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Periodic Variations of CR Muon Intensity in the Period 2002-2004

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Abstract— **Power spectral analysis of cosmic-ray muon intensity record from Belgrade muon detectors in the period 2002-2004 is carried out. Several periodicities are found in data sets from both ground(GD) and underground(UD) (25 mwe) detectors. Periodogram analysis revealed statistically significant peaks in both data sets at solar rotation period 26.5 day (27.0 in the ground data) day and its higher harmonics 13.6, and ~ 8.7 day as well as periods 1 year, 240, 190, 90, 37, 34.5, 20.5 and 1 day. Signals unique for underground detector data are: 25.4, 77, and 162 days, while signals found only in surface detector data are: 22 and 57 days. Similar periodicities are reported in various solar activity parameters, confirming the relevance of cosmic-ray studies as an indirect diagnostic tool of solar activity and representing a strong motive for further investigation of relation between solar activity and CR variations.**

I. INTRODUCTION

The cosmic-rays (CR) arriving at the Earth after propagation through the heliosphere carry information on the interplanetary magnetic field (IMF). The structure of the IMF, on the other hand, varies under the influence of phenomena in which solar activity is manifested. Therefore, variation of CR flux is expected to be good indicator of solar activity.

The CR time series have been analyzed in a search for periodic intensity variations by various authors. Majority of studies is with neutron monitor records, covering lower CR energy than muon detectors. In the frequency range covered by the present study $1.06 \cdot 10^{-8}$Hz-$3.47 \cdot 10^{-4}$Hz (period 0.3-1100 days) several periodicities are reported.

El-Borie et al. [1] have studied periodicities in CR data from eight different stations - six neutron monitors: Deep River, Mt. Wellington, Climax, Hermanus, Rome and Huancayo, as well as two muon telescopes: Nagoya and Mawson, separately for solar minimum and solar maximum epochs. In four consecutive solar minima they found only one consistent peak $\sim$ 27d and its first two harmonics. Another signal present in all periods is $\sim 250 - 285$day. Sporadically, signals with periods 45-54, 66 and 100 days are found.

Mavromichalaki et al. [2] investigated Climax neutron monitor data in the period 1953-1996 searching for periods ranging from a few months to 11 years. Identified signals by maximum entropy method are: 3, 4, 4.5, 5.2, 7.1, 8.4, 9.1, 10 months and 1year and 1.7year.

Joshi [3] also looked for periodicities in Climax data, but in the 22 solar cycle maximum (1989-1991). Author related periodicity of ~ 170 day to strong magnetic field.

Kudela et al. [4] were interested in CR spectra and time evolution of the signals. In the analysis of four neutron monitors: Climax(1951-2000), Calgary(1969-2000), Lomnický Štít(1982-2000) and Huancayo(1953-2000) in the period range 60-1000 days, among found waves ~ 170 day appears to be the most persistent one. Signal at ~ 150 day is not stable, but ranges from 140 to more than 200 days, appearing usually just after solar maxima. The other sporadic signals are 70-75 days and 600-700 days. Solar rotation period $\sim$ 27 days (+ higher harmonics) are also present.

Attolini et al. [5] in the time series from Huancayo (1937-1953) and Climax(1953-1979) neutron monitors detected 1 year periodicity, shifting to 1.3 year near solar minima. The other signals (1.77, 1.58, 1.33 and 1.18 tears), identified as higher harmonics of fundamental frequency (10.67 years) are considered nonsignificant.

Spectral analysis of Voyager1 and Voyager2 anomalous CR data is done by Hill et al. [6]. Authors dedicated most attention to $\sim$ 151day signal, although other signals are present in oxygen, helium and proton data.

Generally, fewer number of studies are dedicated to spectral analysis of muon time series. Muons are produced by higher energy primaries than neutrons, and therefore muon flux variability provides additional information needed for better understanding of solar modulation process. Of course, cosmic-ray and solar variability can not be related in a straightforward manner, due to complexity of mechanism of solar modulation of cosmic rays.

In a number of studies of solar variability, periodicities similar to above mentioned are reported. Lou et al. [7] identified periodicities in coronal mass ejection data from LASCO/SOHO during maximum of solar cycle 23 (1999-2003). This result is highly relevant for the present study, since time interval investigated partially overlaps with ours and since relation between CME and cosmic rays is well established [8]. In the same time interval authors have analyzed data on solar X-flares (clas $>$ M5.0) from the GOES and found a series of periodic signals.

After discovery of $\sim$ 154 days periodicity of solar flare rates by Rieger et al. [9] many investigations are undertaken searching for periodicity in solar parameters variability. Lean and Brueckner [10] found $\sim$ 155 days periodicity in sunspot blocking function, 10.7cm radio flux and sunspot number, as well as the other peaks at 115, 162, 270 and 323 days. The signal with the same period is found in photospheric magnetic flux in solar cycle 21, but not in solar cycle 22 [11]. In the

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same solar cycle, 155 day signal was absent from daily record of sunspot areas [12] (in contrast to $\sim$ 86 day signal), but present in cycles from 14 to 20 (1904-1976) [13]. The signal was also absent from the green corona brightness of the Sun in time interval 1947-1976 [14] where 17.6 month periodicity is located. Another form of solar activity exhibited 152-158 day period: radio burst of type II and IV [15].

Pap et al. [16] presented evidence for periodicities in total solar irradiance and various solar activity indices: 10.7cm flux, Ca-K plage index, projected areas of active and passive sunspot groups and sunspot blocking function.

Another solar parameter relevant for cosmic-ray studies is occurrence of solar proton events. Gabriel et al. [17] found a series of periodicities whose position is cycle dependent.

The $\sim$ 78 day period is detected in 1-8A x-ray index in time interval 1977-1981 [18].

Sturrock et al. [19] searched for periodicity in solar neutrino data and found none.

There is no agreement on physical mechanism of observed periodicities in solar activity. Several explanations are proposed. Wolff [20], [21] suggested that rotation coupling of active bands generated by the solar g-mode oscillations with spherical harmonics l=2 and l=3 may generate 154 day periodicity. Other periodicities could be understood by normal mode of oscillation of slowly rotating star when two inertial r-modes couple with an interior g-mode. Bogart and Bai [22] proposed that cause of periodicities is interaction of active regions rotating at different rates. Lou [23] suggested that periodicities in question can be explained by equatorially trapped Rossby-type waves.

The CR variability investigated simultaneously with solar activity might help discriminating between different models, since they have different consequences on CR transport.

II. Experiment Description

Cosmic-ray muons are detected by two identical plastic scintillator detectors, installed in the Institute of Physics, Belgrade, Serbia. The laboratory is located at geographic latitude 44°51'N; geographic longitude 20°23'E, and altitude 78m above sea level. Geomagnetic latitude of the laboratory is $39^{o}32'$N and vertical geomagnetic rigidity cut-off is 5.3GV.

One detector is situated on the ground level, while the other is in the "Dr. Radovan Antanasijević" underground laboratory (at the depth of 25 m water equivalent). The detectors are of prismatic shape with dimensions 50cm × 23cm × 5cm. Scintillator type is similar to NE102. The scintillation light from each detector is collected by single photomultiplier tube. After amplification, the analog output signal is digitalized by laboratory made A/D converter and then linked to a computer PCI card. The 4096 channel spectrum is automatically recorded every 5 min, with 270 sec dedicated to measurements, and 30 sec being allowed for recording on local hard disc, some quick interventions on the system, and data transmission to second local network computer. The setup enables off-line data analysis without interrupting the measurements.

The recorded spectrum is mainly the spectrum of muon energy deposit ΔE. Daily recorded spectrum from surface detector, together with Monte Carlo simulation of detector response is plotted in Fig.1. The spectrum stretches to about 200 MeV and have a well defined single particle peak corresponding to an energy loss of some 11 MeV. The rise in the low energy part of the spectrum is due to environmental radiation.

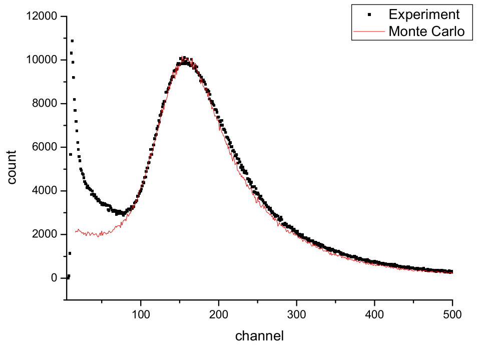

Fig. 1. Energy loss spectrum in plastic scintillator detector and Monte Carlo simulation of detector response to CR muons. The low energy rise is due to environmental radiation, whose contribution to overall spectrum is well separated from that of muons.

Monte Carlo simulation of this ΔE spectrum, based on GEANT4 package, agrees well with the experimental spectrum. With the given geometry, detector response to cosmic and ambient radiation are well separated (as confirmed by MC simulation) and unambiguous YES/NO selection criteria can be applied. All relevant physical processes leading to muon energy loss in interaction with detector is taken into account (ionization, bremsstrahlung, pair creation). Contribution to total energy loss from δ-electrons and other particles, produced by muonic interaction is also accounted for. Reliable detector simulation allows improvement of data analysis.

III. Data analysis and main results

The data from Belgrade muon detectors for the period 2002-2004 (belonging to descending phase of cycle 23) are spectrally analyzed. The time interval covers years following the maximum of solar cycle 23, when the Sun was exceptionally active.

The muon flux is recorded by two plastic scintillator detectors located on the ground level and in the underground laboratory of the Institute of Physics, Belgrade. The experimental setup is described in more detail elsewhere [24]. The muon data averaged over 4 hour period are presented in Fig.1.

The time series in question are incomplete, with 30% of missing data. Lomb-Scargle periodogram [25], [26] analysis method has been used in spectral analysis. This particular method is preferred since it can successfully treat unevenly sampled and gapped time series. Another advantage of Lomb-Scargle method is the well known statistical interpretation of the periodogram. Power spectral density $P(\nu)$, calculated

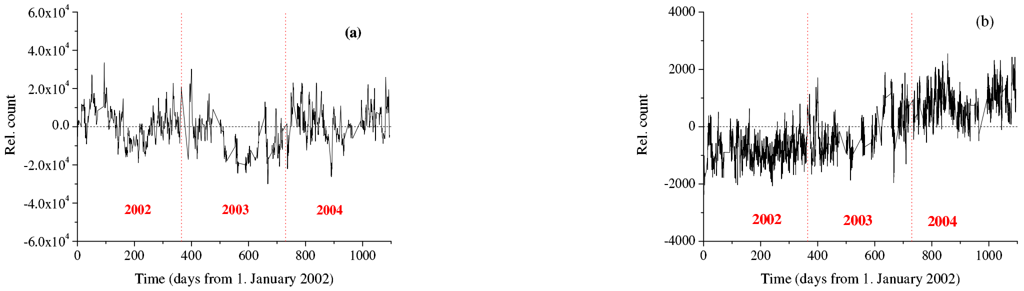

Fig. 2. Muon detector relative counting rate: ground detector (left) and underground detector (right).

on a discrete set of frequencies, has a statistical significance $exp(-z)$, where $z = \frac{P(\nu)}{\sigma_0^2}$ is the power, normalized to the total statistical variance. For a periodogram, calculated on a set of N independent frequencies, probability of observing a single peak above some value z is $p_0 = 1 - F$, where $F = 1 - (1 - e^{-z})^N$ is a false alarm probability. The number of independent frequencies N is estimated according to [27], rather than by following the empirical formula of [28] which is deduced from a quite specific problem and has limited applicability.

Better definition of peak position and a smoother appearance of periodogram is achieved by oversampling (the number of sampled frequencies in a periodogram is larger than the number of independent frequencies). Anyway, the frequency resolution is determined by the spacing between independent frequencies. In our case, with 4 hour averaged data, the investigated frequency range is between Nyquist critical frequency ($34\mu Hz$) and inverse of the total time span ($10.6nHz$). The number of independent frequencies is N=3427 and frequency resolution is $\delta\nu = 10nHz$. If the individual peak width is larger than the frequency resolution it is a signature of a quasi-periodicity with variable period, rather than a true periodicity.

Beside statistical, periodogram analysis faces also spectral problems (spectral leakage and aliasing). Thus, statistical criterion alone, based on false alarm probability is not sufficient for discrimination between true and false periodicities in the time series. One way to address this problem is by harmonic filtering [29]. After calculating the periodogram, usually the strongest signal is subtracted from the data to test its influence on other signals and then the periodogram is recalculated.

Yet another problem might plague the result - the pattern in missing data could cause the presence of false peaks and in the case of noisy data could shift positions of true peaks.

The above mentioned problems are addressed by the CLEAN deconvolution algorithm [30]. The true, undistorted spectrum is obtained by deconvolution of ”dirty” spectrum from spectral window function. The spectrum reffered to as ”dirty” is computed in our case as a Schuster periodogram and it turns out to be almost identical to Lomb-Scargle periodogram. Deconvolution procedure is started from highest amplitude component in the ”dirty” spectrum. A fraction of its amplitude (named gain: $0 < g < 1$) is convoluted and removed from the ”dirty” spectrum, resulting also in removal of its sidelobs in the residual spectrum. In our calculations value $g = 0.1$ is used, but results are not sensitive to change of this value. Residual spectrum is processed in the same manner until the stopping condition is met. We have chosen stopping condition recommended by Vityazev [31], that residual spectrum is not significantly different from pure noise.

The results of spectral analysis of cosmic ray counting rates averaged over 4 hours period are presented in Fig.3 for both the underground and the ground detector data.

The statistically significant peaks identified in the spectra and which survived deconvolution procedure are listed in Table 1 and Table 2. The ΔT_a is an error estimated theoretically, knowing frequency resolution ($\delta\nu = 10nHz$), while ΔT_b is experimentally determined as a half of full width at half maximum of a given signal. These errors are comparable, making it difficult to distinguish between true and quasi-periodicities.

IV. DISCUSSION

A number of statistically significant periodicities are identified by spectral analysis. Most of them are common features of both data sets, but several are unique to one or another detector data. These peaks are particulary interesting, since they appear as a consequence of energy dependent modulation processes.

A periodicity with solar rotation period ($\sim 26.5 \pm 0.3$ day in underground and $\sim$ 27.0 ± 0.3 day in ground data) is easily identified. This signal is well documented in various parameters describing solar activity and it is also present in many cosmic-ray time series. By far less significant are higher harmonics of this solar rotation period ($\sim 13.6 \pm 0.1$ in both data sets and $\sim 8.70 \pm 0.03 (\sim 8.40 \pm 0.03)$ days). The presence (and absence) of these signals might be related to sectorial structure of the interplanetary magnetic field.

In the high frequency region there is a peak at 1day period in the underground data. The same signal is recognized by Lomb-Scargle periodogram, slightly above 99% confidence level, but the signal is not confirmed by CLEAN. This periodicity is partly due to atmospheric effects but also indicates CR anisotropy arising from corrotation of CR particles with interplanetary magnetic field lines. In the surface detector data

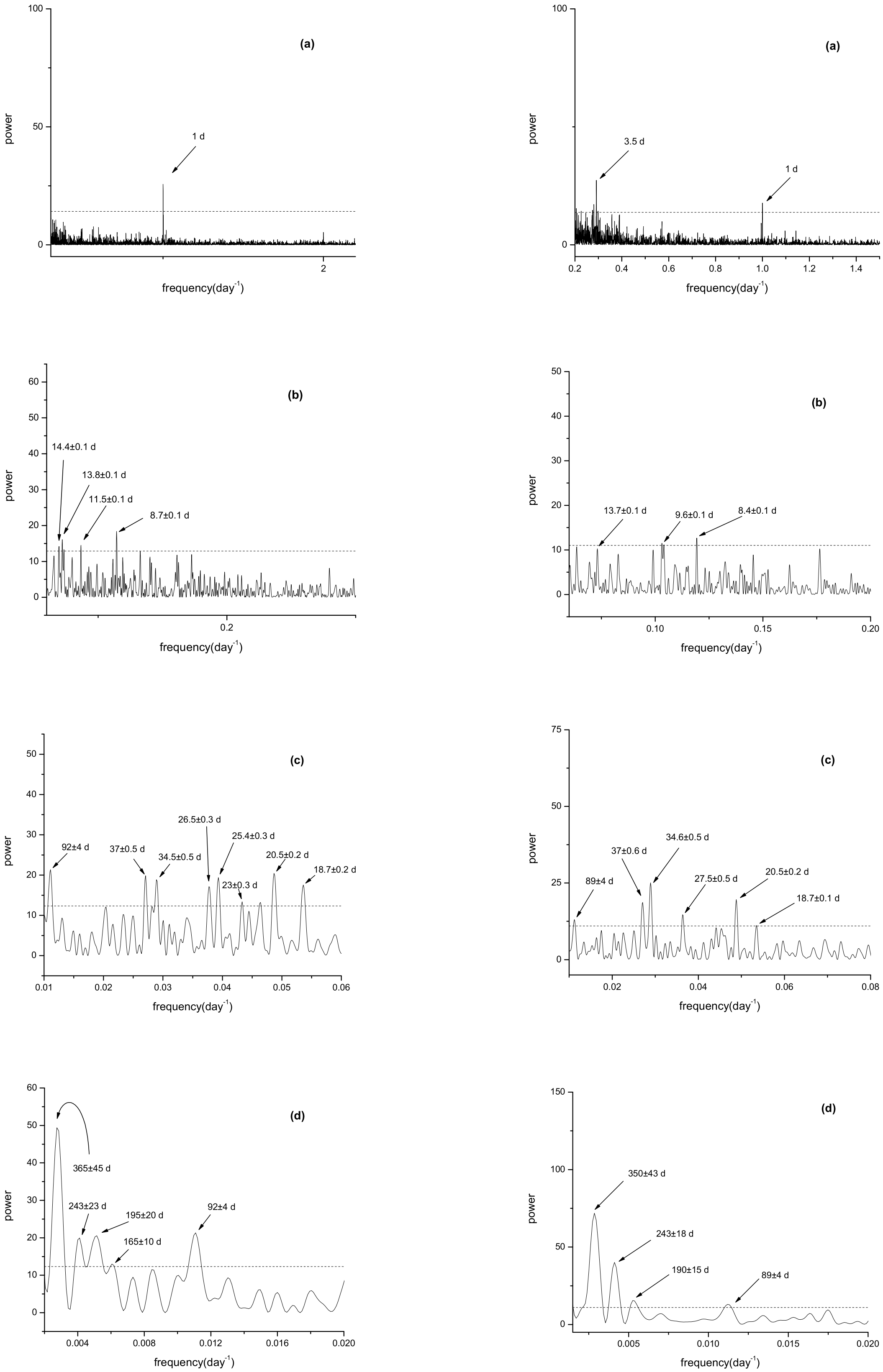

Fig. 3. Power spectra of the underground (left column) and ground (right column) detector data in different frequency range. The 99% confidence level is also plotted.

TABLE I

Periodicities present in the underground data set. Periods are given in days.

T	1	8.7	13.6	20.5	25.4	26.5	34.5	37	77	90	162	194	240	350
ΔT_a	$5 \cdot 10^{-4}$	0.03	0.1	0.2	0.3	0.3	1	0.6	2.5	3.5	11.5	16	24	53
ΔT_b	-	0.1	0.1	0.2	0.3	0.3	0.5	0.5	-	4	10	20	23	45

TABLE II

Periodicities present in the ground data set.

T	5.3	8.4	13.6	20.5	22	27	34.6	37	57	90	194	240	350
ΔT_a	$5 \cdot 10^{-4}$	0.03	0.1	0.2	0.2	0.3	1	0.6	2.5	3.5	16	24	53
ΔT_b	-	0.1	0.1	0.2	0.3	0.5	0.5	0.6	-	4	15	18	43

some evidence is found for $\sim$3.5d and$\sim$5.3d signals, both being higher harmonics of solar rotation period.

A set of periodicities is present in the region of intermediate frequencies: 20.5 $\pm$ 0.2d (both detectors); 22 $\pm$ 0.2d (GD); 25.4 ± 0.3d (UD); 27 ± 0.3d GD (26.5 ± 0.3 UD); 34.5 ± 0.5d (both); 37 ± 0.6d (both); 57 ± 2.5d (GD); 77 ± 2.5d (UD); 90 ± 3.5d (both). Interestingly, the signal with solar rotation period does not appear to be the most pronounced. Proliferation of peaks in this frequency band came as a surprise and one might question wether they represent genuine signal or artifacts of methods of analysis. CLEAN indeed removed several peaks, significant at the 99% level in the Lomb-Scargle periodogram but the above cited remained. The only known case where CLEAN fails is when false signal has the highest amplitude in a periodogram.

High-altitude neutron monitor (NM) data, as reported by [32], exhibit common features with Belgrade muon data. In the analyzed period (1990-1999), 27 day periodicity is present in Climax, Lomnický Štit, Tsumeb and Huancayo-Haleakala data. The 35 day signal (similar to ours 34.5 day) is detected only in Climax data. On the other hand, 37 day signal is found in all NM data, except Huancayo. Lomnický Štit, Mexico and Tsumeb NM have 58 day signal, corresponding to 57 day signal in our GD data. The 78 day wave is present in Mexico and Huancayo NM (77 day in our UD). In all NM 89 day periodicity is also found in all NM data (90 day in our muon data). Interestingly, this periodicity appears in Climax data in descending phase of solar cycle 22 (1992-1994), but not in the solar maximum period. The 115 day variation, otherwise common in NM data, is missing from Climax in the same period (1992-1994). This signal is not detected in Belgrade muon data.

Some rare periodicities also coincide in muon and NM data: 25 day in Alma Ata and Mexico (1992-1994) and 25.4 day in Belgrade UD; 20 day in Mexico 1992-1994, Lomnický Štit 1990-1999 and 20.5 day Belgrade UD+GD;

In the low frequency region, 162 $\pm$ 10 day periodicity is found only in UD. This period correspond to six solar rotations (6$\times$27 =162 day). It is not clear wether this signal can be correlated with variations of many solar parameters with periods ranging from 154 to 158 day. According to [4] $\sim$ 150 days periodicity in cosmic-rays is not stable, but ranges from 140 to more than 200 days, appearing usually just after solar maxima. This period is close to 170 days period found by Joshi [3] for the years 1989-1991 (maximum phase of solar cycle 22) in Climax data. It is the only period exhibiting this periodicity within entire period 1953-1997. Author relates this periodicity to the strong magnetic field via influence of magnetic clouds on CR intensity variation [33], [34].

In the vicinity of our 240 days periodicity El-Borie and Thoyaib [1] found evidence for a peak in several NM data ranging from 250-285 days for different epochs.

Some evidence is found for 1.3 year signal in the GD data, but it is not well spectrally resolved from annual variation and still needs to be confirmed in the more detailed analysis.

As already mentioned in the Introduction, CR intensity variation is correlated with solar parameters. Much progress is made in understanding solar modulation of cosmic rays and with new observational data and continuous research, further improvement is expected. Various indicators of solar activity are proven to produce modulation: magnitude of IMF, heliospheric current sheet tilt. Dynamics component of IMF is associated with Corotating Interaction Regions and coronal mass ejections. In many studies of solar modulation process, CR intensity is correlated with different solar activity parameters: sunspot number, flare microwave flux at 10.7cm, polar coronal holes, CMEs (see for example [35]).

In the study of periodicities of solar coronal mass ejections [7], the most significant peaks are at $\sim 358 \pm 38$d, $\sim 272 \pm 26$d, $\sim 196 \pm 13$d close to $\sim 350 \pm 43$d, $\sim 243 \pm 18$d, and $\sim 190 \pm 16$d in Belgrade muon data. Other peaks (significant at level higher than 3σ) at $\sim 57 \pm 1$d, $\sim 35.9 \pm 0.4$d, $\sim 33.5 \pm 0.4$d, and also $\sim 20.6 \pm 0.2$d are close to $\sim 57 \pm 1$d(GD), $\sim 37.0 \pm 0.5$d, $\sim 34.5 \pm 0.5$d and $\sim 20.5 \pm 0.2$d (GD) in Belgrade muon data.

Daily counts of X-ray solar flares of class $\geq$M5.0, analyzed in the same study, contain periodicity at $\sim 157 \pm 11$d, which might be related to $\sim 162 \pm 10$d in Belgrade muon data. It is a strong indication that CR exhibit Rieger-type periodicity. In a recent study of soft X-ray flare index ($\mathrm{FI}_{\mathrm{SXR}}$) 161d period is revealed in cycle 21 (but not during cycles 22 and 23) [36].

The nature of this periodicity could be better understood if one looks at other signals, expected to be related to the present one. Following Bai and Sturrock [37], if this periodicity is of Rieger-type, it is a manifestation of a hypothetical solar "clock", with a fundamental period of about 25.5days. Periodicities often observed in solar activity data at 51, 78, 103, 129, and 154 days are subharmonics of this fundamental period. In Belgrade muon data, in addition to 162 days signal, 25.4 ± 0.3d and 77 ± 1d periodicities are indentified in UD. None of these periodicities is present in GD. We can not offer an explanation for the observed difference between the two detector data sets.

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