THE BOLLER-STOLOV MECHANISM AND THE SEMIANNUAL AND DAILY MCINTOSH EFFECTS IN GEOMAGNETIC ACTIVITY

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Abstract. According to Boller and Stolov (1974), the probability of instabilities (and the magnetic activity) should be proportional to $A_o + A_1 \sin^2 \psi_M$, where A_o and A_1 are constant and ψ_M is the angle between the solar wind and the dipole axis of the earth. Such an expression permits one to fit very well, in phase and in amplitude, both the semiannual and the daily variation of the magnetic activity as defined by aa or am indices.

Introduction

We previously commented [Mayaud, 1974b] on a new interpretation of the semiannual variation of the geomagnetic activity [Russell and McPherron, 1973] by arguing that it does not account for the UT daily variation observed, whereas the McIntosh hypothesis (angle ψ between the dipole axis and the sun-earth direction) does. In their reply, Russell and McPherron [1974] argued that this daily UT variation originates within the ionosphere. Recently, Berthelier [1975, 1976] and then Svalgaard [1975] pointed out how the mechanism recognized by Russell and McPherron (influence of the polarity of the interplanetary magnetic field) is effective. This mechanism gives rise to annual variations which maximize in the spring or in the fall if the interplanetary magnetic field B_Y is negative or positive; they nearly cancel each other out if there is a balance between the days with opposite directions of B_Y, but they do induce a semiannual variation because each of them is not purely sinusoidal. The mechanism also gives rise to UT daily variations which have opposite phases for opposite directions of B_Y; when the balance mentioned above exists, they do not cancel, especially at the equinoxes, because of the annual variation of their amplitudes. On the other hand, both authors demonstrated that the daily and semiannual variations of the McIntosh effect are still active in the geomagnetic activity. In this report we give results of an analysis of these variations by an analytical expression taken from the Boller-Stolov mechanism.

Boller and Stolov [1970, 1974] suggested that the mechanism responsible for the McIntosh effect is the semiannual and the daily variation of the angle ψ_M in the Kelvin-Helmholtz theory. Instabilities occur when the criterion

$$U^2 > \frac{\rho_I + \rho_M}{4\pi \rho_I \rho_M} [B_I^2 \cos^2 \psi_I + B_M^2 \cos^2 \psi_M] \quad (1)$$

is satisfied. The symbol I stands for interplanetary values outside the magnetosphere, and M stands for magnetospheric values. U is the stream speed of the solar wind at the magnetopause, and ψ is the angle between the local stream velocity U and the magnetic fields. B and ρ stand for magnetic field intensity and mass density. Boller and Stolov consider that the probability of instability (and the activity amplitude (later designated by A)?) may be taken to be a linear function of the difference between U^2 and the right-hand side of the criterion. Let us call P that quantity; it can be written

$$P = U^2 - \frac{\rho_I + \rho_M}{4\pi \rho_I \rho_M} [B_I^2 \cos^2 \psi_I + B_M^2] + \frac{\rho_I + \rho_M}{4\pi \rho_I \rho_M} B_M^2 \sin^2 \psi_M \quad (2)$$

or

$$P = A_o + A_1 \sin^2 \psi_M \quad (3)$$

where A_o and A_1 can be considered as constants when one uses indices averaged from many years for a given value of ψ_M. Thus one can verify whether the ψ_M time variation is sufficient to describe the observed variations.

Analysis of the observed variations by the Boller-Stolov mechanism

First, we use the aa indices [Mayaud, 1973] for the years 1868-1970. Average values are computed for 6° wide sectors of the solar longitude Λ (the origin chosen for Λ is the vernal point; the sectors are centered at $\Lambda = -3° + n$ times 6°, n varying from 1 to 60). They were already studied [Mayaud, 1974a] by using a harmonic analysis method, which results in a phase of +4° in relation to the vernal point, a value near the expected phase of the McIntosh hypothesis; the positive shift was interpreted by a parallax effect of the solar wind speed.

Curves aa of Figure 1 display the result obtained by simulating the aa average values in computing A_o, A_1, and Λ_o by least squares in (3) with

$$\psi_M = 90° + \delta \sin (\Lambda - \Lambda_o) \quad (4)$$

where δ (23°27') is the angle between the geographical axis and the ecliptic plane. Thus only the semiannual variation of ψ_M is taken into account, since its daily variation is not considered. The first line of Table 1 gives values of the parameters resulting from the

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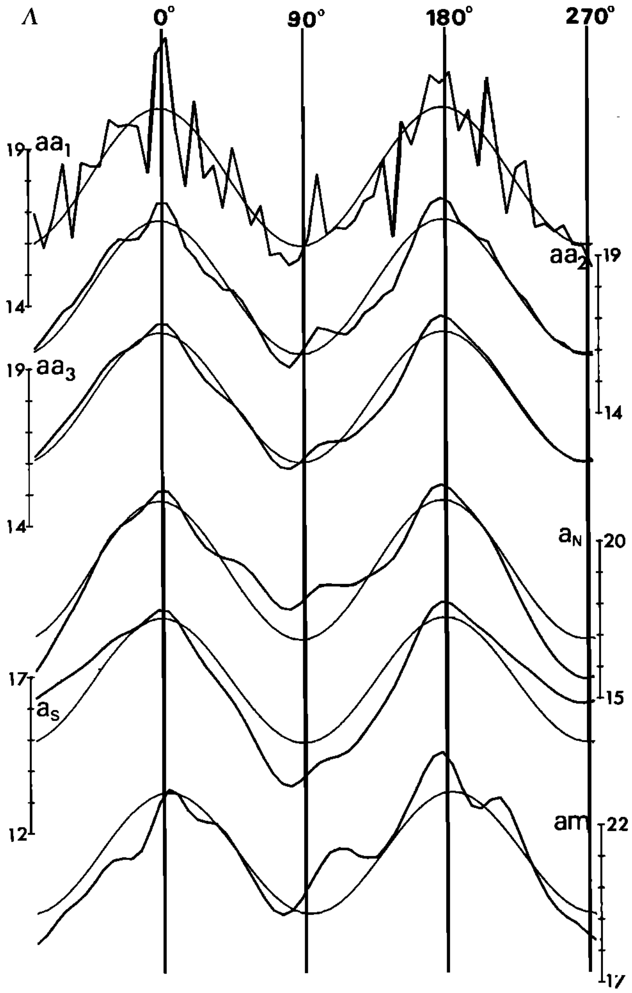

Fig. 1. Variation of the aa, a_N, a_S, and am indices, averaged within 6° wide longitude sectors, as a function of Λ (thick line) and approximation by formulae (3) and (4) (thin line). Three graphs are given for aa indices. For aa_1 the direct average values within each 6° wide sector are used. For aa_2 running averages are made in the following way: if Λ_J is the mid-longitude of a given sector, one takes three times the value for Λ_J, two times the values for Λ_{J-1} and Λ_{J+1}, and one times the values for Λ_{J-2} and Λ_{J+2}. For aa_3 the same process is again applied to the running averages aa_2. Mayaud [1974] showed how the noise existing in aa_1 is not artificial, since it is practically identical in both antipodal observatories from which aa indices are derived. With a_N, a_S and am, only running averages similar to those used in aa_3 are displayed. Ordinate scales are in gammas.

analysis displayed in curve aa_3 of Figure 1. Clearly, the theoretical expression fits very well the observed values.

One can also use the 3-hour averages within each longitude sector and thus directly verify whether the ψ_M variation accounts for both daily and semiannual variations. However, the antipodal observatories used in deriving aa indices are located in the European and Australian sectors, and we previously showed [Mayaud, 1970] that the daily McIntosh effect is partly canceled in these sectors by a local daily variation which maximizes around 1600 LT and is largest in summer. Curves a_N and a_S of Figure 1 show effectively that when one analyzes separately the full average values, within each sector, of the K indices (transformed into amplitudes in gammas) of each of the antipodal observatories (a_N and a_S), there appears an annual component whose phase is reversed from one solstice to the other (Table 1 give values of the parameters obtained). Another factor renders the analysis of the 3-hour indices difficult: the antipodal observatories are only 10 hours apart in longitude, and the local time variation of the activity is not completely canceled.

Using the am indices permits one to avoid the two difficulties described above, but the much shorter time interval covered by the indices (16 years from 1959 to 1974 instead of 103 years) makes the noise observed in curve aa_1 of Figure 1 much more difficult to smooth. Curve am of Figure 1 effectively shows the presence of more noise. In analyzing the 3-hour am values we use for ψ_M its complete expression, which contains the daily variation of the dipole axis in relation to the vector $\vec{U}$. One has

$$\cos\psi_M = \cos[\pi/2 + \delta \sin(\Lambda - \Lambda_o)]\cos\phi + \sin[\pi/2 + \delta\sin(\Lambda - \Lambda_o)]\sin\phi\cos(h - h_o) \quad (5)$$

where $\phi(11.5°)$ is the angle between the dipole and geographical axes and h the hour UT. We compute by least squares A_o, A_1, Λ_o, and h_o. The second part of Table 1 (line am) gives the values thus obtained; they are close to the values obtained in the preceding analysis (line am of the first part of the table) for the first three parameters. In Figure 2 the comparison of curves a, b, and c permits one to appreciate the significance of this analysis in phase and in amplitude of both semiannual and daily variations. If one remembers that the daily variation has a phase that is constantly changing during the year (it maximized at 4.5 UT at June solstice and at 16.5 UT at December solstice; see also curve b), it appears again that the complete theoretical expression fits the 3-hour average observed values well. Note that the value obtained for h_o (i.e., 4.53 UT) is surprisingly close to the theoretical value (i.e., 4.50 UT). This last result is much better than that obtained for the phase Λ_o, which is approximatively 10 days after the theoretical date (the vernal point) in this analysis of am indices instead of about 4 days with the analysis of the 103-year series of aa indices. Note also that the value of the root square residue increases very little (see Table 1) from the analysis of the daily am to that of the 3-hour am; it shows to what extent daily and semiannual McIntosh effects agree with each other.

Discussion of the residues

The residues (curve c of Figure 2), however, are not negligible and have two sources. Part of them corresponds to the noise observed in the am curve of Figure 1 and cannot by reduced. But those observed within each longitude sector

TABLE 1. Values Obtained for the Various Analyses of the Indices

	A_o, γ	A_1, γ	Λ_o, deg	h_o, UT	φ, deg	a, γ	r,* γ
			6° Wide Sector Averages				
aa	−6.1 ± 0.7	+26.7 ± 0.7	4.3 ± 0.7	...	...	...	0.31
a_N	−6.1 ± 1.5	+28.1 ± 1.7	3.6 ± 1.7	...	...	...	0.70
a_S	−6.3 ± 1.9	+25.2 ± 2.1	5.1 ± 2.4	...	...	...	0.87
am	−1.3 ± 1.6	+24.4 ± 1.8	8.9 ± 2.2	...	...	...	0.75
			6° Wide Sector 3-Hour Averages				
am	−0.7 ± 0.4	24.2 ± 0.5	10.3 ± 0.8	4.53 ± 0.09	...	...	0.98
am'	−1.7 ± 0.7	25.2 ± 0.7	10.2 ± 0.8	4.53 ± 0.09	10.7 ± 0.4	...	0.98
am"	−0.2 ± 0.5	23.5 ± 0.6	9.9 ± 0.9	4.53 ± 0.09	...	0.15 ± 0.08	0.98
am"'	+1.2 ± 0.5	22.0 ± 0.5	8.8 ± 0.9	4.53 ± 0.10	...	...	1.00

Results shown on lines aa, a_N and a_S in the above table correspond to a 103-year series of indices for the years 1868–1970; those for the lines am correspond to a 16-year series of indices for the years 1959–1974 (see text for the significance of the various analyses performed with the sample am).

* Root square residue.

present systematic variations which may or may not be significant. One feature is the existence of daily variations in these residues, out of phase with the theoretical curve (curve b) within three or four sectors after June solstice ($\Lambda = 90°$); a similar feature exists after December solstice. Does this fact come from the angle ϕ between dipole and geographical axes, which is not fully effective ? An analysis made in computing the angle ϕ in expression (5) gives a value of 10.7° for that angle (see line am' of Table 1). The daily variation amplitude in the sectors mentioned above is reduced by a ratio of only 0.86. Because the feature under consideration appears to be localized within only a few sectors, and because the value obtained for ϕ by computing it is close to the known value, it seems that the present analysis by the Boller-Stolov mechanism accounts for the quasi-totality of the semiannual and daily McIntosh effects.

Another feature appearing in the residues (curve c of Figure 2) is their large amplitude at the equinoxes. One can wonder whether or not they are due to the Russell-McPherron mechanism, since the daily variations due to that effect are largest at these times [Berthelier, 1976]. Furthermore, since the mechanism brings about a semiannual variation, it is possible that the value obtained for A_1 in our analysis would be too large. Then we add a supplementary term in expression (3), which becomes

$$P' = A_o + A_1 \sin^2 \psi_M + a \cos 2(\Lambda - \Lambda_o') \quad (6)$$

Such a new term would simulate the semiannual variation due to the action of the interplanetary magnetic field. The dissociation of both semiannual variations in such an analysis might seem elusive but one might expect that the large daily variation contained in the term $A_1 \sin^2 \psi_M$ would bring a sufficient constraint in the computation by least squares of A_o, A_1, Λ_o, h_o, and a (the phase Λ_o' is chosen equal to 17°, i.e., the predicted date of this semiannual variation, which occurs on April 7). Line am" of Table 1 gives the result of the computation. The part of the semiannual variation due to the Russell-McPherron mechanism would be very weak with this 16-year am sample (less than a tenth of the McIntosh effect). A further analysis, in which we arbitrarily subtract from the observed values a wave of amplitude a = 0.5 γ(a value which corresponds to that observed by Berthelier [1976] in a 6-year (1964-1969) sample of am indices) before computing A_o, A_1, Λ_o, and h_o, does not give any important variation either in the residues or in the values obtained for the parameters (see line am"' of Table 1).

Concerning the daily variations of the residues at the equinoxes, we cannot make a global analysis of them for two reasons: (1) the analytic expression of the Russell-McPherron daily variations is not given by Berthelier [1976] and (2) the balance between days with opposite directions of B_Y within each longitude sector is much less guaranteed than that for the semiannual variation itself. However, since the predicted daily variation maximizes at 10.5 UT ($B_Y > 0$) or at 22.5 UT ($B_Y < 0$), we analyze the residues of curve c, sector by sector, with a sinusoidal wave which maximizes at 10.5 UT. Curve d in Figure 2 displays the new residues (their average root square residue is 0.90). Very clearly, a significant part of the daily variations appearing in curve c disappears, especially at the equinoxes; however, its attribution to the Russell-McPherron mechanism is rather uncertain because the average value throughout the year of the amplitudes of the sinusoidal wave is −0.48 γ(extreme values are −1.04 and +0.23), which indicates that the sinusoidal wave maximizes in most of the longitude sectors (and, in fact, at both equinoxes) at 22.5 UT. Very probably, any identification of the Russell-McPherron effect would suppose a much longer series when one does not discri-

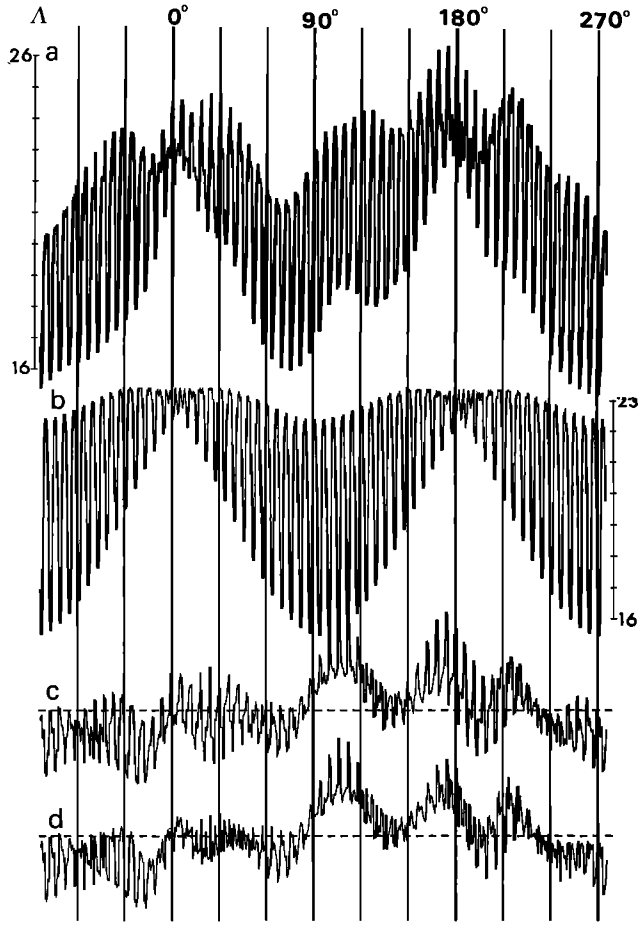

Fig. 2. Variation of the 3-hour am indices (curve a), averaged within 6° wide longitude sectors, as a function of h (within each sector) and Λ. Running averages are identical to those used for curve aa_3 of Figure 1; they are made in terms of Λ for each value of h. Curve b represents the activity amplitude A based on the least squares fit of the observed values by formulae (3) and (5). Curve c represents the residues (differences between observed (curve a) and computed values (curbe b)); the same ordinate scale is used, and the dashed line corresponds to zero. Curve d represents the residues after substraction in each sector of a sinusoidal wave maximizing (or minimizing) at 10.5 UT. Vertical lines drawn at 0°, 30°, 60°, ..., which are the left border of the longitude sectors 0°-6°, 30°-36°, 60°-66°, ..., represent also for each of these sectors the time h = 0.0 UT. Other hours can be readily appreciated, since the theoretical curve b (see Table 1) culminates at 4.53 UT at June solstice or at 16.53 at December solstice. Ordinate scales are in gammas.

minate between days according to the sign of B_Y. The result, obtained by Berthelier [1975, 1976] and Svalgaard [1975], is too clear to be questioned by the present failure. Note that a further analysis of the average variation of the residues of curve d results in a UT daily variation whose amplitude is only 0.13 γ.

Conclusion

1. The analyses performed by the analytical expression used in (3) and (4) or (5) are radically different from a harmonic analysis and cannot be reduced to it. They result in a ready explanation in phase and in amplitude of both the semiannual and the daily variation observed. One can assert that a physical mechanism related to the variation of $\sin^2 \psi_M$ is responsible for these variations. The geocentric theory is plainly confirmed over the heliocentric theory. And when one does not discriminate between days with opposite polarity of the interplanetary magnetic field, most of the semiannual and daily variations observed are due to this physical mechanism.

2. On theoretical grounds the quantity P will be positive only when condition (1) is satisfied or when $A_1 \sin^2 \psi_M$ is close to its maximum value. The fact that we obtain a negative A_o with the long series of aa indices, much more reliable than the series of am indices for the analysis of the semiannual variation, would support the conclusion that the Boller-Stolov mechanism is effective. Note that the numerical value of A_1 is proportional to $[(\rho_I + \rho_M)/4\pi\rho_I\rho_M]\ B_M^2$ and that of the sum $A_o + A_1$ is proportional to $U^2 - [\rho_I + \rho_M)/4\pi\rho_I\rho_M]\ B_T^2 \cos^2 \psi_T$. However, the effects depending on the Russell-McPherron mechanism prevent one from asserting that the A_1 observed value is purely proportional to the physical quantity mentioned above.

3. We know (see, for instance, Mayaud [1970] that the McIntosh effect is proportional to the intensity of the activity. The average levels in the northern and southern hemispheres during the 103 years analyzed are 19.08 and 16.83 γ, respectively. This explains the differences observed between the values of A_1 in the analyses of a_N and a_S (see Table 1).

4. In order to obtain a linear correspondence between observed and theoretical values of the amplitudes of the daily variations resulting from harmonic analyses of both types of quantities, Mayaud [1970] introduced a law of $\sin^8 \psi_M$. Such a result is evidently superseded by the present work. On the other hand, if it is clear that the main part of the UT daily variation appearing in the am indices is not of ionospheric origin, this does not preclude the existence of such ionospheric variations [Mayaud, 1970] in the an and as indices from which am indices are derived. While McIntosh daily variations (such as they are observed and interpreted by the Boller-Stolov mechanism) are in phase in both hemispheres and out of phase from one solstice to another, the UT ionospheric variations mentioned above are out of phase from one hemisphere to another but keep the same phase at any season.

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