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Pulses with Modulation Analysis of Ground Level Proton Events

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Abstract. **By means of awavelet technique we analyze the intensity-time profiles of four relativistic solar protons (RSP) events (23 February** 1956, 14 **July** 2000, 28 **October** 2003 **and** 20 **January** 2005) **observed in the period** 1942 − 2006. **Analysis of galactic cosmic ray data before the occurrence of RSP events shows a peculiar pattern behavior of the periodicities in their time series that may be considered as precursors for forecasting goals. Among the periodicities found in this work, it is to mention the short-term (ST) periodicities, in the order of days, all of them are harmonics of the** 11−**year solar activity cycle, and the ultra-short term (UST) periodicities in the order of minutes-hours. Besides, RSP time series together with those of several solar activity (SA) indexes were analyzed by means of the wavelet coherence spectral method. We have found that most of the established ST-periodicities are also present in sub-photospheric and coronal layers. This synchronization seems to indicate that RSP production may not be a local phenomenon, but involves global regions of the Suns atmosphere.**

Keywords: **Relativistic Solar Protons, Wavelet Analysis, Solar Activity.**

I. INTRODUCTION

The occurrence of solar proton events (SPE) is a very frequent phenomenon, which up to now is considered as a random process associated mostly with solar flares. At the same time, their close relations to solar active centers and even to shock wave phenomena is also presently recognized. In some extent, their occurrence rate follows the 11−year cycle of solar activity (SA). Most of SPEs are observed in the low (non-relativistic) energy range. They cause no effect at the Earths surface and are mainly detected by satellites in the interplanetary space. Sporadically, with an average rate of ∼ 1.1 yr−1, a relativistic solar proton (RSP) event occurs when protons acquire energies above 500 MeV (up to ≥ 10 GeV). The events of this kind are also known as Ground Level Enhancements (GLEs) of solar cosmic rays (SCR). At present, they are usually registered at the Earths surface by the worldwide network of neutron monitors (NM) and meson telescopes (MT). Since 1942 up to now (May 2009), in all, 70 GLEs have been observed [1], the first and last ones having been detecting, respectively, on 28 February 1942 (GLE01) and 13 December 2006 (GLE70). The well-known event of 23 February 1956 (GLE05) is still a biggest one in this numeration. As
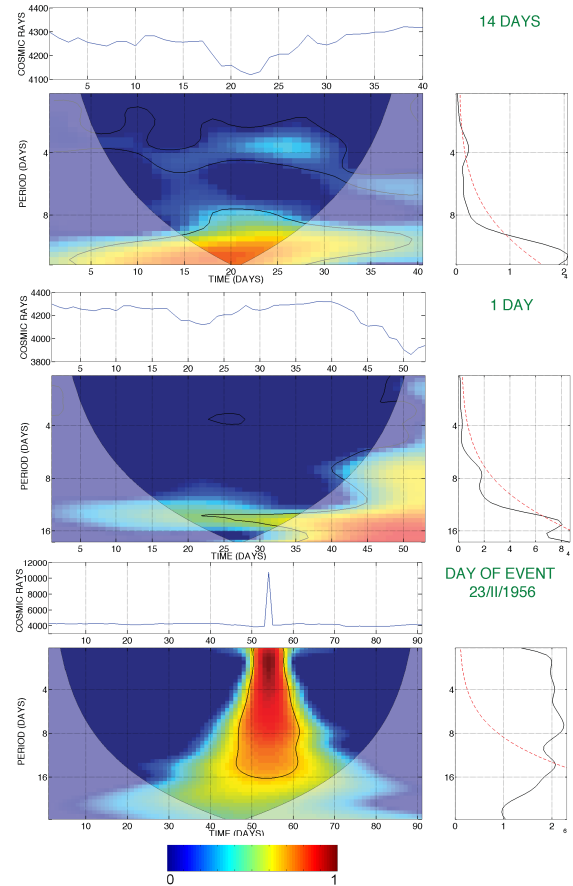

Fig. 1.

known, the events of this kind occur more often in the periods of maximum SA. The study of their energy spectrum and intensity-time profile gives us information about the source properties and the propagation processes, respectively, for instance, about the maximum capacity of the Sun as a particle accelerator engine, magnetic structure of the traversed medium, etc. On the other hand, man-conducted space ships and other space vehicles must be prevented of the radiation hazard of these events.

II. DATA AND METHODS OF ANALYSIS

Data on RSP events from 1942−1960 are very limited due to a reduced number of cosmic ray stations. Data during the events are tabulated in 1 − 5 min. intervals; data prior to the event are presented in the form of hourly or daily tables. On the other hand, data of solar indices

are given in monthly or daily tables, and, in the best case, as hourly data. For the purposes of illustration, we selected four events: 23 February 1956 (GLE05), 14 July 2000 (GLE59), 28 October 2003 (GLE65), and 20 January 2005 (GLE69). First of all, we have studied intensity variations of galactic cosmic rays (GCR), by analyzing spectral evolution of the GCR time series back to 50 days before single RSP events. In the case of GLE05 of 23 February 1956 the Climax station data were used, the other three GLEs mentioned above were analyzed by the data of Oulu station. Within the same task of determining the pattern behavior that may lead to find precursors for future prognostic work, we have analyzed, further, the RSP time series during the GLEs themselves. This analysis was carried out by the Morlet wavelet spectral method to determine the periodicities of oscillation of RSP flux [3]. It was done with the aim to associate them with the known, mainly short-term, periodicities of solar phenomena, or eventually, to determine new periodicities intrinsic to RSP events. In this point, however, it is to keep in mind that the time scale of RSP events is mostly of minutes, and solar indexes are in much longer time scales. So, to develop a coherence analysis, we proceeded to transform the time series of dates of occurrence of the 70 GLEs into a series of Pulses with Modulation (PwM) of the type: $1 =$ event, $0 =$ no event [2]. Then, we apply wavelet coherence analysis of that PWM time series with daily time series of solar sunspots which is widely used as a direct indicator of the solar activity. We also use daily series of the coronal index (CI) of SA, which is a measure of solar irradiance in the coronal green line at 530.3 nm (Fe XIV). The CI is compared with similar full-disk solar indices. The wavelet coherence is especially useful in highlighting the time and frequency intervals where two phenomena have a strong interaction. The right panels of the figures below show the global wavelet spectrum and the color code is given at the bottom. The red color indicates a high intense periodicity, or, a high coherence (1) between both spectra and the blue color indicates a low intensity oscillation, or, a low level of coherence (0). The arrows indicate the phase between the power spectra of two data series involved: horizontal arrows pointing at right (0°) corresponds to a linear positive relationship. Horizontal arrows towards left (180°) correspond to a linear negative relationship. Arrows in the $90^o - 270^o$ interval correspond to a non-linear relationship between both phenomena.

III. RESULTS

Figure 1 shows the evolution of oscillations of GCR several days before the GLE of 23 February 1956, and Figure 2 demonstrates analogous results for the RSP event of 20 January 2005. The upper panels of both figures show the cosmic ray time series including the solar particle increase during the day GLE. The lower panels show the oscillation periodicities of the particle intensity. The abscissa denotes the real time in days, and the panel
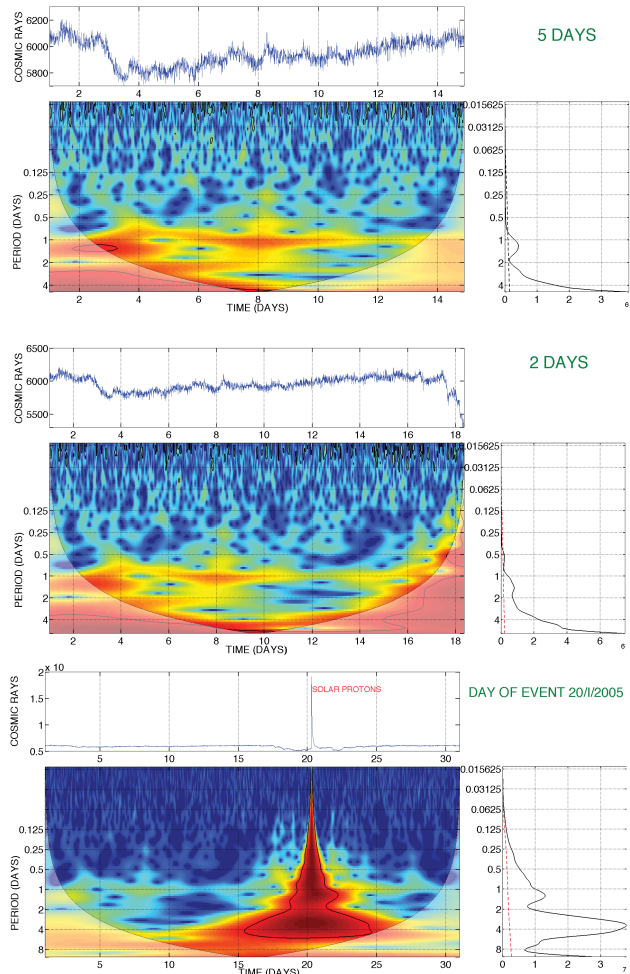

Fig. 2.

at right denotes the frequency in units of days. One can appreciated that the oscillation frequencies evolve with time, from low frequencies many days before the event, increasing the frequency as time approaches the event day. Such evolution may be seen around 15 days before the GLE of 20 January 2005, or even around 40 days before the event of 23 February 1956. A characteristic frequency band is formed in each event: from 14 to 2 days in the GLE05, and from 4 days to some hours in the GLE69. On the day itself of the events, all those frequencies are present simultaneously, forming a kind of wings at low frequencies. Such an evolution behavior is not seen out of the periods of RSP event occurrence.

Figure 3 shows the results of wavelet analysis of the PwM series of GLE occurrence dates. In addition to well-known mid-term (MT) periodicities of SA (0.3, 0.5, 0.7, 1.3, 3.5, 7 and 11 yrs.), we have found periodicities of 2.5, 5-8, 11, 22-30 and 60 days. Hereafter, we usually name them as short-term (ST) periodicities when they are shorter than 3 months. It can be seen that the number of GLEs does not follow the intensity of the solar activity cycle: for instance, relatively weak cycle 23 had more RSP events than much more intense cycle 22. In
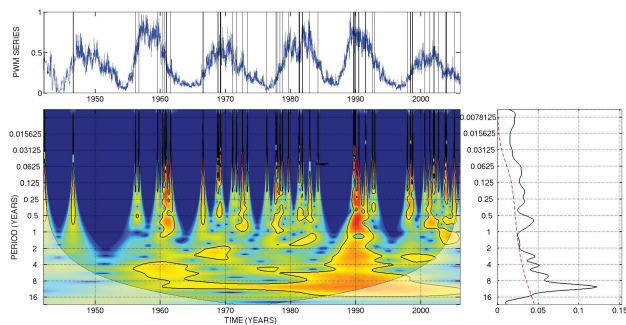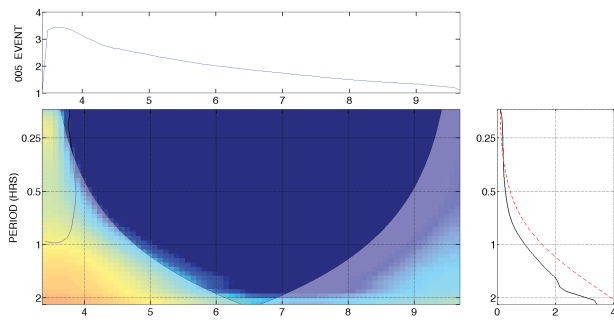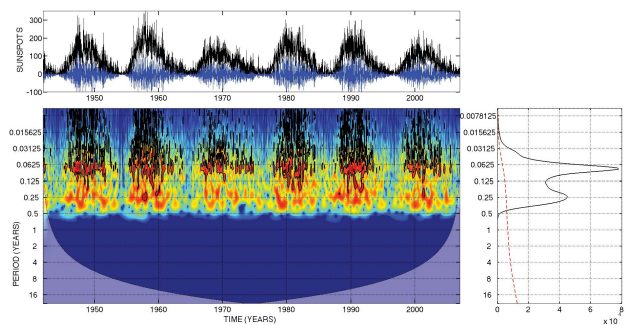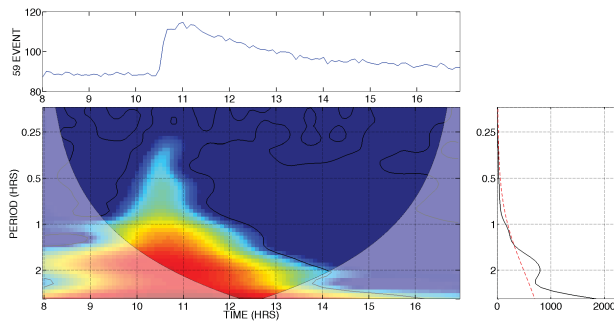
Fig. 3.

Fig. 6.

Fig. 4.

Fig. 7.

Fig. 5.

general, wavelet analysis of each one of the events shows that all pulsate with different periodicities, most of them within the range of 15 min. to 10 hrs., that we will designate here as ultra-short term (UST) periodicities. Figures 4 and 5 present the results of wavelet analysis of the time series of sunspot numbers (SS) and coronal indices (CI), respectively. Beside the MT periodicities, we have found here also the ST periodicities of 2.5, 11-14 and 30 days (SS) and 2.5, 5, 30, and 60 days (CI). As an illustration the results are shown below for the selected 4 events. Figure 6 shows that the proton flux during the biggest event of 23 February 1956 (GLE05) was oscillating with periodicities of 15 min. The RSP flux during the Bastille Day event (14 July 2000, GLE 59) was oscillating with periodicities of 1.3 and 1.7 hrs (Figure 7). Figure 8 demonstrates that during the event of

28 October 2003 (GLE 65) the RSP flux was oscillating with the periods of 15 min, 45 min and 7 hrs. On 20 January 2005 (GLE69) characteristic oscillation periods were 3, 5 and 8 hrs (Figure9). Finally, on Figures 10 and 11 we present the wavelet coherence of the PwM for the GLE occurrence dates versus SS and CI, respectively. We can observe that the controlling periodicity in both cases is that of the 11−year period of solar activity cycle. As it was expected, the higher occurrence rate of RSP events takes place during solar cycle maxima. On the other hand, the occurrence rate of GLEs seems do not depend on the intensity of solar cycles in the SS numbers.

IV. CONCLUSIONS

For the first time, in this work it is presented results on spectral wavelet analysis of GLEs. We have determined specific periodicities characterizing the RSP flux behavior during the 17 − 23 solar activity cycles. Those periodicities are in coherence with the time series indicators of the photosphere (SS) and the corona (CI) periodicities. Among the more prominent here are the periods of 2.5, 5, 11, 22 and 30 and 60 days, all of them are harmonics of the 11−year solar activity cycle. Also, most of the known mid-term frequencies of solar activity are found in the RSP time series. As expected, we confirm here, by wavelet analysis, that the PwM time series of RSP flux contains the periodicity of 11 yrs. Also, the wavelet coherence between the PwM series of RSP events is in phase with the time series during the whole period under analysis (1942 − 2006). The
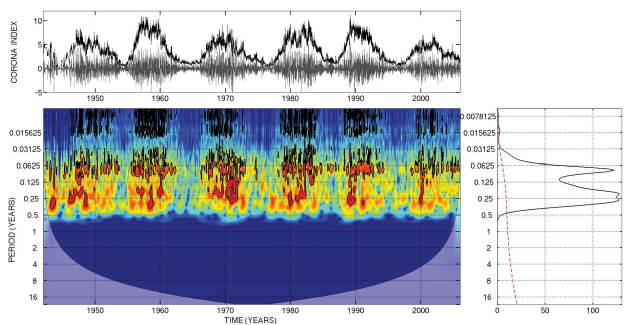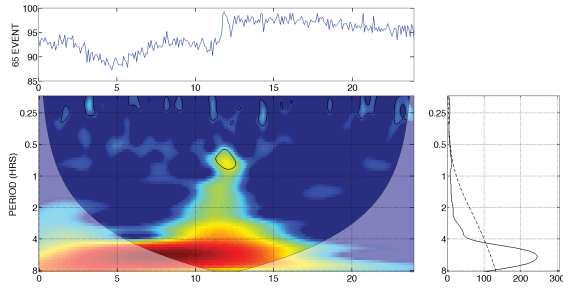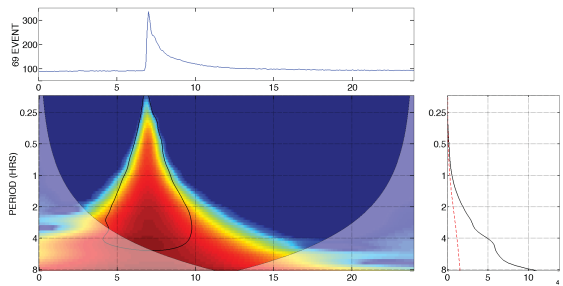
Fig. 8.

Fig. 9.

Fig. 10.

Fig. 11.

tendency to RSP events to occur in priority during solar cycle maxima, may be associated with the presence of the extremely short term periodicities (from minutes to hours) found here, but more work in this direction must be done before drawing any certain conclusion. Since most of the periodicities found here are common to the RSP, SS and CI, by the moment we can infer that there is a synchronization of oscillations between different solar layers, from the sub-photospheric ones up to the corona. This seems to indicate that RSP phenomena is not a local one, specific of chromospheric or coronal structures, but involve global regions of the Suns atmosphere. Perhaps, the more transcendental result is the establishment of one criterion to predict RSP events on basis of a peculiar behavior of GCR oscillations weeks before an event occurrence. We can furnish the Morlet wavelet software to one or more neutron monitor stations, where it can be can surveyed every day the oscillations behavior of cosmic rays, and predict in this way RSP events with an advance of several days. Also, most of the known mid-term frequencies of solar activity are found in the RSP time series. As expected. We confirm here, by wavelet analysis, that the PWM time series of RSP contains the periodicity of 11 yrs.

Also, the wavelet coherence between the PWM series of RSP events are in phase with the time series during all the analyzed time period $(1942 - 2006)$. The tendency to RSP to occur in priority during solar cycle maxima, may perhaps be associated with the presence of the extremely short term periodicities (from minutes to hours) found here, but more work in this direction must be done before drawn any conclusion. Since most of the periodicities
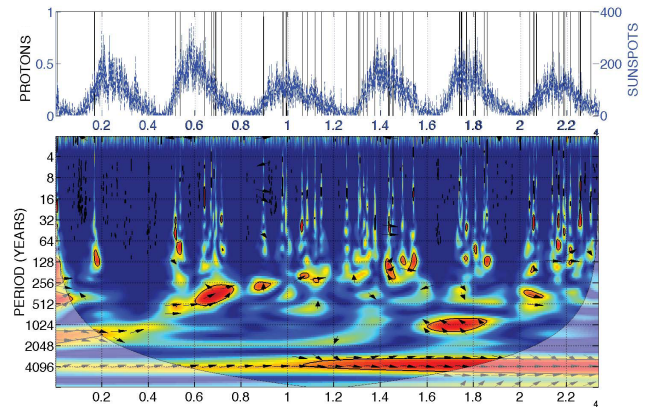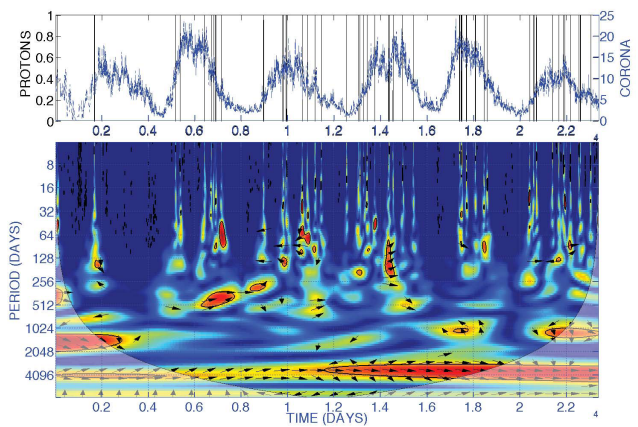
found here are common to the RSP, Sunspots and (CI) by the moment we can infer that there is a syncronization of oscillations between different solar layers, from the subphotospheric ones up to the corona. This seems to indicate that RSP phenomena is not a local one, specific of chromospheric or coronal structures, but involve global regions of the sun atmosphere. Perhaps the more transcendental result is the possibility to develop of one criterion to forecast RSP events on basis of a peculiar behavior of cosmic ray oscillations weeks before an event occurrence.

V. ACKNOWWLEDGEMENTS

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