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PROGNOSIS OF GLE OF RELATIVISTIC SOLAR PROTONS

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ABSTRACT

Ground level enhancements (GLEs) are relativistic solar particles measured at ground level by the worldwide network of cosmic ray detectors. These sporadic events are associated with solar flares and are assumed to be of a quasi-random nature. Their study gives information about their source and propagation processes, about the maximum capacity of the Sun as a particle accelerator engine, about the magnetic structure of the medium traversed, etc. Space vehicles may be damaged by this kind of radiation, as well as electric transformers and gas pipes at high latitudes. As a result, their prediction has turned out to be very important, but because of their random occurrence, up to now few efforts toward this goal have been made. The results of these efforts have been limited to possible warnings in real time, just before a GLE occurrence, but no specific dates have been predicted well enough in advance to prevent possible hazards. In this study we show that, in spite of the quasi-stochastic nature of GLEs, it is possible to predict them with relative precision, even for future solar cycles. Additionally, a previous study establishing synchronization among some periodicities of the several layers of the solar atmosphere, argues against the full randomness of the phenomenon of relativistic particle production. Therefore, by means of wavelet spectral analysis combined with fuzzy logic tools, we reproduce previous known GLE events and present results for future events. Next GLE is expected to occur in the first semester of 2016.

Key words: acceleration of particles – Sun: activity – Sun: flares – Sun: particle emission

1. INTRODUCTION

Ground level enhancement (GLE) of relativistic solar protons are sporadic phenomena that, to a certain extent follow the time behavior of the 11 yr cycle of solar activity (SA); however, they do not follow the intensity of the SA cycle: for instance, cycle 23 had more GLE events than cycle 22, which was a much more intense than cycle 23. In total, 71 GLE have been recorded: the first measurement was on 1942 February 28 (GLE01) and the last one, on 2012 May 17 (GLE71). Though the average occurrence rate is $\sim$0.99 yr^{-1}, the span between events may sometimes be almost 6 yr, as was the case between GLE70 and GLE71.

The sequence of Magnetohydrodynamic processes that take place in the subphotosphere and other solar atmospheric layers demonstrates a very complex evolution in time and space. A huge amount of effort has been expended for many decades to explain this evolution. However, up to the present, only partial aspects of it can be understood and modeled, and of course very few forecast can be made with these theoretical models in order to predict when a solar flare producing relativistic particles will occur. It is often assumed that GLE are random phenomena.

On the other hand, by means of the analysis of GLE data series, we have shown (Pérez-Peraza et al. 2009, 2011) that GLE maintain a cyclic tendency represented by harmonic signals and have determined GLE intrinsic periodicities: mid-term periodicities (in the order of months and years), short-term periodicities (in the order of days), and ultra-short periodicities (in the order of minutes and hours). A wavelet-coherence analysis between the GLE series and the photospheric as well as coronal series indicates that most of the periodicities mentioned above are present from the subphotospheric to the coronal layers. Such synchronization seems to indicate that GLE production is not an isolated local phenomenon but involves global regions of the Sun's atmosphere. This fact seems to argue against the full-stochasticity of GLE; however, up to now no consistent theory can prove it.

The prognosis of SA has been a subject of study since long ago; for this goal several models based on statistical analysis and even on non-linear processes have been proposed, some of them providing successful predictions (Pesnell 2012). However, very few prognoses can be made with these theoretical models in order to predict when a solar flare producing relativistic particles (GLE) will occur. Most efforts to predict solar proton events are mostly addressed to Energetic Solar protons (ESPs) events and not necessarily to GLE. It is often assumed that GLEs are random phenomena. An interesting model has been developed by Dorman (2003, 2006) and applied by Mavromichalaki et al. (2006, 2009) to several GLEs events. Q1

A number of works has been proposed e.g., Bengin et al. (1985), Huston (1990), Feynman (1997), Turner, (1998), the so called PROTONS developed by Smart & Shea (1979) and employed later by (Miroshnichenko et al. 1986), (Heckman, 1992). Such efforts are mostly of statistical nature based on the temporal profile of particles flux during an event, correlations with the characteristics of the flares that produce ESPs, correlations between the flare intensity at a given wavelength with the intensity of particle fluxes at the earth level. These are generally addressed to ESP events. A probabilistic model proposed by King (1974) that considers relativistic protons is based on the number of events observed during a certain interval of time with a probability P that proton fluxes exceed some given energy. It is assumed that the occurrence of events is of random nature and may be described as a Poisson Process. The main objection to this model was that the considered number of events was not statistically enough. The fact is that most of efforts to predict GLE have been limited to attempts based on a real-time survey, which can be considered as alerts

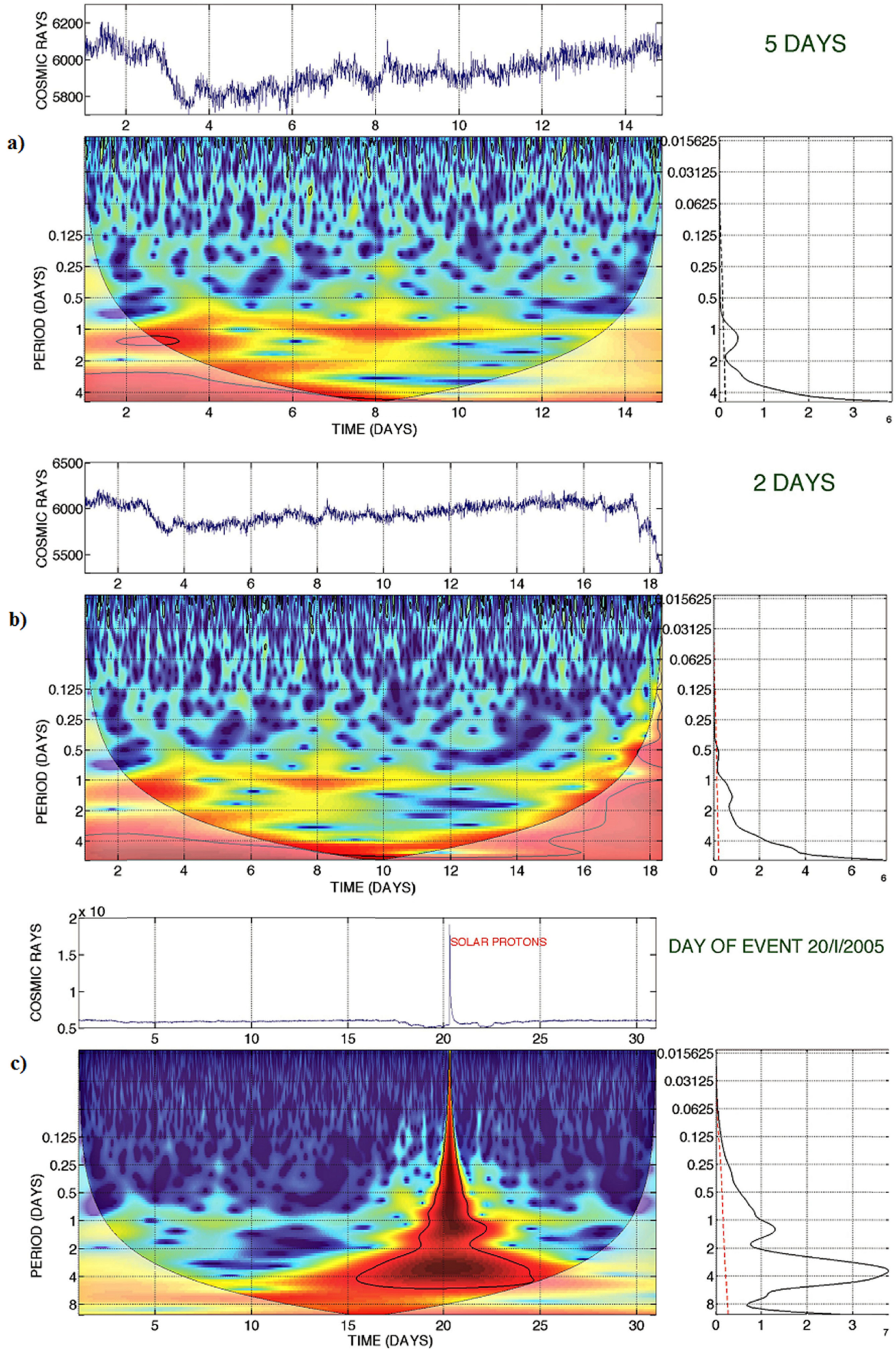

Figure 1. Evolution of oscillations of GCR several days before the GLE69, Pérez-Peraza et al. (2009).

but not a real prognosis, but most of them can be considered as kind of alerts, applying when the event is in course of development.

In a previous work Pérez-Peraza et al. 2009 (Figure 1) it was attempted to develop a *precursor system* for GLEs: such a figure illustrates the Morlet wavelet analysis in connection with GLE69 (2005 January 20). The lower panels show the oscillation periodicities of the particle intensity. The abscissa denotes the real time in days, and the panel 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 in frequency as time approaches the event day. Such evolution may be seen around 15 days before the GLE occurrence. A characteristic frequency is formed in the power spectrum in the lower right panel band from 4 days to some hours in the GLE69. On the day itself of the events, all those frequencies are present simultaneously; forming kinds of wings at low frequencies (which we refer to as the *hat precursor*). Such an evolution behavior is not seen out of the periods of GLEs occurrence. This study has been done for several GLEs in Pérez-Peraza et al. (2009). However, this kind of *precursors* to be of some use require of an organized system of neutron monitor (NM) detectors (at least three stations) coupled with computers having specific algorithms to show the formation of the precursor rapidly, which in the best of cases, would only provide information minutes or hours before the GLE occurrence or even in the course itself of the event.

What we have extracted from those previous studies is that intrinsic harmonics of Galactic Cosmic Rays (GCR) seems to act as precursors of GLE, so that, by ignoring the complex physics involved and using the GCR periodicities, we develop in this work a method for the prognosis of the appearance of GLE several months, even years, in advance.

2. DATA AND ANALYSIS

Data on the GLEs and GCR are furnished by the worldwide network of NM stations. Data from 1942 to 1964 are limited to hourly and daily values from a reduced number of stations. For this particular research a resolution of daily values is quite enough. Data since 1964 with high reliability is available with much higher resolution from many NM stations; for this specific period we have used data from the Oulu station. Data of sunspots (SS) are available in the WEB page http://esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/sunspot.long.data since 1749 up to 2013 with monthly values. We considered data for the period 1940–2013. For our analysis we used the dominating periodicities of both series GCR and SS.

To determine the main oscillation periodicities as well as their time evolution in non-stationary series, such as those for GCR, we apply the Morlet wavelet technique (Torrence & Compo 1998): this is a very well-known tool for analyzing localized variations of power within a given time series at many different periodicities, when one is dealing with a non-stationary series and the coherence between two non-stationary series. The so-called global wavelet spectrum (GWS) 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: harmonics above this average spectrum (the slashed line in the right panels of Figures 1 and 2) represent real signals with levels of reliability higher than 95%. The importance of the GWS is the distribution of signals with the same characteristics to determine which harmonics contain greater power (Torrence & Webster, 1999).

We apply wavelet analysis to the series of GCR daily data and to the monthly series of SS (Figure 2), obtaining their wavelet spectrum and global-energy spectrum (middle panels). In order to discern high frequencies, we apply the Daubechies filter (Daubechies 1992) to remove the 11 yr harmonic, which has quite high energy content and thus hides shorter periods. The dominant periodicities that are present in GCR that we use in our analysis are then: 11, 4.7, 2.8, 1.6, 0.4 and 0.25 yr, whereas those of SS are 11, 4.7, 0.9 and 0.4 yr.

Due that we are only interested in the time intervals of events occurrence, the amplitude is normalized in the timeline because of the irrelevance of other properties such as intensity, profile, particle energy, stabilization, etc. The controlling period from the energetic point of view is that of 11 yr, as indicated by the GWS in Figure 2. We find that the 11 yr periodicity allows for a classification of the 71 events into seven groups (Groups 0–6), plus the current ongoing group 7 as is shown in Figure 2. The first group, group 0, is somewhat uncertain, because we do not know if the event of 1942 February 28 was the first of the group, though we are sure that GLE02 is the last event of group 0 at the end of solar cycle 17. In Table 1 we show the 71 known GLEs distributed according to the classification in Figure 3.

In previous analysis (Pérez-Peraza et al. 2011, 2012, 2013) some of the periodicities with higher energy content present in the series of GLE were studied, as well as in cosmic rays, and it was found that these periodicities show the same behavior during the occurrence of similar kind of GLE (first or last event of the different groups).

The mentioned periodicities were always found close to their maximum value (peak) or minimum (valley) when an event occurred. With these observations and extrapolating forward in time periodic behavior, time intervals were computed where these features or observations were filled and therefore infer that a GLE could occur However, the study in our first approach was limited to empirical findings and information obtained was limited only to determine if the event occurred within the phase peak or valley phase of a certain periodicity.

In this paper we continue with the assumptions of previous works, in behavior of periodicities to describe the occurrence of GLE, but here, using some of the concepts of fuzzy logic, as described by Mendel (1995), we calculate the time intervals in which have to a certain degree similar behavioral characteristics of periodicities, i.e., same phase in all groups for the events of the same type (first in each group, last of each group or intermediate group) and we do not limit the study to the imposition of rules of thumb, as above, selecting only peaks or valleys.

The procedure for calculating time intervals is to create membership functions for the periodicities with higher energy in the wavelet power spectrum of the series of cosmic rays. We note that the amplitude of the dominant periodicities and their behavior (if ascending or descending phase, or on the ridge or valley) during the occurrence of a certain type of events (first, intermediate or last in each group) meets Similar Features for estimating the time intervals in which events (retroactively and forecasts the future) may occur. For example, the first events of all groups are in the downward phase of the periodicity of 11 yr of cosmic rays, while last events occurred in the ascending phase of the same period (Figures 3 and 4). For another period, such as the 4.7 yr, the first events occur mainly during the rising phase of a valley and the latest downturn in the crest (Figure 4). By gathering information on the behavior of different periodicities in the occurrence of certain types of GLE in the past, and making future projection of the oscillatory behavior of the periodicities, we infer that it is possible to predict the occurrence of events.

The membership functions are usually constructed or proposed under the criteria of experts in the area of study or alternatively can be calculated with mathematical data analysis algorithms, that are mainly used in control systems (Chuen 1990). In our study, the membership function is the curve that describes the degree to which an element of the set of amplitudes of a certain periodicity in the occurrence of the 71 GLE belongs by similarity to a subset consisting of the

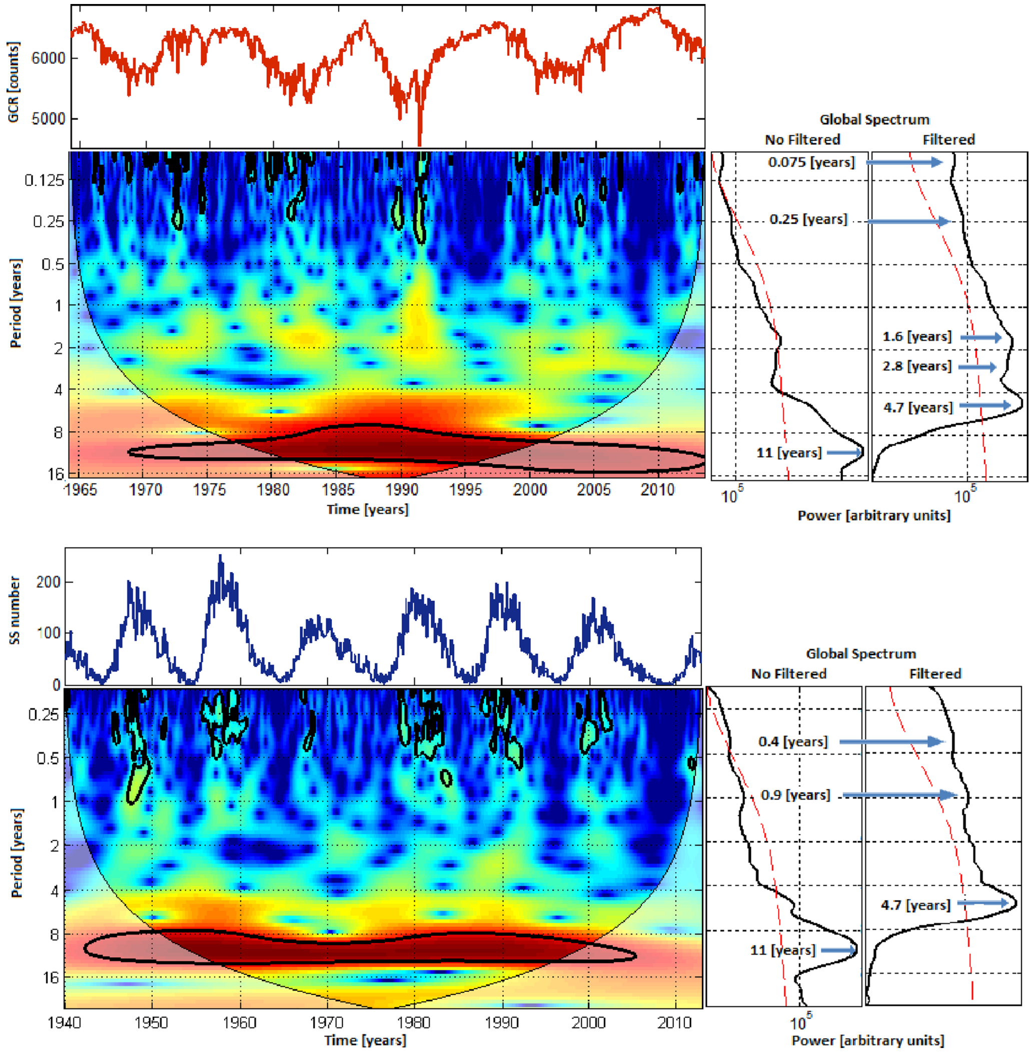

Figure 2. Spectral analysis: upper panel is the GCR flux, middle panel is the wavelet spectrum and right panels is the global energy spectrum before and after filtering. Similarly the Wavelet analysis of sunspots is shown in the lower panels.

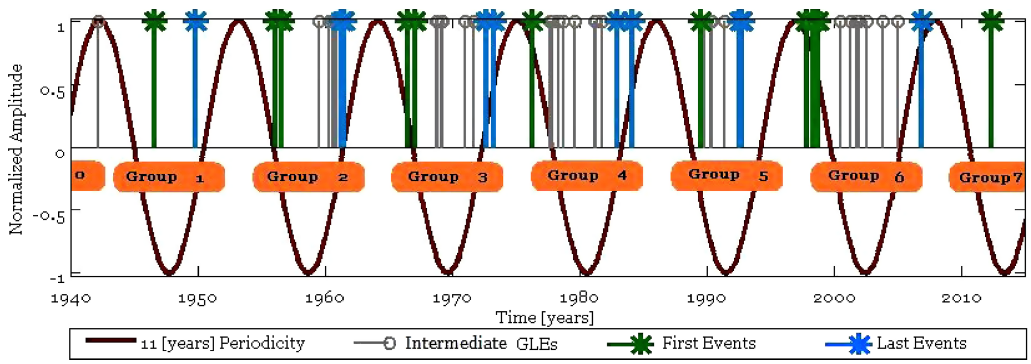

Figure 3. Classification: grouping of GLE into six groups (plus the incipient group 7) according to their predominant harmonic at 11 yr as shown in the above extreme right panel of Figure 2.

amplitudes of the frequency during the occurrence of a particular type of event (first, last or middle). The concept of fuzzy logic appears from the fact that a membership function may describe different GLE with greater or lesser degree. In our analysis, the membership function was constructed with the product of the equations of two standard Gaussian curves as expressed in Equation (1), the mean and standard deviation are obtained with the data; amplitudes of the frequency and its derivative during the occurrence of the events studied.

$$\mu_A = \frac{1}{\alpha_A\sqrt{2\pi}} e^{\frac{-(t-\beta_A)^2}{2\beta_A^2}} \times \frac{1}{\alpha_{dA}\sqrt{2\pi}} e^{\frac{-(t-\beta_{dA})^2}{2\beta_{dA}^2}} \quad (1)$$

Equation (1) represents the membership function of the

Table 1
Classification of GLE as Reported in Mirosnishenko & Pérez-Peraza (2008) According to their Predominant Harmonic at 11 yr as Shown Figure 3

Group	GLE Type	GLE No.	Date	Increase %	Group	GLE Type	GLE No.	Date	Increase %
0	Last	1	1942 Feb 28	6	4	Last	37	1982 Nov 26	4
		2	1942 Mar 07	6			38	1982 Dec 07	26
1	First	3	1946 Jul 25	16			39	1984 Feb 16	15
	Last	4	1949 Nov 19	40	5	First	40	1989 Jul 25	2
2	First	5	1956 Feb 28	4554		Intermediate	41	1989 Aug 16	12
	Intermediate	6	1956 Aug 31	3.3			42	1989 Sep 29	174
		7	1959 Jul 17	10			43	1989 Oct 19	37
		8	1960 May 04	290			44	1989 Oct 22	17
		9	1960 Sep 03	4.5			45	1989 Oct 24	94
		10	1960 Nov 12	135			46	1989 Nov 15	5
		11	1960 Nov 15	160			47	1990 May 21	13
		12	1960 Nov 20	6			48	1990 May 24	8
	Last	13	1961 Jul 18	23.5			49	1990 May 26	6
		14	1961 Jul 20	3			50	1990 May 28	5
3	First	15	1966 Jul 07	1			51	1991 Jun 11	7
		16	1967 Jan 28	17			52	1991 Jun 15	24
		17	1967 Jan 28	17		Last	53	1992 Jun 25	5
	Intermediate	18	1968 Sep 29	3			54	1992 Nov 02	3
		19	1968 Nov 18	3	6	First	55	1997 Nov 06	11
		20	1969 Feb 25	1			56	1998 May 02	7
		21	1969 Mar 30	6			57	1998 May 06	4
		22	1970 Jan 24	16			58	1998 Aug 24	3
		23	1971 Sep 01	14		Intermediate	59	2000 Jul 14	30
	Last	24	1972 Aug 04	10			60	2001 Apr 15	57
		25	1972 Aug 07	5			61	2001 Apr 18	15
		26	1973 Apr 29	4			62	2001 Nov 04	3
4	First	27	1976 Apr 30	4			63	2001 Dec 26	7
	Intermediate	28	1977 Sep 19	3			64	2002 Aug 24	5
		29	1977 Sep 24	7			65	2003 Oct 28	5
		30	1977 Nov 22	13			66	2003 Oct 29	…
		31	1978 May 07	84			67	2003 Nov 02	6
		32	1978 Sep 23	7			68	2005 Jan 17	3
		33	1979 Aug 21	4			69	2005 Jan 20	269
		34	1981 Apr 10	1		Last	70	2006 Dec 13	92
		35	1981 May 10	2	7	First	71	2012 May 17	16
		36	1981 Oct 12	11					

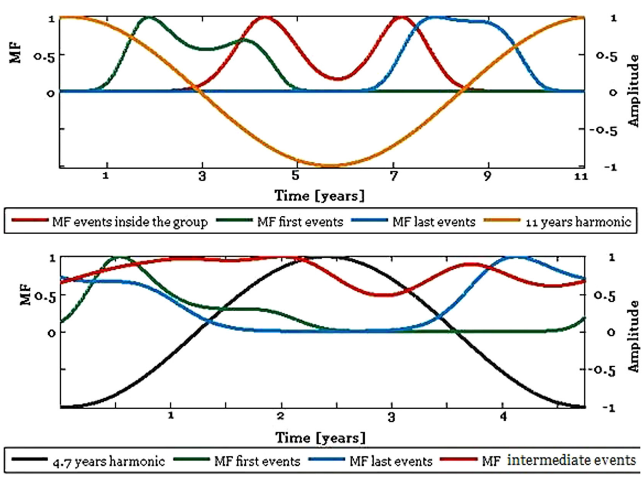

Figure 4. Membership functions calculated for the first, intermediate and last events for periodicity of 11 yr (top) and periodicity of 4.7 yr (below) of the GCR.

frequencies, possibly 11, 4.7, 1.6,… yr, α_A and β_A represent the average and standard deviation of the frequency amplitudes respectively, α_{dA} and β_{dA} are calculated from amplitudes from the derivative of the periodicity, in both cases, the average and standard deviation are calculated with the data of the amplitudes of the frequency at the time of occurrence of the events of interest in the past, i.e., GLE known. Finally, t is the variable that represents the distribution of the amplitudes of the frequencies. Thus, although the proposal of the membership function is somewhat arbitrary, to select the equation of a Gaussian and no other function, we assume that our data can be approximated by a Gaussian bell, and the membership function is related statistically with data that we consider and are not only built on empirical criteria. Using amplitudes of the derivative of the frequencies is intended that membership functions distinguish if the data of the amplitudes of the frequencies are in the ascending or descending phase.

Figure 4 shows the membership function built for the three types of GLE (first, middle and last) to the periodicities of 11 yr (upper panel) and 4.7 yr (lower panel) of cosmic rays. In the upper panel, in orange is a full period of the periodicity of 11 with the normalized amplitude. In both graphs in Figure 3 the membership functions for the first, middle and last events are represented by the green line, red and blue respectively. By definition, the membership functions have unitary maximum amplitude, where the value of 1 indicates the highest membership and 0 there is no membership (Mendel 1995).

Our aim to forecast the amplitude of the membership function is calculated based on the prospective (periodic behavior in the future) behavior of the amplitude of a certain frequency. Putting together the information of the membership functions calculated for all analyzed periodicities leads us to define time intervals for probable occurrence of a certain types of event.

Once the membership functions for each frequency is constructed, the next step is to calculate the intersection (Equation (2)) of them all, resulting thus in the product

$$\prod = \mu_{A \bigcap B \bigcap C \bigcap \ldots} = \mu_A \times \mu_B \times \mu_C \times \ldots \quad (2)$$

Where $\mu_{A \cap B \cap C \cap \ldots}$ denotes intersection function and μ_A, μ_B, μ_C, … the membership functions of each of the periodicities and certain types of events.

The product of the membership functions of all periodicities gives a function of time in which its amplitude indicates the GLE occurrence, depending on conditions of all of the periodicities that meet together.

3. RESULTS

In Figure 5 we show the reconstruction of occurrence intervals for the first, middle and last events of the groups from 1942. Figure 5 shows potential regions where, the quasi-periodic behavior indicates that events may occur in the current group 7 and the degree of membership is then calculated.

Tables 2–7 show the results of our forecasts for GLE in this solar cycle and the next.

The peaks in the blue, red and green lines in the panels of the group 0–7 indicate the reconstructed regions where the events have occurred: first green, red-intermediate and blue-last events. The panel of group 7 in Figures 5 and 6 shows the forecasts for groups 7 and 8 respectively.

Figure 5 shows the membership functions constructed for the events in the previous cycles of SA. It is noteworthy that, under the assumptions made, it is possible that the intervals predicted by the membership functions does not contain any GLE for long periods, or at the most a single event, as for instance in group 1, where intermediate events did not occurred and the first is also the last one in this case (of course, according to our classification of groups). Alternatively, it is also possible that in the same interval there occur more than one event as can be seen in Figure 5 for groups 3 and 5, and there even may occur more than ten intermediate events, as happened during the group 6 in a span of 3 yr (1989–1991). However, according to the opinion of several authors, it is expected that this cycle of activity will be less intense (e.g., Pesnell 2011), so we expect the number of events occurring to be small, as shown in the panel of group 7 in Figure 5: the membership function for intermediate events constructed with the projection of the behavior of the periodicities in the future has only small amplitude peaks compared, for example, with the peak around the 2012 event. So we expect only a last GLE event in the course of 2016. Figure 6 shows the prediction for the possibility of GLEs in the next solar cycle, where an outbreak of GLEs production is expected around 2022–2023, though the first event will probably occurs before.

It must be emphasized that in order to determine definite time intervals of possible GLE occurrences, we have selected the minimum of the amplitudes of the computed membership functions of the known events in which time intervals have been accurately reconstructed by interpolation (e.g., the 1959 July 17, 1972 August 4–7 events, whose amplitudes are relatively small). So, amplitudes which are smaller are systematically eliminated.

Note that the intervals calculated for different kinds of events may overlap; that is, two or three different memberships, may describe in greater or lesser degree, a same time interval. This occurs because of the overall behavior of the periodicities as a whole and therefore on their membership functions which depend on the distribution of amplitudes used for its calculation. This can be appreciated by observing the construction of intervals (with the membership functions of the first and intermediate events) in the panel of group 5 of Figure 5: though the first event of group 5 took place on 1989 July 25, a group of intermediate events occurring between 1989 September and 1990 May are overlapped with the memberships of the first and last events. The last one occurred on 1992 November 2. Q2

As we mentioned before, we may predict intervals where not a single GLE occurs, as for instance during the end of group 6 and the a fraction of group 7 (2006 December 13–2012 May 17), but the presence of small amplitude memberships may possibly denote an increase in SA.

According to our predictions the next GLE is expected to occur during the last trimester of 2015 as indicated in Table 3, interval 5, though the possibility that it may occur in the first semester of 2016 (interval 6 in Table 3) is not null. According to our forecast the last one of group 7 will be in 2017 as indicated in Table 4 and in the panel of group 7 in Figure 5.

The conditions considered allow us to infer that if the occurrence of the GLE can be described by fluctuations in SA, and if SA modulates cosmic rays observed on earth, then to predict the occurrence of GLE using the periodicities of cosmic rays and SS, in a way we are including in our forecast SA, and thus the membership function, calculated with all periodicities, may contain information of the behavior of SA, indicating periods where SA is stronger or at least have a characteristic behavior in the production of energetic particles associated with GLE.

Regarding the *goodness* of our method, it must be emphasized that we identified the occurrence of what seems to represent two low intensity GLEs (2012 January 23 and 2012 March 7 and) appearing as long lasting increases of relativistic solar protons in the CARPET cosmic ray detector in Brasilia (Makhmutov et al. 2013): though not NM data is available, these authors show that the analysis is supported by the characteristics of VLF propagation and riometer records during these events. Observing Figure 5 relative to group 7 we note that there are some indications that they may be located in the group of first events (Table 2, interval 4) with very modest membership. This is precisely the time interval where the 2012 May 17 event (GLE71) has took place, presenting high Membership, and was definitively reregistered by the worldwide network of NM. It should be mentioned that there is an international convention for considering that a real GLE has taken place, at least three cosmic ray stations must have registered it, which is not the case in these two events. However, if those small events were real GLEs, then the later one assumed by the specialist community as GLE71 would be GLE73.

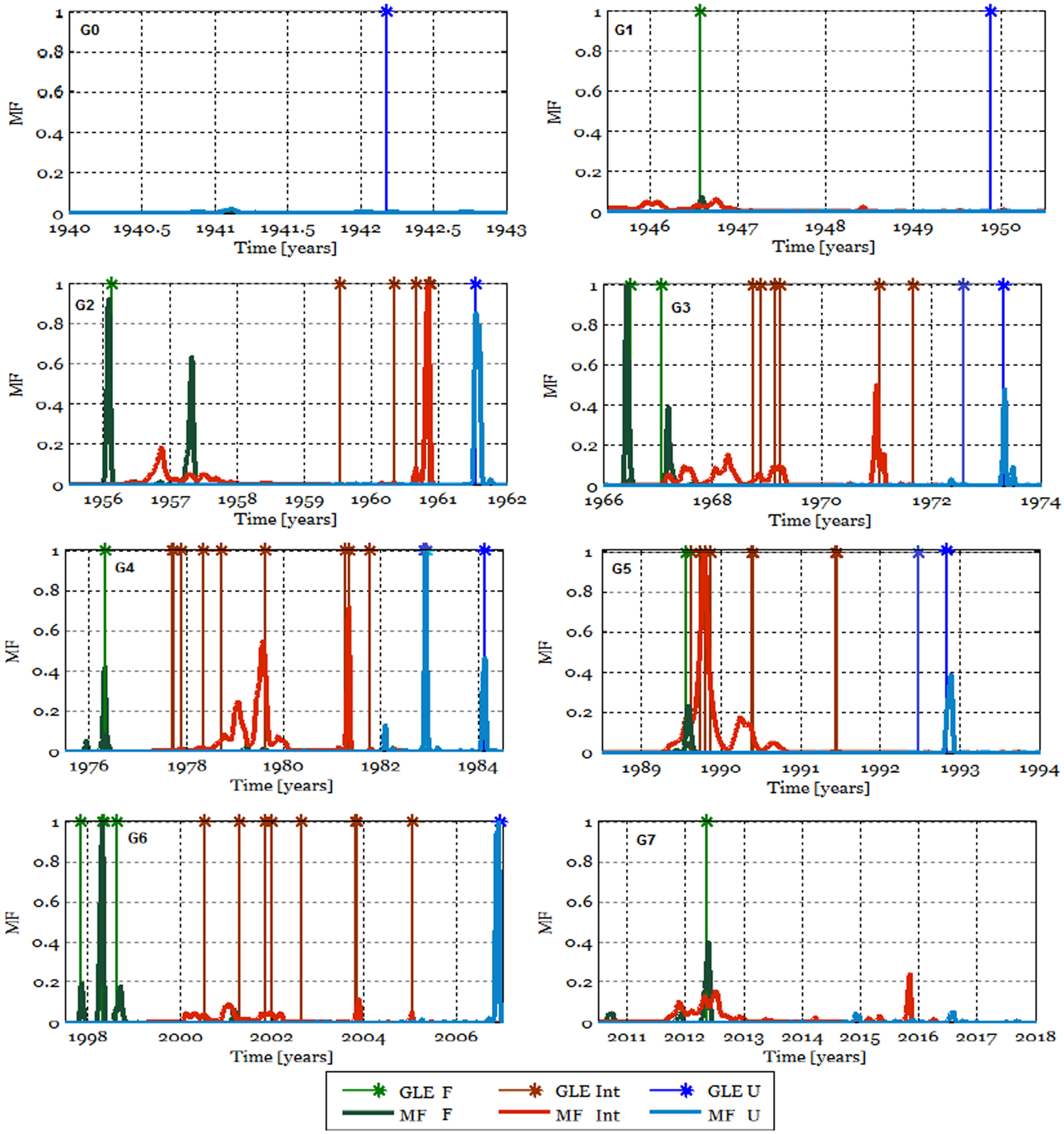

Figure 5. Reconstruction and prognosis of the membership functions calculated for different types of GLE in groups (Groups 0–7) on basis of GCR and SS series.

Table 2
Computed Intervals for the First Events of Group 7

Interval	First G7 Limits Start	End
1	13.08.10	24.10.10
2	19.10.11	26.12.11
3	31.03.12	24.06.12

4. VALIDATION

In order to verify the accuracy of our model, we implement a validation test. This test consists in assuming the events of certain group "*x*" as unknown and with the events of the remaining groups forecast the events of this group "*x*," e.g., we assume the first events in group 1 as unknown and with the first events of the groups 2–7 perform the prognosis of the firts events in group 1. Later the same procedure is done for the events in the other groups. With this validation method we assume that forecasts of a group are independent of the observations within the same group, i.e., the prognosis is

Table 3
Computed Intervals for the Intermediate Events of Group 7

Intermediate G7		
Interval	Limits	
	Start	End
1	23.06.10	29.08.14
2	23.02.14	15.04.14
3	10.08.14	03.10.14
4	01.02.15	31.05.15
5	11.08.15	02.12.15
6	10.03.16	13.05.16

Table 4
Computed Intervals for the Last Events of Group 7

Last G7		
Interval	Limits	
	Start	End
1	12.11.14	17.01.15
2	27.07.15	17.09.15
3	26.10.15	22.12.15
4	27.06.16	02.09.16
5	13.09.16	13.11.16
6	18.08.17	10.10.17

Table 5
Computed Intervals for the First Events of Group 8

First G8		
Interval	Limits	
	Start	End
1	22.06.20	22.09.20
2	12.12.20	24.02.21
3	25.05.21	28.07.21
4	08.10.21	14.10.21
5	15.03.22	14.05.22
6	08.08.22	30.09.22

Table 6
Computed Intervals for the Intermediate Events of Group 8

Intermediate G8		
Interval	Limits	
	Start	End
1	29.05.21	25.11.24
2	25.12.24	21.01.25
3	01.06.25	25.07.25
4	17.11.25	24.03.26
5	15.05.26	07.09.26

Table 7
Computed Intervals for the Last Events of Group 8

Last G8		
Interval	Limits	
	Start	End
1	19.06.25	31.10.25
2	15.04.27	22.06.27
3	08.07.27	01.09.27
5	10.10.27	19.11.27

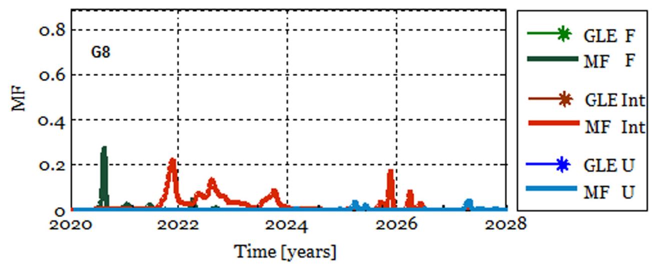

Figure 6. Membership functions calculated for the forecast intervals which may occur during GLE group 8 on basis of GCR and SS series.

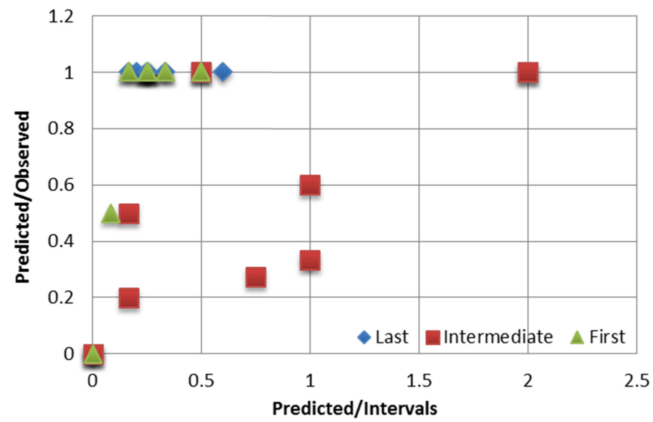

Figure 7. Results of validation of the method for the prognosis of GLE.

performed with features seen in other cycles of SA, this assumption allows us to forecast events in groups 7 and 8 systematically. Here, we do an analysis of certainty comparing our predictions in known groups with actually observed events.

In an ideal case, we expect the number of estimated intervals to be the same as the number of observed events. Additionally, all the events to be predicted successfully, i.e., the number of events known compared with intervals computed in the validation.

Figure 7 shows the results of the validation for the predictions of each type of events (first, intermediate and last). The Y axis shows the ratio between the number of successful forecasts and the number of events observed in each group, X axis is the ratio between the number of hits and the number of intervals computed per group. As mentioned previously, in an ideal situation we would expect the ratio of the number of hits to the number of calculated intervals to be equal to one, this means that our model allows us to predict an event in each interval, and if this is done, provides the accuracy of the method and the model does not calculate fictitious events. In the same way, we would expect the ratio of the number of hits to the number of observed events to be equal to one, indicating a perfect performance in prognosis. Under this discussion, the points in the dispersion should be close to one.

We see in Figure 7 that most of the points corresponding to the first and last events are close to one on the Predicted/Observed axis, indicating that our model has a good certainty to forecast these events, however, the Predicted/Intervals axis has a lower performance, indicating that the method typically calculates a greater number of intervals that the number of observed events. For intermediate events, the performance of the model is acceptable as shown in the Predicted/Observed axis, and our forecasts have a good performance in the number of intervals computed compared to the number of hits.

5. CONCLUSIONS

In the absence of a physical theory to predict with satisfactory accuracy the production of relativistic particles on the Sun with effects at ground level (GLEs), several alert systems in real time have been proposed. Such alert systems would only provide, in the best of cases, information just seconds to hours before the GLE occurrence. In order to overcome such a fallacy, we propose here a method based on spectral analysis and statistical analysis to predict the occurrence time intervals of proximate and future GLEs months and years in advance. The mentioned analysis has been made with the well known wavelet and fuzzy Logic techniques.

The method allows for the reconstruction of the time periods of occurrence of the 71 known GLEs, as well as those that occurred before the advent of cosmic ray detectors. The prediction of the first GLE of the present group (GLE71) has been made with high accuracy (Pérez-Peraza et al. 2011), taking into account that the last (GLE70) took place almost 6 yr before: it was predicted to occur in the interval 4 of Table 2, and effectively it took place on 2012 May 17. The occurrence of GLE 72 is expected to occur sometime in the time interval No. 5 of Table 3 (2015). Forecasting for the next solar cycle are shown in Table 7. It is worth noting that our method leads us to find "missing" GLEs that produce MultiGeV protons on earth, that probably due to their small statistical significance in their intensity were not reported by the worldwide network of cosmic ray detectors, but only by one experiment. If the CARPET results are correct then GLE71 would be GLE73. This would *crash* with the conventional international assumption about the acceptance of the 2012 May 17 event as GLE71, but would imply the possibility that other small particle increases could have occurred, in last decades, as indicated by some small membership peaks in Figure 5, where no event has been associated to any measurable event by cosmic ray detectors.

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