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On the Sources of the 12-Month Wave in the An and As Geomagnetic Activity Indices

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Abstract. Damaske (1977; 1978b) and Mayaud (1977b) suggest two greatly different interpretations for the cause of the 12-month wave existing in the an and as indices (or Kn and Ks indices) or in the indices of the five northern and three southern observatory groups from which the former are derived. The present paper discusses the relative validity of these two interpretations. First, the methods of analysis are compared. It is noticeable that the amplitude modulation of the 24-h UT wave, the main argument of the 1977 Damaske'work, is not studied in his 1978b paper because his method does not allow for a separation of the LT component and of its UT modulation. On the other hand, the inverse problem method used by Mayaud does not suffer from this limitation and is applied to much narrower time intervals over the year (60 periods instead of only 8 as considered by Damaske). Furthermore phases and amplitudes are considered by Mayaud whereas Damaske's discussion is mainly based on the amplitudes. Secondly, Mayaud considers morphological features which clearly appear in the records themselves, and which are related to the DP2 fluctuations (Mayaud, 1978a). Damaske neglects them in his analysis, which questions his result. Thirdly, the observed annual and daily variations of the magnetic activity obviously depend on a geometrical factor related to the angle between the solar wind and the dipole axis (with or without an additional tilt). Regarding the question if this geometrical factor is due to an excitation mechanism or to a modulation mechanism, Damaske's interpretation corresponds to the first assumption. Mayaud's interpretation seems to be interesting in that he notices that the second assumption requires the existence of a 12-month wave, whose phase depends on the longitude, and whose interaction with the 12-month wave due to the DP2 fluctuations fully allows for the large scatter in the amplitude of the 12-month wave observed in the various observatory groups.

Key words: Geomagnetic activity indices – An and as indices – Annual wave of geomagnetic activity.

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1. Introduction

According to Damaske (1978b), changes in the 12-month wave of the geomagnetic activity, as they are observed in the indices of the five northern and three southern observatory groups from which the planetary indices an and as (Mayaud, 1968) are derived, do not invalidate the description of hemispheric activity modulation by the function $\sin^2(\beta+\beta_0)$. This function was introduced by him (1977) in order to interpret the systematic amplitude modulation (with opposite sign in both hemispheres) of the 24-h UT wave existing in the Kn and Ks indices, which necessarily induces a 12-month wave. Indeed, the function $\sin^2\beta$ where β is the time dependent angle between the solar wind and the dipole axis allows for both the 6-month wave and the varying UT daily variation existing in the am index (see, for instance, Mayaud, 1977a, where the symbol ψ_M is used instead of β), but does not allow for any difference of the average amplitude between solstices. Then, Damaske assumes that there exists an additional tilt of the effective dipole axis for each hemisphere in the direction away from the sun (one would have $\beta_0=11°$); such a tilt is equivalent to adding dipoles of constant momentum each upon the revolving main dipole. This interpretation of the varying 24-h wave and of the associated 12-month wave greatly differs from the one proposed by Mayaud (1977b), who refers to a special type of disturbances, much larger in local summer during the local afternoon, and to a modulation of the LT auroral disturbances by $\sin^2\beta$. The present paper intends to evaluate the relative validity of these two interpretations.

2. Annual and Daily Variations of the Indices An and As

Figure 1 displays the daily and annual variations of the indices an and as for the years 1959–1974 (a sample identical to those used by Damaske and Mayaud in their respective analyses) in the following way (see also Mayaud 1977a and b): For every 3-h UT interval, each one of the indices has been averaged over the years mentioned and over the nth interval

$$(n-1)\times 6° < \Lambda < n\times 6°$$

where Λ denotes solar longitude ($\Lambda=0°$ coresponding to the vernal equinox) and n runs from 1 to 60. The resulting eight average values of an and as per interval of Λ thus represent the average daily variation over a period of about six consecutive days at the corresponding time of the year (as given by Λ). The 60 sets of eight values per day and per index (an or as) are then drawn side by side yielding the curves shown within Fig. 1. A modulating function such as the function $\sin^2\beta$ causes a 6-month wave culminating at the equinoxes ($\Lambda=0°$ or 180°) and daily variations made up of a predominantly 24-h wave at the solstices (out of phase from one solstice to the other) and of a predominantly 12-h wave at the equinoxes (see the top-curve of Fig. 2, discussed below and displaying the variation of $\sin^2\beta$). Such features partly appear in Fig. 1 (a 6-month wave and a phase reversal of the daily variation

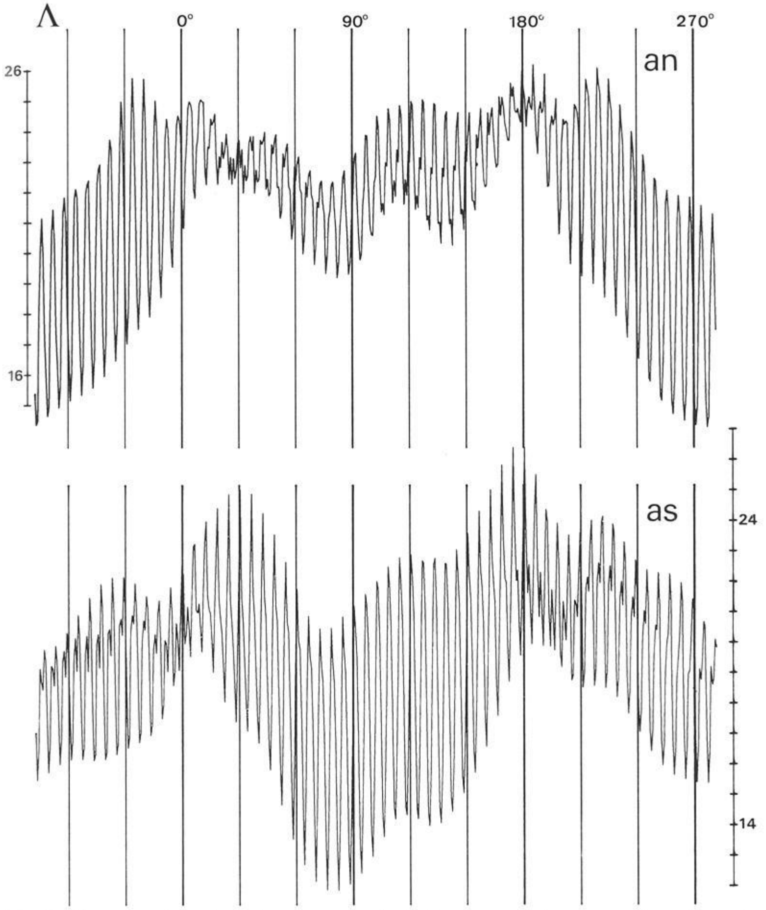

Fig. 1. Average three-hourly geomagnetic indices an and as as a function of solar longitude Λ ($\Lambda = 0°$ corresponding to the vernal equinox) and of the universal time *h* for the years 1959–1974. The Λ-scale shown indicates some of the lower boundary values of the 60 non-overlapping 6° wide Λ intervals within which the original indices have been averaged for every 3-h UT interval of the day. Within every Λ interval the curves contain 8 average an or as values as a function of h (0–3, 3–6, ..., 21–24 UT; the corresponding 60 UT scales are not shown, because of their smallness). Essentially, each curve gives 60 daily variations in the course of the year, drawn as a continuous function. For more explanation, see text

from one solstice to the other), but two other features appear: (a) a significant daily variation is still present at the equinoxes, and its amplitude is greater in the southern hemisphere (Mayaud, 1979, for a discussion of this feature); (b) there exists a large asymmetry in the amplitude of the daily variation from one solstice to the other in each hemisphere (it is what Damaske calls the amplitude modulation or the diurnal UT wave), which is associated with a 12-month wave culminating in local summer. This is the feature which Damaske and Mayaud interpret in different ways.

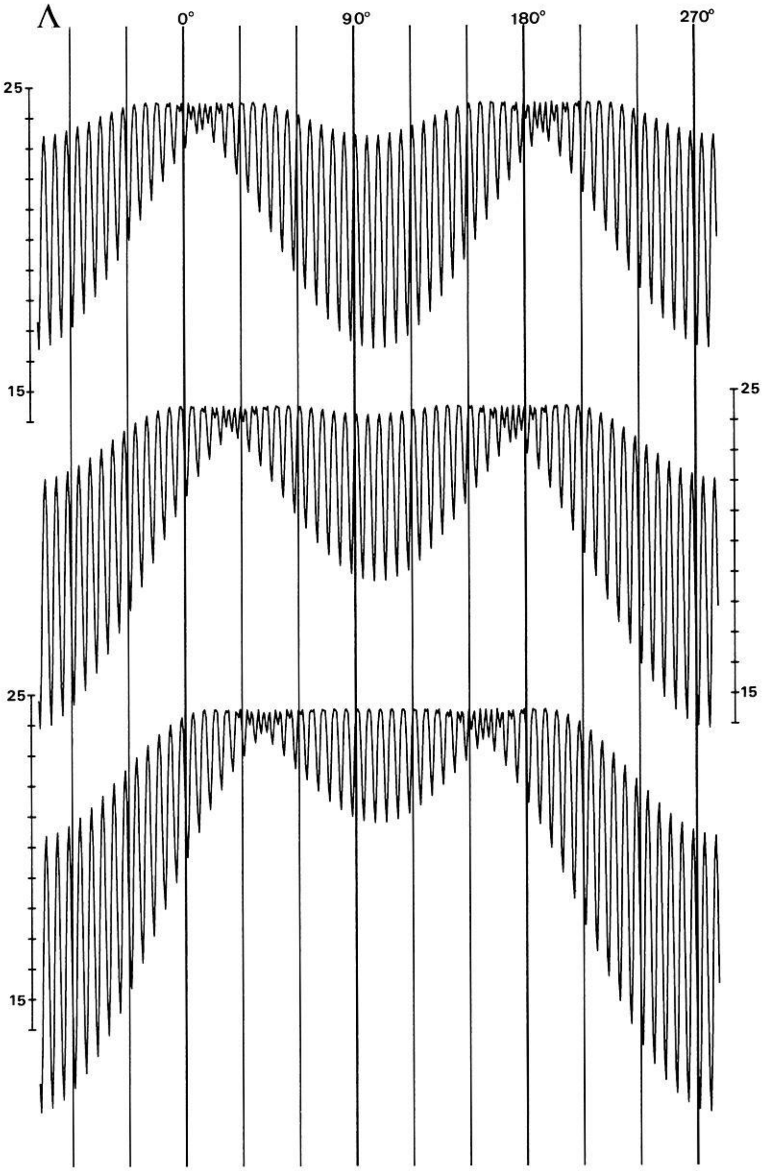

Fig. 2. Annual and daily variations of the function $\sin^2(\beta^+\beta_0)$, as a function (in the manner applied within Fig. 1) of the solar longitude Λ and of the universal time h, for various values of β_0. Top curve: $\beta_0=0°$, mid-curve: $\beta_0=6°$, bottom-curve: $\beta_0=12°$. Note that all these curves are shifted by 10° with respect to the solar longitude $\Lambda=0°$ for taking into account the phase shift of 10° found by Mayaud (1977a) for the index am=(an+as)/2 or the similar shift of 11 days found by Damaske (1977) in the indices an and as

3. Capability of the Function $\sin^2(\beta+\beta_0)$ to Fit the Data

For comparison to the experimental values shown within Fig. 1, Fig. 2 in the same way displays the synthetic function

$$A=A_0+A_1\sin^2(\beta+\beta_0)$$

for different values of β_0. Here, the above-mentioned angle β is considered to be a function of Λ and h (daily hour, in UT) according to the relation (see Mayaud 1977a and b)

$$\cos\beta=\cos(\pi/2+\delta\sin(\Lambda\text{-}\Lambda_0))\cos\Phi$$
$$+\sin(\pi/2+\delta\sin(\Lambda\text{-}\Lambda_0))\sin\Phi\cos(h\text{-}h_0)$$

where $\delta=23°\ 27'$ denotes the obliquity of the ecliptic and $\Phi=11.5°$ is the earth's dipolar offset angle. Λ_0 and h_0 have been chosen according to the results given by Mayaud (1977a, Table 1) for the am index. A_0 and A_1 have been chosen arbitrarily in such a way that the curves in magnitude roughly correspond to the curves shown within Fig. 1. The sign chosen for β_0 corresponds to the additional tilt in the northern hemisphere; similar curves for the southern hemisphere can be easily imagined. The fact that the bottom-curve is drawn with $\beta_0=12°$ instead of the value 11° evaluated by Damaske (1977) does not invalidate the following remarks. Furthermore, one must note that, if the above formula used for $\cos\beta$ is approximate, it is easy to check that differences with the exact formula are negligible. They are largest for $\Lambda=45°+n90°$ (n being an integer) and are of about 1% only. Now, it is obvious that the main feature in the $\beta_0=12°$ curve is similar to the feature (b) mentioned in section 2: The amplitude of the daily variation is graeter in local winter, and the activity level is higher in local summer. Consequently, it might be concluded that the modulating function $\sin^2(\beta+\beta_0)$ is capable of fitting the experimental data.

However, let us first consider a point on which Damaske (1978b) strongly insists: The reliability of the statistical harmonic analysis method used by him, which allows a clear judgement of reality through an 'unobjectionable' test of significance. Such harmonic analyses are performed for individual days (amplitudes and phases of the 24-h and 12-h UT waves) and for sequences of 27-day averages over a fundamental interval of two years (amplitudes and phases of the 12-month and 6-month waves are obtained as the second and fourth harmonics, respectively). In the first case, days are ranked into 8 sectors of 43 days per year, which yields a cloud of 602 points per sector with the 14-year sample used; in the second case, one has a cloud of 7 points (the 7 sequences of 2 years). The limit 2.92 (corresponding to a 0.27% exceeding probability) chosen for the ratio between the vector amplitude and the radius of the probable error circle may be used only at the end of the harmonic analysis, but not to the same extent in the subsequent treatment of the data. Furthermore, non significant vector amplitudes are used in the latter, and when rebuilding the 12-month modulation of the 24-h amplitude wave, phase deviations are ignored. Now, if one computes the value of β, from the ratios g/f given by Damaske (1977) in his analysis of the Kn and Ks indices, as such a value is derived from the 24-h amplitude modulation, one finds that the corresponding values of β_0 are respectively 11°9 and 10°6 in the northern and southern hemispheres. The resulting theoretical ratios between the amplitudes of the 6-month and

12-month waves are equal to 0.49 and 0.54 respectively, while observed values for these ratios, according to his Figs. 19 and 20, are equal to 0.55 and 0.69 hence, they deviate by 12% and 27% in a direction which indicates that the 12-month wave amplitude is too small with respect to the one of the 6-month wave. May one say that the independent check (a full accordance of the observed 12-month and 6-month waves with expectation deduced from the annual amplitude modulation of the 24-h UT wave), considered as the basis of interpretation, is satisfied? The question is all the more sensible since one must remember that, as it will be pointed out in the next section, there exists another source for the 12-month wave observed in the indices, which cannot be ascribed to effects of the additional tilt β_0 of the dipole axis.

Now, a comparison of Figs. 1 and 2 raises several questions. Firstly, the envelopes of the maxima and minima in the curve $\beta_0 = 12°$ of Fig. 2 do not resemble those of the experimental curves of Fig. 1. One has however to be aware that the latter correspond to the linear an and as indices. From Fig. 15 of Damaske (1978a), it is easy to evaluate the values of β_0 for these indices: they are equal to 9.7° and 8.2° respectively. The difference from the result for the Kn and Ks indices is quite significant, and might be questioned. But, whatever be its source (see Sect. 6), it is obvious that the envelope of the maxima, at local summer time, of the an or as indices in Fig. 1 presents a trough which is quite pronounced, while it already hardly marked in the mid-curve of Fig. 2 (that is, with $\beta_0 = 6°$). Again, the 12-month wave amplitude in the indices is smaller than it is in the function $\sin^2 (\beta + \beta_0)$, and this is consistent with the deviations mentioned above between the observed and expected ratios (6-month/12-month amplitude wave). Secondly, the solar longitudes at which the daily variation becomes predominantly a 12-h wave are at a distance of about four times 30° in the $\beta_0 = 12°$ curve of Fig. 2. But in the experimental curves of Fig. 1, this distance is apparently of about five times 30° with an, and probably more with as. Now, Damaske's analysis of the diurnal waves is, to some extent, rather crude since he uses only 8 sectors per year, each of them ocrresponding to a solar longitude sector of approximately 45°. A division by 6° wide sectors, as made in Fig. 2 (and as carried out by Mayaud in all his analyses), shows that it is hardly sufficient for following the extremely rapid deformations of the daily variation at some epochs of the year. Thirdly, the morphological aspect of the experimental curves greatly differs from the one of the theoretical functions. We already said that a significant daily variation appears at the equinoxes (the feature a mentioned in Sect. 2). But, the feature b has to be completed by this additional observation: while, during the local winter in each hemisphere, the daily variation of the indices appears to be rather regular (namely, an almost pure 24-h wave) as the daily variation of $\sin^2 \beta$ [or $\sin^2 (\beta + \beta_0)$] is, it is no longer true during the local summer. At these epochs, the daily variation is greatly distorted, which indicates that another phenomenon is superimposed, and the additional tilt β_0 of the main dipole does not allow for it since the regularity of the daily variation of the function $\sin^2 (\beta + \beta_0)$ is as great at a given solstice as at the other. This additional phenomenon corresponds to a first component of the 12-month wave in the an and as indices, as described by Mayaud (1977b).

4. A Local Time Source of the 12-Month Wave

Bartels et al. (1940) already noticed a summer-winter difference in the activity level from subauroral stations. Mayaud (1956) detected it as being due to a local afternoon phenomenon, but misunderstood its interpretation (see Mayaud, 1978a, on that error). Mc Intosh (1959) referred to this phenomenon, and Mayaud (1965) gave a new and clear illustration of it in displaying statistical daily curves derived from K indices at a chain of European stations. Mayaud (1977b) made a new and extensive study of this particular wave of activity: his Fig. 2 (a 103-year sample of data at two subauroral stations), 3 (a 3-year sample at the European chain of stations mentioned above) and 4 (an 11-year sample at another subauroral station) are an undeniable proof that a particular phenomenon, at work in the *H* component during the local afternoon, is much larger during the local summer but is almost non existent during the local winter. Furthermore, the phenomenon does not depend on the $\sin^2\beta$ modulating function, and was interpreted by Mayaud (1978a) as being due to the DP2 fluctuations. Now, such a phenomenon necessarily induces a 12-month wave in the an and as indices, which culminates at the local summer of each hemisphere. If its amplitude was identical at any geographical longitude, the local time daily variation of the phenomenon would be averaged out in the planetary indices derived from an ideal longitudinal network distribution, and one would have only the 12-month wave. In other words, the envelopes of the maxima and minima of the daily variation in the top curve of Fig. 2 would present a 12-month wave without any change in the range of the UT daily variation due to $\sin^2\beta$. In fact, the analysis of Mayaud (1977b) for each of the five northern and three southern observatory groups from which an and as indices are derived shows that the amplitude of this particular phenomenon varies from one group to another, that is with longitude; hence, a UT pseudo-component is brought about in the UT daily variation of the an and as indices, which is the cause of the irregularities in the daily variation at other seasons than the local winter (see Fig. 1). Furthermore, it is clear in this Figure that the phenomenon thus superimposed appears to be more intense in the northern hemisphere (an) than in the southern hemisphere (as). This is consistent with Fig. 12 of Mayaud (1977b), which indicates that the amplitude of the phenomenon is, on the average, greater in the five northern groups than in the three southern (it is also the reason for which Damaske, 1977) obtains a smaller deviation in the northern hemisphere than in the southern one when comparing the observed and expected ratios of the 6-month and 12-month waves). Finally, it is obvious that, since Damaske (1977) ignores the existence of this particular phenomenon in his analysis, his results may be questioned and, at least, values obtained for β_0 are certainly greatly overestimated.

5. A Universal Time Source of the 12-Month Wave

We have now to compare the respective interpretations of Damaske (1978b) and Mayaud (1977b) concerning the very large scatter in the amplitudes of the 12-month waves observed in the eight observatory groups from which an and as indices are derived. Damaske judges that a superimposed systematic amplitude variation cannot be excluded, and might be described in connection with the asymmetry of the polar oval and associated with fields and processes in the magnetospheric tail. Mayaud accounts for it by the interaction between the 12-month wave due to the DP2 fluctuations and another 12-month wave due to the modulating function $\sin^2\beta$ without any interference of an additional tilt β_0.

A first remark has to be made concerning the analyses themselves. Damaske deals with the single annual variation and neglects entirely the daily variation. Then Mayaud's analysis is more comprehensive since it deals with both, and makes that by grouping the data into 60 solar longitude sectors; this guarantees that deformation on the daily variation may be followed with detail. Furthermore, the inverse problem method used allows for a direct and coherent computation of the parameters of both the daily and annual variations; smallness of, and coherence between the residues obtained for the various observatory groups are considered as being the test of the reliability of the results.

A crucial question in evaluating the respective interpretations is as follows: are the geometrical factors $\sin^2\beta$ or $\sin^2(\beta+\beta_0)$ an excitation mechanism or only a modulation mechanism? First, one knows (Mayaud, 1978b) that the ring current variations do not depend on $\sin^2\beta$ since the corresponding UT daily wave does not exist but only the 6-month wave. The DP2 fluctuations are no more dependent on this geometrical factor. We are then left with the auroral disturbances only, and they must be sensitive to $\sin^2\beta$ since they provide the main contribution to the an and as indices. Now, the main daily modulation in the auroral disturbances is a LT variation, due to the configuration of the magnetosphere, and their excitation mechanism is not the geometrical factor $\sin^2\beta$ (it is recognized nowadays that the interplanetary magnetic field plays a determining role). Hence, let us assume that the LT auroral variation is modulated by $\sin^2\beta$: the modulation of a LT daily variation by the UT wave depending on $\sin^2\beta$ must bring about a 12-month wave whose amplitude and phase vary similarly with longitude in both hemispheres.

Table 1 gives the values of $\sin^2\beta$ at the times of its maximum or minimum around the days close to $\Lambda=90°$ (June solstice) or $\Lambda=270°$ (December solstice). If the longitude of the station (or of a given observatory group from which an or as are derived) is such as the LT maximum of the auroral disturbances occurs at 1030 UT (or 2230 UT), the effect of $\sin^2\beta$ would be symmetrical from one solstice to the other, and no 12-month wave is brought about. It is no longer true at longitudes where this maximum occurs at 0430 UT or 1630 UT. In these cases, the intensity of the maximum will be more reduced at the December solstice than the other solstice. Thus, a 12-month wave is brought about which is out of phase from one longitude (LT maximum at 0430 UT) to the opposite longitude (LT maximum at 1630 UT). And, at intermediate longitudes, its amplitude varies according to a sinusoidal law, passing through a zero value where the LT maximum occurs at 1030 UT or 2230 UT. Obviously, the effect is the same, at a given longitude, in both hemispheres. This fact seems to be misunderstood by Damaske (1978b), who refers to this 12-month wave in saying that it corresponds to a greater activity around LT

Table 1

	0430 UT	1630 UT
June solstice	0.96	0.67
December solstice	0.67	0.96

Values of $\sin^2\beta$ for two epochs

midnight during the winter solstice than during the summer solstice. In fact, the modulation is effective at any time of the day and, at a given longitude, one can have in both hemispheres an increase (or a decrease) either at the June solstice or at the December solstice. Furthermore, the resulting effects of this modulation by $\sin^2\beta$ of the auroral disturbances must be well understood at the level of the planetary indices. Assuming (1) that the network of stations is well distributed with longitude and (2) that the LT auroral daily variation has the same range at any longitude, the 12-month waves existing at each longitude would be averaged out. If not, a UT pseudo-component will exist in the planetary indices, and also a 12-month wave. Let us note (and this is very important in order to understand the scatter of the amplitudes of the 12-month wave in the 8 observatory groups) that, at some longitudes in each hemisphere, the two components of the 12-month wave (the one due to the DP2 fluctuations and the one, just described, due to the modulation of the auroral disturbances by $\sin^2\beta$) may have the same phase or opposite phases.

Now, the model used by Mayaud (1977b) allows for these two components when analysing, by the inverse problem method, the 3-h average values of the 60 solar longitude sectors for the indices of the five northern and three southern observatory groups. His Fig. 9 and 10 show that the consistency of the residues is quite good (any 12-month wave culminating at a given solstice has disappeared, and only the 12-month wave culminating at fall and discussed by Damaske (1978b) is still present because the model does not allow for it), and that the amplitude of the 12-month wave due to the $\sin^2\beta$ modulation varies with longitude as expected; furthermore, the times of the LT auroral variation maximum, when corrected from the $\sin^2\beta$ effect, are quite consistent between the 8 observatory groups, since their average is 22.44 h ± 0.34 in corrected geomagnetic time. Such results are, to some extent, quite impressive since the data analyzed constitute eight series of independent data, and they are obtained without any use of an additional tilt β_0 of the dipole axis. On the other hand, in his analysis of these same data, Damaske (1978b) cannot deal with the method used for the Kn and Ks indices in its totality because a harmonic analysis of the daily variation would not permit him to discriminate between the LT and the UT daily variation at each observatory group. Then, only harmonic analyses of the 27-day averages are performed for each observatory group, which provide amplitude vectors of the 12-month and 6-month waves; this is made both for the quasi-logarithmic indices and the linear indices but amplitude vectors of the 6-month wave are not considered in his paper. With the quasi-logarithmic indices, a large scattering is observed for the 12-

month wave but not for the 6-month wave. Damaske states that 'the average amplitude of the 6-month wave amounts to about two-thirds of the one of the 12-month wave; within the scope of statistical accuracy, this ratio agrees with the theoretical ratio of 0.53 deduced from a value $\beta_0 = \pm 11°$'. In fact, a ratio of $^2/_3$ corresponds to $\beta_0 = \pm 8°7$. Furthermore, ratios of the 6-month and 12-month amplitude vectors for each observatory group fluctuate between 1.28 and 0.44, which corresponds to values of β_0 equal to 4.6° and 13° respectively. May so important variations of β_0 be ascribed to 'the asymmetry of the polar oval which is certainly associated with fields and processes in the magnetospheric tail'? As said above, the non-availability of the 6-month amplitude vectors for the linear indices in Damaske's paper does not permit us to compute the ratios for each observatory group in this case, but the scattering of the 12-month amplitude vectors, as they are illustrated (his Fig. 5, when compared with his Fig. 1), is still larger. In our own line of interpretation, such a scatter is easily interpreted and taken into account by the model because, at some of the observatory groups, the two components of the 12-month wave are in phase while they have opposite phases at others. Let us note that the latter case is the reason why Damaske gets 12-month vector amplitudes below the significance level in some of the observatory groups.

6. Quasi-Logarithmic Indices or Linear Indices?

Damaske (1978b), in his conclusion, states that the quasi-logarithmic indices are more advantageous, when analysing geomagnetic activity modulation, because they are less affected, if at all, by the activity level and then yield the more accurate results thanks to a smaller scattering. This is partly true but calls for the following remarks. Firstly, quasi-logarithmic indices are based on a scale which is greatly distorted with respect to a true logarithmic scale, and one would know the effect of this distortion. In our opinion, the only correct method, if one wishes to use logarithmic values, is to convert the amplitude indices into true logarithms. Anyway, this would accentuate the effect looked for by Damaske. But, if the meaning of an arithmetic average of amplitudes which do not have a gaussian distribution is not always clear, what is the meaning of a geometric average (which is what one uses when taking the average of logarithms)? Secondly, in the present case, it is easy, for instance, to understand the difference found by Damaske (1978b) for the 12-month vector amplitudes of the observatory groups N2 and S8 when one compares those obtained with the quasilogarithmic indices and with the linear indices. These two groups are those where the two components of the 12-month wave (according to our interpretation) have opposite phases. With the quasi-logarithmic indices, the resulting vectors culminate at local summer, while they are greatly reduced in amplitude (with the linear indices) and turn by about or more than 90° (see his Figs. 1 and 5: we do not understand however the phase of the vector S8 in this Fig. 5 when we look at the annual variation of this group as illustrated in Fig. 8 of Mayaud, 1977b). Now, Fig. 4 of Mayaud (1977b) shows that the effect of the DP2 fluctuations is more important at low activity levels than at high activity levels (these fluctuations are merged into the auroral disturbances in the latter case). This means that the quasi-logarithmic indices are fully sensitive to the DP2 fluctuations while the effect of the large auroral disturbances is lessened; hence, the effect of the 12-month wave component due to $\sin^2\beta$ is also lessened. When using any index, one has not to forget that the frequency distributions of the individual indices, possibly different for one or the other phenomenon, can play a significant role.

7. Conclusions

Finally, any evaluation of the relative validity of Damaske's and Mayaud's interpretations of the 12-month wave in the indices of the observatory groups has to consider the following facts. Firstly, Mayaud's analysis is more comprehensive since not only annual variations but also daily variations are taken into account. Secondly, the existence of a 12-month wave due to the DP2 fluctuations which are not modulated by the geometrical factor $\sin^2\beta$, is certain. Thirdly, the modulation by $\sin^2\beta$ [or $\sin^2(\beta+\beta_0)$] may be conceived in two ways: it would be either an additive effect (that is, an excitation effect) or a multiplicative effect (that is, a time modulation). What is the most sensible assumption?

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