THE COSMIC-RAY 1.68-YEAR VARIATION: A CLUE TO UNDERSTAND THE NATURE OF THE SOLAR CYCLE?

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Abstract. Using the maximum entropy method (MEM), the cosmic-ray power spectral density in the frequency range 3×10^{-9}–2×10^{-7} Hz has been estimated for the period 1947–1990. Cosmic-ray intensity data were integrated from the ion chamber at Huancayo and the neutron monitor at Deep River, following the method of Nagashima and Morishita (1980). The estimated spectrum shows power-law dependence ($f^{-1.62}$), with several peaks superimposed. Periodicities of the different peaks are identified and related to solar activity phenomena; most of them were reported in the past. Once the 11-yr variation is eliminated, the most prominent feature in the spectrum is a variation, not reported before, with a period of 1.68 yr (604.8 d). This peak is correlated with fluctuations of similar periodicities found in the southern coronal hole area and in large active regions. The importance that this variation may have to elucidate the solar magnetic flux emergence and the activity cycle is discussed.

1. Introduction

The transport of cosmic rays from the edges of the heliosphere to the near-Earth region is greatly influenced by the interplanetary magnetic field (IMF) structure. The status of the IMF is in turn determined by the different manifestations of solar activity. Therefore, studies of cosmic-ray variations detected on the Earth provide a means to study the magnetic activity of the Sun. One way of studying the cosmic-ray time behaviour, especially when the causes of the variation are not directly observable, is to use statistical methods as is usually done in other fields of physics.

Several authors have studied the frequency distribution of the cosmic-ray intensity fluctuations in the range 10^{-6}–10^{-4} Hz (Owens and Jokipii, 1974; Attolini, Cecchini, and Galli, 1974; Otaola and Hurtado, 1981). The main result of these works is the determination of a relationship between the general characteristics of the power spectral density (PSD) of the cosmic-ray flux and the random component of the IMF. Up to now, the PSD analysis of the cosmic-ray intensity recorded at ground level by polar and non-polar stations has shown in this frequency range (1 cycle/4 months–1 cycle/3 hours) a predominant component of the type f^{-2}, with indications of a change below 5×10^{-7} Hz.

At lower frequencies, the region from which the variations may originate becomes very large. Thus one has to expect a more direct relationship of the cosmic-ray flux changes to the global solar activity and to its recurrences.

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In this work, we present a study of the cosmic-ray PSD in the very-low-frequency range from 10^{-9} to 10^{-7} Hz (1 cycle/30 years–1 cycle/4 months). We use a data set that covers the period 1947–1990, i.e., four solar cycles. To have compatible data for the whole time span it was necessary to integrate registers from two different kinds of detectors: the ion chamber at Huancayo (1947–1957) and the neutron monitors at Deep River (1958–1990). The plan of the paper is as follows: Section 2 briefly describes the data processing and justifies the choice of spectral method to determine the corresponding cosmic-ray PSD fluctuations. Section 3 is dedicated to presenting the results of our spectral analysis. One of the main features of the calculated spectrum is a 1.68-yr variation that becomes the most important once the 11-yr fluctuation has been filtered out. This periodicity is reported here for the first time as a sharp peak in the spectrum. A discussion of the possible solar origins of all the peaks present in the calculated spectrum is given in Section 4. Finally, in Section 5 we present a summary of results together with our conclusions.

2. Data Analysis

In our analysis, we used monthly averages of the ion chamber at Huancayo (January 1947–December 1957), corrected for barometric pressure and instrumental drift by Forbush (1958), and also those of the Deep River neutron monitors (January 1958–December 1962; and May 1962–December 1990). Strictly speaking, the integration of two kinds of intensities is not permissible if the detectors have different rigidity responses to the cosmic-ray flux; they will have different time lags with solar activity, the intensity variations may be rigidity dependent and will not always be the same quantitatively (Forbush, 1958; Moraal, 1976). However, this time lag is considerably smaller than the time scales relevant to the present work ($\geq$ 4 months). Therefore the data normalisation method described by Nagashima and Morishita (1980) is permissible in our case as a first approximation.

In Figure 1, the integrated cosmic-ray intensity over the period 1947–1990 is shown. The cosmic-ray intensity is expressed in percentage decrease with respect to the maximum intensity level reached in May 1965.

Before applying the technique of power spectral analysis to the cosmic-ray intensity series of 44-yr of monthly values, the data were smoothed using an ultra low-pass filter that essentially gives the trend of the input function and effectively removes rapid fluctuations (Behannon and Ness, 1966).

Given our primary interest to investigate periodicities in the constructed time series and search for its possible solar origins, we have chosen the maximum entropy method (MEM) to calculate PSD of the data in Figure 1. The MEM has been proven to be better than other spectral schemes to resolve different frequency peaks (Ulrich and Bishop, 1975; Kanasewich, 1981, Kudela, Ananth, and Venkatesan, 1991).

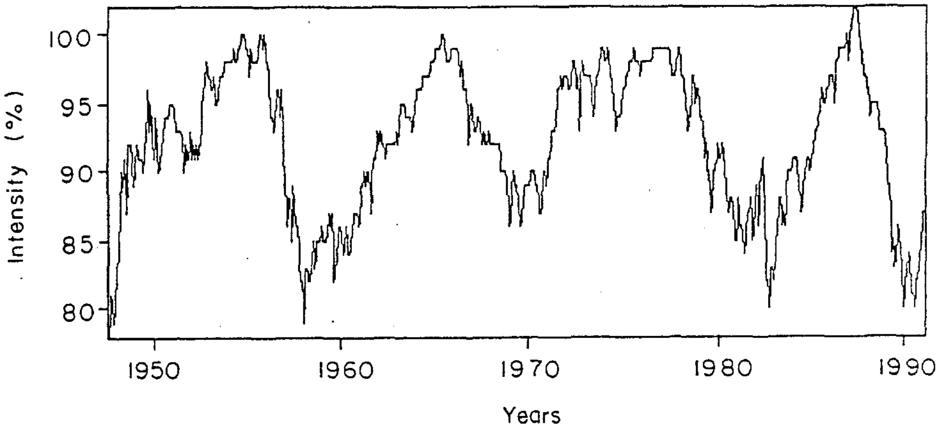

Figure 1. Monthly mean values of the cosmic-ray intensity derived from the ion chamber at Huancayo and the neutron monitors at Deep River, from June 1947 to December 1990. The 100% corresponds to May 1965.

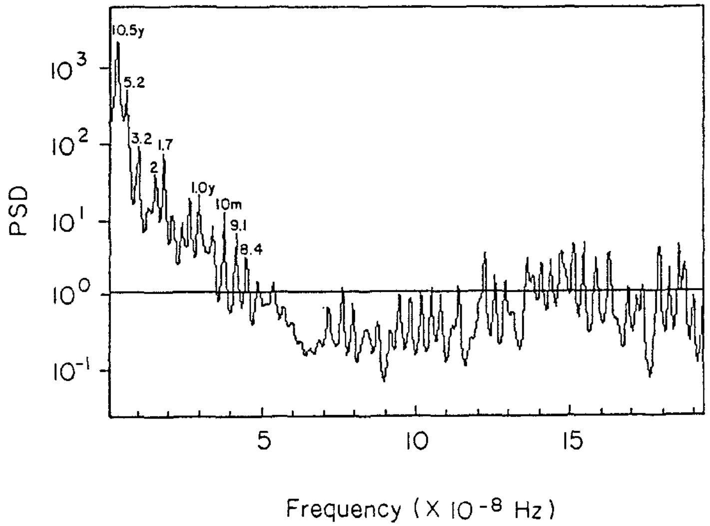

Figure 2. Power spectral density derived from the monthly mean values of the cosmic-ray intensity shown in Figure 1. The power density is expressed in units of percent^2 Hz^{-1}.

3. Results

In Figure 2 we plot the PSD of the smoothed 44-yr monthly average series in the frequency range 10^{-9}–1.9×10^{-7} Hz. From an inspection of Figure 2, we observe:

(i) An $f^{-1.62}$ power-law behaviour of the PSD that levels off around 0.5×10^{-7} Hz. To determine the slope of the PSD, we have used the calculations of the periodogram based on the sine components of the Fourier transforms. The cosmic-ray spectrum at these frequencies is similar to the shape of the power spectrum of the IMF fluctuations (Owens and Jokipii, 1974; Burlaga and Mish, 1987).

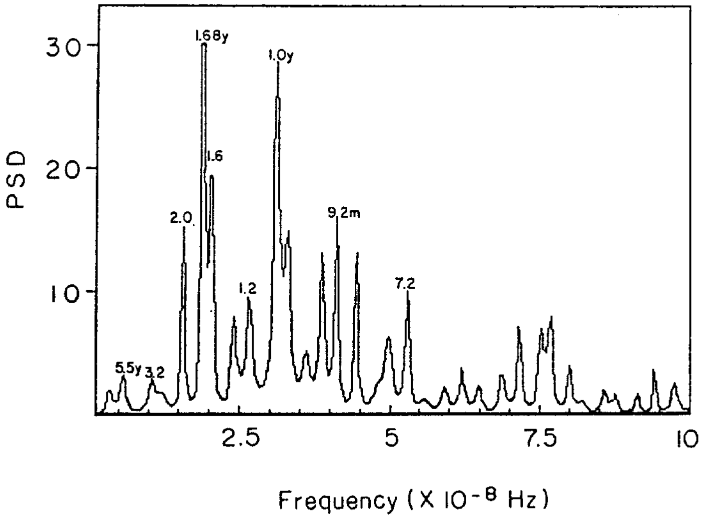

Figure 3. Power spectral density of the cosmic-ray intensity series in which the 11-yr peak has been filtered.

(ii) There are significant peaks in the spectrum that are superimposed on the afore-mentioned general trend. The 10.5-yr peak clearly corresponds to the solar activity cycle. The Earth's rotation period (1 yr) causes a seasonal cosmic-ray variation (Forbush, 1954).

(iii) Other important peaks are also present with periodicities of 5.2 yr, 3.2 yr, 2 yr, and 1.7 yr.

To have a clearer picture of the spectrum, we subtracted the contribution due to the 11-yr variation by filtering the original series using a Gaussian low-pass filter. This removes the first harmonic of the series and permits an analysis of the relative importance of the remaining peaks. The spectrum of the new series is shown in Figure 3. In this figure there are significant peaks at 2.0 yr, 1.68 yr, 1.6 yr, 1.0 yr, and 9.2 m. The most important is that corresponding to a period of 1.68 yr (604.8 d). This is a periodicity not reported previously in cosmic-ray intensity and it is the main topic of this work. Kudela, Ananth, and Venkatesan (1991) made an FFT spectral analysis of the Deep River and Calgary neutron monitors for the period 1965–1989. They found an abrupt change in their spectrum slope at around 20 months (605 d), but since the technique used is more oriented to finding the functional dependence of the PSD, they could not resolve the peak found here. The peak at 1.6 yr may be due to peak splitting caused by the MEM (Ulrich and Thomas, 1975).

We went a step further and calculated the PSD of cosmic-ray intensity during cycles 20 and 21 separately. These data correspond to the Deep River NM-64 neutron monitor and are the most reliable part of all the set used. Results are presented in Figures 4(a) and 4(b). In cycle 20, a fluctuation of 1.3 yr appears as the most important, leaving the 1.68-yr periodicity in a third place in importance, but

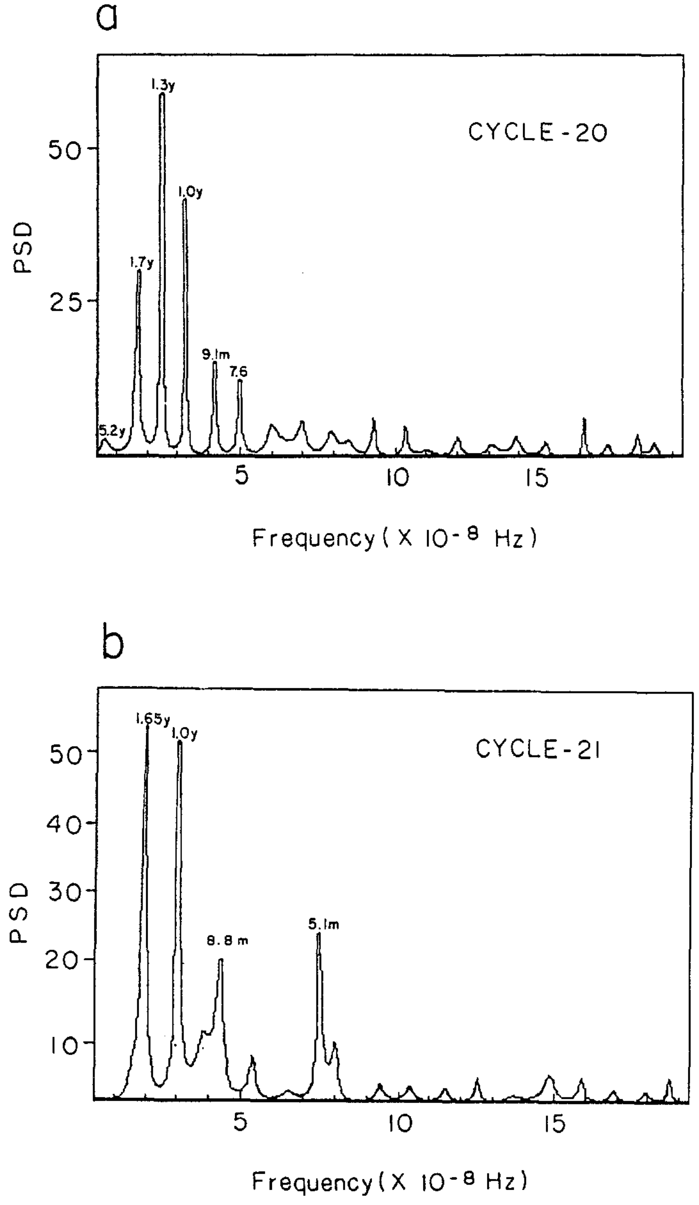

Figure 4. (a) Power spectral density of the cosmic-ray intensity regitered in the Deep River NM-64 during solar cycle 20. The 11-yr peak has been filtered out. (b) Same as (a) but for cycle 21.

still significant. The 1.65-yr variation appears as the most important in cycle 21. Therefore the 1.68-yr periodicity is confirmed as a true modulation effect.

The spectral peaks found must have an explanation in terms of solar activity. We now proceed to analyse them.

4. Discussion

Let us start our discussion with the spectral peaks of Figures 2, 3, and 4 that have been already identified by other authors.

The 5.2-yr variation is present during even cycles and absent in odd cycles (Otaola and Pérez-Enríquez, 1983). This behaviour has also been found in several solar activity parameters such as sunspot numbers, 2800 MHz flux and plage calcium lines (Dodson and Hedeman, 1975) and also in X-ray long-duration event (LDE) flares (Antalová, 1994). Otaola, Pérez-Enríquez, and Valdés-Galicia (1985) suggested that this fluctuation is also related to the cosmic-ray arrival paths into the heliosphere for epochs of different solar magnetic polarity.

The 3.2-yr variation is correlated with a similar variation in sunspot number (Attolini, Cecchini, and Galli, 1987).

The 2-yr variation was reported long ago (Kolomeets, Mukanov, and Shvartsman, 1973). Attolini, Cecchini, and Galli (1987) indicated that the existence of this variation is due to the polarity status of the interplanetary cavity instead of solar activity as represented by the sunspot cycle. This is based on a phase inversion of this fluctuation that is correlated with a similar behaviour of the annual variation.

On the time scales of interest, solar flare occurrence may be a good measure of solar activity to correlate with the newly found cosmic-ray intensity variation at 1.68 yr. It is well known that solar flare occurrence is correlated with cosmic-ray fluctuations on a long time scale (Hatton, 1980; Xantakis, Mavromichalaki, and Petropulos, 1988). The daily number of Hα flares on the whole solar disk during activity cycles 20 and 21 show periodicities of around 155 d and 520 d (5.2 m and 1.4 yr), they are considered to be inherent properties of solar flare activity (Ichimoto *et al.*, 1985). These periodicities do not coincide with the largest peak of our filtered spectrum for the whole series used.

When we analysed the Deep River neutron monitor data separately for cycles 20 and 21, a fluctuation of 1.3 yr appeared as the most important in cycle 20, but it is absent from cycle 21. Richardson *et al.* (1994) found a fluctuation of the same periodicity in the solar wind speed when they analyzed data from 1973 to 1994. This variation is obvious only after 1987, this period corresponds to cycle 22. We have already referted to the 1.4-yr variation in solar flare activity (Ichimoto, 1985). Moreover, Antalová (1994) found a 1.4-yr fluctuation in LDEs present in cycles 20 and 22 but not in cycle 21. All these results together may be an indication that the 1.3-yr fluctuation is only present in even activity cycles, thus revealing another fundamental difference between even and odd solar activity cycles.

An inverse correlation of polar coronal hole area with cosmic-ray intensity was reported some time ago (Hundhausen *et al.*, 1980). Bravo *et al.* (1987) showed a positive correlation between equatorial coronal holes and cosmic-ray intensity. Recently, McIntosh, Thompson, and Willock (1992) studied the total area of coronal holes within latitude bands of 10–50° north and south of the solar equator during activity cycle 21 plus the first three years of cycle 22. These authors found that the total area of southern coronal holes show a 1.66-yr (600-d) periodicity throughout the 13-yr period. The corresponding northern region does not show this periodic behaviour. Hemispheric asymmetries have been reported in a wide range of solar related phenomena as flares (Garcia, 1990), sunspot area (Swinson *et al.*, 1986), magnetic flux (Hoeksema and Scherer, 1987), and radio and X-ray bursts (Verma, 1987), therefore the coronal hole area behaviour is not unexpected.

The reported coronal hole variation would be enough to suggest a solar connection with the cosmic-ray 1.68-yr fluctuation encountered in this work. Furthermore, Antalová (1994) made an analysis of the time evolution of LDEs for the period 1969–1992 (cycles 20, 21 and part of 22) as representative of large active regions. She found significant fluctuation periodicities at 10.5 yr, 5 yr, 2 yr, and 1.6 yr, coincident with those found here in cosmic-ray intensity. Unfortunately there is no information to confirm if the coronal hole north–south asymmetry is also present in LDEs. On one hand, the 1.6-yr variation in LDEs comes as no surprise since it is a confirmation of a correlation between large active regions and coronal holes recently reported by McIntosh (1990). On the other hand, it provides a firm base to sustain the solar origin of the 1.68-yr cosmic-ray fluctuation. This variation points toward a close relationship between cosmic rays and the presence of large magnetic structures in the solar atmosphere and indicates that it is closely related to the large-scale structures of the heliospheric modulation region. Therefore, it seems that the detailed study of this fluctuation may also help in the problem of the interaction of large-scale structures in the interplanetary medium.

The 1.68-yr variation cosmic-ray intensity was found with a data set that covers a much longer period than those observed in solar parameters. Therefore it is an indication that the solar fluctuations are stable and, perhaps also asymmetric. This long-life stability implies a non-random generation the of solar magnetic flux. Thus the result found here is a step forward in understanding one of the most fundamental contemporary problems of solar astrophysics: the nature of the solar cycle.

5. Summary and Conclusions

From the analysis of a 44-yr cosmic-ray intensity record, making use of the maximum entropy method for power spectral analysis and different types of filters, we may summarize the main results of this work as follows:

(1) The cosmic-ray PSD in the region 3×10^{-9}–0.5×10^{-7} Hz has a clearly expressed power-like form $f^{-1.62}$; this follows rather closely the known functional dependence of the IMF spectra at these frequencies.

(2) Superimposed on the power-law behaviour of the spectrum there are significant peaks at the following periods: 10.5 yr, 5.2 yr, 3.2 yr, 2.0 yr, 1.68 yr, and 1 yr. All but the 1.68-yr were already reported and associated with corresponding periodicities of several solar or heliospheric phenomena.

(3) The PSD peak at 1.68 yr becomes the most important when the 11-yr fluctuation is filtered out of the data.

(4) The 1.68-yr variation found here is a stable feature of all the cosmic-ray intensity period analysed. It is the first time this periodicity has been reported as a sharp peak in the cosmic-ray PSD. It seems to be related to a periodicity of 607 d found in the area of equatorial southern coronal holes and to a similar variation in large solar active regions.

Coronal holes and large active regions in the Sun are zones where magnetic flux is generated. The close relation amongst them and their association with the cosmic-ray 1.68-yr variation strongly suggests that we have found one of the characteristic modes of the solar magnetic activity.

Acknowledgements

The results of the research presented here were accomplished by a team of three persons. Unfortunately, just before the final steps, our friend J. A. Otaola passed away. We have kept him in the list of authors to honour not only his memory, but also his paramount contribution to the present work and to our professional careers.

References

Antalová, A.: 1994, *Adv. Space Res.* **14**, 721.

Attolini, M. R., Cecchini, S., and Galli, M.: 1974, *Nuovo Cimento* **C7**, 413.

Attolini, M. R., Cecchini, S., and Galli, M.: 1987, *Astrophys. Space Sci.* **134**, 103.

Behannon, K. W. and Ness, N. F.: 1966, Nasa TND-3341.

Bravo, S., Mendoza, B., Pérez-Enríquez, R., and Valdes-Galicia, J. F.: 1988, *Ann. Geophys.* **6**, 377.

Burlaga, L. F. and Mish, W. H.: 1987, *J. Geophys. Res.* **92**, 1262.

Dodson and Hedeman: 1975, *Solar Phys.* **42**, 121.

Dorman. L. I. and Ptuskin, V. S.: 1981, *Astrophys. Space Sci.* **79**, 397.

Forbush, S. E.: 1954, *J. Geophys. Res.* **59**, 525.

Forbush, S. E.: 1958, *J. Geophys. Res.* **63**, 651.

Garcia, H. A.: 1990, *Solar Phys.* **127**, 185.

Hatton, C. J.: 1980, *Solar Phys.* **66**, 159.

Hoeksema, T. and Scherer, P. H.: 1987, *Astrophys. J.* **318**, 428.

Hundhausen, A. J., Sime, D. G., Hansen, R. Y., and Hansen, S. F.: 1980, *Science* **207**, 761.

Ichimoto, K., Kubota, J., Suzaki, M., Tohmura, I., and Kurokawa, H.: 1985, *Nature* **316**, 422.

Kolomeets, E. V., Mukanov, J. G., and Shvartsman, J. E.: 1973, *Proc. XIII Int. Cosmic Ray Conf.* **3**, 1207.

Kudela, K.: 1992, *Proc. 1st. SOLTIP Symposium* **2**, 108.

Kudela, K., Ananth, A. G., and Venkatesan, D.: 1990, *J. Geophys. Res.* **96**, 15781.

McIntosh, P. S., Thompson, R. J., and Willock, E. C.: 1992, *Nature* **360**, 322.

Moraal, H.: 1976, *Space Sci. Rev.* **19**, 845.

Nagashima, K. and Morishita, I.: 1980, *Planetary Space Sci.* **28**, 177.

Otaola, J. A. and Pérez-Enríquez, R.: 1983, *Proc. XVIII Int. Cosmic Ray Conf.* **10**, 47.

Otaola, J. A., Pérez-Enríquez, R., and Valdes-Galicia, J. F.: 1985, *Proc. XIX Int. Cosmic Ray Conf.* **4**, 493.

Owens, A. J. and Jokippi, J. R.: 1974, *J. Geophys. Res.* **79**, 907.
Richardson, J. D., Paularena, K. I., Belcher, J. W., and Lazarus, A. J.: 1994, *Geophys Res. Letters* **21**, 1559.
Xantakis, J., Mavromichalaki, H., and Petropulos, B.: 1988, *Solar Phys.* **122**, 3.