POWER-SPECTRUM ANALYSIS OF LOCAL GEOMAGNETIC DISTURBANCES AND THEIR RELATIONSHIP TO COSMIC-RAY AND AURORA INTENSITY

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Abstract. Power-spectrum analyses have been carried out on two data sets of the geomagnetic K-index from the Athens and Sofia magnetic Observatories. For the period between 1956–1984, periodicities of about 2.8 and 6 months have been obtained. Similar results were found by the auto-correlation technique. Both periods are significant to 0.05 and 0.01 level, respectively. In our attempt to explain transient geomagnetic disturbances caused by other parameters, the K-index was correlated to cosmic-ray and aurora intensity. The best correlation coefficient between K-variations and cosmic-ray data from Athens Neutron-Monitor Station was 0.58 and between K-index and Auroral activity index was 0.47.

An attempt to interpret these periodicities and relationships has been made.

1. Introduction

All the components of geomagnetic field show distinct periodicities ranging from a few seconds to several thousand years. Periods up to 22 yr are severally connected with solar phenomena while larger periodicities are mostly related to the internal structure of the Earth and its core dynamics, though some periods of a few years could also be of internal origin (Currie, 1973; Liritzis, 1986; Barton, 1983). A review of geomagnetic field variations has been made by Kane (1976), though early attempts for search of periodicities in geomagnetic elements are described in a book by Vestine *et al.* (1947). Regarding the geomagnetic indices, the planetary indices K_P and A_P are known to show long-term and short-term variations. Since the geomagnetic activity depends upon solar emission, it is anticipated that these two should show a parallelism (Kane, 1976). Periodic variations of 11-yr, 22-yr (Cheronsky, 1966) annual, semiannual and diurnal variations (Mayaud, 1970; from his study of a_n and a_m indices in the two hemispheres) and 22-day variations (Russell and McPherron, 1973; Fraser and Smith, 1973; for A_P indices) have been reported. This is the first attempt to spectrally analyse local K-indices that derive from two nondistant magnetic Observatory Stations: the Penteli in Athens and the Panagjuriste in Sofia. Our aim in this work is to search for possible periodicities of local nature in K-index

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and to try to locate the cause of such periodic variations. Therefore certain relationships were examined between the local K-index and cosmic-ray intensity as well as between the K-index and the aurora intensity index.

It has been reported that, rather infrequently, a great magnetic storm will be accompanied by a brief but considerable decrease ($\approx 10\%$) in the intensity of cosmic-rays observed at the ground. In a few cases a smaller increase has been observed during the preceeding solar flare. These changes are not yet explained. Also it is known that the long-term variations of cosmic-ray intensity can be expressed by appropriate solar, interplanetary and geomagnetic indices (e.g., Mavromichalaki and Petropoulos, 1987).

The interaction of solar wind with the Earth's magnetosphere produces various types of geomagnetic disturbances, like magnetic storms, magnetic bays, pulsations, equatorial-ring current etc. Among them the magnetic storm is the most important feature of the the D-field (Chapman, 1964). During a considerable magnetic storm that includes a few DP substorms there will be a similar number of auroral displays contemporaneous with the substorms. On the other hand, sunspots constitute only potentials of solar activity that are actually released by solar eruptions. These are the hallmark of solar-terrestrial interaction. Single energetic flares and periods of enhanced eruptional activity seem to participate, too, in these interaction (Landscheidt, 1988). It was along these lines that we thought of examining any possible relationship between K-index variations and the contemporary respective variations in cosmic-ray intensity from Athens Neutron Monitor Station, as well as, the auroral intensity.

2. Selection of Data

In this work we have used the K-indices of geomagnetic activity obtained from the Penteli Magnetic Observatory in Athens with geographic coordinates $\lambda = 23° 52$, $\varphi = 38° 03$, and $h = 495$ m and the Panagjuriste Magnetic Observatory in Sofia with $\lambda = 24° 11$, $\varphi = 42° 31$ and $h = 556$ m. They span from 1959–84 and 1956–78 respectively. (Note: the horizontal component H of the geomagnetic field is for Athens $26400\gamma \pm \Delta H$, and for Sofia $23000\gamma \pm \Delta H$, where ΔH is the residual of H and varies within 580γ for Athens and 511γ for Sofia). It is known that the K-index is the range (in γ units) of the disturbance variation of the geomagnetic field (Bartels, 1957). The range for K-9 index for Athens and Sofia Magnetic Observatories is 300γ and 350γ respectively. These two data sets in comparison to the monthly sunspot number index (R_z) obtained from solar Geophysical Data Reports (1983) are presented in Figure 1 (a, b, c).

The monthly cosmic-ray intensity data from the Neutron Monitor Athens Station (Super NM-64, magnetic rigidity 8.72 GV) for the period 1970–1978 are also used (Figure 2). The auroral activity index A was provided by the Geophysical Institute of Alaska University. This index ranges in values from 1 (no aurora at the college zenith during the active night) to 9 (a great intensity of all

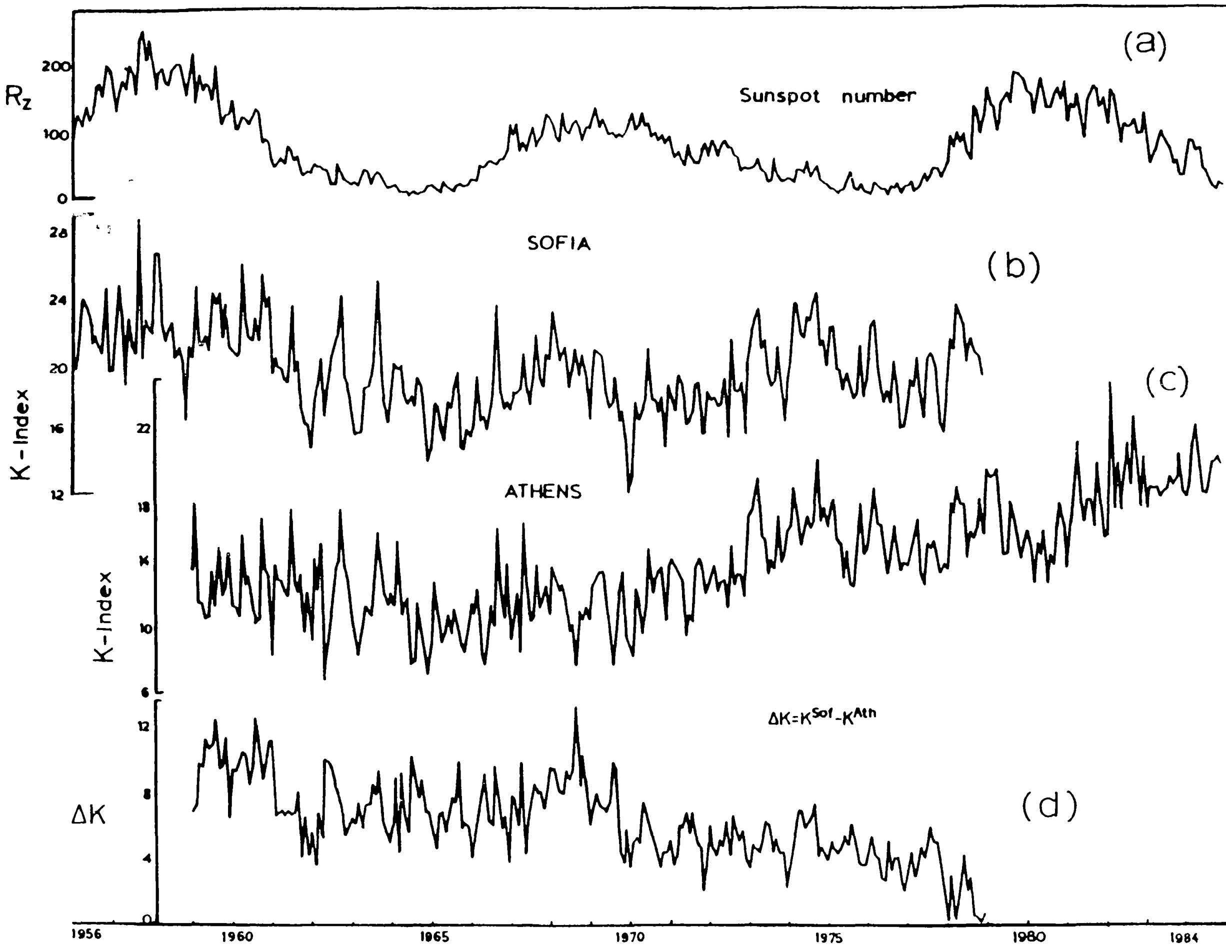

Fig. 1. Time series plots of sunspot numbers R_z, the geomagnetic local K-indices of Sofia and Athens Observatories and their differences $\Delta K = K^{\mathrm{Sof}} - K^{\mathrm{Ath}}$.

emissions). The auroral activity index A simultaneously with the Ha index and sodium (Na) index for the time period 1957–1966 are shown in Figure 3.

The two data series of geomagnetic index K exhibit an almost similar trend characterized by coincident drastic fluctuations (spilly appearance) which imply similar types of occurred storms. Other fluctuations could be due to the error resolution in the recording magnetometer. The correlation coefficient (r) between them was $r = 0.62$. The 11-yr cycle is most pronounced in the period 1964–74. From 1972 onwards there is a tendency of increasing K-index following increased sunspot activity. This in fact occurs for active solar cycles (note the 19th and 21st solar cycles in Figure 1). There is not a direct correspondence between the maxima of K and R_z but a time lag of 1–2 yr has been reported (Mavromichalaki and Petropoulos, 1984).

Note also that the K values for Sofia are higher than those from Athens because the K-9 value for Sofia is higher than that in Athens. We took the $\Delta K = K^{\mathrm{Sof}} - K^{\mathrm{Ath}}$ difference in order to eliminate any common external (magnetic storms etc.) and internal (dipole and nondipole field) effects. In the latter, of

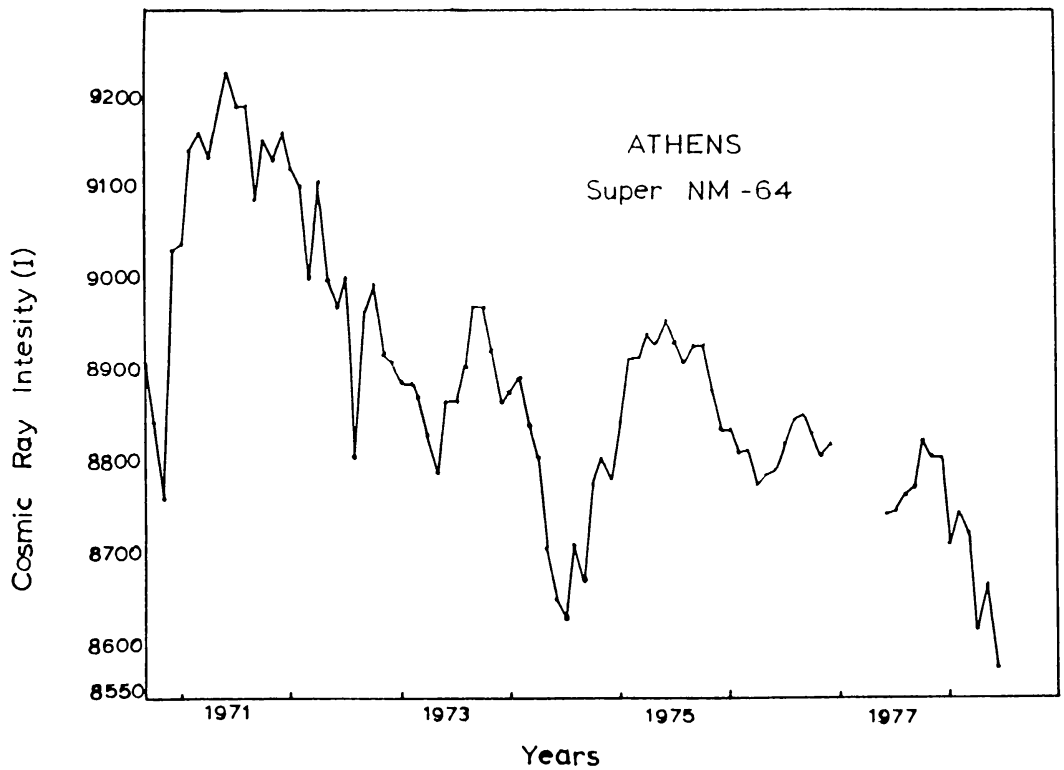

Fig. 2. Cosmic-ray intensity variations from the Athens Super NM-64 Station for the period 1970–1978.

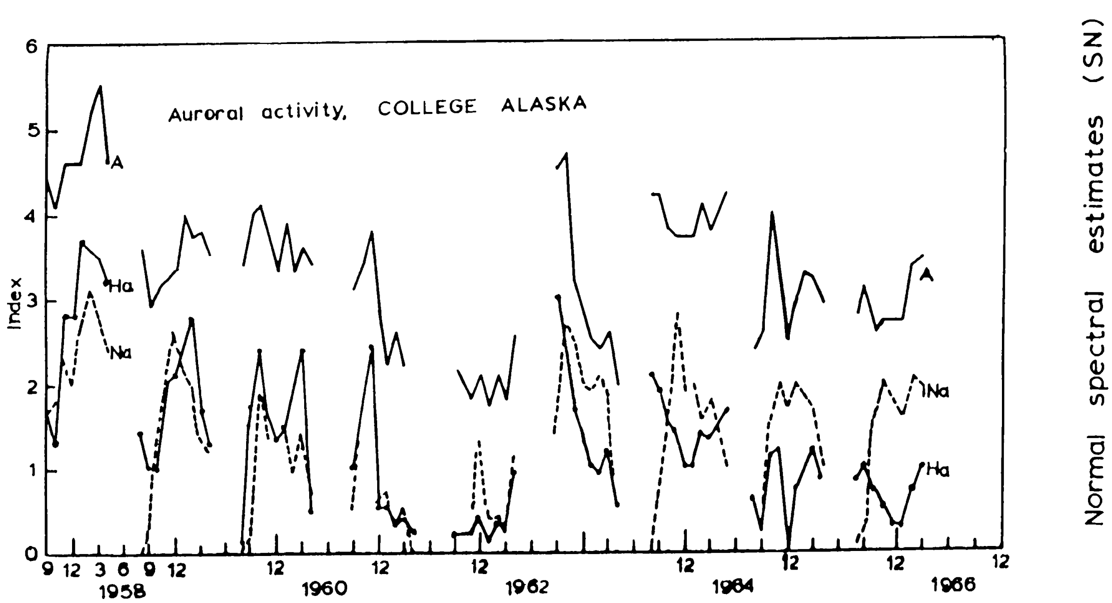

Fig. 3. Auroral activity data of Alaska University covering the period 1957–1966.

course, remains a variable of crustal magnetization which is of localized character. The ΔK values, which are shown in Figure 1, vary between 0–12, being on average 6 ± 6. The individual $(K^{\mathrm{Sof}}_{\max} - K^{\mathrm{Ath}}_{\max})$ and $(K^{\mathrm{Sof}}_{\min} - K^{\mathrm{Ath}}_{\min})$ values for Athens and Sofia are both equal to 5. That is a number almost similar to the average ΔK which implies a consistent trend of variation of these two data series.

One should also note that drastic fluctuations in ΔK occur at the beginning of each year (winter season) while peaks appear around the mid-year.

As expected simultaneous variations of the magnetic component as ΔH residuals are reflected in K-variations. Therefore the high correlation coefficient ($r = 0.856$) is appeared without time lag between the two parameters for the Sofia data set. The poor correlation coefficient between $\Delta K = K^{\mathrm{Sof}} - K^{\mathrm{Ath}}$ and ΔH^{Sof} ($r = 0.27$) might be due to either local crustal changes in Athens Observatory region, or missing K-data entries in the Athens record.

The power (variance) spectra of the above data time series were obtained using the Blackman and Tukey (1959) approach. The spectra were obtained from autocorrelation functions, too, which were truncated at different lags.

3. Results

The power spectral analysis of K-indices separately for Athens and Sofia and the relationships between K with cosmic-ray intensity and K with auroral activity are analytically presented in the following sections:

a. Power spectral analysis of K-indices from Athens and Sofia and their differences ΔK

The power spectral analysis (PSA) for Athens and Sofia data sets are presented in Figures 4 and 5, respectively. For three time lags (60, 80, 100) a significant period of 2.4–2.9 months (95% significant level) was found and a tendency for the 6-month period (93% significant level) for Athens data was appeared (Figure 4). For lags 60 and 80 both periods of 6-month (99%) and 2.9 month (95%) were obtained also for Sofia data (Figure 5).

To our knowledge the mean period of 2.8 months as it was obtained from the data series of the two stations or about 80 days is obtained for first time for local geomagnetic variations or other geomagnetic components, whilst the semi-annual period has been reported to occur in K_P, A_P, a_n, a_s (see introduction) for auroral occurrence (Silverman and Blanchard 1983; Silverman and Shapiro, 1983) and for horizontal and vertical component of the geomagnetic field (Bartels, 1932; McIntosh, 1959; Bartels, 1963). The 6-month periodicity was also reported by Ichimoto et al (1985) for the solar flare activity for the two solar hemispheres interpreted as the time for solar origin storage and/or escape of solar magnetic field. It is pronounced during the equinoxes where the angle φ (in-

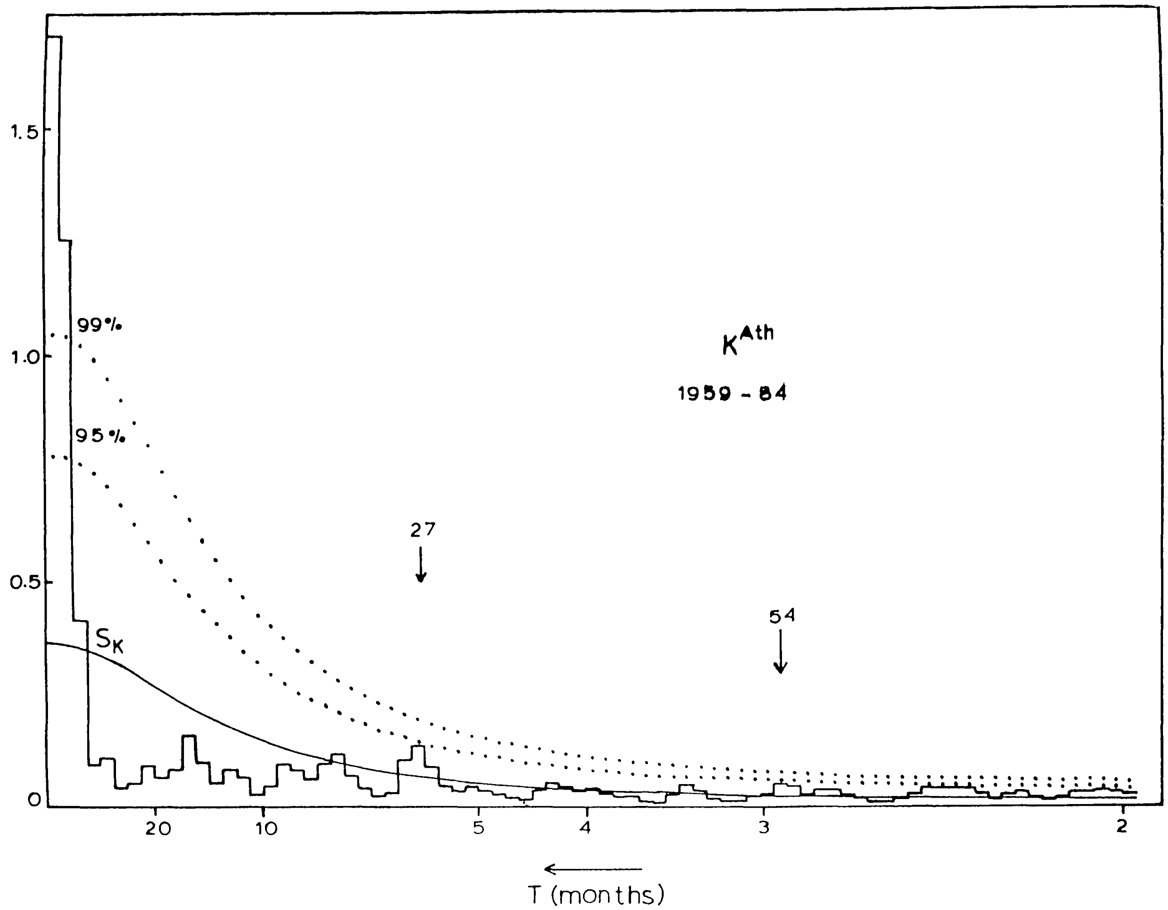

Fig. 4. Power spectrum analysis of Athens geomagnetic K-index for the period 1959–1984. A x^2-test shows the probability of different significances (broken lines) for the existence of certain periodic peaks (arrows numbers indicate lags). The 'red noise' spectrum (solid line) is shown for comparison. The lag number (lag = 80) is the truncation length of the autocorrelation function.

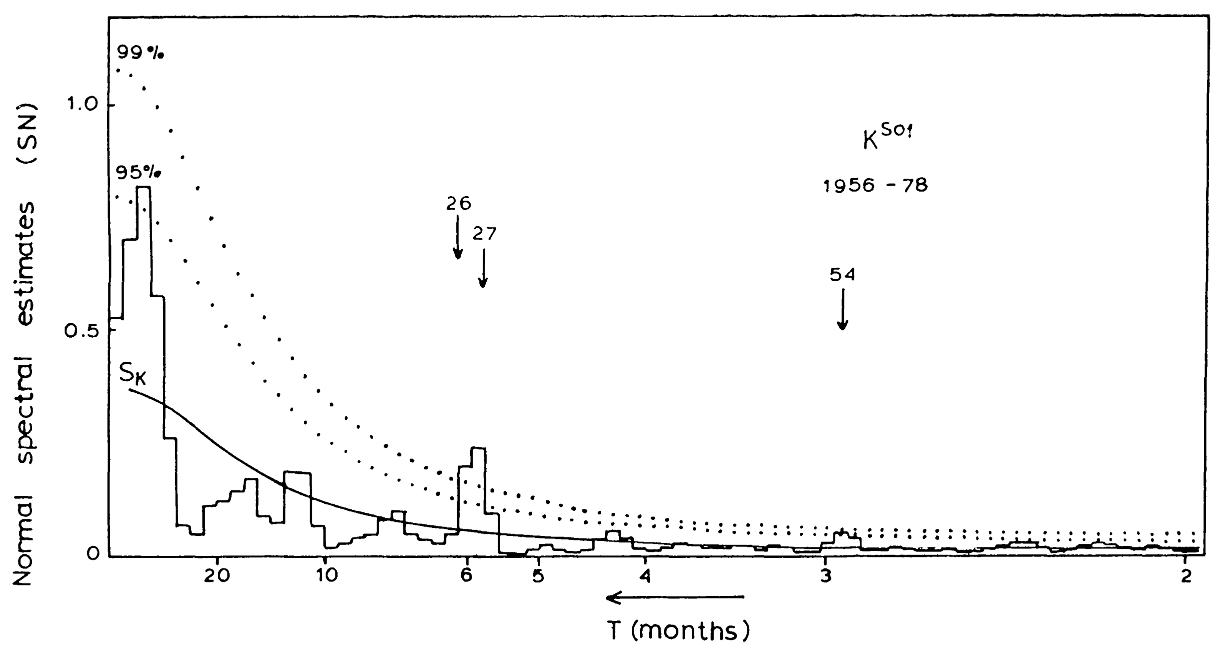

Fig. 5. Power spectrum analysis of Sofia K-index for the period 1956–1978 (lag = 80). Arrows indicate periods for respective lags (in numbers).

clination of the Earth's axis of rotation to the plane of the ecliptic) is at maximum (Silverman and Shapiro, 1983). The 2.8 month period has only recently been found in energetic flares ⩾XI by Landscheidt (1988) (see Discussion).

Similar periodicities were obtained also from autocorrelation analysis of the above data (Figure 6) which reinforces the existence of those two periods.

The power-spectral diagram of the difference ΔK of Athens and Sofia data is given in Figure 7. However, this analysis (60 lags) provided the strong period of 2.8 months (at 99% significant level) for ΔK for the period 1959–78. For the period 1965–75 (20th cycle) the PSA (44 lags) gave also the period of 2.8 months (≈98% significance). Smoothing of ΔK series for 1959–78 (subtracting their

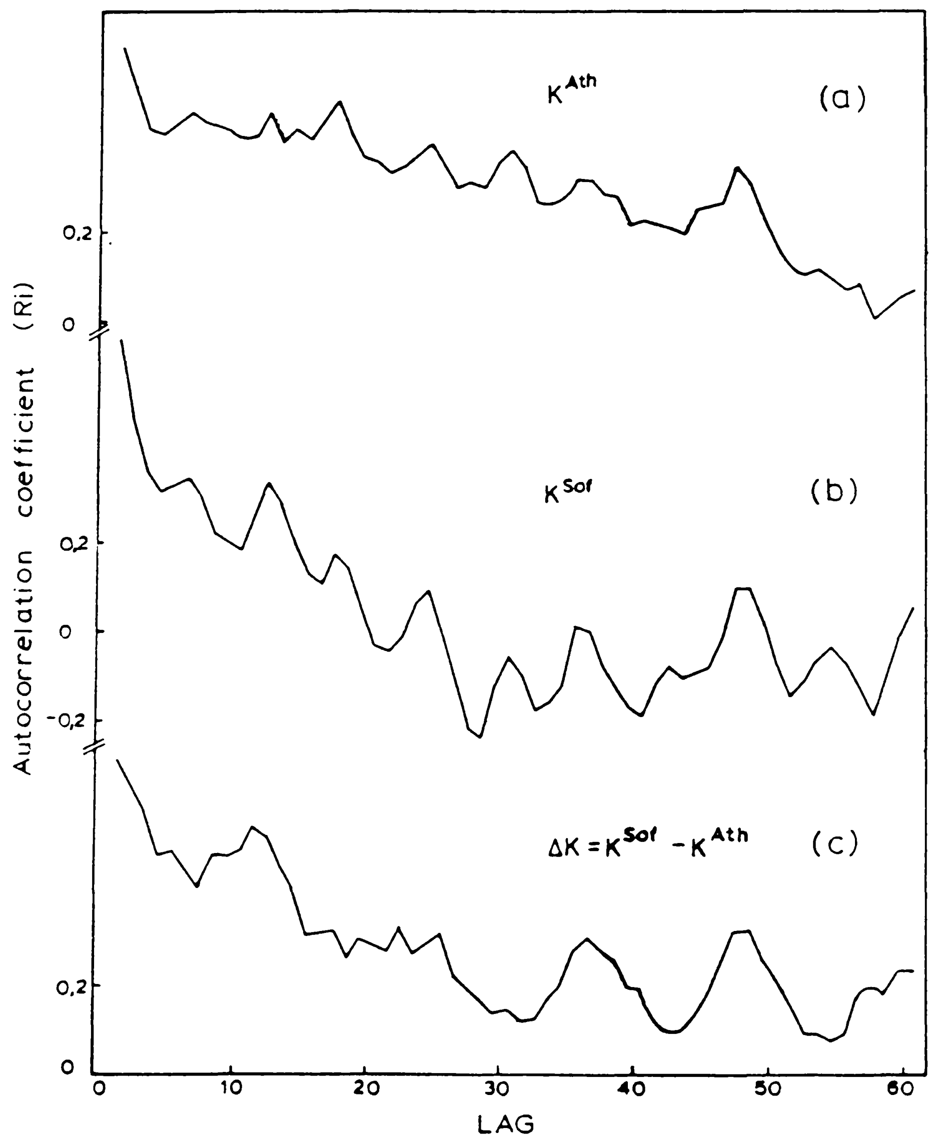

Fig. 6. Autocorrelation functions (a) of Athens K-indices, (b) of Sofia K-indices and (c) their differences with lag maximum scale at 60.

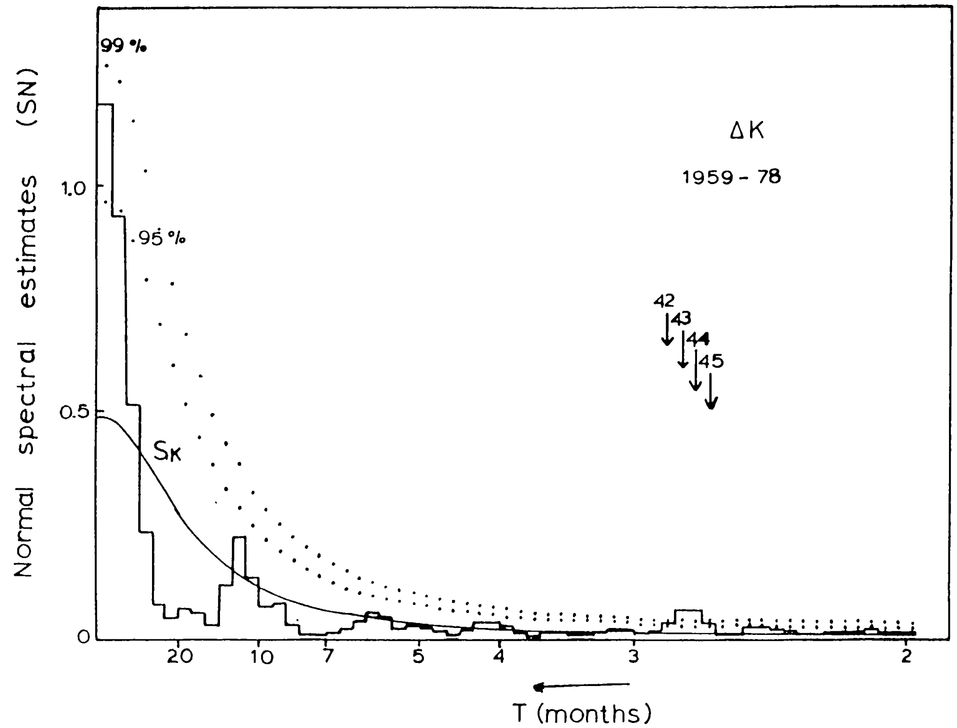

Fig. 7. Power spectrum analysis of the difference $\Delta K = \Delta K^{\mathrm{Sof}} - K^{\mathrm{Ath}}$ (lag = 60). Note the still present 3-month period.

mean value) a PSA (80 lags) gave again the 2.8 months period. We observe that the 6-month period disappears while the ≈ 2.8 months period remains. From all these it is resulted that the ΔK fluctuations are perhaps due to a seasonal effect of geomagnetic storms as it is related to the 2.8 months period.

b. K-INDEX IN RELATION TO COSMIC-RAY INTENSITY VARIATIONS

The time plot of monthly values of cosmic-ray intensity of Athens Neutron Monitor Station (1970–78) is given in Figure 2. The 11-yr modulation of the cosmic-ray intensity is obvious in this figure. No periodicities were found with a power-spectrum analysis (Figure 8) of these data (24 lags). Because of limited data. At any rate it is noteworthy that Xanthakis *et al.* (1988) recently have shown that a period of ~3 months is appeared (~97.5% significance) in a similar spectral analysis of Cosmic-Ray Data at Inuvik Station for the time period 1964–1985. In studying the relationships between the geomagnetic K-index and cosmic-ray intensity, of Athens station, the best cross-correlation coefficient was 0.58 for a time lag of three months. Also the best cross-correlation coefficient between the difference ΔK and cosmic-ray intensity was rather poor ($r = 0.28$) for time lag equal to two months. It is also noted that the cosmic-ray intensity variations does not seem to have any impact on the ΔK variations.

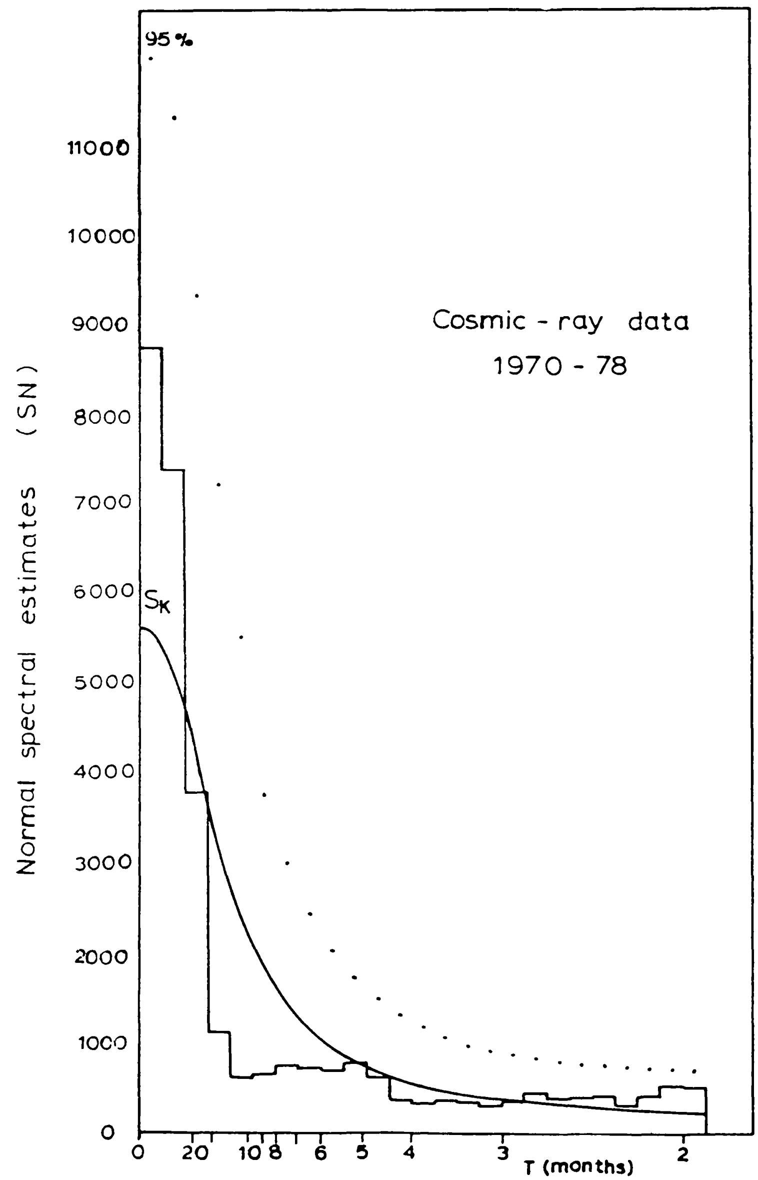

Fig. 8. Power spectrum analysis of cosmic ray data of Athens station (lag = 24).

c. Auroral activity index in relation to K-indices

The best correlation coefficient between auroral activity A-index of Alaska and geomagnetic K-index of Sofia was found 0.468 for time lag equal to two months. The poor correlation is rather due to the fact that K-index is derived by magnetic Observatories with geomagnetic latitudes lower than the latitude of 58°, while A-index is derived from stations with higher geomagnetic latitudes. Nevertheless in certain times in two past strong magnetic storms have been producing auroral features in low latitudes implying a strong link between those two effects (e.g., in Tokyo 1957/58, South U.S.A. 1975) (Akasofu and Chapman, 1962). Therefore,

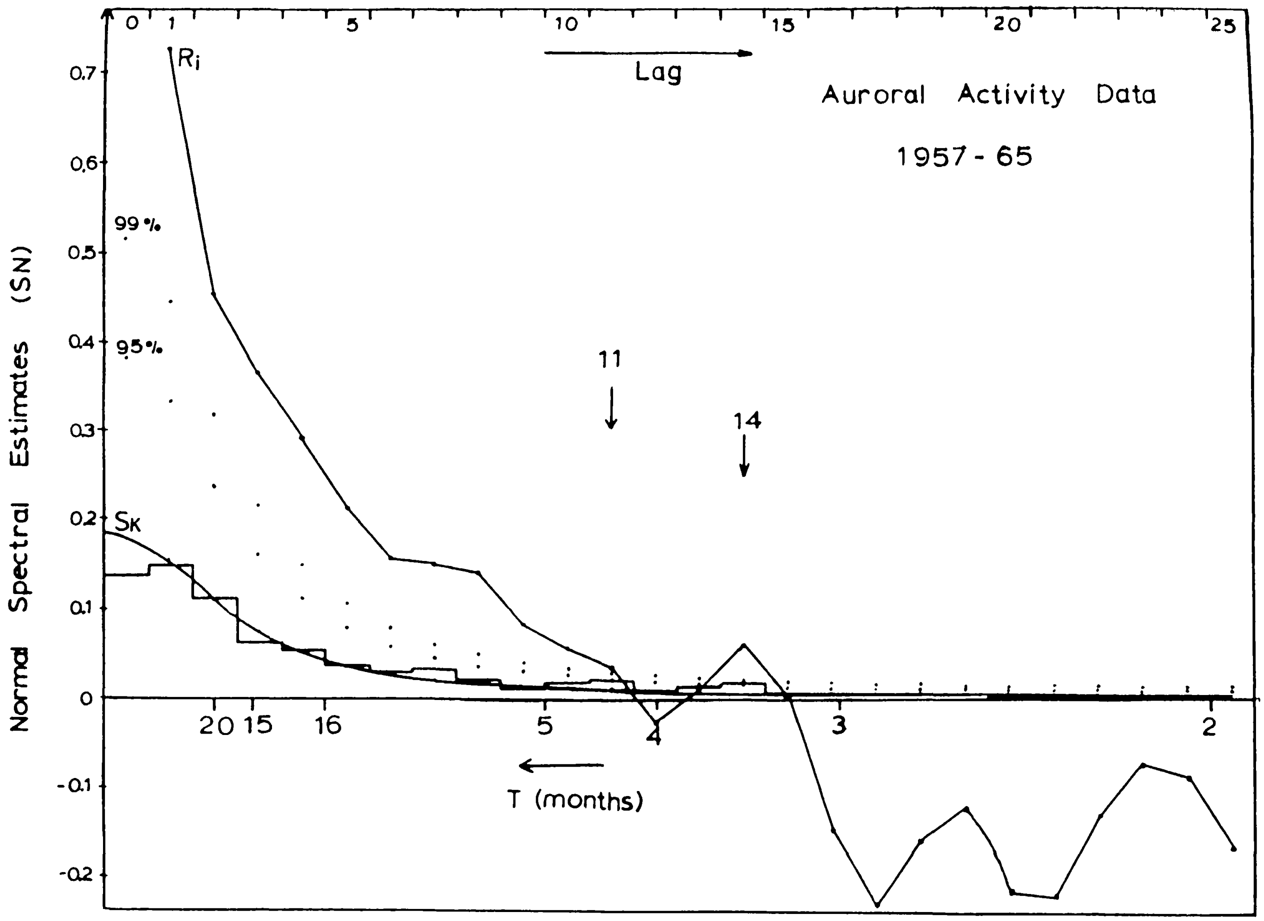

Fig. 9. Power spectrum analysis of auroral activity A-index for the period 1959–1966 (lag = 25). The autocorrelation coefficient R_1 is also given.

during very strong geomagnetic storms the auroral electrons are diffused to lower geomagnetic latitudes. This fact results in the production of geomagnetic disturbances in mid latitude's which are weakly coupled with those carriers of magnetic field.

A power spectral analysis of the auroral activity data of Alaska College showed period of 3.5 and 4.6 months (at 95% significant level) with 25 lags (Figure 9). These periods are to our knowledge obtained for first time. From a first glance the geomagnetic K-index and the auroral A-index exhibit different periods of approx ≈ 3 and 4 months respectively and one could rather explain this as a random relationship but this is probably due to limited auroral data.

4. Discussion

The geomagnetic activity is a result of the variable solar wind. The coupling between magnetosphere and solar wind therefore causes the geomagnetic storms (transient disturbances) and auroral occurrence.

The solar wind includes as variables the solar wind speed, the interplanetary magnetic field and the output area of the streamers, while its directional incidence to the poles enhances or reduces the auroral frequency and intensity.

If cosmic-ray particles are taken into account also in producing collision, excitation and ionisation of atoms and molecules in the Earth's upper atmosphere as well as interacting with the magnetic field's lines, then the geomagnetic disturbances ought to correlate with solar wind, aurorae, cosmic ray variations. Correlations for the auroral, solar and magnetic activity have already been reported (e.g., Liritzis and Petropoulos, 1987).

In fact the magnetic activity (quiet, disturbed) varies from day to day over a wide range. This disturbance is superimposed on a regular daily variation, which is of solar and lunar origin. These disturbances unlike the geomagnetic secular variation, produce no large or long enduring changes in the Earth's field.

The annual variation in the frequency of days classed as disturbed, shows that they are more numerous near the equinoxes than near the solstices exhibiting a 6-month periodicity (Chapman, 1964).

A semiannual variation of auroral occurrence for the period 1883–1931 has also been reported by Silverman and Blanchard (1983) making use of Wilson Bentley's auroral observations in northern Vermont, with spring-fall maxima consistent and similar to the mid-latitude stations.

The most likely factors influencing auroral frequency by analogy with magnetic activity are the solar wind velocity and the direction and the intensity of the interplanetary magnetic field.

Shapiro (1969) concluded, on the basis of a study of filtered geomagnetic data (Ci), that the basic factor involved in the semiannual variation was the inclination of the Earth's axis of rotation to the plane of the ecliptic. The semiannual variation mostly depends in some fashion on the relative configuration of the terrestrial magnetic field and the solar field (see, for example, Russell, 1975; Prabhakaran Nayer and Revathy, 1982). In the absence of a change in the configuration of the terrestrial field, a weakening of the semiannual variation must result from a lessening of the solar radial field. However the above may be derivative of the heliographic latitudinal dependency of solar wind velocity and a possible tilted solar magnetic dipole.

Regarding the mean period of 2.8 months of the K-index it has not been reported to our knowledge a similar period elsewhere and its cause remains at present unknown. Nevertheless, an approx three months recurrency was found for the 5577 Å $(2p^4\,{}^1D - 2p^4\,{}^1S)$ in the [OI] airglow intensity as measured in the Maruyama Observatory for the period 1957–1961 (Ward and Silverman, 1962) but was attributed to limited data sample in order to justify the single/double spring maximum observed in Sacramento Peak Observatory for the period 1955–1960, that breaks this recurrency. Whilst Sacramento Peak data showed a correlation between K_P and [OI], the Maruyama data did not show such a relationship (see also Silverman *et al.*, 1962). Silverman (1970) explains this as due to the fact that [OI] varies with K_P as a function of the magnetic latitude.

The same sensitivity of 6300 Å ($2p^4\,{}^3P - 2p^4\,{}^1D$) OI for temporal geomagnetic latitudes has been noted by Truttse (1968) using IGY data with no dependency of emission on Dst field below about 35° geomagnetic latitude. It seems therefore, that the observed approx. 3-month periodicity in the 5577 Å [OI] of the Maruyama Observatory might be indeed a genuine period which reflects the mean 2.8 months period found in our K-indices. This suggestion is based on the rational of the exciting relationship between geomagnetic activity variations and solar activity, mentioned earlier.

Although any quantitative appreciation of influencing parameter of galactic (exosolar) origin on the variations of some physical meteorological phenomena is considered negligible or unknown (e.g., C^{14} atom production by galactic cosmic rays) any possible relationship between periodic phenomena of galactic origin and terrestrial phenomena must not be excluded. In fact power spectral analysis applied to light curve of RR Tauri (a young star) exhibited periods of 80, 200, 533 days, with some variations in the peak position and power for different decades (Silverman *et al.*, 1971). The spectral type of RR Tauri is Aze and it is located in a small nebula at the edge of the Taurus clouds. Thus the approx. 2.8 month period may be of galactic origin, which is another important short period of external origin (otherwise periods below 22 years are considered to be of solar origin).

Nevertheless, a prominent period of 2.8 months was also obtained by Landscheidt (1988) from an analysis of energetic solar eruptions (X-ray bursts $\geqslant$X1) from 1970 to 1982.

In fact, astronomers hold that flares show a stochastic distribution, but closer examination (see also Ichimoto *et al.*, 1985) discloses cycles of solar flares with mean periods of 9 yr, 2.25 yr and 3.3 months; whilst, other flare cycles in the range of months are related to variations in $\mathrm{d}T/\mathrm{d}t$, the impulses of the torque of the sun's center of mass. From the spectral analysis with maximum entropy that uses the Burg algorithm, the most prominent amplitudes found by Landscheidt represent the torque cycle itself, the harmonic 4.8 months, the harmonic 1.2 months with a neighboring peak at 1.1 month's and a strong amplitude at 2.8 months, that seems to drop out of this sequence, as 2.8 months would be the fitting harmonic between 4.8 months and 2.4 months. But this shift is the result, according to Landscheidt, of the interference with another cycle in the same range.

Indeed, a strong 100-day cycle is formed by the change in the angular acceleration of the vector of the tidal forces of the planets Venus, Earth and Jupiter, that shows a very strong relationship to energetic X-ray bursts $\geqslant$X1 (Landscheidt, 1984). The mean length of this cycle being 3.367 months and the harmonic of the torque cycle of 2.4 months, when combined, yield the mean value of 2.88 months, which is near the strong amplitude of 2.8 months. (The maximum entropy spectral analysis was based on 82 filter coefficients. The frequency was measured in millicycles per sampling interval of half a month. It should be noted that impulses of the torque which drive the Sun's motion around the center of mass of the solar system in the ecliptic plane, relative to the Sun's center, are the special quantitative criterion of relationships with the secular and supersecular cycles of solar activity. Such impulses of the torque are evidently, also, modulating the radiocarbon variations in the atmosphere).

A Blackman–Tukey power spectrum of the same sample yielded similar results, and MEM analysis of the same sample based on 104 filter coefficient showed a finer resolution but with no shift in the frequencies.

A further possible interpretation regarding the genuity of the 2.8 months period may also be given in terms of a linear response of the K-index forced by extraterrestrial parameters. Thus, the response of the system, that includes the K-variation, can be expressed as the sum of a sinusoidal oscillation at frequency w_f, the periodic external forcing (the solar flares from X-ray bursts in our case) and of additional sinusoidal oscillations at the characteristic frequency w_1 of the system.

But, in the case of the 2.8 months period, for the energetic flares, the nonlinear system is most probable, since the response contains a component at the forcing frequency, w_f (the 3.367 months cycle, mentioned above) and the 2.4 months torque cycle harmonic.

The relationship between local K-index and cosmic-ray intensity is not strong and this harmonizes with similar observations made by other authors. For example, Chirkov and Kuzmin (1979) have reported that the correlation coefficient between cosmic-ray intensity I and geomagnetic activity variations (C-index) is 0.9 for odd cycles of solar activity and $0.4 \approx 0.5$ for even cycles. These differences in correlation coefficients are caused by a different relationship between C and solar wind speed in odd and even cycles of solar activity. Moreover, Balasubrahmanyan (1979), Mavromichalaki and Petropoulos (1984) have showed that Bartel's index A_P correlates well with cosmic-ray intensity without pronounced phase lags. On the other hand the mean 4-month period in auroral intensity has not been reported elsewhere and might be due to limited data. The latter may also explain the lower than expected correlation with our local K-indices.

As regards the 4.6 month period in auroral intensity, we can report that a similar period at 4.8 months has been also obtained by Landscheidt (1988) from an analysis of energetic solar eruptions (X-ray bursts $\geqslant$XI). Perhaps this period would be the fitting harmonic between the aurora's 4.6-month period and the K-indices 2.4-month period. This could be the result of the influence of the geomagnetic field variations to the auroral intensity.

Conclusions

The geomagnetic K-index variations from Athens and Sofia observatories exhibit significant periods of approx. 3 (2, 8) and 6 months.

The former is similar to 5577 Å [OI] airglow intensity and the light curve of

RR Tauri, as well as to single energetic flare activity variations (X-ray bursts ⩾ XI) (Landscheidt, 1988) and it is found for first time in local geomagnetic indices. The latter is similar to K_P, A_P, a_n, a_s indices, to vertical and horizontal components of the geomagnetic field, to auroral frequency of occurrence in northern Vermont for the period 1883–1931, the inclination of Earth's axis of rotation to the plane of the ecliptic in conjunction to the heliographic latitudinal dependency solar wind velocity and a possible tilted solar magnetic dipole, and to solar flare activity.

The relationship between local K-index and cosmic ray intensity ($r = 0.58$) is not strong and this harmonises with similar observations made by other authors.

The auroral intensity index is poorly correlated with our local K-index, though, with a complete auroral data set one could expect a higher correlation and a similar periodicity of approx. 3 months.

Thus, the global interaction of the solar-terrestrial phenomena, are also reflected in the data of a regional scale, while the obtained periodicities new and others reported in the K-index and its correlation to other parameters) might help to understand the new quantitative relationships and mechanisms of such interactions.

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