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On the Annual Wave of Hemispheric Geomagnetic Activity

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Abstract. A harmonic analysis of geomagnetic indices *Kn* and *Ks* introduced by Mayaud (1967) yields a persistent annual wave in hemispheric activity with a maximum near the summer *solstice* (northern hemisphere) or the winter *solstice* (southern hemisphere). It shows up with nearly the same phase for each of the five northern (or three southern) longitude sectors on which the deduction of the hemispheric indices is based. The results are in accordance with expectation derived from a modified hemispheric modulation function as suggested by the annual amplitude variation of the diurnal UT wave. Apparent discrepancies in the corresponding results for the linear equivalent amplitudes *an* and *as* are shown to be due to an increased amplitude scattering together with a residual of an incompletely eliminated *planetary* 12-month wave in activity *sequences*.

Key words: Geomagnetic activity – Annual wave.

1. Introduction

The most prominent periodicities in the terrestrial modulation of geomagnetic activity are the well-known semi-annual wave and the universal time (UT) variation. Both effects are determined by the varying angle β between the direction of the solar wind flow and the earth's dipole axis. The existence of a UT variation and the terrestrial origin of the semi-annual wave have first been stated by Bartels (1925, 1928, 1932) realizing that the dates of maximum activity are in favour of the equinoxes rather than of the dates where the earth reaches maximum heliographic latitude, thus indicating a purely terrestrial characteristic.

As a daily pendant of the semi-annual wave the UT variation for certain observatories shows a diurnal component for the solstices and a semi-diurnal component for the equinoxes (McIntosh, 1959). The existence of such universal waves was further established by synchronization of appropriate geomagnetic indices (Mayaud, 1967, 1970) and by the harmonic analysis method (Meyer,

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1973, 1974) yielding results in the same form as expected from a modulation function governed by the square-sine of the solar wind angle β. This concept holds true also for the annual amplitude modulation of the diurnal and semi-diurnal waves in geomagnetic activity as far as the earth as a whole is concerned (Damaske, 1976, 1977).

However, when treating separately northern and southern hemispheres the amplitude of the diurnal UT wave turns out to be systematically shifted towards higher (smaller) values in the respective meteorological winter (summer) half-year. The effect has quantitatively been detected from a 14-year series of hemispheric quasi-logarithmic indices *Kn* and *Ks* (Damaske, 1976, 1977) as well as from the corresponding linear indices *an* and *as* (Damaske, 1978). It can fully be accounted for by adding a constant angle β_0 to the time-dependent angle β, with opposite sign on both hemispheres. If such an alteration is really effective, the modified modulation function requires – besides the 6-month wave – the existence of an additional 12-month wave in hemispheric activity itself, due to the asymmetry between summer and winter half-years. The phase of the annual wave in activity modulation is again opposite on both hemispheres corresponding to a maximum at the respective meteorological summer *solstice*. In fact, from hemispheric daily indices *C9n* and *C9s*, i.e., ten-step quasi-logarithmic character figures derived from daily means of *an* and *as* by the same conversion table as yields *C9* from *ap* (Bartels, 1957; see also Siebert, 1971; Damaske, 1977), a significant annual wave has been obtained with phase and amplitude being in full accordance with expectation from the annual modulation of the diurnal UT wave and the modified modulation function $\sin^2(\beta+\beta_0)$. For a detailed description including deductions of all formulas see Damaske, 1976, 1977.

If the disclosed concept of a hemispheric modification of geomagnetic activity modulation is correct, the additional annual wave should appear also in the separate sector values of *K* from which (after latitude standardization) the indices *an* and *as* are calculated (Mayaud, 1968). Its amplitude is expected to be of the same order of magnitude for each of the five northern sectors and the three southern sectors as well, while the phase is being reversed on both hemispheres.

The average annual variation for each separate sector using the sector values after transformation into equivalent amplitudes has been calculated by Mayaud (1977) with data from 1959 to 1974. In addition to the planetary activity modulation following the square-sine of the angle β which he refers to as the McIntosh effect, Mayaud (1977) interprets the results by two other components. The first component has its maximum during the summer solstice of each hemisphere and is assumed to be caused by additional activity, especially in the *H*-component, around 15 h LT. This should give rise to a longitude-dependent amplitude variation being largest on the meridian of the geomagnetic pole in each hemisphere. The second component would correspond to a larger activity around local midnight during the winter solstice than during the summer solstice. This interpretation allows also for the anomalous phase reversal of the annual wave which Mayaud finds for the South American sector. It is the purpose of the present investigation to check by actual harmonic analysis the sectorial data with respect to amplitude and phase behaviour of the respective annual wave, aiming at a better understanding of the origin of the hemispheric annual wave.

2. Results of Harmonic Analysis

Although the synchronization method is an approved and useful tool for the detection of real periodicities, classical harmonic analysis offers a more accurate investigation of amplitudes and phases of the various periodic components. At the same time it permits to calculate the probable error for each single harmonic, thus allowing a clear judgement of reality through an unobjectionable test of significance.

For the analysis of geophysical time-series with respect to yearly periodicities, i.e., annual waves and semi-annual waves or even higher harmonics, the fundamental interval is the period of one year. Usually the analysis is based on the 12 monthly mean values per year. However, for problems of geomagnetic activity, because of its recurrence tendency, it is more reasonable to start from 27-day means, instead. This leads to the methods of harmonic sequence analysis (Meyer, 1973), where the fundamental interval is two years giving annual and semi-annual waves as the second or fourth harmonic, respectively.

The results for the annual wave in 27-day means of sectorial K-values, obtained from the eight biannual periods from 1959/60 till 1973/74, are shown in Fig. 1 for all eight sectors. Especially marked on the dial are the days of summer solstice (June 22) and winter solstice (December 22). The amplitude scale is given in units of K. The probable error circle, defined by an exceeding probability of 50% for the unknown "true" value (Bartels, 1932; see also Meyer, 1974) is approximately the same for each vector and, therefore, is presented only once around the origin. The phase reversal between northern and southern hemispheres, as derived from the modified modulation function $\sin^2(\beta+\beta_o)$, is immediately apparent by the nearly opposite directions of the five northern sector vectors $N_i(i=1,2,3,4,5)$ and the three southern sector vectors $S_j(j=6,7,8)$. The ratio between the vector amplitude and the radius of the probable error circle exceeds for most of them the 2.92 limit (corresponding to a 0.27% exceeding probability) for a definite statistical significance. Only the results for the central Siberian sector N_2 and the South American sector S_8, when being judged separately, do not yet meet these rather pretentious demands for significance. Nevertheless, since the directions of the vectors are again in full accordance with expectancy for the respective hemisphere, their reality need not be doubted, thus indicating the existence of an annual wave on both hemispheres over the entire longitude range. The theoretical dates of the annual wave maximum as deduced from the modified modulation fuction $\sin^2(\beta+\beta_o)$ are the two solstices. The observed phase for the northern hemisphere corresponds to a maximum early in July, whereas in the southern hemisphere the calculated annual maximum lies at about the middle of December.

In spite of the relatively large probable error circles of the single vectors, a superimposed systematic amplitude variation, especially for the northern hemisphere, cannot be excluded from the present results. If such an effect really exists,

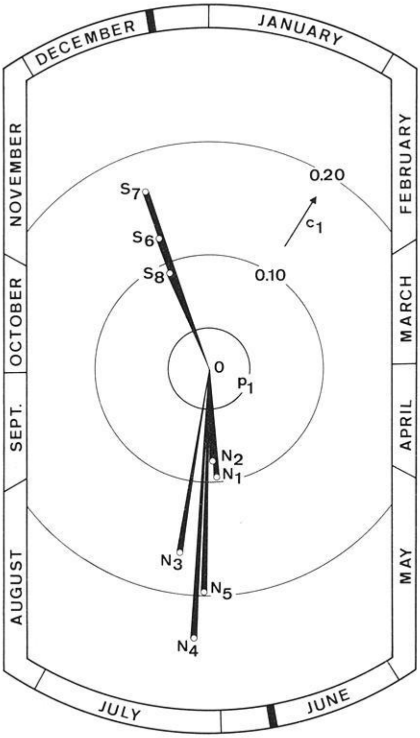

Fig. 1. Harmonic dial for the annual wave in quasi-logarithmic indices K (years 1959–1974) for eight northern and southern longitude sectors. The northern sectors cover the areas as follows: N_1: the western coast of the Pacific Ocean; N_2: central Siberia; N_3: Europe; N_4: the western coast of the Atlantic Ocean; N_5: the eastern coast of the Pacific Ocean. The vectors for the southern hemisphere refer to: S_6: Australia; S_7: the western part of the Indian Ocean; S_8: South America. The amplitude scale is given in units of K, p_1 denotes the probable error. Marked black on the dial are the two solstices

it would imply a longitudinal dependence of the sectorial annual wave amplitude. Such a longitudinal amplitude modulation might well be described in connection with the asymmetry of the polar oval which, on the other hand, is certainly associated with fields and processes in the magnetospheric tail.

To further investigate the small but apparently systematic phase deviations from the theoretical value, the scattering of the results for the annual wave has been compared with the one of the corresponding results for the well-known semi-annual wave calculated from the same eight double-years from 1959 to 1974 (Fig. 2). The notation of the eight vectors is the same as before. The amplitudes are again given in units of K with the (average) probable error circle about the origin of the dial. All vectors except the one for the sector S_8 independently reveal statistical significance. But as for the annual wave, the phase of the vector S_8 leaves no doubt on the real existence of a semi-annual wave also in the South American sector. Moreover, the phases of all eight vectors closely correspond to the expected days of maxima, i.e., the equinoxes. The good agreement among the results for the sectorial semi-annual waves is also demonstrated by the relatively small amplitude scattering. The average amplitude amounts to about two-thirds of the one for the annual wave. (Note that the scale in Fig. 2 is enhanced by a factor of two as compared with Fig. 1). Within the scope of statistical accuracy this ratio agrees with the theoretical ratio of 0.53 deduced from a value of $\beta_o = \pm 11°$ (Damaske, 1976, 1977).

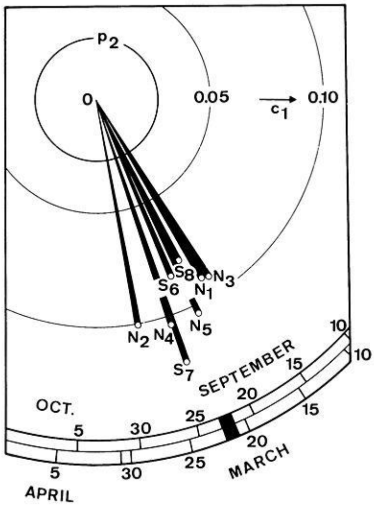

Fig. 2. Harmonic dial for the semi-annual wave in quasi-logarithmic indices *K* (years 1959–1974) for the same longitude sectors as for the annual wave in Fig. 1. The amplitude scale is again given in units of *K*. The theoretical times of wave maxima are the equinoxes

The close correspondence of the average semi-annual wave phase with expectation from theory makes it necessary to look for a physical interpretation of the perceptible phase deviation of the average annual wave. A harmonic analysis carried out with altered boundaries of the fundamental interval and leading to quantitatively the same results, ensures that the effect cannot be caused by any superimposed non-cyclic variation. Fig. 3 shows that the systematic deflection of the annual wave vectors toward the left-hand side of the harmonic dial is also present in the results obtained from the hemispheric daily character figures *C9n* and *C9s*. The vector *N* for the northern hemisphere indicates a wave maximum in the first decade of July. For the southern hemisphere (vector *S*) the date of wave maximum precedes the theoretical time at the winter solistice by approximately the same amount. The pure hemispheric wave, which is clearly present in both vectors, can be obtained by making use of the known phase reversal between the vectors for the two hemispheres. Reversing the sign for one of them, e.g., the vector *S*, yields the average true hemisphere annual wave *N-S*, while any other systematic components are reduced. In fact, the phase of the vector *N-S* corresponds to a wave maximum only three days after the solstices. Substracting this real hemispheric annual wave from either vector *N* or *S* gives the total average vector $N+S$. Though still being statistically insignificant, it may well indicate the presence of another (systematic) annual component, now with equal phase in both hemispheres.

Such a planetary annual wave can also be perceived in other type of data, e.g., means of *Ap* (Siebert, 1971; see also Meyer, 1973). It is especially well pronounced in the years 1959–63, i.e., during the declining branch of the solar cycle 19. As has been shown by Meyer (1972, 1973), it is primarily present in recurrent *sequences* of activity (i.e., sequences of daily values at intervals of 27 days), with arbitrarily alternating phase corresponding to a wave maximum at either one of the equinoxes. Hence, it is partially averaged out when monthly or 27-day means are being analysed. The same morphology of an annual plane-

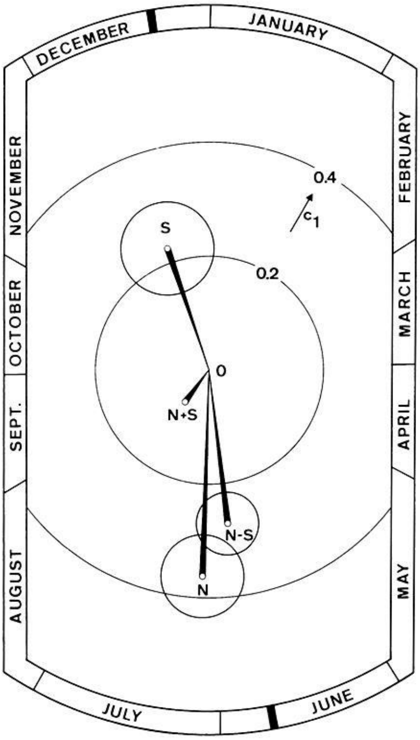

Fig. 3. Annual wave in 27-day means of hemispheric daily character figures *C9n* (northern hemisphere, vector *N*) and *C9s* (southern hemisphere, vector *S*) from the years 1959–74. $N-S$ represents the average annual wave after elimination of the north/south phase reversal; $N+S$ is the total average without taking into account the phase reversal. The circle about the end-point of a vector denotes the probable error

tary wave in geomagnetic activity (with a maximum either in spring or fall) has been found by Berthelier (1976) on the basis of 6 years of indices *Am* and *AE*, and which is attributed to the alternate polarity of the interplanetary magnetic field.

A harmonic analysis of 27-day means of planetary daily character figures *C9m* (derived correspondingly from the three-hourly *am*) for the years 1959–1974 yields a quantitatively similar average result (Fig. 4, vector *M*) as has been obtained for the total average from both hemispheres (vector $N+S$ in Fig. 3). On inspection of the single results for double years which are spread preferably into two opposite directions of the harmonic dial centered at about the dial sectors for March and September (Fig. 4), it is evident that the planetary annual wave has not yet been averaged out completely, even for a full solar cycle. This finding makes it sure that the perceptible deflection of the hemispheric annual wave vectors (*N* and *S* in Fig. 3) into the same direction of the harmonic dial is indeed due to a non-vanishing residual of the planetary annual wave in recurrent activity sequences. The reality of this residual is further supported by the distinct conservation tendency for the single results in Fig. 4. The prevailing phase of the sequential annual wave clearly corresponds to an autumnal maximum throughout the years 1959–1966, then changing sign to a predominating spring maximum until at least 1974.

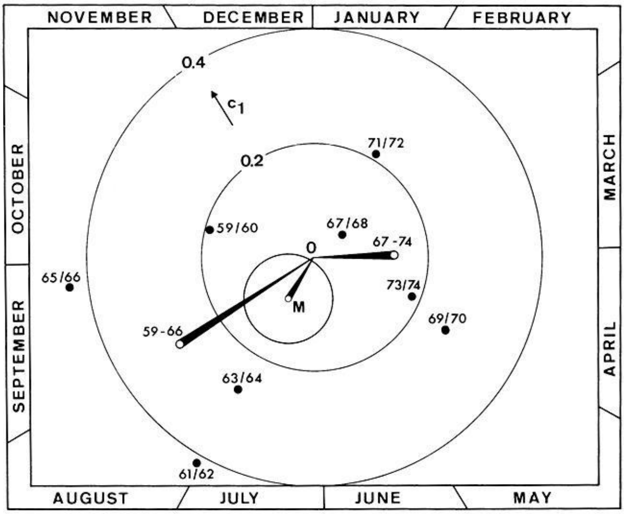

Fig. 4. 12-month wave in 27-day means of the planetary daily character figure *C9m*, for each single double-year from 1959/60 to 1973/74 and for all years (vector *M*). Shown are also the group averages for the years 1959–1966 and 1967–1974

The use of quasi-logarithmic indices implies that the amplitudes of the harmonic components are less sensitive to the general activity level than the results based on linear indices (Meyer, 1973). For the geomagnetic indices *am*, *an*, and *as* the specific amplitude dependence of the diurnal and semi-diurnal UT waves has been set forth in detail by Damaske (1978). As the activity level is primarily governed by sources outside the magnetosphere, it should equally influence the results for each of the eight sectors when equivalent amplitudes instead of quasi-logarithmic indices are analysed. In particular, the planetary 12-month wave in single activity sequences should likewise affect the characteristics of the hemispheric annual wave.

A harmonic analysis of 27-day means of sectorial equivalent amplitudes derived from the sectorial *K*-values by the original conversion table of Mayaud (1968), again for the years 1959–1974, yields essentially the same results for the annual wave (Fig. 5) as from the quasi-logarithmic indices. Only the amplitude scattering is noticeably larger, as expected from the above considerations. And also the deflection of the vectors toward the left-hand side of the dial is somewhat more impressed than for the corresponding results in Fig. 1, thereby affecting especially the vectors with smaller amplitudes. On account of the probable error circle and, in addition, regarding the single vector direction in comparison with the direction of the others, the vectors N_1 and N_2 as well as S_8 in Fig. 5 have no statistical significance at all and thus on no account may give rise to any peculiar interpretation.

For a special investigation of the vector S_8 for the South American sector, Fig. 6 shows once more the single results for the eight double-years from 1959–1974. The clear distribution of the vectors into two opposite dial sections as well as the two group averages for 1959–1966 and 1967–1974 in connection

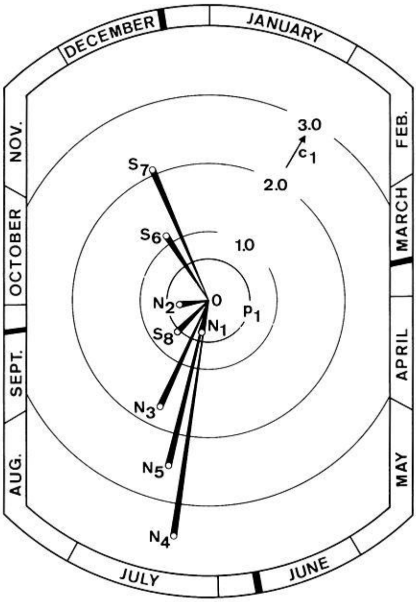

Fig. 5. Same as Fig. 1, but for the annual wave in equivalent amplitudes. In addition to the solstices, the two equinoxes are also marked as black bars on the dial

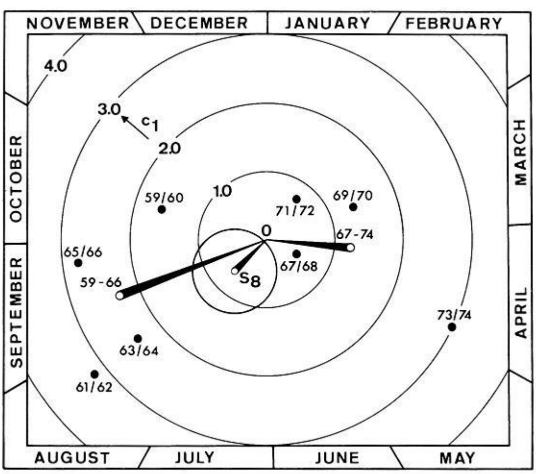

Fig. 6. Same as Fig. 4, but for the annual wave in the equivalent amplitudes for the South American sector only. The total average vector S_8 is identical to the vector S_8 in Fig. 5

with the conservation tendency, make it evident that the vector S_8 as a total average must again be traced back to a non-vanishing residual of the planetary 12-month wave in activity sequences. There is no other systematic annual component detectable in the available data, much less a significant phase reversal, i.e., an annual wave with a maximum at the June solstice.

3. Conclusions

A persistent annual wave in hemispheric magnetic activity, calculated from quasi-logarithmic K-indices with data from 1959 to 1974, clearly exists for all eight longitude sectors, in accordance with the modified modulation function $\sin^2(\beta+\beta_0)$ deduced from the annual amplitude modulation of the diurnal UT wave. In particular, the north/south phase reversal of the hemispheric annual wave is definitely present over the entire longitude range. Apparent discrepancies in the corresponding results from equivalent amplitudes a, especially for the South American sector, are mainly due to a larger amplitude scattering, although a superimposed systematic amplitude modulation cannot be excluded from the present results. In addition, a small residual of the *planetary* 12-month wave in recurrent activity *sequences* found by Meyer (1972, 1973) leads to a systematic phase deflection (relative to the predicted phase) of the calculated hemispheric annual wave. As long as the statistical error for the sectorial annual wave vector is not reduced considerably, the deviations of any single sector result should not give rise to the suggestion of additional mechanisms for an interpretation of the whole hemispheric annual wave.

The comparison between the annual results from (linear) equivalent amplitudes and quasi-longarithmic indices anew illustrates the advantage of the latter measure for the analysis of geomagnetic activity modulation with regard to the study of solar-terrestrial relationships. Modulation amplitudes calculated from quasi-logarithmic values are in general much less affected, if at all, by the level of activity, therefore, yielding the more accurate results because of a smaller scattering. Hence, if not investigating specifically the effect of a varying activity level, preference should be given to quasi-logarithmic measures. Their advantage is again demonstrated for the annual wave in the hemispheric daily character figures *C9n* and *C9s* with all characteristics being in quantitative agreement with expectation from the modified modulation function $\sin^2(\beta \pm 11°)$.

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