Abnormal Features of the Regular Daily Variation $S_R$

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Abnormal features of the regular daily variation $S_R$ could be of great interest for a full understanding of the physical sources of this phenomenon, especially of the tides and electric conductivity conditions in the $E$ layer. The subauroral part of the $S_R$ (a positive deviation from the night level, increasing polewards and occurring during a few hours at any longitude when the sun is crossing the meridian of the magnetic pole) and the polar cap $S_R$ (Mayaud, 1965b) on the one hand, the concept of the invasion of Price and Wilkins (1963) on the other hand are reviewed and updated. With respect to the former, one shows that they cannot be caused by the action of the azimuthal component $B_Y$ of the interplanetary field, and one suggests that their source could be strong localized dynamo effects inside the polar caps, bringing about a special and single current vortex in these regions. Some equatorial counter-electrojet effects contradict the concept of the invasion and suggest the existence of vortices with reversed direction of rotation of the currents, as it would be the case for other counter-electrojet effects (Mayaud, 1977).

1. Introduction

In a recent paper (Mayaud, 1977), we pointed out how, on some occasions, the regular daily variation $S_R$ can undergo reversals in component $H$ (positive deviation from the night time level during the day at subauroral latitudes, while the observed deviation is normally negative) or in component $Z$ (positive deviation during the day at a near-focus station of the northern hemisphere, while the deviation should be negative). Such abnormal features were related to equatorial counter-electrojet effects, a phenomenon which can also be considered as an abnormal feature of the $S_R$ variation; indeed, negative deviations in component $H$ at equatorial latitudes are reversals of the same variation $S_R$.

In general, statistical planetary analyses of the $S_R$ variation (take, for instance, the $S_q$ studies) fail to grasp the above features because they are lost in the averages. However, they could be of great interest for a full understanding of the physical sources of the $S_R$ variation, especially of the tides and electric conductivity conditions in the $E$ layer. We will try here to review and update two other abnormal features previously described in Mayaud (1965b, c). Table 1 indicates the coordinates of the observatories used.

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2. The Subauroral and Polar Parts of the \( S_R \)

When looking at planetary current vortices resulting from \( S_q \) analyses, it is obvious that, at latitudes higher than that of the focus, the \( S_R \) deviation from the night-level in \( H \) component is wholly negative, and the intensity of this negative deviation becomes larger and larger polewards. Figure 1 gives an example of the \( S_R \) variation for a particular summer day at various northern stations. At Aquila, a focus station, the \( S_R \) in \( H \) is slightly negative around 0900 LT, and slightly positive around 1300 LT; the night level is prematurely reached at 1700 LT, and the field seems to be fairly constant after that time. At Hartland (about 10° north), the \( S_R \) is clearly negative from 0600 LT until about 1600 LT, but an abnormal positive deviation begins after that time and lasts most of the night. At Lerwick (about 10° further north), negative and positive deviations are larger during about the same time intervals. The increase of the negative deviation is normal, but that of the positive is once again abnormal. At Kiruna (again about 10° further north), the lower sensitivity of the records and a negative perturbation beginning at about 2100 LT render the comparison more difficult, but the above remarks are still valid. Thus there clearly exists on this particular day, at subauroral latitudes, an abnormal positive deviation of the \( S_R \) in \( H \) component during the afternoon and the evening whose intensity increases polewards.

Figure 2 demonstrates that this is a permanent feature of the \( S_R \) variation of \( H \). An eleven-year series of data, based on the five international quietest days of each month, is used; the average \( S_q \) curves are given for the three classical seasons. With respect to Fig. 1, Toledo, Abinger, and Tromsø* replace Aquila, Hartland, and Kiruna respectively while Eskdalemuir is an intermediate station between Abinger and Lerwick. MAYAUD (1965b) pointed out how the right night-time zero-level can

\* The Tromsø curves are based on the “quiet hours”, as defined in the year-books of this observatory. See MAYAUD (1965a), where it is shown that such curves are comparable with “quiet days” curves of lower latitudes in shape but not in amplitude.

Table 1. Geographic coordinates of the observatories.

| Ab  | Abinger  | +51°11' 359°37' | Mb  | Memambetsu | +43°45' 144°12' |
|     |          |                |     |            |                |
| AA  | Addis-Ababa | +09°02' 38°46' | Nu  | Nurmijärvi | +60°30' 24°39' |
| Ag  | Agincourt | +43°47' 280°44' | Si  | Sitka      | +57°04' 224°40' |
| Am  | Amberley  | +43°09' 172°43' | SJ  | San Juan   | +18°23' 293°53' |
| Aq  | Aquila    | +42°23' 13°19'  | SM  | San Miguel | +37°46' 334°21' |
| Ar  | Argentine Island | -65°15' 295°44' | Sr  | Srednikan  | +62°26' 152°19' |
| Es  | Eskdalemuir| +55°19' 356°48' | Sv  | Sverdlovsk | +56°44' 61°04'  |
| Fr  | Fredericksburg | +38°12' 282°38' | Tk  | Tashkent   | +41°25' 69°12'  |
| Go  | Godhavn   | +69°14' 306°29' | Tl  | Toledo     | +39°53' 355°57' |
| Ha  | Hartland  | +51°00' 355°31' | Tr  | Tromsø     | +69°40' 18°57'  |
| Ka  | Kakioka   | +36°14' 140°11' | Tu  | Tucson     | +32°15' 249°10' |
| Kg  | Kerguelen | -49°21' 70°15'  | Vi  | Victoria   | +48°30' 236°36' |
| Ki  | Kiruna    | +67°50' 20°25'  | Wk  | Wilkes     | -66°15' 110°21' |
| Le  | Lerwick   | +60°08' 358°49' | Ya  | Yakutsk    | +62°01' 129°40' |

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Fig. 1. Records of $H$ and $D$ components on July 25th, 1960 at Kiruna (Ki), Lerwick (Le), Hartland (Ha) and Aquila (Aq). Arrows: positive variation (eastwards in $D$) of 100 gammas.

Fig. 2. $S_q$ curves of $H$ for the three seasons (d: December solstice; e: equinoxes; j: June solstice) at Tromsø (Tr), Lerwick (Le), Eskdalemuir (Es), Abinger (Ab) and Toledo (Tl). Arrow: positive variation. Scale: 2 gammas/hr.
be chosen at about 0200–0300 LT; from such a zero-level, it is quite clear that there exists a positive deviation around 1800 LT, which increases polewards. Figure 3 illustrates from Lerwick records the day-to-day variability of this abnormal positive deviation in phase, in duration and in intensity; again, in these records, the nighttime level is probably the level of the trace around 0200–0400 LT. It would be an over-simplification to assume that the positive deviation under consideration begins in the afternoon when the trace crosses the night-time level just defined. When looking at long series of records, it is obvious that, during several hours, two phenomena are superimposed on each other: (1) the negative deviation due to the normal $S_R$, and (2) the positive deviation which we are describing. In many aspects, this is comparable to the superimposition of the equatorial counter-electrojet effects upon the equatorial electrojet effects (see Mayaud, 1977).

One can wonder why such a large positive deviation does not come out in the planetary $S_q$ analyses which commonly include data recorded between $\pm 60^\circ$ latitudes (that is, up to stations like Lerwick). Figure 4 explains such a failure. A full discussion of all these curves, and particularly the secondary maximums not related to the positive deviation described above for the longitude of Lerwick, is given by Mayaud (1965b). We wish to emphasize here that an occurrence of the positive deviation under consideration around the same UT hour (say, about 1830 UT) at any longitude can account for the drastic variation, in summer (j), of the shape of the $S_q$ curves from one longitude to another. This is obvious for the columns Si-Vi (Sitka-Victoria), Ag-Fr (Agincourt-Fredericksburg), Le-Ha (Lerwick-Hartland), Nu (Nurmijarvi), but not so obvious for the others. Figure 5 gives $H$-records at three southern stations for a summer day, compared in universal time. At any of these stations whose latitude is higher than that of the focus, a positive deviation is abnormal: it occurs around 1600 LT at Amberley (Am), around 0800 LT at Kerguelen (Kg) and around 0100 LT at Argentine Island (Ar) (see Mayaud, 1965b, for the discussion of the night-time level at this station). This is equivalent to currents flowing clockwise at subauroral latitudes all around the auroral zone. Statistical $S_q$ curves for such southern stations indicate that the average UT hour at which the phenomenon culminates is about 0400 UT instead of 1830 UT in the northern hemisphere.
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Fig. 4. \( S_R \) curves of \( H \) for the three seasons (d, c: dashed lines; f: full lines) at various observatories. In a given row, observatories have approximately the same latitude; in a given column, they have approximately the same longitude. The latter can be appreciated in each column by the square, drawn at 1830 UT. Arrow: positive variation. Scale: 2 gamma/hr.
Both times are those at which the Sun crosses the meridian of the invariant magnetic pole in each hemisphere. In the northern hemisphere, the direction of rotation of the currents would be counter-clockwise, but we saw that their effects are not so clear at the longitudes where the local midnight is around 1830 UT. This is probably due to the shape of the northern auroral zone: while the southern one is almost circular, the shape of the northern is rather elongated, and the currents would flow at higher latitudes on such longitudes which are opposite to the meridian of the magnetic pole. A supplementary fact can be stated: in Z component, statistical $S_{Q}$ curves do not show any significant abnormal features. This would indicate that the current flow is rather wide.

Finally, this abnormal feature of the variation $S_{R}$ can be described as follows. While the classical $S_{R}$ vortices, with their foci at mid-latitudes, permanently exist but stay in a fixed position with relation to the Sun, and do not vary significantly in intensity (hence the variations brought about are synchronous in local time), another current system is not permanent at subauroral latitudes but occurs regularly during a certain part of each 24-hr universal time interval. This means that its intensity varies rapidly during that period, so that it gives deviations which are synchronous in universal time from one longitude to another. It is difficult to conceive that the source of such a phenomenon could be located at subauroral latitudes. Because its intensity culminates when the Sun crosses the meridian of the magnetic pole, one is led to search for a source inside the polar caps; the apparent configuration of the effects (a current flow around the auroral zone) and the seasonal variation observed (weakness of the intensity at winter-time) also suggest that the source would be there.
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Any identification of a regular daily variation $S_R$ inside the polar caps is extremely difficult because of the great frequency and the great intensity of the disturbances, especially in summer time. A first remark can be made: any use of statistical $S_q$ curves as derived from the five international quietest days is greatly misleading, because disturbances are included in the data. Thus the $S_q^e$, first described by Nagata and Kokubun (1962), is rather due to irregular variations or disturbances which last a relatively short time-interval. The accumulation of such disturbances, positive or negative according to the time of the day, results in an average variation lasting the 24 hr of the day; since the field sources of such a variation are discrete events which occur irregularly, they are not "permanent" sources as it should be with the regular $S_R$ variation. Thus, as said by Nishida and Kokubun (1971) in their review of $S_q^e$ and other related phenomena, "$S_q^e$ seems to be the feature observed in the slightly disturbed condition, rather than in absolutely quiet periods as its name might imply." To some extent, a symbol as $S_{q(q)}$ would be more convenient. Anyway it is obvious that the $S_q^e$ current system, with its two vortices flowing inside the polar cap, cannot be related to the subauroral current system described above (a single vortex flowing around the auroral zone).

Figure 6 presents an example of what could be the variation $S_R$ inside the polar cap at an antarctic station. During this very quiet day, one observes a very large perturbation in $H$ (its range is of 200 gammas): from the apparent constant level during the night, the field undergoes a positive deviation, then a negative deviation; furthermore, this variation is quite "regular" (in the geometrical sense). In component $D$, some disturbances are probably present (for instance, around 0500 LT), but a westerly deviation seems to be present during the daytime. Such variations are quite distinct in their morphology from the disturbances, and look like the variations $S_R$ observed at latitudes lower than that of the auroral zone. In Fig. 7, $H$-records of an arctic station are displayed. In a and b, a regular variation similar to that of Wilkes is observed, except that one has a negative deviation followed by a positive one (in b, a disturbance during the first two hours prevents the trace from reaching the night-level as it does at the other extreme). In the third record (c), the field undergoes an almost regular variation whose phase and shape are entirely different; furthermore, positive and negative deviations are strongly asymmetrical with respect to the zero-level (estimated from neighbouring days). Mavaud (1965b)

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Fig. 6. Records of $D$ and $H$ at Wilkes on January 30th, 1960. Arrows: positive variation (eastwards in $D$) of 500 gammas.
pointed out how this variation is similar in phase and in shape to those of the $S_d$ curves (derived from the five international disturbed days), while one can recognize in the $S_q$ curves the superimposition of a residue of the $S_q$ curves and of an average variation similar to that observed in the records a and b. Furthermore the seasonal variations of the $S_d$ curves and of such an average variation are greatly different: the latter is much larger during the summer (the law observed for the subauroral phenomenon), while the former is largest at the equinox. This difference indicates that the two variations do not have the same origin. Should the variations observed in Fig. 6 at Wilkes and in Fig. 7 (a and b) at Godhavn be identified as the regular daily variation $S_R$, i.e. a variation corresponding to "permanent field sources?" We think so, in spite of the difficulty of finding significant examples when studying long series of records. Besides, we believe that one can now understand the reason (or, at least, one of the reasons) for which the difficulty exists: these regular features are more or less distorted and hence masked by the effects of the azimuthal component $B_y$ of the interplanetary magnetic field (SVALGAARD, 1968; MANSUROV, 1969; and for a full description of this effect: BERTHELIER et al., 1974; FRIIS-CHRISTENSEN and WILHJELM, 1975), which change signs with $B_y$.

However, one could wonder why the field perturbations driven by the $B_y$ component would not be a part of the $S_R$ variation. We believe that they are not so for the following reasons. (1) The intensity of the $B_y$ component is highly variable at a time scale of a few hours or less, and "irregular variations" are thus caused. By classifying and averaging hourly values according to the sign of $B_y$, one obtains significant statistical daily variations, but the morphology of the raw data should not be forgotten. (2) The phenomenon is not a permanent feature since it disappears when the $B_y$ component tends towards zero.

On the other hand, the polar cap variations described above, which we claim as being $S_R$ variations, have the same morphology as that of the $S_R$ at other latitudes. They can be recognized as a permanent feature when one distinguishes in the $S_q$ curves what is a residue of the disturbances and what looks like the deviations observed in particular very quiet days (note that the effects of the $B_y$ component are
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obviously averaged out in the $S_q$ curves. Their intensity is much larger, in summer
time, than that of the normal features of the $S_R$ variation at subauroral latitudes.
Then it is difficult to conceive that they are the extension, through the polar caps, of
the $S_R$ vortices whose foci are at mid-latitudes. Now, since there are tides in the
polar regions and, as well, an ionization, it is quite conceivable that strong and
localized dynamo effects are driven in these regions, where the main magnetic field
is quasi-vertical and rather intense. Because of the distance between geographical
and magnetic poles, the ionization due to the solar wave radiation greatly varies
with longitude for a given invariant latitude, and the same is true for another possible
source of ionization: the more or less free entry of the quiet solar wind. This
other source of ionization cannot be excluded since $S_R$ variations are still visible in
winter time at polar stations. These last remarks converge towards the same prop-
erty: an important variation, with longitude, of the intensity of the phenomenon
driven, and a maximum of this variation at the longitude where the Sun crosses the
meridian of the magnetic pole.

This is the most outstanding property which results from the description made
of the abnormal feature of the $S_R$ variation at subauroral latitudes. Does a link exist
between this feature and the $S_R$ variation described for the polar caps? Mayaud
(1965b) assumed that the former is the trace of an equatorward expansion, at any
longitude around the auroral zone, of the latter at times when it becomes more
intense. He stated that the single coherent example for component $Z$ which he
found when he investigated that phenomenon was a proof of such a link: it is repro-
duced in Fig. 8. The $S_R$ of $H$ which we consider as typical at Godhavn is associated
with a negative deviation in $Z$. At a mid-latitude station, such a $Z$ variation corre-
sponds to a counter-clockwise current system, which is also the direction of the
equivalent current flowing at northern subauroral latitudes. Such an argument is
not a proof, but only an indication of a possible link between both phenomena.

We believe that the existing data (especially because of the network of available
stations) do not permit one to built a map of the $S_R$ variation currents inside the
polar caps. However, theoretical models concerning dynamo effects in the polar

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Fig. 8. Records of $H$, $D$ and $Z$ at Godhavn on October 14th,1960. Arrows: positive
variation (eastwards in $D$) of 200 gammas.
regions could point out how strong localized effects can be driven there, and display
the possible existence of a special vortex of currents whose intensity would be larger
when the Sun crosses the meridian of the magnetic pole. In that way, the abnormal
feature observed at subauroral latitudes might be understood.

3. The Concept of the Invasion

Figure 9 is taken from the classical work of Price and Wilkins (1963); it re-
presents for June solstice of the Second Polar Year the instantaneous configuration,
at 0800 UT, of the $S_q$ potential. One could consider that the equipotential lines
represent the current lines in the ionosphere. If so, the northern vortex is much
more intense than the southern one; furthermore it deeply invades the southern
hemisphere at morning hours. This means that the daily variation in the southern
hemisphere begins with a positive deviation in $H$ and an easterly deviation in $D$ over
a large range of southern latitudes (in particular, at latitudes higher than that of the
focus). A similar phenomenon at December solstice would correspond in the nor-
thern hemisphere to a similar positive deviation in $H$, but to a westerly deviation in
$D$. In both cases, it appears as an abnormal feature since, given the direction of
currents in the vortices, one normally observes an easterly (or westerly) deviation
in $D$ at morning hours in the northern (or southern) hemisphere, and at latitudes
higher than that of the focus, the deviation in $H$ is a negative one.

Figure 10 displays the daily variation in three stations of the northern hemi-
sphere; two of them (Hartland and Lerwick) are at a latitude clearly much higher
than that of the northern focus. One observes, at morning hours, a positive devia-
tion in $H$ and a westerly deviation in $D$. It begins at about 0400 LT in $H$, and sooner
in $D$. Such features well correspond to the concept of the invasion of the southern
vortex into the northern hemisphere. The permanence of this feature in $H$ is clear
from Fig. 2: there exists in the $S_q$ curves a small maximum, which culminates at
about 0600–0800 LT at all the stations at December solstice, whose intensity

![Fig. 9. Equipotentials of $S_q$ at 0800 UT during June solstice, 1933. The
local meridian is placed at the centre. These equipotentials may be
expected to be similar in form to the current lines of the equivalent
electric current system (after Price and Wilkins, 1963).](image)
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Fig. 10. Records of $H$ and $D$ at Lerwick (Le), Hartland (Ha) and Aquila (Aq) on January 30th, 1960. Triangles: local noon. Arrows: positive variation (eastwards in $D$) of 50 gammas.

Fig. 11. $S_q$ curves of $D$ for the three seasons (d: December solstice; e: equinoxes; j: June solstice) at Tromsø (Tr), Lerwick (Le), Eskdalemuir (Es), Abinger (Ab) and Toledo (Tl). Arrow: easterly variation. Scale: 2 gammas/hr.
slowly decreases polewards; in this respect, its behaviour deeply differs from the
afternoon maximum at June solstice discussed in the preceding section. Figure 11,
with similar $S_q$ curves for component $D$, shows that the westerly deviation in $D$ is
also a permanent feature: there exists a westerly deviation around 0400–0500 LT.
A careful examination of individual records reveals that the deviation at such times
is truly westwards: indeed, the value of the field varies from day to day at these
hours while it is constant (taking the secular variation into account) around mid-
night, at the moment of an east maximum in the traces. Note that the $S_q$ curves
of Fig. 11 for summer (j) show that the slope of the variation during the night in-
creases polewards: this is easy to understand since the duration of the day-time be-
comes longer and longer. But the existence of a variation during most of the night
in winter time is difficult to understand, given the conditions of the ionization at
latitudes as high as Lerwick (60°).

However, the chief point that we wish to make here results from Fig. 12. It
represents the $H$ record of Addis-Ababa for the same day as that displayed in Fig.
10. At this equatorial station, a negative deviation in $H$ appears in the morning
hours, which is typical of the equatorial counter-electrojet at this longitude during
December solstice (Mayaud 1967, 1977). Such a negative effect at equatorial lati-
itudes strongly contradicts the concept of the invasion extensively used by Mayaud
(1965c, 1967) in interpreting the morning features of the $S_q$ variation in winter time.
Are both phenomena, this negative deviation in $H$ at Addis Ababa and the positive
deviation in $H$ at subauroral latitudes, the trace of a secondary northern vortex
whose direction of the current would be reversed (that is, clockwise in the northern
hemisphere)? There exist two indications of a possible link. (1) These deviations
have the same morphological aspect and begin at the same local time. (2) Accord-
ing to Fig. 13, a significant variation of the intensity of the “invasion” occurs with
longitude. At these stations, which are approximately located at the average lati-
itude of the northern focus (San Juan (SJ) is a little equatorwards), the shape and
the amplitude of the $S_q$ curve of component $Y$ greatly vary in winter time (d).
Now, the morning westerly deviation is noticeable only from Tashkent to San
Miguel (note however the further problem raised at Tucson: it seems that the pheno-
menon still exists there, but 2 or 3 hr sooner in local time). This longitude sector
is also the one where, at equatorial stations (Mayaud, 1977), a weak and long
morning negative deviation in $H$ is observed.

Fig. 12. Record of $H$ at Addis Ababa on January 30th, 1960. Arrow: positive deviation of
50 gammas.
Again, as in the preceding section, such arguments do not prove the link between the abnormal features of the $S_R$ described at equatorial latitudes and at subauroral latitudes. We believe however that they call for further investigation. In particular, are such features yet another indication of the existence of current

![Diagram of $S_q$ curves of $Y$ for the three seasons (d: December solstice; e: equinoxes; j: June solstice) at Kakiola (Ka), Tashkent (Tk), Aquila (Aq), Toledo (Tl), San Miguel (SM), San Juan (SJ), Tucson (Tu), and Kakioka again. All these stations are at the average latitude of the focus, except San Juan which is a little equatorwards. Component $Y$ is used instead of $D$ component because any variation, with longitude, of the angle between magnetic and geographic meridians introduce secondary deformations of the $D$ curves from one longitude to another. Arrow: easterly deviation. Scale: 2 gammas/hr. The square corresponds to 1200 UT and permits one to evaluate the longitude of each station.](image-url)
vortices whose direction of rotation is reversed, as suggested by GOUIN and MAYAUD (1969) and MAYAUD (1977) for explaining the counter-electrojet?

4. Conclusion

It does not seem that statistical planetary analyses, up to now, have been sensitive to the apparent anomalies of the variation $S_R$ described above. The same is true for the equatorial features previously reviewed and more or less related to abnormal features observed at other latitudes (MAYAUD, 1977). To some extent, there exists a common denominator for all these apparently abnormal features: from an observational point of view, that is when one scrutinizes the records, one gets the impression that any abnormal feature is distinct from the variation which one can consider as normal, and there is an overlap of the time intervals during which both the abnormal feature and the normal variation are present. The choice of the zero-level itself is already a difficult problem. Carrying out an exact separation between both effects during this overlap is much more difficult, and would be the crucial point for investigation. In spite of such difficulties, any further research on these abnormal features would be a key-point for a better understanding of the physical sources of the variation $S_R$.

We thank the World Data Center Cl for kindly communicating us the record of Addis Ababa reproduced in Fig. 12.

REFERENCES


