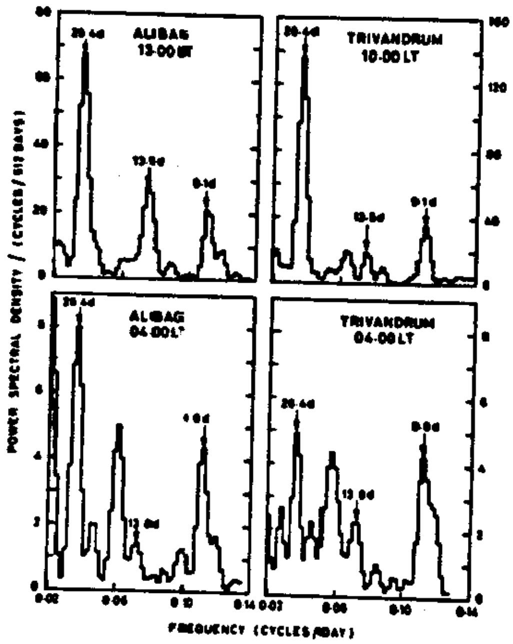

Figure 1. Power spectra of series of hourly averages for two particular hours at Trivandrum and Alibag.

3. Results and discussion

3.1 *27-day and 14-day signal in Indian zone*

All the stations in the Indian zone are within 6° of 75° E longitude so that the local time may be taken to be 5 hours ahead of UT. Power densities at the two frequencies as a function of local time for four stations are shown in figure 2. The graphs at once suggest a strong dependance of the solar rotation signal on time of day with peak magnitude being a function of latitude. Close to the dip equator the power density varies from about 10 nT^2 (unit bandwith) at predawn hour to a peak value of about 135 nT^2 before local noon. At low latitude (Alibag) the power density varies between about 5 and 70 nT^2 and the time of peak amplitude shifts to post-noon hours, similar to the earlier results of Bhargava (1973). At both Trivandrum and Alibag the local time change is dominantly diurnal in contrast to the stations close to and on either side of the Sq focus. At Sabhawala and Tashkent, in addition to the early afternoon peaks (similar to Alibag) a forenoon secondary maximum becomes apparent. This semi-diurnal pattern in strength of the 27-day signal is similar to the Sq (H) variation at Sabhawala having a 12-hr periodicity comparable in amplitude to the diurnal component (Srivastava and Prasad 1979; Rangarajan and Ahmed 1981). The reduction in peak power-density as a function of latitude (θ) is not matched by the $\cos^2\theta$ dependance of ring current effect indicating that the 27-day oscillation and its equatorial enhancement cannot be fully explained by the ring current intensity modulation alone. Bhargava and Rao (1970) found that during the declining phase (1961–63) of solar cycle 19, the power density of the solar rotation signal was comparable at Alibag

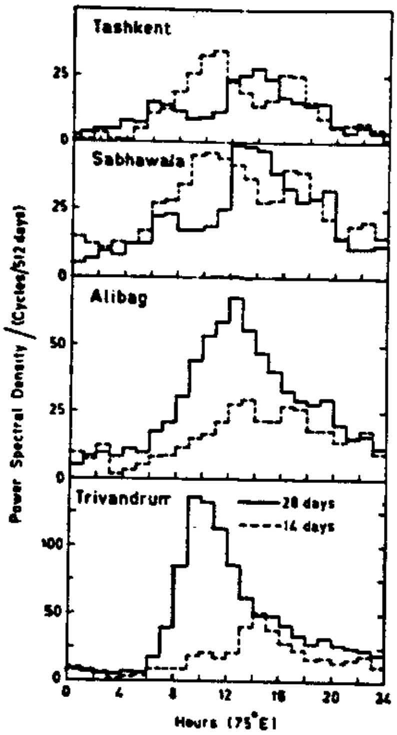

Figure 2. Power spectral densities for 28-day and 14-day signals as functions of 75° E time for stations in the Indian zone.

and Trivandrum. The present results, on the other hand, clearly show an enhancement by a factor of 2 in the peak power close to noon time. These differences can be attributed to the fact that when the data covering a large time-span and mean daily values are utilized, the significant features and fine structure could be obscured due to the opposite relationship of solar transients and stable coronal activity as indicated by Hansen *et al* (1976). The difference in time of peak power between electrojet and low latitude station outside the belt is consistent with the suggestion of Onwumechilli (1967) that the electrojet field leads the Sq field by more than an hour. It is known that harmonics of fundamental periodicities appear in the spectrum because of non-sinusoidal nature of the variations. If the 14-day spectral line were only a harmonic of the basic 28-day periodicity the local time behaviour of the amplitude at this frequency will be expected to be similar with reduced magnitude at all hours. Examination of the LT pattern for the 14-day line clearly indicates that while this expectation is largely fulfilled at Alibag, close to the Sq focus (and on either side of it) there is clear evidence that the significant oscillation of the *H* field has a basic periodicity of 14 days.

Recently Briggs (1979) showed that a 27-day oscillation could be noticed in the mid-latitude solar daily variation field (S_R), markedly so during the declining phase of the solar cycle. To eliminate magnetospheric part he took the difference of the *H* field at two nearby stations. He suggested that the effect may be mainly due to a 27-day recurrence tendency in the amplitude of the tidal winds in the dynamo region. As the power densities and the local time variations obtained in our analysis are suggestive of significant contribution from the Sq field, we have computed the power spectra for the differences (TRD-ABG) and (ABG-SBH) (see table 1 for station codes) for the same period. The corresponding variations are depicted in figure 3. Rush and Richmond (1973) and Kane (1978) have shown that such differencing procedure for stations in the same longitude zone but separated in latitude give the time variations of only the ionospheric (electrojet or Sq) part of the field as the magnetospheric contribution is largely removed.

Significant power at the solar rotation frequency confined to just a few hours before local noon for the (TRD-ABG) data clearly indicates a 27-day oscillation of the electrojet strength. The signal derived from (ABG-SAB) difference, indicative of Sq field of ionospheric origin, has nearly the same magnitude for peak power. It may, therefore, be inferred that apart from ring current modulation, both Sq and electrojet field also undergo 27-day oscillations during the declining phase. As the magnitudes of the two are comparable, it is quite likely that the ionospheric wind system rather than the electrical conductivity shows similar oscillations as inferred by Briggs (1979). Electrical conductivity is more likely to be affected during periods of high solar activity.

3.2 *Comparison of 27-day signal at a pair of stations in day and night hemispheres*

The two magnetic stations, Alibag and Teoloyucan, are located nearly in the same geographic latitude and differ by nearly 180° in longitude. The pair is thus suitable to establish clearly whether the strength of the signal depends on universal (UT) or local time (LT). Power density change of the 27-day signal as a function of local time for these two stations are shown in figure 4. It is immediately seen that at low latitudes the variation is governed by local time (LT) with peak power close to local noon. There is a noticeable difference in the power between the two stations during the afternoon hours. This may be because of the difference in their dipole latitudes, with Teoloyucan being higher by about 20°, leading to a reduction in the magnitude of the contribution of the asymmetric ring current envisaged as the responsible mechanism for the forenoon/evening asymmetry at Alibag by Bhargava (1973). However a similar difference in strength of asymmetry is not reflected in the chain of Indian zone (figure 2). In fact, as has been pointed out earlier in this paper, at Sabhawala and Tashkent the daily variation pattern for the strength of the 27-day signal assumes a semi-diurnal form,

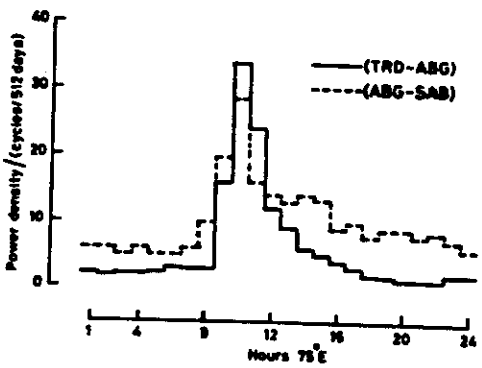

Figure 3. Power spectral density of the 28-day signal as a function of 75° E time for the differences (TRD-ABG) and (ABG-SAB)

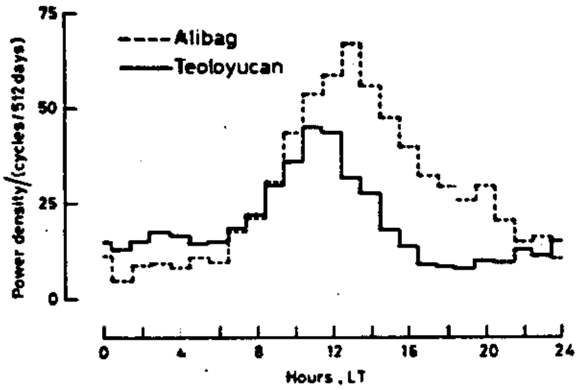

Figure 4. Power spectral density of the 28-day signal as a function of local time for the stations Alibag and Teoloyucan.

whereas at Teoloyucan it is diurnal. This goes to show that the position of Sq focus becomes important for the quite time currents which prevail during a period of low sunspot activity. Dip latitude will play a major role in disturbance fields. In the present context the effect appears to be a combination of geographic and dip latitudinal dependances.

In recent times it has been suggested (Crooker and Siscoe 1981) that since the dusk-centred partial ring current hypothesis for low latitude asymmetry in the disturbance field suffers from ionospheric closure and orientation problems, it should be abandoned in favour of a system of distributed Birkeland currents. Fukushima and Kamide (1973) estimated the contribution of Birkeland currents to longitudinal asymmetry at various geomagnetic latitudes from 0° to 40° using a partial ring current system which would consist of a west-ward flowing partial ring current in the equatorial plane, the field-aligned Birkeland current and an east-ward electrojet in the auroral zone ionosphere. They found that the contribution of Birkeland currents to the asymmetry is larger than that of the partial ring current. However, whereas the contribution of the partial ring current decreases with increasing geomagnetic latitude, that of the Birkeland currents increases with increasing geomagnetic latitude. The total asymmetry due to the whole current system (including the electrojet in the auroral zone) was found by these authors, to decrease with increasing geomagnetic latitude in their model calculation we point out that if the asymmetry is attributed to Birkeland currents alone it may be difficult to explain a decrease in the asymmetry with increasing geomagnetic latitude as we find above in the case of Alibag and Teoloyucan. A more thorough study of the asymmetry at different latitudes is required in order to arrive at a current system responsible for the low-latitude asymmetry.

3.3 *27-day oscillation in the Japanese sector*

The three stations chosen in this sector are between 8 and 9 hr, east of Greenwich and separated by about 4 hr from the Indian zone. The power density changes with time of the day are shown in figure 5. Similar to the Indian zone, the peak power falls off systematically with increasing latitude and the local time dependance changes from a dominantly diurnal to a dominantly semidiurnal mode. The pattern of the 14-day

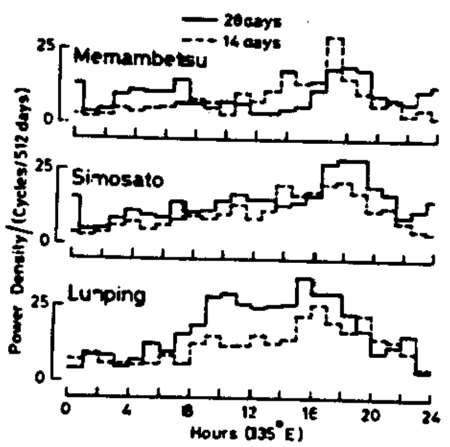

Figure 5. Power densities for 28-day and 14-day signals as functions of 135° E time for stations in the Japanese sector.

spectral power again indicates it to be an independent periodicity close to the Sq focus. Thus it may be inferred that for a fairly wide longitudinal region in northern hemisphere, the local-time and latitudinal modulation of the solar signal are similar and consistent.

3.4 27-*day oscillation of the field in southern hemisphere*

The local-time change in power densities of the 27- and 14-day spectral lines for three selected southern hemisphere stations are shown in figure 6. The noteworthy aspect of the plot is the significant reduction in the peak power density at low latitude station, Hartebeesthoek, when compared to the stations in the Indian zone. Similar north-south asymmetry has been shown to exist in irregular geomagnetic activity by Mayaud (1970) and Rangarajan (1979). At Hermanus, close to southern Sq focus, the amplitude variations are again semidiurnal, while at lower latitude it is diurnal. At Kerguelen, located further south, amplitude of the solar rotation signal appears highly anomalous. The peak power of 150 nT^2 at dawn is comparable to the noon values in electrojet region (Trivandrum). With increasing daylight, the power density rapidly diminishes reducing almost to zero indicative of a completely different generating mechanism for the field oscillation at this location in contrast to that at other latitudes. In order to check whether the anomalous features are observable at a geomagnetically conjugate station, the data for Nurmijarvi were also analysed. Power density variations with time for the 27-day line, also shown in figure 6, are radically different both in magnitude and diurnal pattern as compared to Kerguelen. The magnitude at Kerguelen is comparable to other locations at lower latitudes, bringing out clearly the anomalous nature of long-period oscillations at Kerguelen. The significant difference between Kerguelen and other stations utilized in the analysis, is that it is located in the middle of the Indian ocean as an isolated island. The fact that even in the mean daily values of the field the conjugate station Nurmijarvi has a significantly reduced magnitude (~ 5 nT^2 compared to ~ 16 nT^2 at Kerguelen) suggests that the anomaly must arise from the current systems associated with island stations (Price 1969). Greater insight into this aspect can be obtained when the analysis is extended to cover

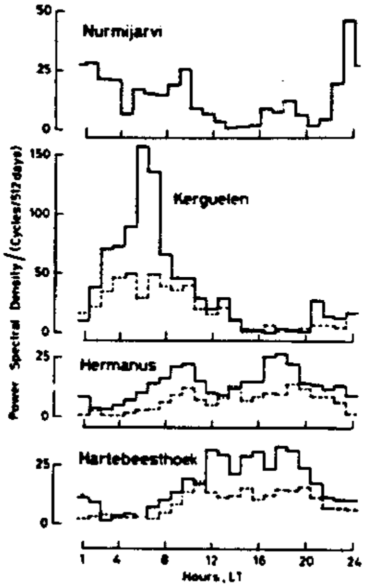

Figure 6. Power spectral densities for 28-day and 14-day signals as functions of local time for three stations in the southern hemisphere are shown in the three lower diagrams. The topmost diagram shows the power density for the 28-day signal as a function of local time for Nurmijarvi, a station in the northern hemisphere geomagnetically conjugate to Kerguelen.

other periodicities and for other island stations. Such work is in progress and will be reported later.

3.5 *27-day oscillation in mean daily H field*

Mean daily field of H at low latitudes, to a considerable extent, represents the intensity of the ring current (Bhargava and Rao 1970). Spectra derived from the mean daily field once again indicate a dominant 27-day oscillation. Power density variation as a function of geographic as well as dipole latitude is shown in figure 7. Since the ring current field will be symmetric with respect to the equator, moduli of latitudes (positive values) only are considered. It is evident that there is a systematic decrease of the strength of the solar rotation signal with latitude. Kerguelen which indicated anomalous local time dependance again deviates from the linear trend. Correlation of the strength of the signal appears slightly better with geographic as compared to dipole latitude.

If the 27-day oscillation of mean daily field arose on account of an equatorial ring current alone, one would expect the power density for the 27-day oscillation to show an approximately $\cos^2\theta$ dependance on the dipole latitude in the low- and mid-latitudes. However, we find that the calculated power densities show an almost linear dependance on the dipole latitude and the geographic latitude. The slightly better correlation of the signal strength with geographic latitude than with dipole latitude once again cannot be explained on the basis of ring current modulation. Bhargava and Rao (1970) have pointed out that during the minimum activity phase of a solar cycle, the solar daily variation appears to dominate over the ring current effects even in the mean daily field and as we have observed earlier for the Indian zone, during this phase

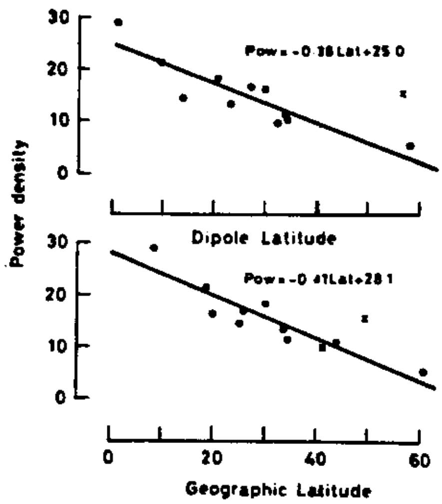

Figure 7. Dependance of power density for the 28-day signal in mean daily values of *H* on dipole latitude (top) and on geographic latitude (bottom). Straight lines are least squares fits with adjustment made for the anomalous behaviour at Kerguelen (marked by X).

of a solar cycle, the solar daily variation undergoes 27-day oscillations possibly through the ionospheric wind system. This wind system is controlled by the geographic equator and this calls for a more organised dependance of the 27-day power density of the mean daily field on the geographic latitude. In the presence of transient causes such as solar flares it would be difficult to detect this 27-day oscillation of the ionospheric wind system. Hence the period that we have chosen for our analysis as being totally free of such transient solar activity, enabled us to pick up this signal.

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Long and short term relationships between solar wind velocity and geomagnetic field at low latitudes

G K RANGARAJAN
Indian Institute of Geomagnetism, Colaba, Bombay 400005, India

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Abstract. Solar wind velocity control of low latitude geomagnetic field both on long and short term basis is studied. It is shown that semiannual averages of the low latitude field is inversely related to solar wind velocity and that there is a dominant local time dependence of the relationship. Strongest correlation are confined to the local afternoon hours. It is also shown that for a duration when the solar wind velocity exhibits significant recurrent pattern the low latitude geomagnetic field also depicts strong solar synodic rotation periodicity of 27 days with significant coherence with velocity. The low latitude field on a short term basis is influenced by variable solar wind velocity with a delay of about 1–2 days. During the period of systematic recurrent pattern in solar wind velocity even the quiet-time night field at equatorial and low latitudes show a strong dependence on velocity indicative of the solar wind control of the quiet-time proton belt encompassing the earth.

Keywords. Solar wind; ring current; quiet-time proton belt.

1. Introduction

With the availability of *in situ* observations of solar wind velocity from Mariner 2 space craft, Snyder *et al* (1963) first showed that significant correlation exists between the variations in the daily average bulk speed of the solar wind and the geomagnetic activity index ΣKp. Olbert (1968) later found a correlation coefficient (cc) of 0·78 using IMP-1 data of the solar wind. While there have been several papers reporting the relationship governing solar wind speed and geomagnetic activity some authors have also shown that the velocity does not play as crucial a role in geomagnetic activity as the variability in the interplanetary magnetic field (IMF) especially its direction (Garrett *et al* 1974; Bobrov 1975).

Satellite measurements of solar wind parameters now cover more than a solar cycle. Long term variations in solar wind velocity have been indicated (Intrilligator 1977) but Gosling and Hansen (1971) showed that there was no solar cycle ($\approx$ 11 yr) variation in solar wind speed in cycle 20, beginning from 1964. Crooker *et al* (1977) used the 6-monthly averages of solar wind speed to indicate the existence of a good correlation with geomagnetic activity index Ap. The cc was 0·86 for Ap with V^2 and 0·81 with V. They also suggested that the southward component of IMF may be a crucial parameter for geomagnetic activity when short-period variations are considered, but the importance of Bz diminishes as the averaging interval increases. During solar maximum the correlation between the bulk speed and the geomagnetic activity is generally poor due to flare-induced geomagnetic disturbances (Burlaga 1975).

To decide whether solar wind speed is a geoeffective parameter even on a shorter time scale, it is essential to identify a period where the solar wind streams are persistent for several solar rotations and are not vitiated by solar transients. One such interval where the daily average solar wind speed showed very systematic oscillations has recently been provided by Gallaher and D'Angelo (1981).

In this paper, we study the long and short-term relationship of solar wind velocity with low latitude geomagnetic field using the 6-monthly data of Crooker *et al* (1977) for the interval 1962 to 1975 and the daily average solar wind speed between June 9 and December 31, 1974 extracted from the plot given by Gallaher and D'Angelo (1981).

The advantage of utilising low latitude fields in such studies arises from the fact that it can be directly related to the equatorial ring current effect whereas index *Ap* will be representative of both auroral substorm effects and equatorial ring current effects.

2. Long term relationship

2.1 *Data analysis*

Mean monthly hourly values of horizontal intensity based on observations on all days and restricted to five international quiet (IQ) days of the month from July 1962 to December 1975 were first corrected for non-cyclic changes and the differences were computed for each hour UT. The difference eliminates seasonal and secular change in the data and provides magnitudes of field change due mainly to magnetospheric sources. Six-monthly averages were computed for each of the low latitude stations listed in table 1. The choice of stations is motivated by the fact that (i) Trivandrum lies in the equatorial electrojet belt in the Indian zone (ii) Alibag and Hyderabad are stations outside the jet influence (iii) Sabhawala is close to the focal latitude of the northern hemispheric Sq current system (iv) Kakioka is a lower mid-latitude station well isolated from the Indian zone so that local time dependence of the solar wind velocity influence can be established and finally (v) Hermanus is again a lower mid-latitude station in the southern hemisphere to bring out N-S asymmetry, if any. It may be noted that Kakioka, Hermanus and Alibag are magnetic stations whose data are utilised along with San Juan and Honolulu for derivation of the equatorial Dst index which is considered dominantly as a measure of equatorial ring current. These 6-monthly averages of differences of hourly values for all days and 5 IQ days in each month are then correlated with the corresponding solar wind velocity data.

Table 1. Geomagnetic and geographic positions of the low latitude stations.

Station		Geographic		Geomagnetic	
Name	Code	Lat.	Long.	Lat.	Long.
Trivandrum	TRD	8°29'N	76°57 E	1·2°S	146·4°E
Hyderabad	HYB	17°25'N	78°33 E	7·6°N	148·9°E
Alibag	ABG	18°38'N	72°52 E	9·5°N	143·6°E
Sabhawala	SAB	30°22'N	77°48 E	20·8°N	149·8°E
Kakioka	KAK	36°14'N	140°11 E	26·0°N	206·0°E
Hermanus	HER	34°25'S	19°14 E	33·3°S	80·5°E

2.2 *Results and discussion*

Difference in mean daily field (ΔH) between all days and quiet days at Hyderabad averaged over 6-months are shown as a function of solar wind velocity in figure 1. The correlation coefficient is -0.656 between ΔH and V and is only marginally higher at -0.661 for ΔH and V^2. In contrast to the positive correlation of the solar wind velocity with Ap which is an index of magnetic activity and therefore increasing with increased disturbance, the negative sign indicates that as the velocity increases the mean daily field decreases. This cc is lower than 0·8 obtained for Ap index by Crooker *et al* (1977). If I.D. days only were considered this correlation may improve. However, the correlation pattern for different hours will not show smooth variation as the ID days are more often due to flare induced disturbances. Obviously solar wind velocity control of the high latitude magnetic field is more direct as evidenced by several investigations linking V with auroral electrojet indices AE. Despite the scatter of points in figure 1 the negative trend is unmistakable, especially if one omits the few points corresponding to low solar wind velocity (≤ 400 km/sec). The cc computed restricting horizontal field difference data to one hour at a time for 6 stations are shown in figure 2. Any local time variation in correlation is expected to be indicative of the asymmetric nature of the ring current which is known to be inflated in the evening sector. In view of the geographic locations of these stations, these variations are indicative of the planetary control of the solar wind velocity on low latitude geomagnetic field. For 22 pairs of points considered in the analysis the cc is significant at 95 % if its modulus exceeds 0·423. In figure 2 the horizontal line represents zero value for different stations, each shifted downward by 0·1 unit of cc. The actual value for the last hour is indicated on the right side. At Alibag

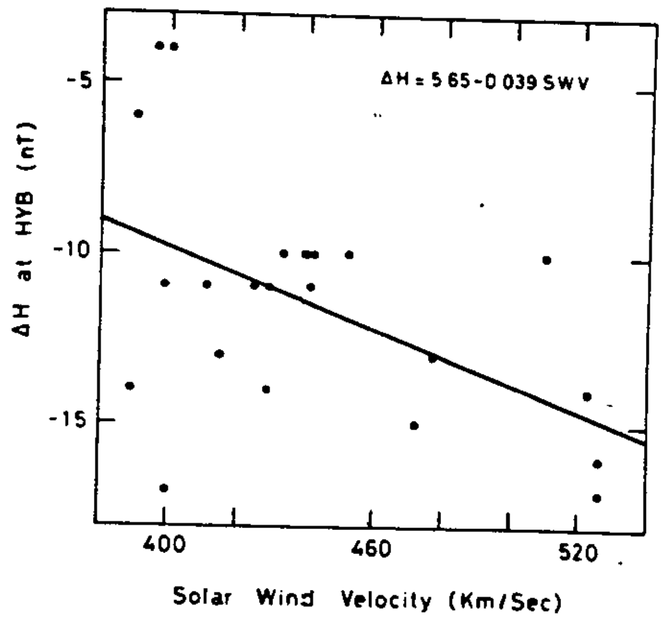

Figure 1. Scatter plot of the difference field H (all days) $- H$ (quiet days) at Hyderabad as a function of solar wind velocity. Six-monthly averages are utilised. The straight line is the least squares best fit to the data.

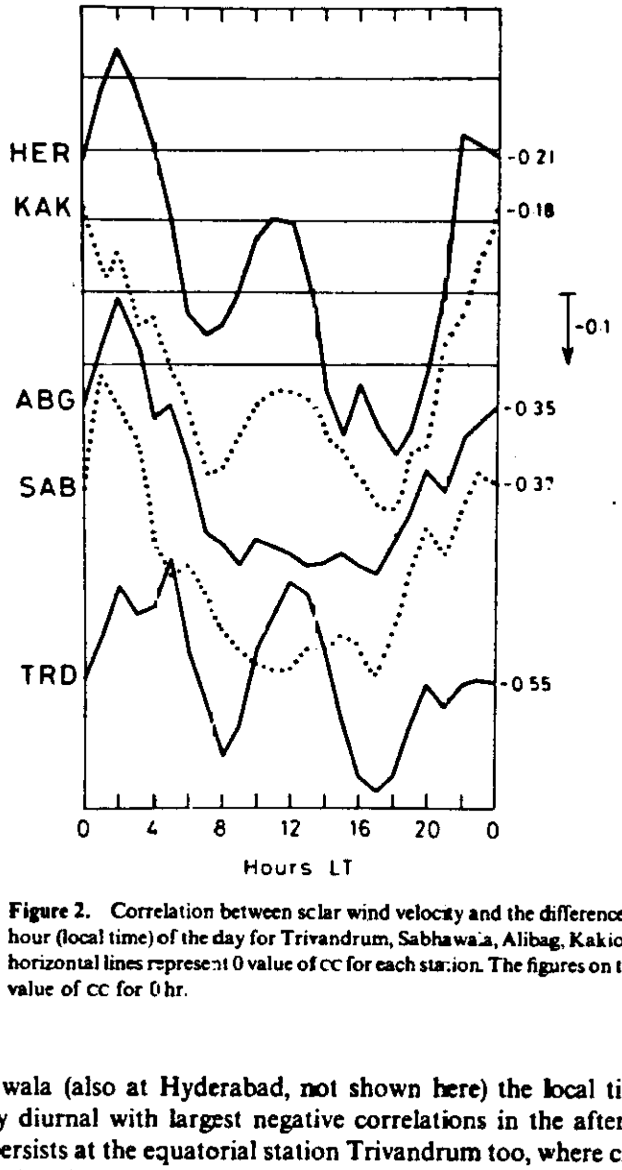

Figure 2. Correlation between solar wind velocity and the difference field restricted to each hour (local time) of the day for Trivandrum, Sabhawala, Alibag, Kakioka and Hermanus. The horizontal lines represent 0 value of cc for each station. The figures on the right gives the actual value of cc for 0 hr.

and Sabhawala (also at Hyderabad, not shown here) the local time dependence is dominantly diurnal with largest negative correlations in the afternoon hours. This tendency persists at the equatorial station Trivandrum too, where close to local noon, the correlation becomes insignificant suggesting that the electrojet field is not completely eliminated by the differencing procedure and its presence and known day-to-day variability may cause reduced correlation with solar wind bulk speed. The asymmetric nature of the variations in correlations and hence by inference of that of the equatorial ring current field is borne out clearly by the cc plots for Hermanus and Kakioka well separated in longitude. An interesting point to note, however, is the reduction in magnitude of the correlation close to local noon similar to Trivandrum, but not exactly of comparable magnitude.

From these figures it may be inferred that the long-term average of solar wind bulk speed has perceptible influence on the low latitude geomagnetic field causing a reduction in the horizontal intensity due to increase in speed. This enhanced geomagnetic activity is a manifestation of the equatorial ring current modulation with greater intensity in the evening sector at all low latitude stations. Close to the dip equator the pattern seems to be complex, due to the enhanced day-time conductivity.

3. Short term relationship

Mean daily value of solar wind velocity for the period June 9, 1974 to December 31, 1974 were scaled from the plot given by Gallaher and D'Angelo (1981). We utilise the mean hourly values of Hyderabad as representative of low latitude horizontal intensity variation during this period in the declining phase of solar cycle.

3.1 *Results and discussion*

Power spectra of mean daily horizontal intensity restricted to three hourly averages at a time, clearly indicated the presence of dominant periodicity near 27 days and its harmonics (14 and 9 days). In figure 3 we show the power density of the 27-day spectral peak as a function of 75°E time for Hyderabad. The forenoon/evening asymmetry in the strength of the signal first reported by Bhargava (1973) is clearly seen. The signal is weakest for the 3-hour interval centred on 3 LT and is largest at 15 LT. Cross spectra were computed between the solar wind velocity and horizontal intensity data for different hours. All the spectra indicated high coherence at frequencies corresponding to the 27-day periodicity and its harmonics. A typical spectrum for the 3-hour interval centred on 15 hr LT and the solar wind velocity spectrum for the period range 50 days to 8 days is shown in figure 4. While the spectral peak near 27 days is almost coincident in

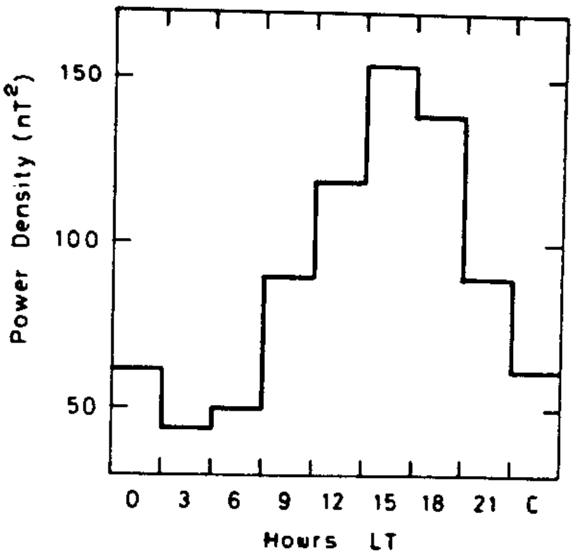

Figure 3. Local time dependence of power density of the 27-day spectral peak derived from 3-hourly H field at Hyderabad for the period June to December 1974.

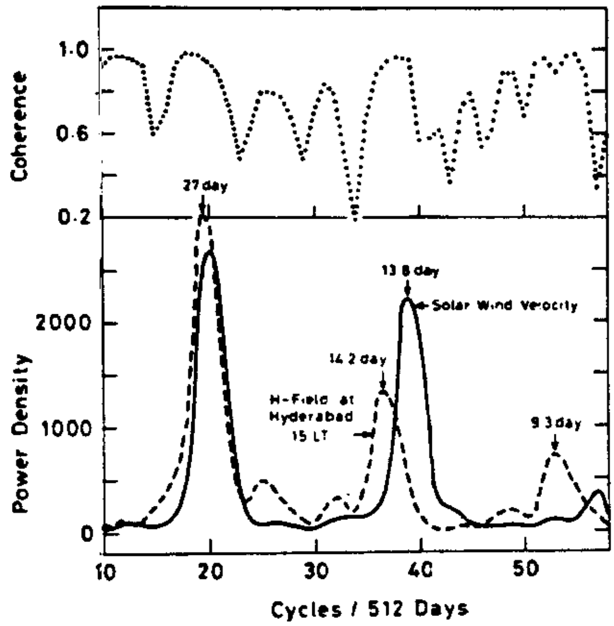

Figure 4. Spectrum of horizontal intensity at Hyderabad for the 3 hr interval centred on 15 LT in the period range 50 days to 9 days. Coherence between solar wind velocity and H field in this frequency band is also shown.

frequency, that for the two harmonics for the geomagnetic field appears shifted relative to that for solar wind velocity.

To clearly establish the solar wind velocity dependence of the low latitude geomagnetic field and to estimate the time lag between the causative mechanism and the effect, we computed lagged CC between the mean daily solar wind velocity and the 3-hourly average field at Hyderabad centred on 15 hr LT and 3 hr LT (corresponding to maximum and minimum power density for the 27-day signal). The correlations were calculated for different lags between -10 and $+10$ days. The change in CC with lags is shown in figure 5. For 205 pairs of points, CC in excess of 0·18 is significant at 99% confidence level. It is clearly seen from the figure that irrespective of the strength of the recurrence activity of the low latitude field the plots of correlation vary quite similarly with largest negative values a day or two later. It can, therefore, be inferred that the solar wind velocity is an important parameter in causing geomagnetic field depressions even on a short term basis. This result is consistent with a similar feature observed for auroral substorms by Murayama and Hakamada (1975), Maezawa (1978) and others. In contrast to the conclusions of Bobrov (1975) that the influence of V on geomagnetic activity is small, we find that during periods when the solar wind speed varies systematically it is an efficient geoeffective parameter.

4. Quiet-time field and solar wind velocity

The existence of a low energy proton belt under magnetically quiet conditions has been established for satellite observations by Davis and Williamson (1963) and Frank (1967).

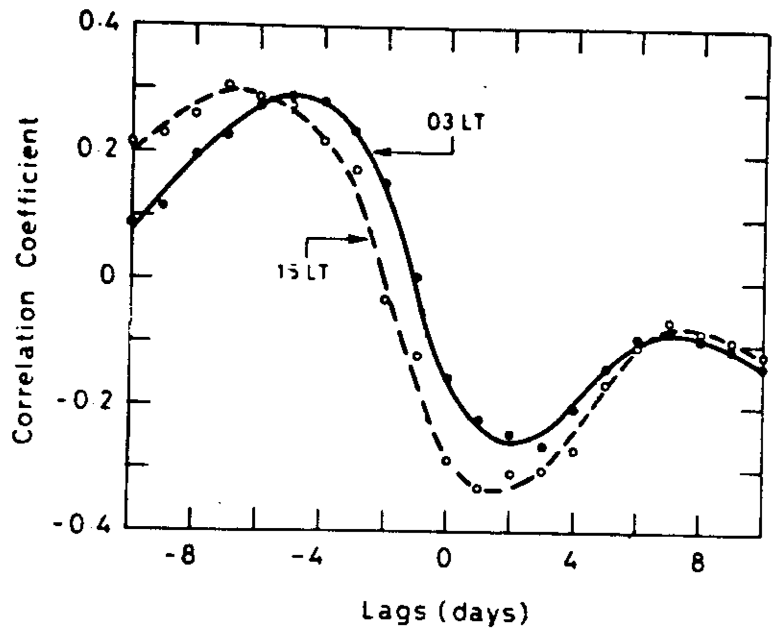

Figure 5. Lagged correlation between the horizontal intensity at Hyderabad and solar wind velocity for two intervals centred on 3 hr LT and 15 hr LT (corresponding to minimum and maximum power density for the 27-day line).

The magnitude of the field depression due to the quiet-time ring current has also been estimated by several authors (Hoffman and Bracken 1965; Schield 1969; Burton *et al* 1975). Yacob and Bhargava (1971) established the presence of the equatorial ring current even under extremely calm magnetic conditions from the mean daily horizontal intensity at Alibag.

The interval June 9 to December 31, 1974 considered for analysis is marked by long durations of geomagnetic calm intervals with index *Ap* of magnetic activity for 4 consecutive days or more, being less than 10 on several occasions. Though the solar wind velocity for the later half of 1974 varied between maximum value near 750 km/sec and minimum near 300 km/sec the maximum bulk speed corresponding to the calm intervals was less than about 500 km/sec. It would therefore be of interest to find whether the equatorial geomagnetic field during quiet times has any measure of dependence on solar wind velocity. In this connection, the recent finding (Rangarajan 1981) that the electrojet strength appeared to be inversely related to proton density in the solar wind even during the flow of stable solar wind past the earth is also relevant.

In figure 6, we show the scatter plot of the mean midnight field of horizontal intensity (derived from hourly values centred on 18, 19 and 20 UT) at the four stations Trivandrum, Hyderabad, Alibag and Sabhawala, after correction for a small secular change during the 6 month period as a function of solar wind velocity. It is indeed remarkable that even as the solar wind speed changes from the average quiet time value of near 300 km/sec to the value only upto about 525 km/sec the equatorial geomagnetic field shows a discernible decrease of nearly 20 nT. The correlation between the two parameters is also highly significant with a value of −0·6. The mechanism through

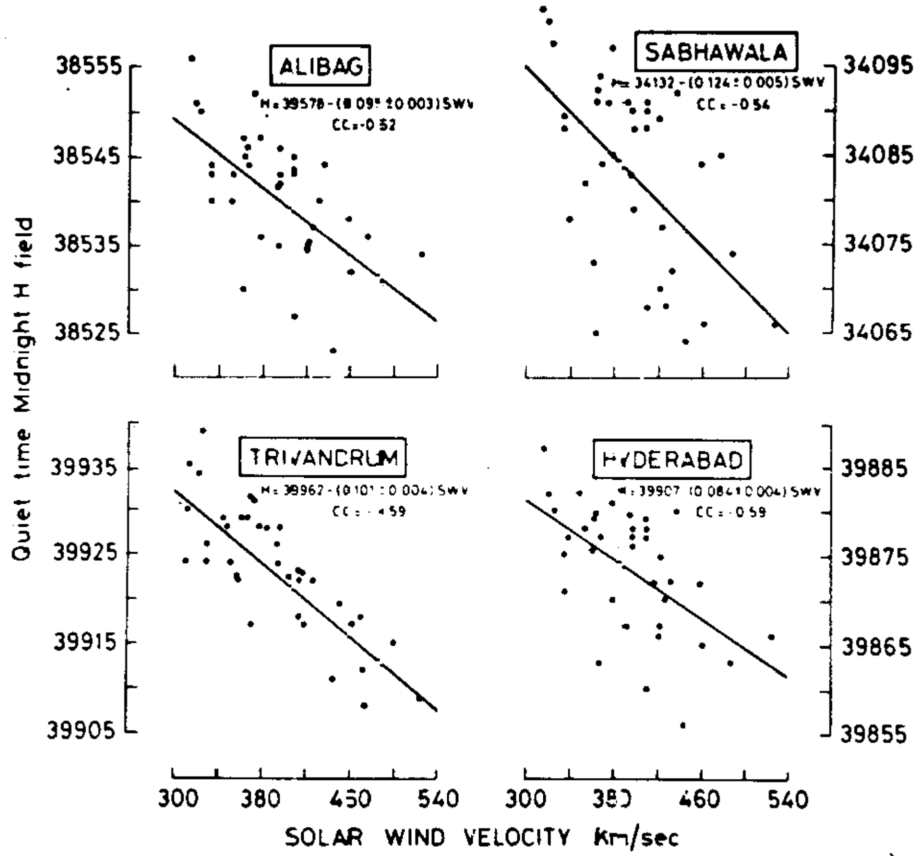

Figure 6. Scatter plot of the quiet-day night time field at Trivandrum, Hyderabad, Alibag and Sabhawala as a function of solar wind velocity. The straight line is the least squares best fit to the data in each case.

which the field decrease is manifested is evidently the quiet time proton belt whose strength enhances with increasing solar wind speed.

Acknowledgement

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