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On the Origin of the Annual Wave in Hemispheric Geomagnetic Activity

J. Meyer [1] and D. Damaske [2]

[1] Institut für Geophysik, Universität Göttingen, Herzberger Landstraße 180, D-3400 Göttingen, Federal Republic of Germany
[2] Institut für Geophysikalische Wissenschaften, Freie Universität Berlin, Rheinbabenallee 49, D-1000 Berlin 33

Abstract. The modulation of hemispheric magnetic activity (as measured by *Kn* and *Ks*) displays a specific modification compared to planetary activity (*Km* indices), in terms of both the diurnal UT variation and the appearance of an additional annual wave. To allow for the observational results Damaske (1976, 1977) suggests a modification of the planetary modulation function $\sin^2\beta$ (where β is the angle between the solar wind flow and the earth's dipole axis) through an additional constant angle β_0. In a quite different interpretation Mayaud (1977, 1978), while retaining the modulation function unchanged, attributes the observed modifications to the combined action of various sources: the main component involving certain LT features in connection with DP2 fluctuations, and a second component related to a universal modulation of the LT variation. The present paper demonstrates that the latter interpretation fails quantitatively in explaining sufficiently all of the observed hemispheric effects.

Key words: Geomagnetic activity – Annual wave – Hemispheric activity indices.

Introduction

Despite the well-known 6-month wave in geomagnetic acitivty, the search for a persistent 12-month wave has long met with failure, as long as the analysis has been based on monthly means of daily values. Only during the past decade, with a refinement of the methods and a new type of data, has the existence of *two* different annual waves definitely been revealed, the two being distinguishable in respect of both their morphological structure and origin.

The first of these two annual waves has been established by Meyer (1972, 1973) through a harmonic sequence analysis of daily values at intervals of 27 days, i.e., one solar rotation. Its amplitude is large (almost 3 times that of the semiannual wave) for years before and including sunspot minima, whereas the wave is almost vanishingly small in years around sunspot maxima. Its phase changes arbitrarily with a wave maximum close to either one of the two equinoxes. Hence the wave is partially averaged out when utilizing monthly means and thus could not be detected by ordinary harmonic analysis of monthly values. Meyer (1972, 1973) has interpreted this kind of annual wave as a temporary north-south asymmetry of the large-scale solar wind structure within single solar sectors in connection with the same magnetospherical modulation mechanism responsible for the semiannual wave. The results of Berthelier (1975; Fig. 1a, b) indicate that the polarity of the interplanetary field with its quasi-persistent sector structure may also be essential for producing the observed effect.

The second kind of annual wave was disclosed by Damaske (1976, 1977, 1978) from 27-day means of *hemispheric* activity indices, again through a harmonic sequence analysis. In the case of the quasi-logarithmic indices (*Kn, Ks*), the amplitude of this hemispheric annual wave is also larger than that of the semiannual wave and appears to be independent of the solar cycle (with a slightly, but not significantly, larger magnitude for the southern hemisphere). Its phase, however, is nearly opposite in each hemisphere, corresponding to a wave maximum close to the respective meteorological summer solstice. Hence, this wave is again averaged out when utilizing planetary, i.e., worldwide indices and thus could not be detected in *Km* or *Kp*. Damaske (1976, 1977) reduces this annual wave, as an additional hemispheric effect, to a modification of the modulation function $\sin^2\beta$ describing the modulation of *planetary* magnetic activity (where β is the angle between the direction of the solar wind flow and the earth's dipole axis). Physically, this modification implies a modified modulation mechanism without involving additional excitation.

In effect, the hemispheric annual wave corresponds to the observed winter-summer difference in geomagnetic activity (Wulf 1971), as well as to the annual wave noticed in ratios (Mayaud 1972) or differences (Berthelier 1975; Fig. 1c) between the magnetic activity in each hemisphere. However, the qualitative methods applied have in no case led to an accurate determination of the amplitude and phase of the observed periodicity. Recently Mayaud (1977) has investigated further the annual wave in hemispheric activity indices, again by various superposed epoch analyses. His analyses also include separate studies for the eight (i.e., five northern and three southern) longitude sectors from which the hemispheric indices are derived. He suggests that the annual wave is due mainly to two additional and independent sources whose effects are then superimposed on the general planetary modulation through $\sin^2\beta$: the one consisting of additional activity around local afternoon, predominantly during summer, in connection with the DP2 fluctuations; the other being related to a multiplicative modulation of the local time (LT) variation of activity, again by the function $\sin^2\beta$ (see also Mayaud, 1979). The purpose of the present paper is to examine quantitatively to what extent the two components of this source model can actually contribute to the observed hemispheric annual wave and whether this model may possibly provide an equally valid or still better representation of the observational results than does the modified modulation function.

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The Modified Modulation Function

The classical method of investigating a given periodicity in geophysics is the statistical harmonic analysis developed by Bartels (1932, 1935; see also Chapman and Bartels 1940) and, for many years, applied successfully by Bartels and his co-workers. The strength of this method is that, through combination with a variance test, it yields at the same time quantitative statements on the significance of the results. The harmonic sequence analysis introduced by Meyer (1972, 1973) is a modified version especially suited to the study of annual variations in solar-terrestrial relationships.

With regard to planetary activity indices (such as the 3-hourly *Km* and daily *C9*), a complete harmonic analysis of daily and annual variations has yielded harmonic constituents which are in full accordance (within the limits of statistical error) with the ones obtained by a Fourier expansion of the modulation function $\sin^2\beta$, in terms of both phase and amplitude ratio (Damaske 1976, 1977). All significant periodicities (diurnal, semidiurnal waves including their annual amplitude modulation, and the semiannual wave) and *only* these are represented by the expanded planetary modulation function. Accordingly, $\sin^2\beta$ provides a complete representation of planetary activity modulation.

Likewise, a comprehensive harmonic analysis of quasi-logarithmic *hemispheric* indices (3-hourly *Kn, Ks* and daily *C9n,s*) has revealed, as specific features, a modification of the diurnal UT wave and an additional (hemispheric) annual wave (Damaske 1976, 1977). Apart from merely statistical scattering it appears that the seasonal average vectors in the harmonic dial for the diurnal wave are systematically shifted towards the mean vector direction during meteorological winter. The same finding is readily apparent in a corresponding shift of the annual amplitude modulation curve for the diurnal wave in either hemisphere. It is equivalent to an additional diurnal wave in both hemispheres, with *constant amplitude and phase* throughout the year. Its maximum occurs near the hour of planetary wave maximum in local winter, i.e., at 04.30 hours UT in the southern hemisphere and 16.30 hours UT in the northern. Thus the total diurnal wave appears enhanced in local winter and diminished during local summer. Damaske (1976, 1977) accounts for the observed hemispheric modification of the diurnal wave by a modification of the modulation function $\sin^2\beta$ through an additional constant angle β_0 (with $\beta_0 = \pm 11°$, as computed from the amplitude ratio of the planetary diurnal wave to the additional wave). Subsequently, by another Fourier expansion, he was able to deduce, from the modified modulation function $\sin^2(\beta+\beta_0)$, the particulars of all significant (and *only* the significant) periodicities in *Kn* and *Ks* including the hemispheric annual wave, within the limits of statistical error. Hence, the modified modulation function provides again a complete representation of hemispheric magnetic activity modulation.

The numerical value of $\pm 11°$ for β_0 ($+11.9°$ and $-10.6°$ for the northern and southern hemispheres, respectively) may well appear somewhat high. But it must again be emphasized that it is the result of a strictly quantitative harmonic analysis which corresponds to a statistical least-square method. As such, the calculated value is of course subject to statistical error. (In fact this is the reason why we are using an integer average of 11°). Hence, any deviation of observational results from that predicted with a certain value of β_0 has to be judged not by its relative amount as Mayaud (1979) does but, instead, relative to the respective probable error circle. In the case of the observed annual wave in the hemispheric *Kn* and *Ks*, the deviation of the result clearly lies within the range of one standard deviation (which is 1.20 times the probable error) from the predicted annual wave (see Damaske 1976, Fig. 32; or Damaske 1977, Fig. 19). From the sample group of years investigated, the value calculated comes out as an amount necessary to allow for the observed modification of geomagnetic acitivity modulation, once a modification of the modulation function $\sin^2\beta$ through an additional constant angle β_0 has been allowed.

Since β refers to the internal dipole of the main geomagnetic field, β_0 can be described formally by an additional tilt of an "effective dipole axis" which is equivalent to an additional external dipole for either hemisphere possibly due to the large-scale magnetospheric current systems in connection with the asymmetric polar oval (Damaske 1976, 1977; Meyer and Damaske 1978). Any physical interpretation of this formal result may, admittedly, be regarded as only tentative. Clearly there has to be made a distinction between definite results of a quantitative analysis of experimental data and their physical explanation.

The DP2 Annual Wave Source

Mayaud (1977, 1979) suggests, as an alternative to the modified modulation function, two main source components, the first consisting of additional magnetic activity especially in the horizontal component around 15.00 hours LT, which Mayaud relates to the DP2 fluctuations. He finds that in either hemisphere the effect is much larger during local summer and almost vanishing in local winter. In the way Mayaud understands and describes the phenomenon, its amplitude variation with longitude would induce an additional UT component in the hemispheric *Kn, Ks* (or *an, as*) which should then account for the observed modification of the diurnal UT variation during local summer. Besides the fact that such a local time effect would create an annual variation in hemispheric indices only if the daily average is also affected (see Damaske and Meyer 1980), the suggested source model fails absolutely in providing a possible explanation for the additional diurnal UT wave in local *winter,* which occurs with the same amplitude and phase as in local summer (see above). Moreover, any additional UT component that is confined to local summer (or any other meteorological season) would be retained instead of being eliminated when averaged over both hemispheres. But such an elimination of the specific hemispheric effects is required for correspondence with the observed *planetary* activity modulation following the $\sin^2\beta$ law. (In particular, since *am* is the average of *an* and *as,* it is quite clear that the activity modulation bearing on *am* has to display exactly the average of the modulation curves for *an* and *as*).

Hence, although the reality of the peculiar LT effect Mayaud discusses is not disputed, it turns out that this phenomenon does not explain sufficiently the observed modification of hemispheric magnetic activity modulation as far as the diurnal UT variation and the annual wave are concerned. It remains to be examined whether the second component of Mayaud's source model might allow for all the deficiencies discovered.

Modulation of the Diurnal LT Variation

The second component of Mayaud's (1977, 1979) annual wave source model is based on the assumption that the daily LT variation at every station undergoes a multiplicative modulation by the planetary modulation function $\sin^2\beta$ (without including the additional angle β_0). As any LT variation can be written formally as a UT variation with longitude dependent phase, such a modulated sinusoidal LT variation can be expressed (in relative units) by

$$\sin^2\beta \times \cos(t-\lambda+\lambda_0) = \sin^2\beta \times \{\cos t \cos(\lambda-\lambda_0) + \sin t \sin(\lambda-\lambda_0)\}, \quad (1)$$

where t is the hour angle of universal time (15° per hour), λ being the (eastward) longitude of the station, and λ_0 a constant phase angle corresponding to the daily maximum of the LT variation. (If the formulation is applied to the southern hemisphere, another phase angle of 180° has to be added to account for the reverse sign of the daily variation at an antipodal station). Replacing $\sin^2\beta$ by its Fourier expansion (Damaske 1976, 1977) and forming daily averages (to determine the annual variation) yields:

$$\frac{1}{2\pi}\int_0^{2\pi} \sin^2\beta \times \cos(t-\lambda+\lambda_0)\,dt = \tfrac{1}{2}(0.146\cos\alpha - 0.003\cos 3\alpha)\cos(\lambda-\lambda_0), \quad (2)$$

where α describes the seasonal variation, i.e., increasing by 360° per year with $\alpha=0$ at the beginning of the (northern) summer solstitial day (22 June). All other terms in Eq. (1) have vanished on account of the orthogonality conditions for trigonometric functions.

From Eq. (2) it is immediately apparent that for any longitude λ (or longitude sector) an additional annual wave indeed occurs with constant phase and a longitude dependent amplitude including change of sign, namely: $0.073\cos(\lambda-\lambda_0)\cos\alpha$. (The other harmonic constituent in Eq. (2), of 4 month period, is negligibly small). But this annual wave is completely cancelled out when averaged over all values of λ, i.e., over a full hemisphere. Thus, even when considering the non-homogeneous net of stations, it cannot give a noticeable contribution to the annual wave observed in hemispheric indices *Kn, Ks* or *an, as*.

When averaging Eq. (1) directly over all values of λ (hemispheric averages), for a certain time t (or a certain 3-hour interval), all terms vanish identically because $\sin^2\beta$ is independent of λ. This means that a modulated LT variation also cannot contribute to the UT variation in hemispheric indices. The observed modification of the diurnal UT wave in *Kn* and *Ks* relative to the one in *Km* can in no part be attributed to a universal modulation of the LT variation in the way Mayaud suggests. Such an effect can definitely be excluded from any explanation of the characteristic features of hemispheric activity modulation.

The assumption of a purely sinusoidal LT variation implies no loss of generality. As can easily be shown by Fourier expansion of a non-sinusoidal LT variation, the inferences concerning the annual wave remain unchanged. Additionally, there is a small but persistent (sinusoidal) activity variation with longitude. But again all constituents vanish when averaged over the whole hemisphere, with respect to daily values as well as a particular 3-hour interval.

Conclusions

To summarize, quantitative examination of the two alternative annual wave interpretations has ascertained that the modified modulation function provides at least a complete description of hemispheric activity modulation, as far as magnetic activity is measured by *Kn* and *Ks*. Against this, Mayaud's concept of two additional sources does not explain satisfactorily the observed *hemispheric* effects. Nevertheless, his suggestion of a modulated LT variation may well contribute to an understanding of any superimposed amplitude variation of the annual wave in *sectorial* indices which cannot quite be excluded from the present material (Damaske 1978). It would be highly desirable to investigate this effect further with respect to a higher statistical significance.

References

Bartels, J.. Terrestrial-magnetic activity and its relations to solar phenomena. Terr. Magn. Atmos. Electr. **37**, 1–52, 1932 (reprinted by Carnegie Institution of Washington, 1959a)

Bartels, J.: Random fluctuations, persistence, and quasi-persistence in geophysical and cosmical periodicities. Terr. Magn. Atmos. Electr. **40**, 1–60, 1935 (reprinted by Carnegie Institution of Washington, 1959b)

Berthelier, A.: Influence de la polarité du champ magnétique interplanétaire sur la variation annuelle et sur la variation diurne de l'activité magnétique. C.R. Acad. Sci. Paris, Sér. B: **280**, 195–198, 1975

Chapman, S., Bartels, J.: Geomagnetism, vol. 2. Oxford: Clarendon Press 1940

Damaske, D.: Der Weltzeitgang der erdmagnetischen Aktivität als magnetosphärischer Modulationseffekt. Geophys. Abh., Inst. Geophys., Freie Universität Berlin, Heft 5, Berlin: Reimer 1976

Damaske, D.: Magnetospheric modulation of geomagnetic activity, I. Harmonic analysis of quasi-logarithmic indices *Km, Kn,* and *Ks*. Ann. Géophys. **33**, 461–478, 1977

Damaske, D.: On the annual wave of hemispheric geomagnetic activity. J. Geophys. **45**, 81–90, 1978

Damaske, D., Meyer, J.: Comment on "On the sources of the 12-month wave in the *an* and *as* geomagnetic activity indices" by P.N. Mayaud. J. Geophys. **48**, 54–55, 1980

Mayaud, P.N.: The *aa* indices: A 100-year series characterizing the magnetic activity. J. Geophys. Res. **77**, 6870–6874, 1972

Mayaud, P.N.: Analyse d'une série centenaire d'indices d'activité magnétique, IV Les diverses composantes de l'onde annuelle aux latitudes subaurorales. Ann. Géophys. **33**, 479–501, 1977

Mayaud, P.N.: Morphology of the transient irregular variations of the terrestrial magnetic field, and their main statistical laws. Ann. Géophys. **34**, 243–276, 1978

Mayaud, P.N.: On the sources of the 12-month wave in the *an* and *as* geomagnetic activity indices. J. Geophys. **46**, 261–271, 1979

Meyer, J.: A 12-month wave in geomagnetic activity. J. Geophys. Res. **77**, 3566–3574, 1972

Meyer, J.: Zur Modulation der erdmagnetischen Aktivität. Geophys. Abh., Inst. Geophys., Freie Universität Berlin, Heft 3, Berlin: Reimer 1973

Meyer, J., Damaske, D.: Geomagnetic evidence for large-scale magnetotail current systems. J. Geomagn. Geoelectr. **30**, 207, 1978

Wulf, O.R.: Winter-summer difference in geomagnetic activity. J. Geophys. Res. **76**, 1837–1840, 1971

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