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ABSTRACT

The data obtained from the underground muon telescope at a depth of 40 m.w.e. in the period 1958-63 are analysed for solar first and second harmonics. It is found that the observed solar diurnal wave is well explained in terms of the corotation model with an upper cut-off rigidity. The value of upper limit varies between 110 GV and 75 GV showing a decreasing tendency in the weakening period of solar activity. The semidiurnal variation is found to be consistent with the perpendicular density gradient model of Quenby and Lietti and appears to extend up to rigidities about 135 GV.

АННОТАЦИЯ

Данные,полученные от подземнего мюонного телескопа на глубине 40 м.в.э. были проанализированы в периоде 1958-63 гг. по первой и второй гармонике солнечно-суточной вариации. Наблюденная солнечно-суточная волна хорошо объясняется на основе коротационной модели в предположении верхнего предела жесткости обрезания. Величина верхнего предела меняется между 110 Гв и 75 Гв и имеет тенденцию снижения в периоде ослабления солнечной активности. Полусуточная вариация совместима с моделью перпендикулярного градиента плотности Quenby и Lietti,верхный предел которой был найден примерно 135 Гв.

KIVONAT

A dolgozat a 40 m.w.e. mélységben müködő budapesti földalatti müonteleszkóp adatait dolgozza föl a szoláris napi periodicitás első és második harmonikusára nézve. Az észlelt szoláris napi hullám jól magyarázható a korotációs modell keretében egy felső levágási merevséget feltételezve. A felső határ értéke 110 GV és 75 GV között változik és a gyengülő naptevékenység időszakában csökkenő tendenciát mutat. A félnapos változás eredménye összhangban van Quenby és Lietti merőleges sürüséggradiens modelljével, ennek érvényességi határát 135 GV-nek találtuk.

1. INTRODUCTION

In the intensity variations of cosmic rays, in addition to transient effects, some periodic time variations may be observed. The 11-year wave can be explained by the cycle of solar activity, the 27-day recurrences by the rotation of the Sun, while anisotropies manifest themselves as diurnal variations because of the rotation of the Earth. The galactic radiation arriving from the outside of the solar system is subject to solar modulation which results in lower intensity as well as anisotropy in the directional distribution. When investigating solar modulation effects we can obtain useful information first of all from the solar daily variation. The convection-diffusion theory developed by Parker /1965/ which provided a satisfactory explanation of modulation effects giving a solar daily amplitude about 0.6 % independently of rigidity /corotation effect/. The lack of solar diurnal wave for particles of rigidities greater than $\sim 10^{12}$ V suggests the existence of an upper cut-off rigidity above which the solar cavity has no effect on cosmic ray propagation the gyroradii of the particles being in the order of magnitude of the scale of solar modulation region. Naturally when calculating diurnal wave the effect of Earth's orbital motion must be added to this. The first solar harmonic having the largest amplitude among the Fourier-components of intensity variation in the rigidity range 10^{11}-10^{12} V is of main interest to us, we aim to determine the value of cut-off rigidity and how it changes in time during a solar cycle. Many observations made so far have also shown the existence of second solar harmonic having maximum about 3 hr. Unlike the diurnal, the amplitude of semidiurnal wave increases with rigidity. As it has been shown by several authors /Subramanian and Sarabhai 1967, Quenby and Lietti 1968/ if a cosmic ray density gradient perpendicular to helioequator is assumed such semidiurnal variation may be produced. We also endeavour to estimate the upper threshold rigidity up to which the aforementioned model applies.

2. EXPERIMENTAL APPARATUS

The Budapest measuring apparatus consisting of two identical semi-cubical meson telescopes with sensitive area 1.47 m^2 is placed at a depth of 18 m underground /corresponding a 40 m.w.e. absorber/. The station /geographical coordinates: 47.5 N, 18.9 E/ has been operating since February 1958 /for detailed description see Sándor et al. 1960/. Bihourly counting rates - mean: 53 000/hour - were registered, the meteorological effects were also taken into account by use of surface barometric pressure and height of the 200 mb isobaric level. So far the analysis of the data obtained in the period 1958-63 has been performed. The correct determination of phase requires that both the average asymptotic directions and the response characteristics of our telescope be known. As the form of response functions defined as rate of primaries giving rise to secondaries is not known accurately yet, we used the most recent results of calculations based on new measurements of high energy physics /Gaisser 1974/. The data of asymptotic directions are taken from Shea et al. 1965.

3. STATISTICAL METHOD, RESULTS

Since we have a great amount of statistical data and the effect sought is very small /of the order of 0.1 %/ the statistical analysis must be performed very carefully. In this work we follow the method of simultaneous regression analysis developed in Kóta, Somogyi/1969/ and Gombosi et al. /1975/, that is the amplitudes and phases of harmonic waves are determined simultaneously with meteorological coefficients. The intensity variation is described in the following form:

$$I(t) = I_o\left[1+\beta_p(p-\bar{p})+\beta_h(h-\bar{h})+\sum_{k\ell}\sum(A_{k\ell}\cos k\omega_\ell t+B_{k\ell}\sin k\omega_\ell t)\right] \qquad /1/$$

$$k=1,2 \; ; \; \ell=1,2,3$$

where p stands for the atmospheric pressure at sea level and h denotes the height of 200 mb isobaric level /$\bar{p}$, $\bar{h}$ are mean values/. ω_i refers to first and second harmonics of solar, sidereal and antisidereal frequencies respectively. In order to determine the estimated values of parameters the maximum likelihood method has been used. However, the /1/ expression does not include instrumental effects, the instability of the apparatus may cause some changes in the mean counting rate I_o, too, for instance the exchange of several GM detectors may give rise to sudden shifts or its wearing out lead to a slow drift. These effects were tried to be taken into account by dividing the duration of the measurement into several intervals and supposing linear variation of I_o in each of them. Also the sidereal and antisidereal waves were determined since the solar modulation gives rise to such waves, too /Nagashima et al. 1972, Kóta 1975/.

Having solved the maximum likelihood equations we obtain the following values of meteorological coefficients:

barometric $\beta_p = (-0.0455 \pm 0.0004)\%/mb$
decay $\beta_h = (-0.72 \pm 0.02)\%/km$

Both results are in good agreement with other muon telescope data c.f. Jacklyn /1970/.

3.1 Solar diurnal anisotropy

It has been confirmed by numerous measurements of neutron monitors that the rigidity spectrum of diurnal anisotropy is well described in following form:

$$\xi = \begin{cases} \xi_{cor} + \xi_{orb} & \text{for } P \leq P_c \\ \xi_{orb} & \text{for } P > P_c \end{cases} \qquad /2/$$

where ξ_{cor} stands for the corotational /0.63 %, T_{max} = 18 hr/ and ξ_{orb} for the orbital anisotropy /0.046 %, 6 hr/ both being independent of rigidity. It has been pointed out by several authors /see e.g. Pomerantz et al. 1971/ that the free-space amplitude remains constant throughout the solar cycle while the P_c upper cut-off rigidity varies only. As our telescope works in the rigidity range of P_c one of our aims is to evaluate the P_c spectral parameter more accurately than in measurements made at lower energies.

The analysis of the data for whole period /1958-63/ has yielded that

$$A(\omega) = (0.080 \pm 0.004)\%$$
$$T_{max}(\omega) = (15.5 \pm 0.2)hr$$

denoting the amplitude with $A(\omega)$ and time of maximum with $T_{max}(\omega)$ /$\omega = (24\ hr)^{-1}$ being the solar frequency/. Results obtained from analysis made for individual years are listed in Table 1. and shown in Fig. 1 and Fig. 2.

Table 1.

	$A(\omega)x10^4$	$T_{max}(hr)$
1958	7.8 ± 1.2	14.3 ± 0.5
1959	11.2 ± 1.1	16.1 ± 0.4
1960	11.4 ± 0.9	16.2 ± 0.3
1961	5.7 ± 0.7	15.5 ± 0.5
1962	7.1 ± 0.6	15.9 ± 0.3
1963	8.0 ± 0.9	13.1 ± 0.5

As it can be seen in Fig. 2 the assumption /2/ was rightful since our measuring points are close to theoretical curve /except for 1963, this may be caused by instrumental effects/. The values of P_c determined as the closest point in the curve are shown on Fig. 3 together with some data available for same period from other stations /Thambyahpillai 1975/. In the solar cycle the activity of the Sun reached its maximum in 1958 and minimum in 1965. It can be seen that in the period of weakening solar activity P_c shows decreasing tendency, too. The mean magnetic field strength at 1 A.U. in the ecliptic plane is about 3.5 gamma so the gyroradius of a particle having rigidity of the average value of $P_c/\bar{P}_c$=85 GV/ is about 0.6 A.U. This may give some information about the thickness of solar modulation region.

3.2 Semidiurnal anisotropy

The semidiurnal anisotropy increasing linearly with rigidity assumed on basis of few and not very accurate measurements /c.f. Quenby and Lietti 1968/ may be explained by a symmetrical cosmic ray density rising away from solar equatorial plane /Subramanian and Sarabhai 1967, Quenby and Lietti 1968/. The reason of this gradient is that at higher heliolatitudes, the spiral magnetic field lines being less tightly wound, particles travel shorter distances and a maximal density is produced in $\vartheta = 0$ plane /ϑ : heliolatitude/. The density gradient rising this way gives second harmonic with maximum at 3 hr /at right angle to field direction/.

In the model of Nagashima et al. /1972/ a pitch angle distribution around field lines is supposed which also may result in second harmonic with 3 hr phase, but gives no information about rigidity dependence. Above about 50 GV the adiabatic nature of particle propagation ceases so we do not expect the Nagashima pitch angle distribution model to extend to higher rigidities.

Prefering the first model on the basis of calculations made by Kóta /1975/ we have got the amplitude

$$A(2\omega) = 0.27 \frac{R^2}{2r^2} \frac{1}{U} \frac{\partial^2 U}{\partial \vartheta^2} \qquad /3/$$

where R is the gyroradius of the particle, r is the radial distance from the Sun and U denotes particle density. The rigidity spectrum of semidiurnal variation is assumed in following form:

$$A(2\omega) = \begin{cases} kP & \text{if} \quad P \leq P_{max} \\ 0 & \text{if} \quad P > P_{max} \end{cases} \qquad /4/$$

By using the response functions of Gaisser /1974/ this expression gives the curves shown on Fig. 4 in function of P_{max}. The harmonic analysis performed on our data provided the results listed in Table 2.

Table 2

	$A(2\omega)x10^{-4}$	$T_{max}(hr)$
1958-63	3.6 ± 0.4	1.6 ± 0.6
1958	2.4 ± 1.2	2.9 ± 0.9
1959	3.4 ± 1.1	1.4 ± 0.6
1960	4.2 ± 1.0	1.7 ± 0.4
1961	3.3 ± 0.7	1.6 ± 0.4
1962	3.3 ± 0.7	1.5 ± 0.4
1963	4.9 ± 1.1	1.7 ± 0.4

Harmonic dial shown in Fig. 5 indicates that our results can be explained in terms of the model mentioned above provided the value of k remains constant and the P_{max} rigidity limit changes only during solar cycle similarly as in expression /2/ for the first harmonic. From this assumption the calculation yields P_{max} = (135 ± 10)GV and k = $4 \cdot 10^{-5}$. However, this calculation should be considered with caution because different choose of k /which is allowed by statistical errors/ may shift the P_{max} value considerably /greater value of k leads to smaller P_{max}/. Naturally the /4/ spectral form is a rather rough approximation but as the experimental results provide only two data and we are unable to measure in narrow rigidity bands we cannot determine the spectrum more accurately. As the high rigidity behaviour of second harmonic is hardly known of course we cannot expect P_c and P_{max} to be identical, they are characteristic parameters of different phenomena. Nevertheless, the fact that they turn out in the same order of magnitude shows that the solar modulation ceases above 100 - 150 GV.

4. CONCLUSIONS

Muons detected by the Budapest underground telescope come from primaries mainly in the energy range 10^{11} - 10^{12} eV. Thus the major effect in intensity variations is expected to be of solar origin rather than result of galactic anisotropy. The analysis for solar variations yielded the following results:

/1/ In agreement with a large number of neutron monitor and some muon telescope data /Pomerantz et al. 1971/ the corotational effect can entirely account for solar diurnal variation. The cut-off assumed in rigidity spectrum has been found to depend on solar activity, its value is significantly lower at weak than at strong activity period. Its mean value /85 ± 3/ GV has been determined more accurately than by previous measurements and found in good agreement with the results of Jacklyn /1970/ and Thambyahpillai /1975/.

/2/ The phase of the semidiurnal variation has been found to be consistent with the prediction of Subramanian et al. /1967/ and Quenby et al. /1968/

which favours the assumption of density maximum in the solar equatorial plane. Several experimental data gathered in Quenby et al. /1968/ indicate an amplitude rising linearly with rigidity between about 5 and 50 GV. In lack of data at higher rigidities, we assumed a spectral form of /4/ is maintained up to a threshold rigidity, P_{max}. This P_{max} has turned out in range of P_c but there is no recognizable decreasing tendency in the 1958-63 period. As regard the model of Nagashima et al. which predicts the same phase for the solar semidiurnal variation, a possibility is offered to distinguish between the two models by examining either the second sidereal harmonic or the first daily harmonic arising from second spherical harmonic in space /referred to as "special first daily harmonic"/. As for the former the two models predict opposite phases, however, the expected amplitude is much smaller so larger statistics would be required to prove it. The special first harmonic, on the other hand, could be selected by using multidirectional telescope.

In this work our aim is concentrated to the upper limit of modulation rather than the three dimensional structure of anisotropy, this latter task /sidereal, antisidereal waves/ will be discussed elsewhere.

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FIGURE CAPTIONS

Fig. 1 : Yearly values of the amplitudes and phases with standard statistical errors

Fig. 2 : Harmonic dial for first solar harmonic of years 1958-63 in comparison with theoretical curve

Fig. 3 : Upper cut-off rigidity changes over the period 1958-65: Budapest - points with errors /B/, dashed line - Hobart muon telescope, full line - Cheltenham/Huancayo neutron monitor

Fig. 4 : Harmonic dial of semidiurnal wave. The curves refer to different values of k, in function of the P_{max} limit

Fig. 5 : The harmonic dial for individual years 1958-63

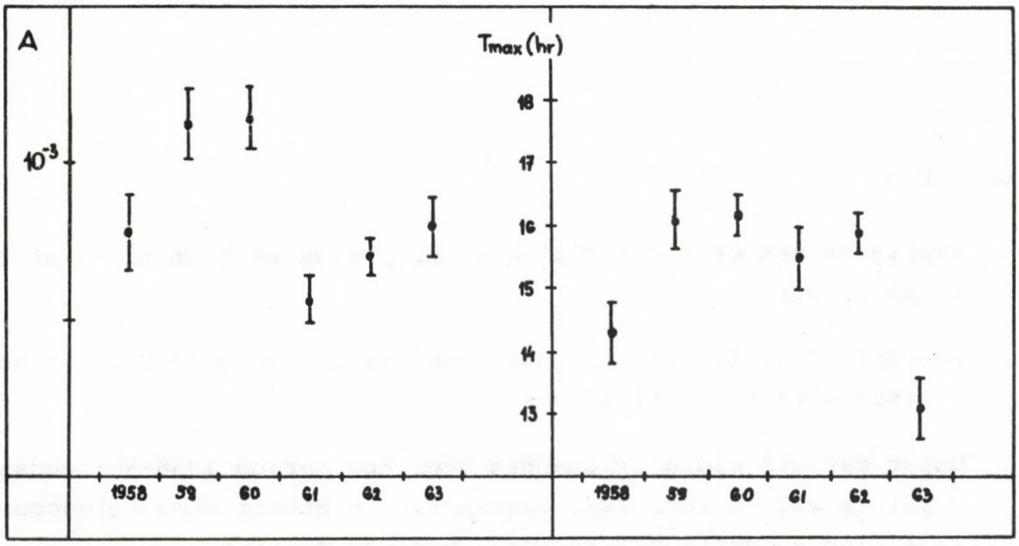

A
10^{-3}
Tmax (hr)
18
17
16
15
14
13
1958
59
60
61
62
63
1958
59
60
61
62
63

Fig.1.

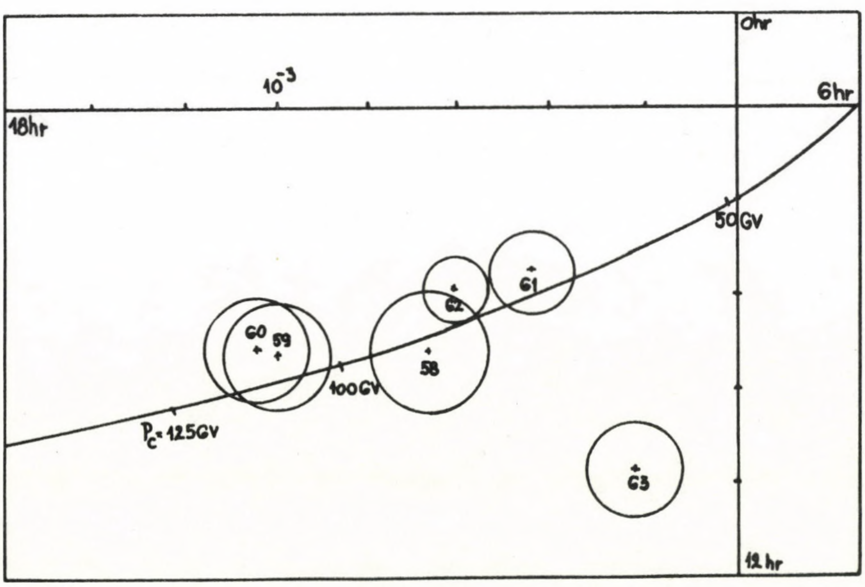
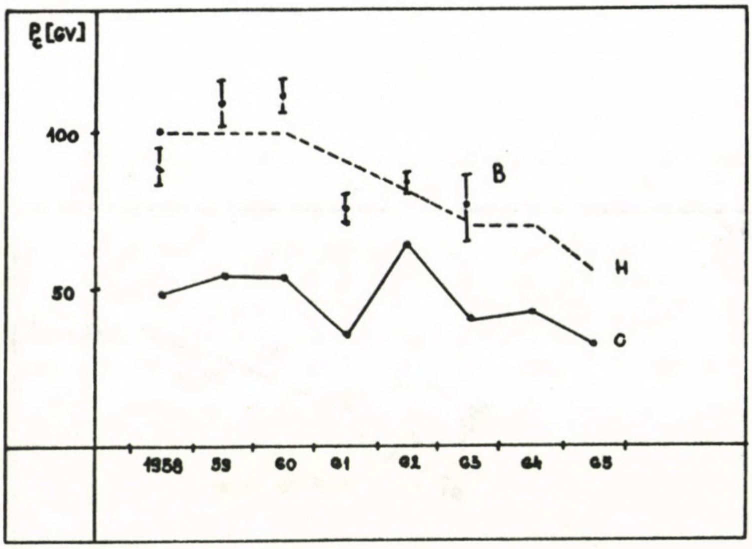
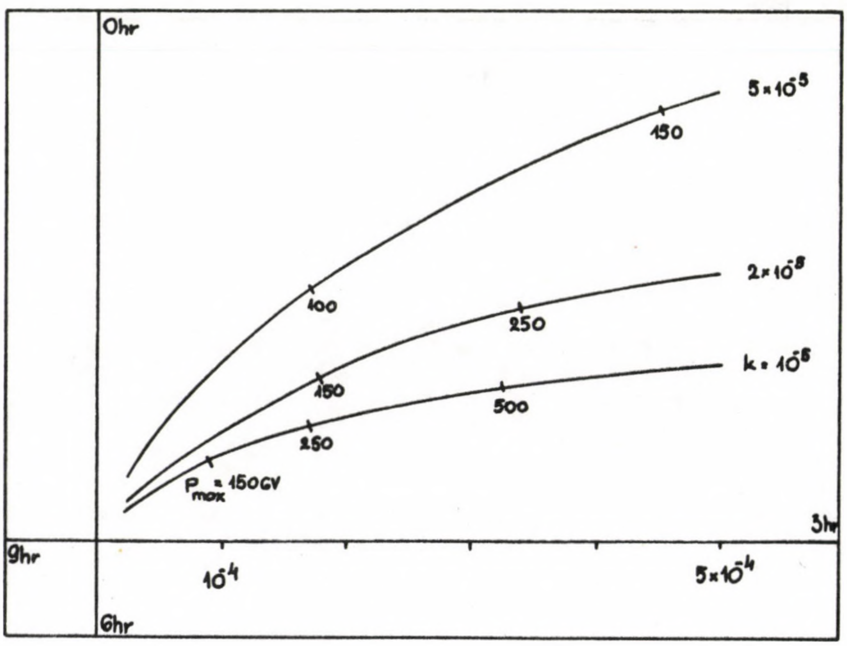

0hr
10^{-3}
6hr
18hr
50GV
61
62
60
59
58
100GV
P_c=125GV
63
12 hr

Fig.2.



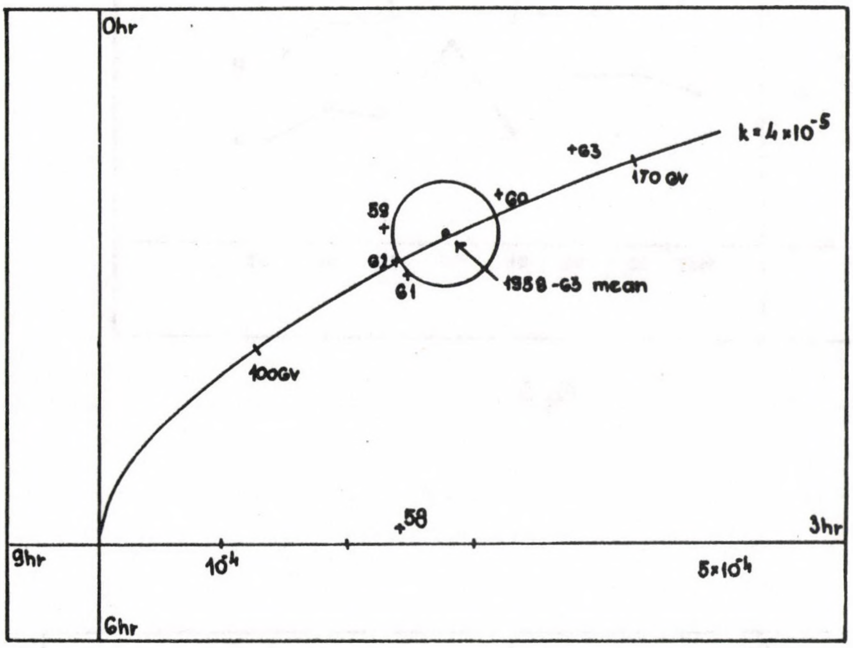
P_c [GV]
100
50
B
H
C
1958
59
60
61
62
63
64
65

Fig. 3.



0hr
5×10⁻⁵
150
2×10⁻⁵
100
250
k = 10⁻⁵
150
500
250
P_max = 150 GV
3hr
9hr
10⁻⁴
5×10⁻⁴
6hr

Fig. 4.



0hr
9hr
3hr
6hr
$k = 4 \times 10^{-5}$
+63
170 GV
+60
59
62
61
1959-63 mean
100GV
+58
10^4
5×10^4

Fig.5.

62.377

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