Characteristics of storm-time geomagnetic daily variation

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(Received 20 March 1971)

Abstract—Quiet and disturbed day daily variations \( (S_q, S_d) \) and their difference \( S_D = S_d - S_q \) are studied for the \( H \) component for 1964 for Sverdlovsk, Alibag, Annamalainagar and Trivandrum (all in 60–80°E longitude) after correcting for \( D_{st} \) effects which are estimated in two ways; (i) \( D_{st} \) obtained as average of Tashkent and Sahrawal near the \( S_q \) focus; and (ii) \( D_{st} \) obtained from Sugiura and Cain (1970). The results show that (a) \( S_q \) is a predominantly day time phenomenon of mostly ionospheric origin, (b) \( S_d \) is diurnal for mild disturbances and semi-diurnal for large disturbances and consists of a morning increase, a sharp noon decrease giving a reverse current, a recovery to positive current by 20–22 hr LT, followed by a decay to zero level. Implications regarding ionospheric and non-ionospheric contributions are discussed.

1. Introduction

It is recognised since long that, apart from the quiet day daily variation \( (S_q) \) of geomagnetic field, there is an ‘additional disturbance daily variation \( S_D \)’ during stormy periods and the type of \( S_D \) differs from that of \( S_q \). Thus, for middle and low latitudes, \( S_q \) variation is greatest during the day hours having a sharp peak shortly before noon. In contrast, \( S_D \) variation is mainly diurnal with an early morning peak. These and several other details have been given in their comprehensive analysis of storm morphology by Chapman (1918, 1927, 1935, 1952) and Sugiura and Chapman (1960).

In earlier days, both \( S_q \) and \( S_D \) were attributed to ionospheric current systems of appropriate form and strength (Vestine et al., 1947). For the equatorial region, the presence of an ‘electrojet’ in the \( E \)-region is now well established. For other latitudes, experimental evidence is somewhat sketchy (Matsushita, 1968). There is also a possibility of contributions from sources of non-ionospheric origin e.g. magnetospheric currents (Olson, 1970) and experimental evidence from OGO-2 observations (Langel and Cain, 1968) supports it. Recently, Sarabhai and Nair (1969) have suggested that ‘the daily variation of \( H \) (horizontal component of geomagnetic field) at a low latitude station (e.g. Alibag, India) outside the effect of the electrojet is due to a decrease of the ambient field on the night side rather than an increase during the daytime.’ The suggestion is based on an experimental observation that the daily range \( \Delta H (= H_{\text{max}} - H_{\text{min}}) \) shows a negative correlation with \( H_{\text{min}} \) and a negligible correlation with \( H_{\text{max}} \). Bhargava and Jacob (1971) have shown that increasing values of geomagnetic disturbance index \( Ap \) are associated with increasing values of daily variation range and decreasing values of daily means of geomagnetic field and have interpreted these relationships as supporting the suggestion of Sarabhai and Nair mentioned above. Bold as this suggestion is, to us it seems to be based on dubious premises, for the following reasons.

Firstly, Sarabhai and Nair have not made any distinction between quiet and disturbed days with the result that their hypothesis would apply to \( S_d \) (actual daily variation on disturbed days) rather than to \( S_q \); because it is only during disturbed periods that \( H_{\text{min}} \) would change appreciably. Thus, in a plot of \( \Delta H \)
versus $H_{\text{min}}$, a large range in $H_{\text{min}}$ values would be obtained only due to disturbed days. It is interesting to note that a similar analysis carried out for quiet periods (low $Ap$ values) leads to quite different results, (Kane, 1970). Thus, if days of low $Ap$ values (0–8 only) are chosen, the range $\Delta H$ shows positive correlation with $H_{\text{max}}$ and negligible correlation with $H_{\text{min}}$, leading to the conclusion that the daily variation $Sq$ is essentially a daytime phenomenon. MATSUSHITA (1971) has done a similar analysis and has come to a similar conclusion. Thus, it is quite clear that the suggestion of Sarabhai and Nair is not valid for quiet periods and hence for $Sq$.

Let us examine now whether their suggestion (that the daily variation is a nighttime decrease) is valid for disturbed periods, i.e. for $St$. Here the experimentally established fact is that the daily range $\Delta H (= H_{\text{max}} - H_{\text{min}})$ does show a significant negative correlation with $H_{\text{min}}$ and daily mean $H_{\text{mean}}$ and a negligible correlation with $H_{\text{max}}$. But its interpretation as indicative of a nighttime decrease of $H$ as a source of $\Delta H$ is unreliable for two reasons. Firstly, during disturbed periods (geomagnetic storms), the $H$ level is changing violently from hour to hour and the daily range $\Delta H$, if defined as $(H_{\text{max}} - H_{\text{min}})$, is bound to give larger values. This is a common error which arises due to ignoring long-term (non-cyclic) changes of the mean level. Standard methods of correcting for this effect are either (i) to define range $\Delta H$ as the difference between $H_{\text{max}}$ (or average of some values near it) and an average of early dawn and late night hours of the same day or (ii) to obtain running averages over 24 consecutive hourly values, deduct these from the original hourly values with due care of centering hour, and to evaluate range $\Delta H = (H_{\text{max}} - H_{\text{min}})$ from the hourly values so corrected. In the absence of such a correction, a negative relationship between $\Delta H$ and $H_{\text{min}}$ (when $H$ level has a steady, long-term decrease) will be geometrically obvious but physically meaningless. Sarabhai and Nair or Bhargava and Yacob have not applied such a correction before evaluating the daily range $\Delta H$.

However, a more serious flaw of such an analysis is the following. It is assumed here that $\Delta H$ vs. $H_{\text{min}}$ (or $H_{\text{max}}$) is a two variable relationship. This may not be so. During stormy periods, level of $H$ (and hence of both $H_{\text{max}}$ and $H_{\text{min}}$) changes violently for reasons which may have nothing to do with daily variation. Thus, storm time $H$ changes ($D_s$ effects) are caused by ring currents situated at several earth radii (Cain et al., 1962). These may pollute the $\Delta H$ vs. $H_{\text{min}}$ relationship which one would normally like to associate with daily variation in the method adopted by Sarabhai and Nair. This is the usual pitfall of the adoption of the two variable correlation method when a third variable is likely to be present and is ignored (Kane, 1971).

For the various reasons given above viz. not confining to quiet periods, not correcting for non-cyclic, long term changes before evaluating daily range $\Delta H$ and, not correcting for $D_s$ effects, we feel that the negative correlation between $\Delta H$ and $H_{\text{min}}$ (and $H_{\text{mean}}$) obtained by Sarabhai and Nair and Bhargava and Yacob cannot be interpreted straightaway as indicative of nighttime decrease as a source of daily variation.

The purpose of the present paper is, first to point out this difficulty and second, to attempt correction for the $D_s$ effects and to see whether one can get some insight into the nature of $Sq$ and $SD$ so obtained.
2. Experimental Data and Analysis

The period chosen was the quiet Sun year 1964 when there were plenty of quiet days as well as some disturbed days. Data chosen were for the equatorial stations Trivandrum (Geomag. latitude $-1.1^\circ$) and Annamalainagar ($+1.8^\circ$) and the mid-latitude stations Alibag ($+9.5^\circ$), Sabhawala ($+20.5^\circ$), Tashkent ($+32.6^\circ$) and Sverdlovsk ($+48.5^\circ$), all in the longitudes of about $60^\circ$-$80^\circ$E. Figure 1 shows the daily variation curves of $H$ at all these places on a typical quiet day (15 June 1964; $Ap = 6$). It seems that the northern focus where the phase of $H$ changes, lies somewhere between Tashkent and Sabhawala in this longitude belt. Defining the range $\Delta H$ simply as $\Delta H = (H_{\text{max}} - H_{\text{min}})$ without applying any corrections for $D_s$ effects, a plot of average values of $H_{\text{max}}$ and $H_{\text{min}}$ vs. $\Delta H$ groups for all days (quiet as well as disturbed) is as shown in Fig. 2(a) for the station Alibag. It shows a negative correlation between $\Delta H$ and $H_{\text{min}}$ but negligible correlation between $\Delta H$ and $H_{\text{max}}$ and is the basis for the suggestion of Sarabhai and Nair (1969). However, if analysis is confined to quiet days only ($Ap 0-8$), one obtains a plot as shown in Fig. 2(b) which shows quite opposite results (Kane, 1970), indicating that at least $Sq$ is a predominantly day time phenomenon. For the same period, dividing the same data into several $Ap$ groups, evaluating the average daily variation (24-hourly values) for each and calculating range $\Delta H$ as $(H_{\text{max}} - H_{\text{min}})$ and daily mean $H_{\text{mean}}$ as average of 24-hourly values without applying corrections for $D_s$ effects, one gets
plots of $\Delta H$ and $H_{\text{mean}}$ vs. $Ap$ as shown in Fig. 3 for Alibag showing increasing $\Delta H$ and decreasing $H_{\text{mean}}$ associated with increasing $Ap$ as claimed by BHARGAVA and YACOB (1971) and interpreted as supporting the suggestion of Sarabhai and Nair.

If corrections for $D_{st}$ effects are applied, it is obvious that Fig. 2(b) will not change appreciably because $D_{st}$ effects are negligible during quiet periods. But Fig. 2(a) and Fig. 3 may change appreciably as disturbed days are included here. To correct for $D_{st}$ effects, the $D_{st}$ must be evaluated for every hour of every day of 1964. This can be done in two ways:

(i) Since the phase of the daily variation of $H$ changes at the focus, the hourly values of $H$ at a station under the focus will have negligible daily variation and hence all changes in $H$ there could be attributed mainly to $D_{st}$. In the present case, an average of the hourly values of Tashkent and Sabhawala would serve as a good measure of $D_{st}$ in their latitude. To obtain the $D_{st}$ for equatorial region, these values should be multiplied by a factor sec $\theta_{TS}$ (1.12) where $\theta_{TS}$, the average geomagnetic latitude of Tashkent and Sabhawala, is 26°.6. This procedure is the same as applied by SUGIURA (1964). For any other geomagnetic latitude $\theta$, the equatorial $D_{st}$ values so obtained (by multiplying average of Tashkent and Sabhawala by sec $\theta_{TS}$) should be further multiplied by $\cos \theta$. 

Fig. 2. Plots of $H_{\text{max}}$ and $H_{\text{min}}$ vs. daily range $\Delta H$ for Alibag
(a) For all 365 days in 1964
(b) For 213 quiet days in 1964 ($Ap = 0-8$).
(ii) Using data from mid-latitude stations at different longitudes, hourly values of $D_{st}$ were first obtained by Vestine et al. (1947). For the year 1964, similar values of equatorial $D_{st}$ are given by Sugiura and Cain (1970). These could be used for equatorial region directly and for other latitudes $\theta$, after multiplying by $\cos \theta$.

Using the average of Tashkent and Sabhawala and multiplying by $\sec \theta_{TS} \cos \theta$, the $D_{st}$ effects at Trivandrum, Annamalainagar, Alibag and Sverdlovsk were obtained for every hour of every day of 1964. These will be referred to henceforth as $D_{st}'$. Similarly, using values given by Sugiura and Cain, the $D_{st}$ effects obtained will be referred to as $D_{st}''$. All data were divided into groups of days having similar $Ap$ values and the average daily variations of $H$ values as well as $D_{st}'$ and $D_{st}''$ values were obtained for each $Ap$ group. Whereas averages for every individual value of $Ap$ from 0 to 53 were evaluated, values for five major groups of $Ap$ viz. $Ap = 0-7, 8-15, 16-26, 27-45$ and 46-53 are presented for convenience in Fig. 4. Here, the vertical scale gives $H$ value in gammas and is the same for all $Ap$ groups. Thus, levels are directly comparable. Figure 4(a) shows Alibag $H$ variation by simple grouping, i.e. without applying any correction for $D_{st}$ effects. It shows that for increasing $Ap$, the whole pattern of the 24-hourly values drops down, the minima $H_{min}$ dropping much more than the maxima $H_{max}$. The daily mean $H_{mean}$ shown as big dots at 12 noon of each curve also shows a declining tendency. The difference $\Delta H = (H_{max} - H_{min})$ increases enormously for very high $Ap$. All these can be suitably replotted to give plots like those in Fig. 2(a) and Fig. 3. However, the faultiness of the same can be easily appreciated when one finds that even Tashkent
and Sahawala (or their average) show plots similar to Figs. 4(a), 2(a) and 3 even though one does not expect any daily variation effects of $H$ under or near the focus!

Figure 4(b) shows plots for $D_{st}'$ (full lines) and $D_{st}''$ (dotted lines) at Alibag. For high $Ap$, one can see that the large fall in Alibag is mostly a $D_{st}$ effect. Figure 4(c) is the daily variation corrected for the two $D_{st}$ effects and is obtained by subtracting 4(b) from 4(a). In Fig. 4(c), the first curve for $Ap = 0-7$ may be considered as $S_{q}$ corrected for all $D_{st}$ effects. It is not different from the first curve of Fig. 4(a) as expected; because for low $Ap$, $D_{st}$ effect is negligible. The second, third, fourth and fifth curves of Fig. 4(c) represent the disturbed day daily variations $S_{d}$ in increasing order of disturbance.

Curves like those in Fig. 4(c) for Alibag can be obtained for other stations also. These are shown in Fig. 5 for Sverdlovsk, Alibag, Anamalainagar and Trivandrum. As before, full curves and dotted curves represent use of the two types of $D_{st}$ (dotted for $D_{st}''$ of Sugiura and Cain). All curves of any station have a directly comparable ordinate scale. The curves in the first column represent $S_{q}$ (for $Ap = 0-7$) and the rest represent the disturbed day daily variations $S_{d}$. If $S_{q}$ is deducted from $S_{d}$, we get the additional disturbance daily variation $S_{D} = (S_{d} - S_{q})$. These are shown in Fig. 6 for the same four stations and the same convention for full and dotted curves as in Fig. 5. Thus, Figs. 5 and 6 depict the $S_{q}$, $S_{d}$ and $S_{D}$ variations at these stations on directly comparable ordinate scales.

3. RESULTS AND DISCUSSION

The characteristics of $S_{q}$, $S_{d}$ and $S_{D}$ as seen from Figs. 5 and 6 may be summarised as follows:
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Fig. 5. Daily variation plots of $H$ corresponding to various $Ap$ groups for Sverdlovsk, Alibag, Annamalainagar and Trivandrum after correcting for $D_{st}'$ (full lines) and $D_{st}''$ (dotted lines). The first column plots represent $S_q$; and the rest, $S_d$, for any station.

(1) Figure 5 shows the actual daily variations $S_q$ and $S_d$. For $Ap$ values up to about 26, the position of $H_{\text{max}}$ remains unaltered, irrespective of whether $D_{st}'$ is used or $D_{st}''$. For higher $Ap$ values, there is a distinct increase in $H_{\text{max}}$. In the case of $H_{\text{min}}$, the characteristics seem to depend a great deal upon the type of $D_{st}$ used. For $D_{st}'$ (full curves), $H_{\text{min}}$ remains almost steady, with only a slight decrease of about 5 gamma below zero level for higher $Ap$. The daily range $\Delta H = H_{\text{max}} - H_{\text{min}}$ does increase for higher $Ap$ but the increase (about 50 per cent) is mainly due to increasing $H_{\text{max}}$ rather than decreasing $H_{\text{min}}$. However, for $D_{st}''$ (dotted curves) $H_{\text{min}}$ does decrease by almost 30 gamma at mid-latitudes (Alibag) as well as at the Equator (Trivandrum). Thus, if $D_{st}''$ is used, the increased $\Delta H$ range with $Ap$ will have to be attributed to increasing $H_{\text{max}}$ as well as decreasing $H_{\text{min}}$ at all latitudes. Thus, the findings from $D_{st}'$ indicate that both $S_q$ (as seen from Fig. 2(b)) and $S_d$ (as seen from Fig. 5) are caused by increased $H_{\text{max}}$ rather than decreased $H_{\text{min}}$ thus obliterating completely the basis on which SARABHAI and NAIR (1969) based their nighttime decrease hypothesis. On the other hand, if $D_{st}''$ is used, their hypothesis is supported half-way ($\Delta H$ increase contributed by both $H_{\text{max}}$ increase and $H_{\text{min}}$ decrease instead of $H_{\text{min}}$ decrease alone), but for $S_d$ only and not for $S_q$.

(2) Figure 6 gives the characteristics of $S_D$, the additional disturbance daily variation. Here again, the full and dotted curves show different features. Thus,
concentrating on $D_{st}'$ correction (full curves), the $SD$ seems to be of semi-diurnal nature with very prominent increases (parallel additional currents) in the morning up to 10 hr, a sudden fall giving decreases (reverse currents) near about noon, followed by recovery to zero level further followed by some increases during afternoon and later, a fall to zero level by midnight. If $D_{st}''$ correction is considered (dotted curves), the morning increase is still there followed by a sharp drop and current reversal near noon; but the reversal then persists till about 21–22 hr. Thus, the early morning increase and noon decrease is a common feature while the afternoon recovery in case of $D_{st}'$ and night recovery in case of $D_{st}''$ is a distinguishing feature. The dotted curves are, therefore, predominantly diurnal in nature, except for very high $Ap$ when two maxima, one at 10 hr and another at 22 hr appear. This is only in partial agreement with Sugiura and Chapman (1960) who report a predominantly diurnal nature of $SD$ on the first, second and third storm days of all types of storms. It is likely that the semi-diurnal nature of $SD$ for high $Ap$ in our case may be a characteristic of a quiet Sun year like 1964. This is being investigated further. The magnitudes of the effects for $Ap = 46–53$, in our case are given in Table 1 in units of gamma.

Thus, the morning increase is roughly the same at the Equator and mid-latitudes; but the noon decrease is larger at the Equator, while the afternoon or night increase is smaller at the Equator.

In terms of current systems, the above results would imply that during disturbed
periods, additional currents, parallel to the conventional $Sq$ current system, are operative during morning hours. By about noon, these currents disappear and are even reversed, the magnitude of the reversed currents being comparable to the morning currents, equatorial regions showing larger magnitudes. The afternoon recovery is a doubtful point but a recovery at 21–22 hr to zero level and even small parallel currents at that time seem to be real.

It is difficult to pin-point the sources of these current systems. In a later paper, Nair et al. (1970) have shown that the difference in the daily ranges at Trivandrum and Alibag correlates well with the E-region drifts at Trivandrum. However, we found that the range at Trivandrum alone also correlates well with E-region drifts at Trivandrum. Thus, at least some part of the additional $\Delta H$ range at Trivandrum during disturbed periods (SD) in the morning hours, must be of ionospheric origin. Since Alibag also shows morning increases, the ionosphere at Alibag also must be affected in a similar way and by a similar amount, in contrast to the 1:3 ratio expected for Alibag and Trivandrum (Nair et al., 1970). The noon-time current reversal, more prominent at the Equator, is a baffling feature. There is no evidence for any reversal of direction in the $E$- or $F$-region drifts at noon hours during storms, nor of any drastic reduction in electron densities in the $E$-region. Thus, a non-ionospheric source is indicated. It could be magnetospheric. During quiet periods, Olson (1970) estimates small magnetospheric contributions of about 10 gamma only. However, during storms, the position of the magnetopause can change violently as seen from the ATS-1 data (Coleman and Cummings, 1968). Thus, larger distortions and hence larger abnormal daily variation effects can be expected during storms. It would be very interesting to study simultaneous data from ATS satellites (at 6.6 Earth radii) and from ground based observatories to see what type of daily variation effects are obtained at the two locations after correcting for $Dst$ effects during magnetic storms.

(3) For Sverlovsk beyond the $Sq$ focus, where daily variation effects are supposed to be reverse of those at Alibag, the range $\Delta H$ does increase because of enhancement of the day time depression at noon with increasing $Ap$. However, peculiar extra effects are observed in the afternoon and night hours which are similar to those at Alibag and lower latitudes. It looks as if the source of the variations is quite far away from the Earth for these hours and there is no reversal at the conventional $Sq$ focus. Sugirua and Chapman (1960) have mentioned that the focal latitude for $SD$ is much higher than that for $Sq$. Our analysis locates it beyond Sverlovsk, if at all.

In particular, strong, similar currents at 21–22 hr (LT) at all latitudes considered here seem to be a striking feature, with indications that the source may be non-ionospheric.
(4) A comment on the difference between the two types of $D_t$ (viz. $D_t'$ and $D_t''$) may be appropriate. Whereas $D_t'$ is obtained from the mean of Tashkent and Sabhawala, $D_t''$ of Sugiura and Cain is obtained as an average of three stations (viz. Hermanus, Honolulu and San Juan) in mid-latitudes but differing longitudes. Thus, if there are any symmetric $Sd$ variations present at the latitude of Tashkent and Sabhawala, these will be visible in $D_t'$ but not in $D_t''$. In Fig. 4(b) where these two are compared for Alibag latitude, there is a small diurnal wave (range about 10 gamma) in $D_t'$ even for low $Ap$ values. In contrast, $D_t''$ is almost devoid of diurnal effects. Olson (1970) mentions that even during quiet periods, the center of the ring currents causing $D_t'$ is displaced towards the Sun, causing a daily range of about 2 gamma. Since the range in $D_t'$ is larger (about 10 gamma), we conclude that this indicates an $Sq$ effect remaining in the average of Tashkent and Sabhawala. For larger $Ap$ values, the difference between $D_t'$ and $D_t''$ is quite large, almost 30 gamma at about 18 hr LT. Considering the possibility of a residual $Sq$ effect in $D_t'$ and hence residual $Sd$ effect also, one would be inclined to rely more on the conclusions drawn from the use of $D_t''$ rather than of $D_t'$. On the other hand, because of the non-coincidence of the geographic and geomagnetic dipole axes, the $Sd$ effects at the same LT may not be similar at all longitudes. In this eventuality, $D_t'$ may be a better approximation than $D_t''$.

4. Conclusions

The findings of the present analysis may be summarised as follows:

(i) $Sq$ is a predominantly day-time phenomenon of mostly ionospheric origin at all latitudes, including the Equator.

(ii) Disturbance daily variation $Sd$ has a range larger than $Sq$. The increase is contributed by both increase in $H_{\text{max}}$ as well as decrease in $H_{\text{min}}$.

(iii) The additional disturbance daily variation $SD = Sd - Sq$ is diurnal for medium disturbances and semi-diurnal for large disturbances and is composed of:

(a) A rising current, parallel to normal $Sq$, from midnight to about 10 hr LT.

(b) A sudden drop to zero level and further, a reversal of direction between 10–13 hr LT.

(c) A recovery to zero level in the afternoon (doubtful ?) but definitely by about 20 hr LT.

(d) A small parallel current at about 21–22 hr dropping to zero by midnight.

(iv) The features of $SD$ from 10 hr to midnight are remarkably similar at a wide range of latitudes indicating possible non-ionospheric origin for the same. In contrast, the morning increase seems like an enhancement of normal $Sq$ at all latitudes.

Acknowledgement—Thanks are due to the Department of Atomic Energy, Govt. of India for financial support.

REFERENCES

1952 Annali Geofis. 5, 481.
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<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Journal</th>
<th>Pages</th>
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<tr>
<td>COLEMAN P. J. JR.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matsushita S.</td>
<td>1971</td>
<td><em>Radio Sci.</em> 6, 279.</td>
<td></td>
</tr>
<tr>
<td>Olson W. P.</td>
<td>1970</td>
<td></td>
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