Indian J. Phys. **82** (1) 95-104 (2008)

Note

IJP

Periodicity of ~155 days in solar electron fluence

Partha Chowdhury

Department of Physics, West Bengal University of Technology, Kolkata-700 064, West Bengal, India

P C Ray

Department of Mathematics, Government College of Engineering and Leather Technology, Kolkata-700 098, West Bengal, India

and

Saibal Ray*

Department of Physics, Barasat Government College, North 24 Parganas, Kolkata-700 124, West Bengal, India

E-mail saibal@iucaa.ernet in

Received 29 June 2007, accepted 30 October 2007

Abstract : In this paper we have investigated the occurrence rate of high energetic (E > 10 MeV) solar electron flares measured by IMP-8 spacecraft of NASA for solar cycle 21 (June 1976 to August 1986) first time by three different methods to detect periodicities accurately. Power-spectrum analysis confirms a periodicity ~155 days which is consistent with the earlier result of Chowdhury and Ray [1], that "Rieger periodicity" was operated throughout the cycle 21 and it is independent on the energy of the electron fluxes.

Keywords : Solar cycle, flares, particle emission.

PACS Nos. : 96.60.qd, 96.60.qe, 96.60.Vg

The Sun often exhibits different periodicities on many different time scales not only in electromagnetic radiation but also in energetic particle events. As a long term periodicity, the 11-year sunspot cycle (Hale cycle) and for short terms 27-day rotational periods are most prominent and the regime between these extremes of time scales is called the 'mid range' [2]. During solar cycle 21 a quasi-period of ~154 days was first discovered by Rieger *et al* [3] in solar γ-ray and soft X-ray flares recorded by the Gamma-Ray Spectrometer (GRS) on-board the Solar Maximum Mission (SMM) and subsequently confirmed in microwave burst data [4] and also in H_α flares [5].

*Corresponding Author

Afterwards a number of researchers have extensively searched the mid-term quasi-periodicities (one to several months or longer) of different solar flare activities, energetic particle fluxes, sunspot numbers, areas, photospheric magnetic flux or interplanetary magnetic field for solar cycle 21 [6–18]. Most of these studies indicate a periodicity ranging from 152 to 158 days, but it appears to be dominant especially in the time phase from ~1979 to 1983 corresponding to the solar activity maximum. Besides this other quasi-periods ~129, ~103, ~84, ~78 and ~51 days of different solar data during maxima of various cycles [2,19–23] were reported time to time by different researchers. Recently, Forgacs-Dajka and Borkovits [24] indicated that the mid-term periodicities are manifest in almost all solar data (sunspot numbers, solar flare index, solar radio flux, IMF, proton speed *etc.*) with the exception of the coronal index and 10.7 cm solar flux.

In a recent paper Chowdhury and Ray [1] have studied the periodicities of electron fluence data of two different energy bands ($E > 0.6$ MeV and $E > 2$ MeV) for cycles 21 to 23 and reported ~152 day periodicity for solar cycle 21 for both energy bands. Therefore, our aim in the present investigation is to extend the work of Chowdhury and Ray [1] for the data of more energetic electron fluence ($E > 10$ MeV) for complete solar cycle 21 (June 1976 – August 1980). This is done here first time by different power spectrum analysis methods to determine periodicities accurately because they can provide better information on properties of the Sun.

A. Data :

The data employed in this study are the daily-averaged electron fluences observed by IMP-8 spacecraft of NASA in energy range > 10 MeV and are residual after the background is subtracted. This electron flux data for period 1 June 1970 to 31 August 1986 were taken from OMNI database compiled by the National Space Science Data Centre (NSSDC) and available at the website http://nssdc.gsfc.nasa.gov/space/imp-8.html.

The daily electron flux data were taken in regular manner and the small data gaps found present have been filled in by using an interpolation technique.

Figure 1 is the plotting of original daily averaged data with gaps whereas Figure 2 is the plotting of daily averaged data where gaps filled up with interpolated data. The original (raw) data actually varies from 0 to 5 and some of the data given as –1 which means the error data (*i.e.* gap data) which are interpolated. Since most of the data are ~10^{-3} (*i.e.* very near to zero) to get the clear picture we have plotted from –0.01 to 0.03 in Figure 1 and in Figure 2 we have plotted from 0 to 0.05 after interpolation.

B. Analysis method :

To investigate the occurrence rate of peak electron flux accurately we have adopted three different spectral decomposition techniques, *viz.*, (1) the fast-Fourier transformation

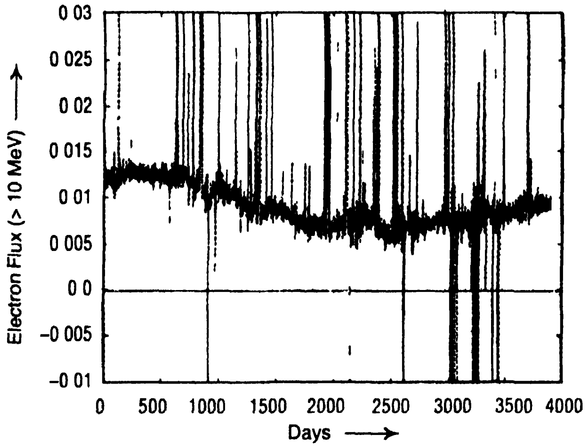

Figure 1. Plot for original daily averaged data with gaps

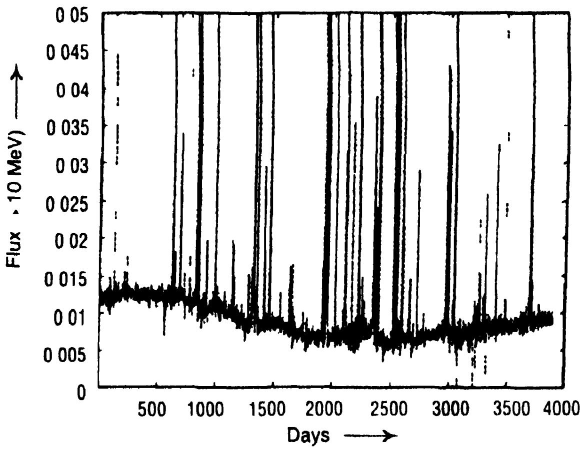

Figure 2. Plot for daily averaged data where gaps filled up with interpolated data

(FFT), (2) the maximum entropy method (MEM) and (3) the Lomb-Scargle periodogram (LSP) Finally, we have made a comparative study among the results of all these spectral analysis methods.

(a). Fast-Fourier transformation (FFT) .

To trace out periodicities of electron flux data of IMP satellite, we first have applied the conventional Fourier Power Spectral Analysis technique The frequency of observation was one datum per day and the Nyquist critical frequency was 0 5 per day.

The fast-Fourier transform is derived from the discrete-Fourier transform to reduce the computational time considerably and at the same time accuracy of the output obtained from FFT are within tolerable limits.

(b). Maximum entropy method (MEM) :

The results of FFT are replicated by MEM which tries to avoid the limited resolution and power 'leaking', due to windowing of data, present in the former method. Burg [25] developed this new form of spectral variance analysis which belongs to the class of methods that fits a statistical model to the data and it shows higher resolutions, especially at low frequencies producing narrow peaks.

The Winer-Khinchin theorem states that the Fourier transform of autocorrelation of any signal is equal to the power spectrum. Van den Bos [26] has shown that the parameters of a maximum entropy spectral estimation are equivalent to the 'ones' in the auto-regressive (AR) model of a random process in real domain. To compute the power spectra by MEM we have applied the algorithm proposed by Press *et al* [27] (details of the algorithm and other technique of MEM is available in the book of Press). In order to justify the validity of the peaks found from the Fourier analysis and Entropy method, the confidence limits (also known as fiducial limits) for different peaks obtained from the power spectra were calculated [1,28–30]. All these confidence levels are above 99%. In effect, we are attempting to determine the interval within which any hypothesis concerning the periodicity of a certain solar event might be considered tenable and outside which that hypothesis would be considered untenable. The confidence limits (CL) are evaluated by generating a sample of 100 data points equally on both sides of a particular peak. This method is repeated for all the peaks under consideration within a spectrum. The peak that is sharp gives the minimum value of standard error (SE_m) and the interval between the *CL* is reduced, increasing the probability of its being near T_{ave}, where T_{ave} is the mean value of the time period of the sample data points.

A detailed mathematical formalism has been provided in the article by Chowdhury and Ray [1] and hence here we shall only mention some of the essential definitions as appeared above. The confidence interval or limit provides the lower and upper limits to which the population parameter has a high probability of being included. The population parameter standard deviation σ can be calculated from the following formula

$$\sum T^2/(N-1)-\left(\sum T\right)^2/N(N-1)^{]0.5}. \quad (1)$$

The standard error (*SE*) is the standard deviation of the sample mean (from sampling distribution) is estimated as

$$SE_m = \sigma / N^{0.5}. \quad (2)$$

The confidence limits (*CL*) for 99% confidence can be computed as

$$CL = T_{ave} \pm 2.58(SE_m). \quad (3)$$

(c). The Lomb-Scargle periodogram (LSP) :

As mentioned earlier that using an interpolation technique we fill small gaps in time series and later to confirm the periodicities obtained by FFT and MEM technique, the parent (non-interpolated) data sets were analyzed by Lomb-Scargle method by calculating the Scargle normalized periodogram [31] following the procedures of Horne and Baliunas [32]. This method successfully handles time series with missing data and provides estimates of the level of significance of the periodogram peaks. The periodogram is determined from the raw daily data, transformed to zero-mean time series, but without smoothing, binning or interpolating (a detailed description of this method is available in the article by Chowdhury and Ray [1]).

A. Criteria for the analysis :

In selecting the periodicity the following criteria were used :

(1) As the time series for complete cycle 21 contains ~3700 data points, only the time periods lying below 1000 days have been considered.

(2) Periodicities ~27 days and its integral multiples were discarded as they coincide with the synodic rotation period of the Sun and its harmonics. So, these periodicities bear the impression of the Sun's synodic rotation and nothing else. Alter discarding these peaks in this way, the remaining peaks were chosen in the decreasing order of power.

(3) Only the periodicities which are prominently present in all the three different methods have been selected for final consideration.

(4) For periodicity search through FFT and MEM, importance has been given not only to the power of a peak but also on the sharpness of that particular peak. In FFT and MEM the peaks above 2.58σ limits were only considered along their *CL* values.

B. Results of the analysis :

Figure 3, Figure 4 and Figure 5 display the results of periodicity of energetic electron flux ($E > 10$ MeV) for solar cycle 21 (1976–1986) and the results are shown in Table 1.

Table 1 and Figure 3, Figure 4 and Figure 5 indicate that periodicities ~54 days and ~155 days are common in all the three different methods. However, periodicity 54 days (which can be considered as 2 × 27 days) is a sub-harmonic of solar rotation period and hence discarded. So, the only peak ~155 days is prominently present in all techniques and in Scargle method it is close to 0.1% significance level. Therefore, the occurrence rate of energetic ($E > 10$ MeV) electron flares for solar cycle 21 is ~155 days. Now, it will be useful to compare and discuss our analysis in the light of periodicities reported in other solar activity indicators. In cycle 21, near 155 days

Table 1. List of periods (in days) detected with their standard errors for confidence limits, in daily electron flux data for solar cycle 21 (1 6 76–31 8 80) with electron energy > 10 MeV

	Identified periods in spectral power peaks				
	A	B	C	D	E
		(a) FFT			
T_{ave}	155 67	53 26	18 27	9 34	51 06
SE_m	0 0188	0 0021	0 0003	0 00006	0 0021
		(b) MEM			
T_{ave}	155 38	53 28	18 27	9 34	9 13
SE_m	0 2691	0 0306	0 0036	0 0010	0 0009

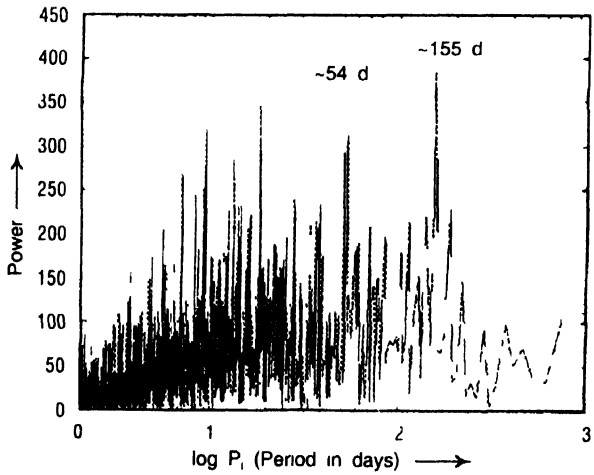

Figure 3. Plot for the Power spectrum of energetic electron flux data (E > 10 MeV) for the solar cycle 21 by FFT

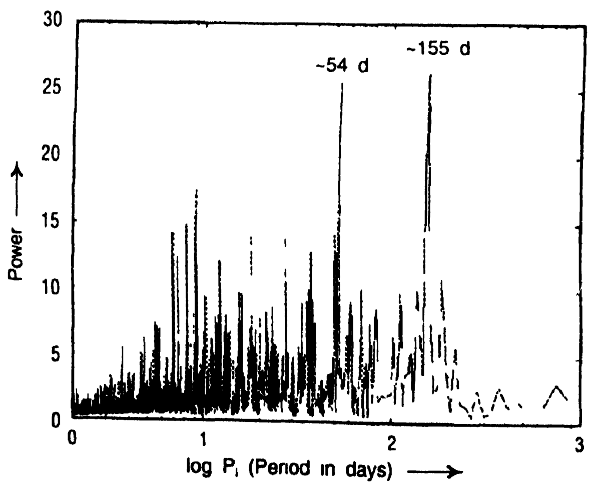

Figure 4. Plot for the Power spectrum of energetic electron flux data (E > 10 MeV) for the solar cycle 21 by MEM

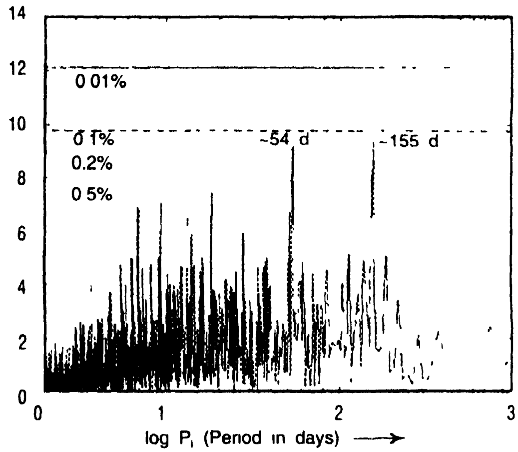

Figure 5. Plot for the Power spectrum of energetic electron flux data (E > 10 MeV) for the solar cycle 21 by LSP

periodicity was first detected by Rieger *et al* [3] and later reported in other studies. During the same cycle, it was detected in energetic proton flares [11,33], in ground-based H_α and microwave flares [4,5,13], in interplanetary magnetic field data [16]. Lean and Brueckner [34] noted this periodicity in sunspot blocking function and in 10.7 cm radio flux during solar cycles 19, 20 and 21. Carbonell and Ballester [35,36] suggested that a periodicity ~150–160 days had been significant during all solar cycles from 16 to 21. Recently Chowdhury and Ray [1], in an analysis of electron fluence data for two different energy bands (E > 0.6 MeV and E > 2 MeV), detected significant periodicity ~152 days for cycle 21. The present analysis confirms that "Rieger periodicity" was prominently present all over the cycle 21 for electron flares which is in contrast to the opinion of Lean [9] that this periodicity in sunspot areas occur intermittently in each cycles during the epoch of maximum activity.

Figure 3, Figure 4 and Figure 5 plot the Power spectrum of energetic electron flux data (E > 10 MeV) for the solar cycle 21 : (a) by FFT; (b) by MEM: (c) by LSP.

It is important to note that no satisfactory theory exists for ~155 days periodicity but several suggestions have been made time to time by several authors. Ichimota *et al* [5] suggested that it results from strong 'magnetized streams' appearing in stack plots of synoptic magnetic charts. But, it has been refuted by Bai and Sturrock [8], because although the flares occurring in these active regions [37,38] show the periodicity so do those outside of the active region. Lean and Brueckner [34] linked it with the magnetism of sunspots and suggested that the escape of magnetic field from the Sun is the cause. Mayfield and Lawrence [39] showed that flare production is correlated with the total magnetic energy of an active region. Recently, Ballester *et al* [17,40] have confirmed ~160 days periodicity in the photospheric magnetic flux even for cycle 21 and 23. Based on these analysis researchers [17,35,36] have proposed that the periodic emergence of magnetic flux, manifested as sunspots, triggers the periodicity in high-energy solar flares, probably by reconnection between old and new magnetic flux. It is interesting to note that Oliver *et al* [15] detected that during solar cycle 21 there was a perfect time-frequency coincidence between the occurrence of the periodicity in both sunspot areas and high energy flares.

On the other hand, as a possible cause of this periodicity Bai and Cliver [33] have proposed that this behavior could be simulated with a damped, periodically forced nonlinear oscillator, which shows periodic behavior for some values of the parameters and chaotic behavior for other values. Bai and Sturrock [20] and Sturrock and Bai [21] suggest that the Sun contains a 'clock' with a period of 25.8 days (later modified to 25.5 days) and the different solar periodicities are sub-harmonic of that fundamental period. Bai and Sturrock [42] studied the longitude distribution of major solar flare's of the cycles 19–22 and explained this hypothetical clock as being an obliquely rotating structure (either magnetic or hydrodynamic) rotating with a period of 25.5 days about an axis tilted by 40° with respect to the solar rotation axis. Interestingly ~155 (which is ~6 × 25.5) days is a integral multiple of the proposed 25.5 days. Thus our result seems to be consistent with that of Bai and Sturrock [42] made conclusion that ~155 days periodicity is a global phenomenon involving the whole Sun and 25.5 days is the fundamental period of the Sun. It is pertinent to mention here that ~155 days is independent on the flux intensity of electron flares. However, the reason behind the 'clock mechanism' is still unknown [40].

Pap *et al* [12] and later Bouwer [43] suggested that temporary existence of 154 (±13) days periods in solar activity indices are related to a strong emerging magnetic field. Bai [38,44] and Sammis *et al* [45] showed that, major solar flare production is associated with super active regions of exceptional longitudinal extent, typically containing very large sunspots having complex magnetic configuration. Furthermore, Bai [2] has determined that during solar cycle 21, a double hotspot system having rotation rate 27.41 days was operated in the northern hemisphere of the Sun. The synodic period of 27.41 days corresponds to the sideral period ol 25.50 days. Fan *et al* [47] suggest that due to buoyancy magnetic fields are usually transported from bottom to the upper part of the solar convection zone and this hotspot system may play key role in this movement. The nearly same value of periodicity of electron fluences and photospheric magnetic flux [17] and other solar magnetic activities make us conclude that electron emission is so intimately connected with the internal solar dynamics that, the periodicities of one is reflected in the other. The further study of the other solar activities is needed in order to access the significance of the ~155 days periodicity.

Acknowledgments

The use of IMP-8 observations from NSSDC OMNI data base is gratefully acknowledged. The authors are grateful to Dr. Natalia Papitashvili, Dr. Robert McGuire of NASA/Goddard Space Flight Center and Dr. Clifford Lopate of the University of

New Hampshire for providing the necessary data and information in this context Useful discussion with Dr I G Richardson, NASA/Goddard Space Flight Centre, Maryland, USA about the periodogram analysis is also gratefully acknowledged

References

[1] P Chowdhury and P C Ray *Mon Not R Astron Soc* **373** 1577 (2006)

[2] T Bai *Astrophys J* **591** 406 (2003)

[3] E Rieger *et al*, *Nature* **312** 623 (1984)

[4] R S Bogart and T Bai *Astrophys J* **299** L51 (1985)

[5] K Ichimota, J Kubota, M Suzuki, J Toshmura and H Kurokawa *Nature* **316** 422 (1985)

[6] B R Dennis *Sol Phys* **100** 465 (1985)

[7] P Delache, F Laclare and H Sadsoud *Nature* **317** 416 (1985)

[8] T Bai and P A Sturrock *Nature* **327** 601 (1987)

[9] J L Lean *Astrophys J* **363** 718 (1990)

[10] Droge W *et al*, *Astrophys J Suple* **78** 279 (1990)

[11] S Gabriel, R Evans and J Feynman *Sol Phys* **128** 415 (1990)

[12] J Pap, W K Tobiska and S D Bouwer *Sol Phys* **129** 165 (1990)

[13] J N Kile and E W Cliver *Astrophys J* **370** 442 (1991)

[14] R Oliver, J L Ballester and M Carbonell *Sol Phys* **137** 141 (1992)

[15] R Oliver, L Ballester and F Baundin *Nature* **394** 552 (1998)

[16] H V Cane, I G Richardson and T T von Rosenvinge *Geophys Res Lett* **25** 4437 (1998)

[17] J L Ballester, R Oliver and M Carbonell *Astrophys J* **566** 505 (2002)

[18] N A Krivova and S K Solanki *Astron Astrophys* **394** 701 (2002)

[19] T Landscheidt *Sol Phys* **107** 195 (1986)

[20] T Bai and P A Sturrock *Nature* **350** 141 (1991)

[21] P Sturrock and T Bai *Astrophys J* **397** 337 (1992)

[22] T Atac and A Ozguc *Sol Phys* **233** 139 (2006)

[23] B Joshi, P Pant and P K Manoharan *Astron Astrophys* **452** 657 (2006)

[24] E Forgacs-Dajka and T Borkovits *Mon Not R Astron Soc* **374** 282 (2007)

[25] J P Burg *Maximum Entropy Analysis PhD Thesis* (Palo Alto Stanford University) (1975)

[26] A Van den Bos *IEEE Trans Inf Theory IT* **17** 493 (1971)

[27] W H Press *et al*, *Numerical Recipes in C* (Cambridge Cambridge University Press) (2001)

[28] A Haber and R P Runyon *General Statistics* (Reading MA Addison- Wesley Co) p192 (1969)

[29] T K Das and T K Nag *Sol Phys* **181** 177 (1999)

[30] T K Das and T K Nag *BASI* **31** 1 (2003)

[31] J D Scargle *Astrophys J* **263** 835 (1982)

[32] J H Home and S L Baliunas *Astrophys J* **302** 757 (1986)

[33] T Bai and E W Cliver *Astrophys J* **363** 299 (1990)

[34] J L Lean and G E Brueckner *Astrophys J* **337** 568 (1989)

[35] M Carbonell and J L Ballester *Astron Astrophys* **238** 377 (1990)

[36] M Carbonell and J L Ballester *Astron Astrophys* **255** 350 (1992)

[37] T Bai *Astrophys. J.* **314** 795 (1987)

[38] J T Bai *Astrophys J* **318** L85 (1987)

[39] E B Mayfield and J K Lawrence *Sol. Phys.* **96** 293 (1985)

[40] J L Ballester, R Oliver and M Carbonell *Astrophys J* **615** L173 (2004)

[41] T Bai *Astrophys J* **397** 584 (1992)

[42] T Bai and P A Sturrock *Astrophys. J.* **409** 476 (1993)

[43] S D Bouwer *Sol Phys* **150** 385 (1992)

[44] T Bai *Max '91 Workshop 2 : Developments in Observations and Theory for Sol. Cycle 22* (eds.) Robert M Winglee and Brain R Dennis (Greenbelt NASA) p46 (1989)

[45] I Sammis, F Tang and H Zirin *Astrophys. J.* **540** 583 (2000)

[46] T Bai *Astrophys J* **585** 1114 (2003)

[47] Y Fan, G H Fisher and A N McClymont *Astrophys. J.* **436** 907 (1994)