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Classification of GLE´s as a Function of their Spectral Content for Prognostic Goals

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Abstract: **In this work, we attempt to determine characteristic signatures of Ground Level Enhancements (GLE's) of Relativistic Solar Particle (RSP) for the following tasks: (1) the study of common periodicities between RSP_and solar activity processes at different layers of the solar atmosphere. Among the periodicities found here there are the Ultra short-term (UST) periodicities, in the order of minutes-days, some of which are similar to those of the different layers of the solar active atmosphere. (2), we present a method that allows to predict a tentative date for the occurrence of the next GLE, (GLE71), December 2011-February 2012.**

Keywords: Solar Relativistic Particles, Prognosis of GLEs

1 Introduction

GLEs of relativistic solar protons (RSP) are relatively rare (sporadic) phenomenon with an average rate of ~1.1 yr^{-1}. Their occurrence during solar cycles 17-23 follows, to a certain extent, the time behavior of the 11-year cycle of solar activity (SA); however, they do not follow the intensity of the solar activity cycle, as for instance, cycle 23 had more GLEs events than cycle 22, which was a much more intense one. In total, 70 GLEs have occurred, the first and last ones, on 28 February 1942 (GLE01) and 13 December 2006 (GLE70) respectively. They receive a specific number (e.g., see Table 1 in [1]). Their study is particularly important: it gives us information about the source and the propagation processes, i.e., about the maximum capacity of the Sun as a particle accelerator engine, magnetic structure of the traversed medium, etc. Besides it is known that man-conducted spaceships and other space vehicles must be prevented of the radiation hazard of RSP from GLEs. Though it is often assumed that GLEs is random phenomenon, however, in this work we show that they keep a cyclic tendency represented by pseudo-harmonic signals.

By studying individual GLEs, in a previous work [2] we have determined the intrinsic periodicities of such RSP events: so, in addition of the ~1.1 yr^{-1}, we have found by means of wavelet-analysis *mid-term* periodicities of solar activity (0.3, 0.5, 0.7, 1.3, , 3.5, ,7 and 11 yrs.), some of them agreeing with solar activity periodicities, *short-term* periodicities (2.5, 5-8, 11, 22-30 and 60 days), the later three periodicities are in the range of characteristic flare periodicities [3] and *ultra-short* term periodicities in the order of minutes-hours.

A further argument against the stochasticity of GLEs was obtained by means of a wavelet-coherence analysis between RSP series and photospheric and coronal series: results indicate that most of the periodicities mentioned above are present from sub-photospheric to coronal layers. Such a syncronization seems to indicate that RSP production is not an isolated local phenomenon but involves global regions of the Sun atmosphere.

In this work we show that (1) periodicities of GLEs can be clasiffied in terms of their enhancement intensity (2) considering only their temporal distribution from 1942-2006 it is possible to predict the occurence of future GLEs.

2 Data and method of Analysis

Data on the GLEs are furnished by worldwide network of neutron monitor (NM) and muon telescope (MT) stations. Data from 1942-1964 are very limited to a reduced number of stations in houly presentation. Data since1964 are available in 1-5 min tables from many NM stations; for this period we use mainly data from Oulu station.

To determine the main periodicities of oscillation of non stationary series (GCR and (RSP fluxes in individual events of GLE's) as well as their time evolution we apply here the Morlet Wavelet technique, which is a useful tool for analyzing localized variations of power, within a given time series at many different periodicities when one is dealing with non-stationary series [4]. The significance level of the coherence is estimated by using only values inside the *cone of influence* (COI). This U shape mask limits the region of 95% of confidence. The lighter gray color indicates a high intense periodicity, or, (a high coherence between two series) and the stronger gray color indicates a low intensity oscillation. The statistical significance level is estimated using Monte Carlo methods with red noise.

The right panel in Fig.1 shows the *Global wavelet spectrum* (GWS*)*, which is an average of the power spectra at each resolution level, i.e. it assumes that the time series has an average power spectrum relative to the red noise of Fourier: picks for above that average spectrum (the slashed line) represent real signals with levels of significance higher than 95%. Irrelevantly of unities (since we are comparing the same variable, whatever it is), the importance of the GWS is the distribution of signals of the same characteristics to determine which are the harmonics that contain higher power [5].

When in a given series, the intensity of individual event is very assorted (as that of GLEs, which enhancements with respect the Galactic Cosmic Ray (GCR) background varyng from <1% to ~ 4000%) it is convenient to use the *Pulse with Modulation* (PwM) technique [6]. This technique is used here for the goal (2) of this work, where we are interested only in the time distribution of the GLEs series irrelevantltly of other properties such as intensity, profile, stabilization, etc. Under this principle, days with GLEs take the value 1 and days with no events the value 0. Besides, for studies of coherence of series which observational scales are very different (as comparing RSP or GCR, with different solar activity indexes) it is also recurred to the PwM technique [2].

3 Results.

3.1 The Ultra short periodicities

For any further study regarding source phenomena in relation to the generation of RSP in GLE, we consider that is of fundamental importance to determine the Ultra Short periodicities associated to individual events, because the time scale of the source processes is in the range of minute to hours So, for the goal (1) here we applied the wavelet-Morlet analysis to the 70 events and found that the characteristic periodicities of events can be classified in three groups according to the enhancement of each event, as shown in Table 1: *group A*, those events with enhancement up 6%, *group B*, overlaping *group A* with enhancements from 5%-17% and *group C* overlaping *group B* with enhancements from 12% up to 4000%.

The spectral power of Group A is very low, just as a tenuous disturbance scarcely detectable within the background of similar GCR signals. The minimum period describing this kind of perturbations is of 12 hrs, though the higher periods are similar to those of Group B and C. The maximun enhancement of thes GLE is that of events 12 and 21(ref. [1]) with 6%, and the minimum with 1% events 15, 20, 34. Group B covers a wide range of periods from 3-12 hrs. The lowest intensity events of this group are events 25, 53, 64, 65 with enhancements of 5%, while the more intense were events 16 and 17 with enhancements of 17%.

The power spectra of these events is high enough to perturb the wavelet spectrum signal of GCR, with an individual characteristic behavior.

Events of highest power are those of group C are able to completely disturb the wavelet spectrum of the GCR background. This group presents periodicities as low as 11 min (considering that sample data are of 5 min). The lowest enhancement in these kind of events is just 12% (events 41 and 61) while the highest overpass 4000% (event 5).

Enhancement %		INTRINSIC PERIODS OF THE GLEs (days)									
GROUP		4	2	1	0.5	0.25	0.125	0.0625	0.03125	0.015625	0.0078125
A (24 events)	(<1 - 6]	X	X	X	X						
B (23 events)	[5 - 17]	X	X	X	X	X	X				
C (23 events)	[12 >17)	X	X	X	X	X	X	X	X	X	X

Table 1.

It should be mentioned that events with similar enhancement may contain different spectral power, even at similar periodicities. Such a behavior may be related with with peculiarities of the source processes.

3.2 Prognosis of future GLEs

For this goal, we consider only the time distribution of GLE, disregarding enhancement intensity and other properties. Even if all events have different magnitud we proceed to transform the time serie of occurrence dates of the 70 GLE's into a series of *Pulse Width Modulation*) [6] of the type: 1 = event, 0 = no event, so that thir difference states only in the date of occurrence (Fig. 1).

In order to find the temporal association between the pulses, we apply wavelet analysis to this transformed series during the interval 1942-2006, as is shwon in Fig. 2, which interpretation is done in terms of Section 2. It is obtined the mot confident periodicities among which the most prominent are in the range 0.29 to 16 years. It can be oberved that the most prominent, the controling pulse, is at 10.9 years.

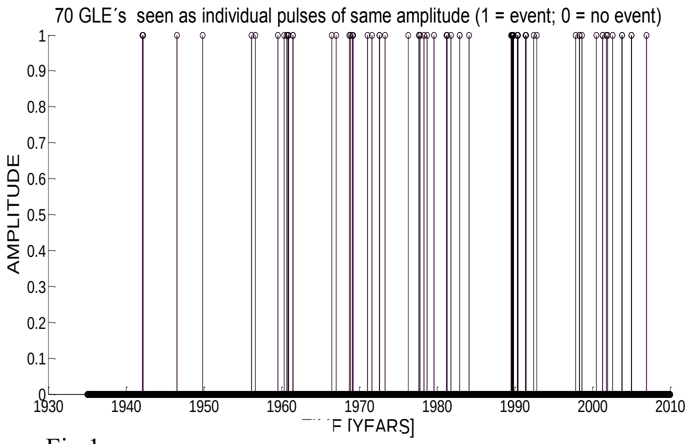

Fig.1

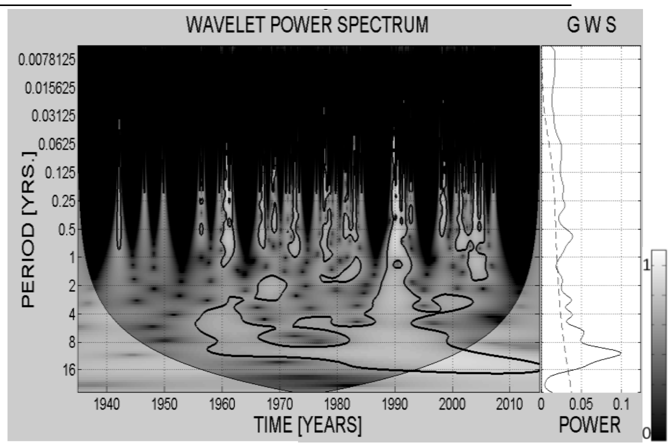

Fig.2

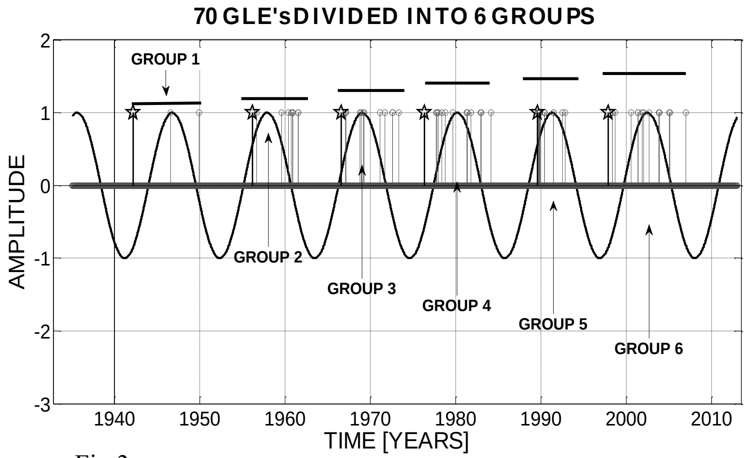

Fig.3

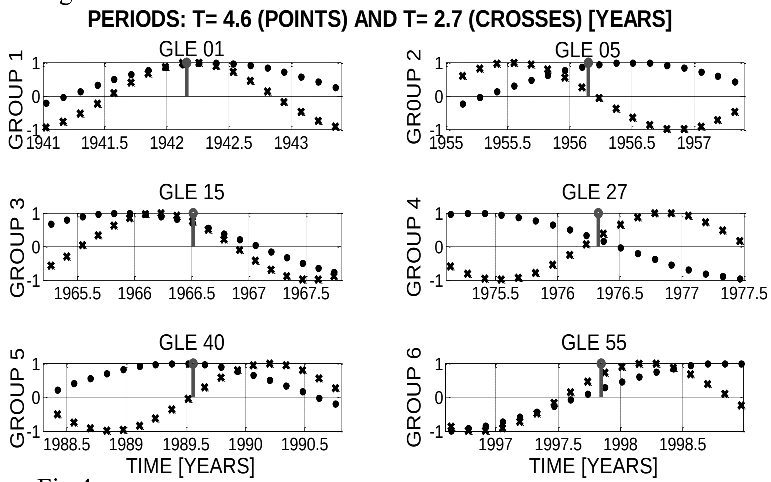

Fig.4

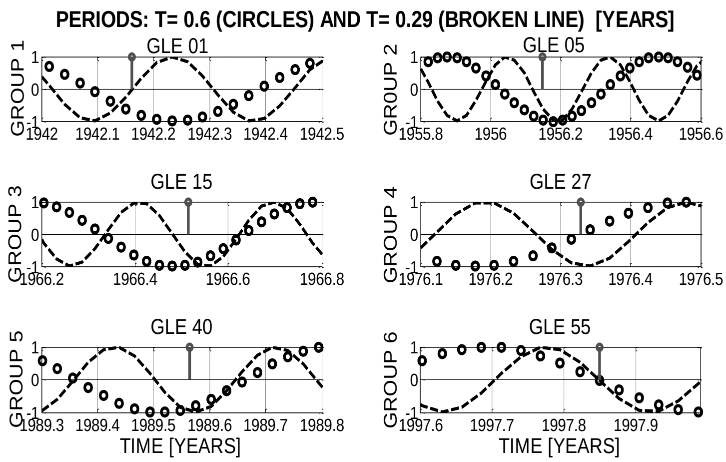

Fig.5

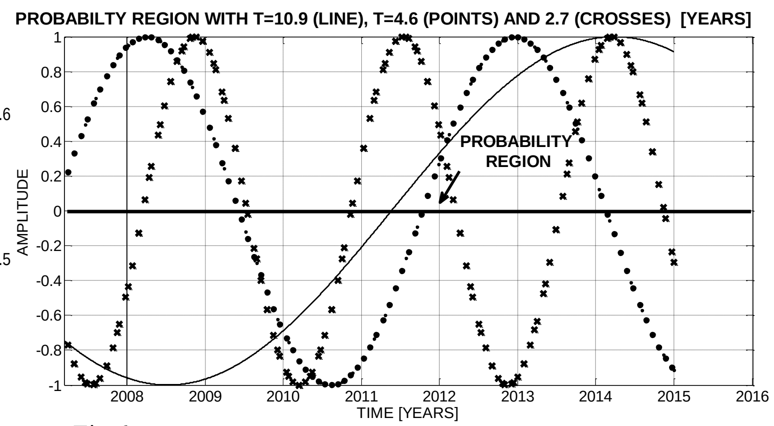

Fig.6

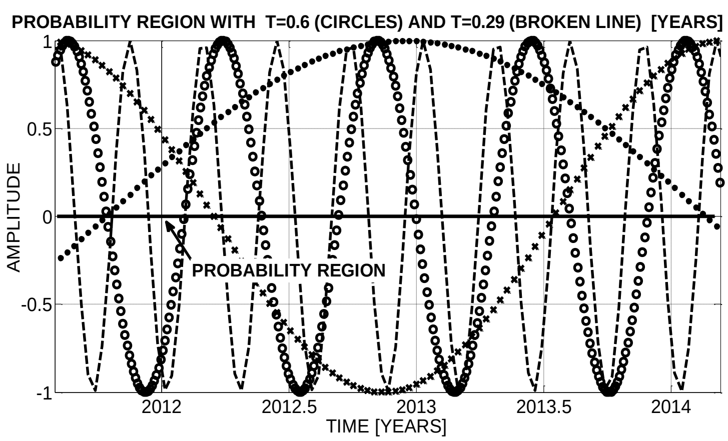

Fig.7

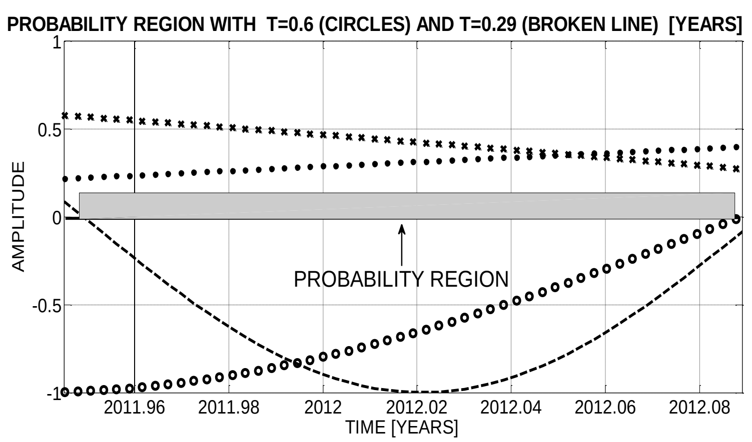

Fig.8

Such quasi–harmonic are converted into harmonic pulses by applying the Fourier anti-transformate (Figs. 3-8). It is found that the 10.9 periodicity, which controls the wavelet spectrum, allows for a classification of the 70 events in 6 groups, as is shown in Fig. 3, where the initial event of each group is indicate with a hat-star. First group is quite uncertain, because we do not know if the event of 1942 was the first of the group-1.

Fig. 4 shows for the periodicities of 4.6 and 2.7 years, that the first event in all the 6 groups falls in the positive part of the harmonic (here after designated as the *crest*).

Fig. 5 shows for the periodicities of 0.6 and 0.29 years, that the first event in all the 6 groups falls in the negative part of the harmonic (the *valley*).

Fig. 6 shows the *probability region* for the occurrence of the first event of group 7 according to the periodicities of 10.9, 4.6 and 2.7 years, as it is delimited by the 3 crests.

Fig. 7 shows the *probability region of occurrence* according to the periodicities of 0.6 and 2.9 years, as it is delimited by the 2 valleys. Also it can be seen that such delimited region is covered by the crests of the 4.7 and 2.9 years periodicities (points and crosses respectively).

Finally Fig. 8 is a close up Fig. 7 that allows us to visualize better the *probability region of occurrence* of the GLE71 in the interval - **December 12, 2011 and February 2, 2012** -.

The region of probability is then found according to the following five conditions :

(i)It is found in the region delimited between a maximum and a minimum associated with T= 10.9 years.

(ii) It is found in the region delimited by a crest associated with T = 4.6 years.

(iii) It is found in the region delimited by a crest associated with T = 2.7 years.

(iv) It is found in the region delimited by a valley associated with T = 0.6 years.

(v) It is found in the region delimited by a valley associated with T = 0.2.9 years.

Each one of the harmonics represents a probability region for the occurrence of the first event; however, the first condition establishes a very wide range of around 5 years, which does not offers us very useful information. To refine the information we use successively shorter harmonics up to a minimum of 0.29 years, which allows us to delimit a reasonable time interval of occurrence. Data with a resolution of 1 min or shorter would probably would lead us to determine periodicities shorter than that of 0.29 years, within the frame of the assumption of events of same magnitude.

4 Discussion and Conclusions

By using classical wavelt-Morlet analysis we have done a classification of the RSP periodicities in 3 main groups according to the magnitude of enhancement of the GLEs. Such study has been oriented to ultra short periodicities which are in the time scale of the RSP production processes at the source. These periodicities agree with those of several solar activity layers, confirming that their generation is not a local isolated phenomenon but there is apparently a well organized synchronization .

Besides, we present a method that combines wavelet analysis with the Pulse with Modulation technique to predict future GLEs of RSP. This leads us to a tentative date interval between **December 12, 2011 and February 2, 2012** for the occurrence of the next event, GLE71. According to Fig. 7 a subsequent GLE will take place by the middle of 2013.

Because the wavelet spectrum gives a qualitative picture of the phenomena, in order to obtain a quantitative picture we have applied the *Principal Component Analysis* [7] combined *with Diffuse Analysis Techniques,* using the series of Galactic Cosmic Rays before each event, instead of the wavelet spectrum and we have found just the same time interval for the occurrence of the next GLE. It is worth nothing that the signal of pulses which represent the temporal distribution in section 3.2 and the PCA signals from GCR contain similar harmonics, even if both type of signals are of different nature. This follows perhaps to the fact that both signals are modulated by the Sun. Such results will be reported elsewhere.

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