Proceedings of ICRC 2001: 3773 © Copernicus Gesellschaft 2001

ICRC 2001

On the wavelet approach to cosmic ray variability

K. Kudela[1], M. Storini[2,3], A. Antalová[1], and J. Rybák[1]

[1]IEP/SAS, Watson str. 47–4353 Koaice - Slovak Republic
[2]IFSI/CNR - Via del Fosso del Cavaliere, 100 - 00133 Roma, Italy
[3]Raggi Cosmici, c/o Dip. di Fisica, UNIRoma3, Via della Vasca Navale, 84 - 00146 Roma, Italy
[1] AI/SAS, 059 60 Tatranská Lomnica, Slovak Republic

Abstract. A wavelet transform (time scale ~60 to ~1000 days) is applied on the long-term time series of daily means of cosmic ray intensity observed by neutron monitors at different cutoff rigidities. No persistent periodicities with the same amplitude are found for the whole period analyzed. The temporal evolution of quasiperiodic variations at ~150 days, ~1.3 years and ~1.7 years is examined. While the ~1.7-y quasiperiodicity (the most remarkable one in the studied interval) is strongly contributing to the cosmic ray intensity profile of solar cycle 21 (particularly in 1982), the ~1.3-y one (which is better correlated with the same periodicity of the interplanetary magnetic field strength) is a characteristic feature for the decreasing phases of the cycles 20 and 22. Transitions between them are seen from the wavelet power spectra plots. Obtained results give a support to the claimed difference in the solar activity evolution during odd and even solar activity cycles.

1 Introduction

Various periodicities, with a duration longer than the diurnal one, have been reported by many authors after the inspection of the cosmic ray time series, especially those obtained by neutron monitors (NMs), and related to periodicities driven by solar activity. In addition to the power spectrum density (PSD) derived by usual FFT methods (Attolini et al., 1975; Xanthakis et al., 1989; Kudela et al., 1991 among others), other techniques have been used in the past for the identification of significant cosmic ray periodicities (see, for instance, MEM method by Valdes-Galicia et al., 1996). Contrary to conventional spectral analysis, the wavelet transforms are suitable for the description of nonstationary processes containing multiscale features, singularity detection and analysis of transient phenomena. Hence, wavelet technique is used in many geophysical applications (see Kumar and Foufoula-Georgiou, 1997 and references therein). Nevertheless, this approach is not frequently used in cosmic ray studies; only few exceptions can be found (Astafyeva and Bazilevskaya, 1999; Kudela et al., 1999).

We present wavelet transform results from the time series of daily averages of the nucleonic intensity recorded by NMs at four different cut-off rigidities, over a period up to four solar cycles, and describe the PSD temporal evolution at three periodicities, namely 150-160 days, ~1.3 and ~1.7 years.

2 Data and method of investigation

The counting rate of four NM-data sets have been examined, namely the daily means of stations with the effective cutoff rigidities (R_e) and covering the following time intervals: Calgary (CA: R_e= 1.07 GV, 1969-2000), Climax (CL: R_e=3.02 GV, 1951-2000), Lomnický Štít (LS: Re=3.95 GV, 1982-2000) and Huancayo/Haleakala (H/H: R_e=13 GV, 1953-2000). For the whole time interval the usual FT was used for deducing the power spectrum density (PSD). For checking the temporal evolution of the contribution of the different periodicities to the signal, the method of the continuous wavelet transform described by Torrence and Compo (1998) was used. The Morlet mother function was applied with the nondimensional frequency equal to 6. The wavelet power spectrum (WPS) significance was derived according to the global one. To examine the existence of periodicities >27 days, the normalized variation method, introduced by Stamper et al. (1999) was used assigning the new time series x'(t) from the original one, x(t) as:

Correspondenceto: K. Kudela (kkudela@kosice.upjs.sk)

$$x'(t) = (x(t) - X(t,w))/S(t,w),$$

where X is the average and S is the standard deviation of x within the interval (t-w,t+w) and w=300 days in this work. In the following this method is named as F filter.

3 Main results

The longest data set (CL NM) was checked by the usual FT method. The power spectrum density (PSD, in relative units) as a function of the period T (in days, being the frequency f=1/T), is showing the slope $f^{-1.72\pm0.01}$, if fitted in the whole frequency range (Fig. 1). However, the slope is flatter in the interval ~40-800 days, with clear signatures of ~27-d (with its slighter second harmonic) and ~11-y periodicities.

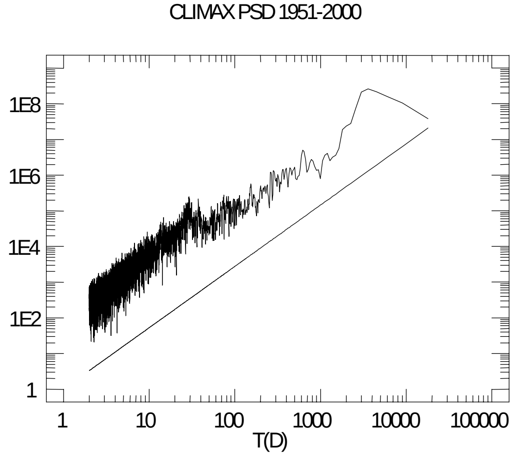

Fig. 1 - Periodogram (obtained as the sine FT) of daily average count rates of CL NM after the GLE elimination. The fit $f^{-1.72}$ is plotted (line) for comparison.

The spectral shape of H/H data is similar to the one of CL, while the other two are slightly different (the spectral index has a little bit larger error but is consistent with the one of CL); there are two reasons for that: shorter time periods are covered and at lower rigidities (especially for CA NM) the GLEs are contributing to the time series. Between the ~27-d and ~11-y periodicities there is a more complicated structure with indications of presence of weaker signals at ~150-d and ~600-700-d. The effect of F is enhancing the amplitudes of the periodicities if they persist as a slight signal in the original data (Fig. 2). The periodicity with a center at ~154 days is present together with another one at about 170-d in CL data, which was also reported by Joshi (1999). At higher rigidities there is a more complicated structure in the range 140-170-d and probably the effect of shorter time series (LS) is influencing this structure. On the other hand, stations more sensitive to higher energies like H/H and LS are showing a signature of increase at 70-75-d, which is less pronounced at CL and CA.

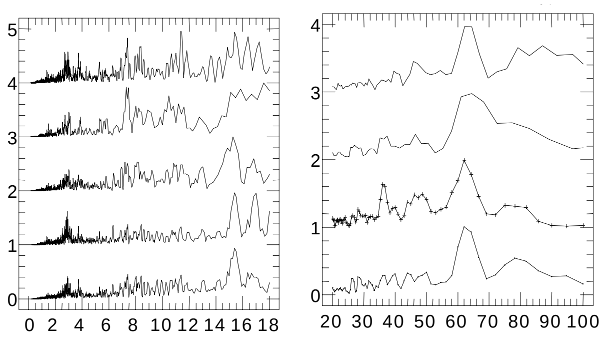

Fig. 2 - Periodograms (left and right panels) of NM time series at two intervals of periodicities (in tens of days). From bottom to top: CL, CL with F filter, CA, LS, and HH. Maximum values of PSD in the respective intervals are adjusted to unity and shifted by 1 with respect to previous profile.

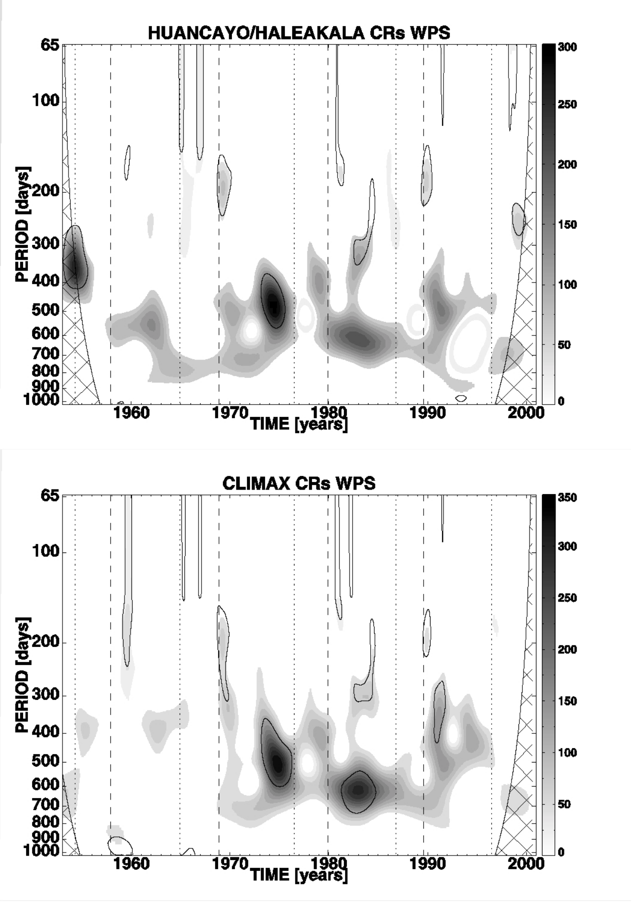

Fig. 3 - WPS of H/H (top) and CL (bottom) normalized variations (F filter was applied) obtained by wavelet transform. Values are multipled by 0.01 and 0.1 respectively to plot the results in similar scales. Missing cosmic ray data were obtained by linear approximation from two neighbour values. The contours correspond to the 95% significant level. Dashed and dotted vertical lines depict solar activity maxima and minima, respectively.

At longer periodicities there is a clear peak at ~ 620-d at CL (well seen also at CA and HH), while the yearly variation, observed also in the near-Earth solar wind speed (Zieger and Mursula, 1998) and the possible 1.3-y periodicity are better discernable when F filter is applied on data. A slight signature of increase in the range 440-500-d is seen too, also appearing at the HH profile.

The temporal evolution of the cosmic ray time series periodicities was analyzed by the continuous wavelet transform in the period range between 64 and 1024 days on the daily basis. The WPS of CL and HH normalized variations (Fig. 3) clearly outline that the periodicities mentioned in Fig. 1 and Fig. 2 are not persistent with the same amplitude during the whole interval studied.

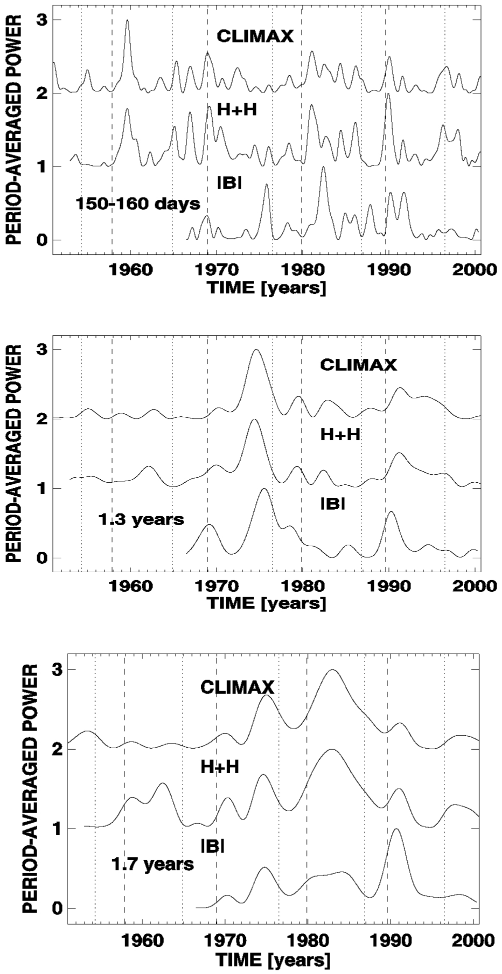

Fig. 4 - Averaged WPS in the analyzed period (upper panel: interval 150.6-157.3 days; middle panel: 464.5-485.0 days; lower panel: 602.3-629.0 days) for CL, H/H and IMF strength |B|. Dashed and dotted vertical lines depict solar activity maxima and minima, respectively. The values of H/H and CL were shifted by 1 and 2, respectively. The F filter was applied.

Focusing on the mentioned target periodicities Fig. 4, upper panel, shows the comparison of the NM intensity WPS temporal profiles at ~150 days at two different cutoff rigidities. The WPS temporal profiles for periodicities ~1.3 and ~1.7 year are shown in the middle and lower panels. Fig. 4 displays also the WPS temporal profiles of the daily averages of IMF intensity (|B|), available from IMP satellites (http://nssdc.gsfc.nasa.gov/omniweb) .

4 Discussion and conclusion

The shortest quasiperiodicity checked here on cosmic ray data (~150 days; upper panel of Fig. 4) was found earlier in the IMF strength and solar wind speed at 1 AU (Cane et al., 1998). Consistently with results from Cane et al. (1998) the IMF power average in 1978-1982 is larger than in 1968-1972. Fig. 3 indicates that this quasiperiodicity in cosmic rays is not stable and it ranges from 140 to more than 200 days, appearing usually just after the solar maxima. The comparison of the middle and lower panels of Fig. 4 reveals that, for the examined ranges of periodicities, both cosmic ray data sets have a similar power evolution. Looking at the three panels we may assert that the three selected periodicities contribute differently to the “global signal” in time. For the cycle 21 the power at 1.3-y has smaller values if compared to the neighbour cycles. The largest value of power for this periodicity is observed at both cosmic ray stations during the decreasing phase of cycle 20 (1974 year). This strong contribution to the CR signal is seen also in Fig. 4a reported by Valdes-Galicia et al. (1996). It should be mentioned that for the period 1972-1976 (when the power at ~1.3-y has the largest contribution to both signals: cosmic rays and |B|) Hundhausen et al. (1980) reported an enhanced correlation between cosmic ray intensity and the area of polar coronal holes. On the other hand, the periodicity at 1.7-y is more importantly contributing to cosmic ray intensity during the cycle 21, if compared to the neighbours. The IMF strength at the Earth’s orbit is showing better correspondence to cosmic ray behaviour at 1.3-y than that at 1.7-y. A 1.3-y periodicity is also present in the post-1986 data in solar wind speed (Richardson et al., 1994; Gazis et al., 1995), in the North-South component of IMF B, as well as in Ap index time series (Paularena et al., 1995). Recently, Mursula and Zieger (2000) studied this periodicity in the solar wind speed from 1964 onward and in Kp index from 1932 onward. They showed this variation has a character of quasi-periodicity occurring during the even solar cycles, what is in good agreement with our results, for the last three solar cycles. However they found a new, somewhat longer periodicity (period 1.5-1.7 years) during odd cycles. This ~1.7 year periodicity was found in cosmic rays by Valdes-Galicia et al. (1996). It was also examined in connection to large scale photospheric motions (Valdes-Galicia and Mendoza, 1998) and identified in the occurrence of sudden storm commencements (Mendoza et al., 1999). Earlier, this periodicity was reported for coronal hole areas in the cycle 21 (McIntosh et al., 1992).

Wavelet results (Fig. 3) indicate that there are no stable periodicities in cosmic ray intensity (in the sense of “solar clock”) in the whole range between ~60 to ~1000 days examined here. The quasiperiodicity which is seen clearly in the integral power spectra over past 47-49 years, is that of ~1.7-y. It is observed similarly at two stations with different energies of primaries. For the last three cycles, in agreement with Valdes-Galicia and Mendoza (1998), its contribution is stronger during the post maximum years of the odd cycles (here seen clearly in the cycle 21) when, after the magnetic field reversal of the Sun, the cosmic rays penetrate through the current sheet into the heliosphere if compared to the even cycle when their predominant drift via polar latitudes is suggested (e.g. Kota and Jokipii, 1983, Jokipii, 1998). Since the solar modulation is governed by the solar wind structures with the frozen in IMF, similarities between the cosmic ray behaviour and the time evolution of solar wind structures are expected. Fig. 3 shows that while on both NM data the more dominant "quasiperiodicity" with the center ~1.7-y is seen in the odd cycle 21 (1981-1984), the more dominant contribution to the signal from ~1.3-y "quasiperiodicity" is observed in the cycles before and after it. If alternating periodicities are a systematic feature of consecutive cycles, it implies the relevance of identified differences between even and odd solar activity cycles (Storini, 1997a,b; Storini and Sýkora, 1995). In fact, this alternation could support differences in the space-time evolution of coronal holes (and hence in the active region locations) during even and odd cycles (e.g. Mursula and Zieger (2000) remarks from solar wind studies). However, more work is needed on the subject because it is not straightforward to relate cosmic ray variability directly to solar periodicities, having in mind the different access of particles from interstellar medium into the inner heliosphere during periods with different polarity of the solar magnetic field.

Acknowledgements. The Slovak grant agency (VEGA grants 2/1147/21&2/7229/20) and the IFSI/CNR-IEP/SAS cooperation via PNRA/MURST supported this work. We thank the University of Chicago, "National Science Foundation Grant ATM-9912341" and H. Graumann, U. of Calgary for NM data. C. Torrence and G. Compo are acknowledged for the computing code (http://paos.colarado.edu/research/wavelets). Thanks are also due to V.N. Obridko for suggesting the use of the F filter.

References

Astafyeva, N.M. and Bazilevskaya, G.A., Long-Term Changes of Cosmic Ray Intensity: Spectral Behaviour and 27-Day Variations, *Phys. & Chem. of the Earth* (C), **25**, 129-132, 1999.

Attolini, M.R., Cecchini, S., Guidi, I., and Galli, M.,The shape of power spectrum of cosmic ray at ground level up to 7 x 10^{-3} Hz, *Planet. Space Sci*., **23**, 1603-1610, 1975.

Cane, H.V., Richardson, I.G., and von Rosenvinge, T.T., Interplanetary magnetic field periodicity of ~153 days, *J. Geophys. Res*., **25**, 4437-4440, 1998.

Gazis, P.R., Richardson, J.D., and Paularena, K.I., Long term periodicity in the solar wind velocity during the last three solar cycles, *Geophys. Res. Lett*., **22**, 1165-1168, 1995.

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

Jokipii, J.R., Cosmic Rays, in *From the Sun: Auroras, Magnetic storms, Solar flares, Cosmic rays*, ed. S.T. Suess, B.T. Tsurutani, **AGU**, 123-131, 1998.

Joshi, A., Cosmic Ray Periodicity at 170 days, *Solar Phys.*, **185**, 397-403, 1999.

Kóta, J. and Jokipii, J.R., Effects of drift on the transport of cosmic rays. VI. A three-dimensional model including diffusion, *Astrophys. J.*, **265**, 573-581, 1983.

Kudela, K., Ananth, A.G., and Venkatesan, D., The Low-Frequency Spectral Behavior of Cosmic Ray Intensity, *J. Geophys. Res*., **96**, 15,871-15,875, 1991.

Kudela, K., Yasue, S.-I., Munakata, K., and Bobik, P., Cosmic Ray Variability at Different Scales: a avelet Approach, *Proc. 26th ICRC*, Salt Lake City, **7**, 163-166, 1999.

Kumar, P., and Foufoula-Georgiou, E., Wavelet Analysis for Geophysical Applications, *Rev. of Geophys*., **35**, 385-412, 1997.

McIntosh, P.S., Thompson, R.J., and Willock, E.C., A 600-day periodicity in solar coronal holes, *Nature*, **360**, 322, 1992.

Mendoza, B., Lara, A., Maravilla, D., and Valdes-Galicia, J.F., Magnetic emergence and geomagnetic activity, a close correlation, *Solar Phys*., **185**, 405-416, 1999.

Mursula, K., and Zieger, B., The 1.3 year variation in the solar wind speed and geomagnetic activity, *Adv. Space Res*. **25 (9)**, 1939-1942, 2000.

Paularena, K.I., Szabo, A., and Richardson, J.D., Coincident 1.3 year periodicities in tha ap geomagnetic index and the solar wind, *J. Geophys. Res*., **22**, 3001-3004, 1995.

Richardson, J.D., Paularena, K.I., Belcher, J.W., and Lazarus, A.J., Solar wind oscillations with a 1.3 year period, *Geophys. Res. Lett*., **21**, 1559-1560, 1994.

Stamper, R., Lockwood, M., Wild, M.N., and Clark, T.D.G., Solar causes of the long-term increase in geomagnetic activity, *J. Geophys. Res*., **104**, 28,325-28,342, 1999.

Storini, M., Modulation of galactic cosmic rays during solar activity minima, *Report CNR/IFSI-97-1*, Frascati - Italy, 1997a.

Storini, M., Cosmic Rays for Solar-Terrestrial Physics, *Il Nuovo Cimento*, **20C**, 871-880, 1997b.

Storini, M., and J. Sýkora, Even-odd solar-cycle differences of the green corona brightness, *Contr. Astron. Obs. Skalnaté Pleso*, **25**, 90-108, 1995.

Torrence, Ch., and Compo, G.P., A Practical Guide to Wavelet Analysis, *Bull. Amer. Meteorol. Society*, **79**,. 61-78, 1998.

Valdes-Galicia, J.F., Perez-Enriquez, R., and Otaola, J.A., The Cosmic Ray 1.68-year Variation: a Clue to Understand the Nature of the Solar Cycle?, *Solar Phys.*, **167**, 409-417, 1996.

Valdes-Galicia, J.F., and Mendoza, B., On the role of large-scale solar photospheric motions in the cosmic ray 1.68-yr intensity variation, *Solar Phys.*, **178**, p. 183-191, 1998.

Xanthakis, J., Mavromichalaki, H., and Petropoulos, B., Time evolution of cosmic ray intensity modulation, *Solar Phys.*, **122**, 345-351, 1989.

Zieger, B., and Mursula, K., Annual variation in near-Earth solar wind speed: Evidence for persistent north-south asymmetry related to solar magnetic polarity, *Geophys. Res. Lett*., **25**, 841, 2000.