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Fractal character of G index of IPS data for the period 1991–1994, obtained from multiscale wavelet analysis

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Abstract

In the study of the impact of solar activity on the terrestrial magnetosphere, the interplanetary medium plays a major role. Interplanetary scintillation (IPS) is a powerful tool that can be used to study the three-dimensional structure of the heliosphere and to monitor the presence of large scale perturbations in the interplanetary medium originating at the Sun, such as coronal mass ejections. In this paper, the scintillation values, g, that were taken for several years at the dipole array of Cambridge (UK) to make daily sky maps were used to calculate another index, G, which we assume to represent the density structure of the inner heliosphere. We performed wavelet and power spectrum analyses to obtain the local correlations of fluctuations at different scales of the daily G index, for the period 1991–1994. We found evidence of self-organization in the data and thus propose that the interplanetary medium is close to a critical state, at least for certain periods, and that this may explain the noncyclic components of solar activity.

Keywords: Fractals; Interplanetary scintillation; Heliosphere; Wavelets; Power spectrum

1. Introduction

The technique of interplanetary scintillation (IPS) allows the plasma concentration of the inner heliosphere to be probed remotely. Therefore, with the use of IPS it is possible to track density structures which originate near the Sun and propagate outward into interplanetary space. The technique gives also the possibility of calculating whether a specific large-scale perturbation moves in the direction of the Earth as well as its time of arrival to the Earth environment. Since these structures carry intensified fluxes of energy and momentum which prompt geomagnetic activity, IPS measurements are important to predict such activity.

The amplitude of radio signals that pass through the inner heliosphere is modulated by the movement of irregularities of the solar wind plasma across the line of sight. This modulation is known as *interplanetary scintillation or IPS*. The amplitude of the scintillation, ΔS, is proportional to the amplitude of fluctuations in the plasma density, but some authors like Erskine et al. (1978) have suggested that the amplitude of these fluctuations (and therefore of ΔS) is proportional to the absolute concentration of plasma particles, N. Therefore, the measurement of ΔS can be used to calculate N.

Hewish and Duffett-Smith (1987) used data comprising a period of 14 months close to the peak of the solar activity cycle 21, and reported that the 16 geomagnetic storms (with $Ap \geqslant 40$) during that period were preceded (from 1 to 7 days) by observations of intensified scintillation. These results suggest a relationship between intensified scintillation and geomagnetic activity. However, according to Hapgood and Lucek (1999) much work is still needed to determine the circumstances in which we can use *IPS* as a predictor of geomagnetic activity.

However, some authors (see for instance Lucek et al., 1996), have questioned this finding because even though

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there are observations of *IPS* perturbations that are followed by geomagnetic activity, there seems to be doubts concerning the statistical significance of the correlation between intensified scintillation and geomagnetic activity. In fact, Lucek et al. (1996) examined the sky maps of Cambridge and found an important number of false alarms. The use of index I_{35} proposed by Harrison et al. (1992) does not improve on the situation. Harrison et al. used this index to show that the correlation between *IPS* and the index of geomagnetic activity *Ap* takes the shape of a triangular distribution, as shown in the dispersion plot of *Ap* vs. I_{35} measured one day before.

Hapgood and Harrison (1994) investigated this triangular distribution in detail. They concluded that the flux of momentum and energy in the solar wind, which establishes a maximum level of geomagnetic activity, is determined in great extent by the density of the solar wind, which is correlated with I_{35}. This correlation is reflected in the envelope of the triangular distribution.

In the observations, the scintillation degree of a radio source is characterized by its scintillation index g. In order to calculate g, the observable parameters needed are the source intensity at a given time $I(t)$, and its fluctuation around the mean $\Delta I(t)$, sometimes also denoted by "I_{rms}". In this paper, we use the calculation of the g index, which measures the scintillation level of all sources that lie in a part of the sky extending in declination between −10 and 75 degrees, and between 40 and 110 degrees in elongation. From these g values, which represent pixels in a map rather than real sources, since these change their position continuously along the year, we calculate another index, G, considering all g-values for each day to obtain a value which we assume represents the whole g-map, and therefore the density structure of the inner heliosphere. This makes it possible to obtain local correlations of fluctuations at different scales of the plasma close to the Sun, on a daily basis. The G index was calculated from the IPS index g based on data obtained with the dipole array of Cambridge (UK), for the period 1991–1994 as provided to us by Detman from NOAA. This is done through wavelet and power spectrum analyses of G for the period in question, as well as for several subperiods. We then compare the results for the different subperiods.

The results indicate the presence of self-organization in the data. Self-organization is, according to Nicolis (1989), the capacity of a system which is out of equilibrium to move from one stable process to another in a set of metastable processes without the control of any external agent. This seems to be true specially when the Sun is more active (1991), although the influence of CMEs cannot be ruled out. On the other hand, both wavelet and power spectrum analyses show the absence of a

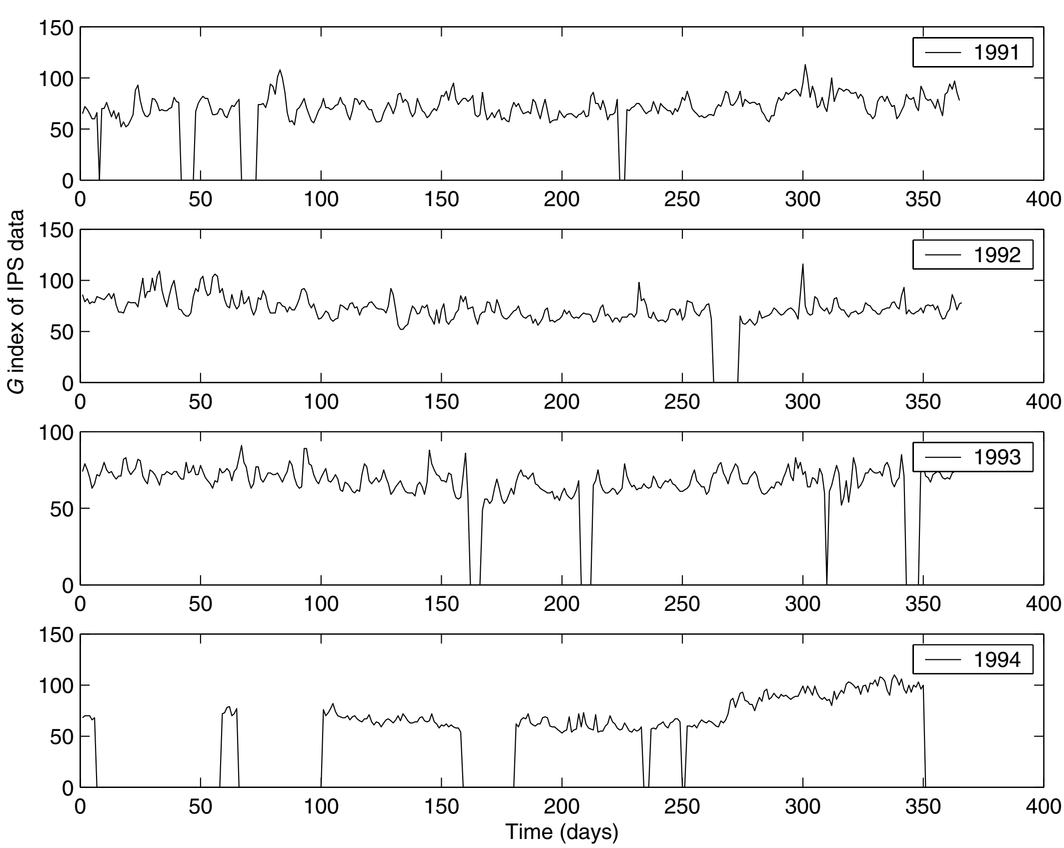

Fig. 1. Time series of G index of IPS data from Cambridge Radio Telescope, for the period 1991–1994. Here, each panel corresponds to one year. The series shows many gaps in the data.

characteristic scale in G, with power law tendencies indicating that G is fractal, at least during certain times. Furthermore, as the power spectral index is not constant, G seems to be multi-fractal. The fact that the spectral index is close to one may be indicative of a case of self-organized criticality.

The concept of self-organized criticality (SOC) was introduced for the first time by (Bak et al., 1987), to explain the invariant properties of complex dynamic systems far from equilibrium. They showed that for dissipative inhomogeneous systems (impulse, conductive, or propulsive), the natural state is one in which no space or temporal scales exist, i.e., is a state of SOC. Therefore, we discuss our results in the context of the natural tendency of some phenomena to move toward criticality when no external agents are present. This behavior is lost when large solar activity events such as CMEs are more frequent.

2. The inner heliospheric index G

The $\Delta I(t)$ fluctuation is defined as $\Delta I(t) = I(t) - \langle I(t)\rangle$, where the quantity inside the brackets is the ensemble average of I considering that the average was taken over a sufficiently long time, and the mean intensity of the source is defined as $I_0 \sim \langle I(t)\rangle$. Then the most basic definition of the scintillation index is

$$g = \left(\frac{\langle \Delta I(t)^2\rangle}{\langle I(t)\rangle^2}\right)^{1/2}. \tag{1}$$

As seen from this equation, the basic definition considers no other important parameters in the scintillation phenomenon. This leads to new definitions and modifications of the scintillation index. For instance, Rickett (1973) proposed a scintillation index that is a function of the wavelength of observation λ and elongation ε, as $g = 0.06\lambda(\sin\varepsilon)^{-1.6}$. In (Readhead et al., 1978) showed that the scintillation index is a function of the elongation and the state of the solar wind (both quiet and perturbed) and considered that the denominator in Eq. (1) must be changed so that

$$g = \left(\frac{\langle \Delta I(t)^2\rangle}{\langle \Delta S\rangle^2}\right)^{1/2}, \tag{2}$$

where ΔS represents the normal scintillation for a specific source at a certain elongation, which has been observed though several years.

The g index is a measure of the scintillation level of all sources in a part of the sky that lie in a plane perpendicular to the Sun–Earth line extending in declination between -10 and 75 degrees, and between 40 and 110 degrees in elongation. Although the observed scintillation signal represents an integration along the line of sight between the observer

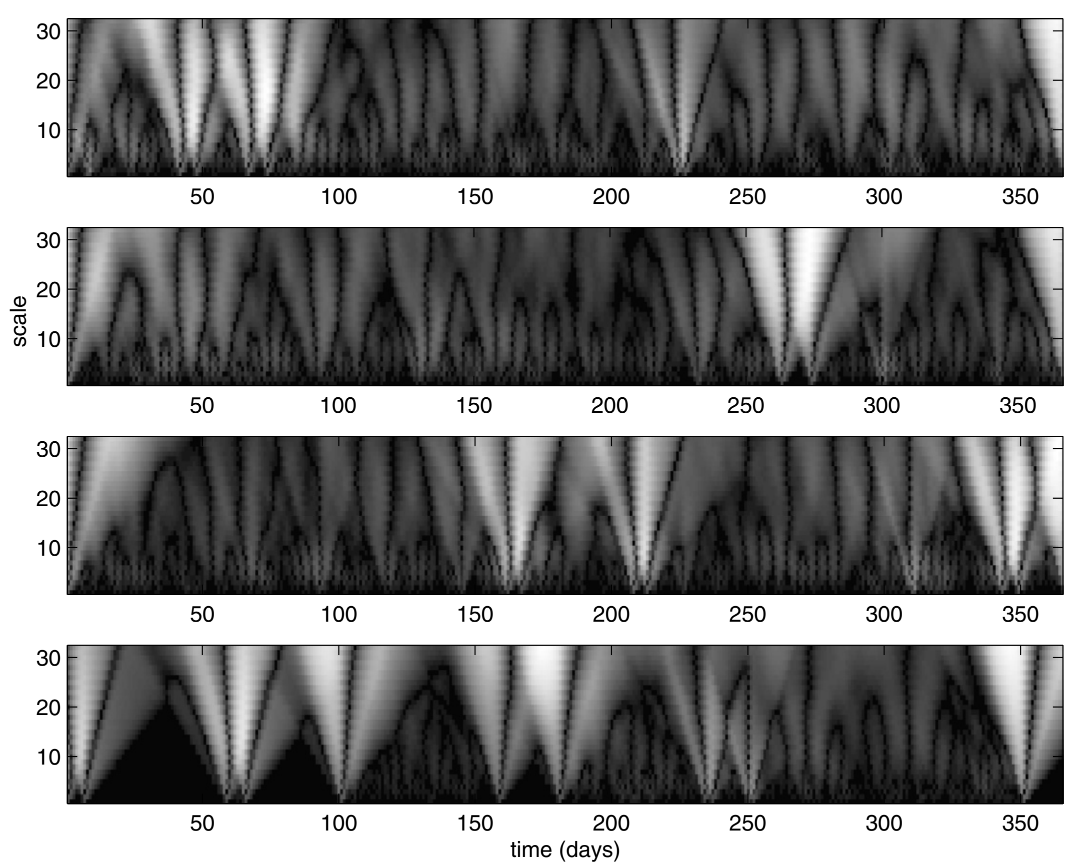

Fig. 2. Multiscale wavelet analysis performed on the data series of the G index, for the period 1991–1994. Here again, each panel corresponds to one year. The scales involved go from 11.4 to 365 days.

and the radio source, the largest contribution to the scintillation comes from the point where the line of sight passes closest to the Sun, since this is where the density is highest. As it was mentioned before, these g-values represent pixels in a map rather than real sources, since these change their position continuously along the year. From them, we calculate another index, G, considering all g-values for each day to obtain a value which we assume represents the whole g-map. We do that by simply adding up all values of g that are used to make the daily maps of Cambridge. We assume that G corresponds to the scintillation state of the inner heliosphere. The g data from which we have calculated G were kindly provided by Thomas Detman from NOAA. Fig. 1 shows the time series of the G index for the years for which we have data, that is, 1991–1994. As it can be seen there are some gaps in the data and at times, when the solar activity is stronger, the data look very noisy.

3. Wavelet analysis of the IPS daily G index from Cambridge array

The wavelet technique is a very powerfull tool for data processing as it is very efficient at detecting specific features such as pattern recognition and directional filtering in signals and images (see Antoine, 1999). The wavelet analysis was originally developed to study non stationary signals; nevertheless, it has resulted in a very important tool for object detection and fractal analysis. As we are interested in this last application, we performed a wavelet analysis of the G index for the period mentioned above, again year by year. We used for this analysis a continuum wavelet transform because unlike the discrete one it can operate through all scales, and it can be shifted smoothly over the full domain of the analyzed function. Also, we chose the "sym2" wavelet because it is nearly symmetrical, although a "db" wavelet would work just as well. The results are shown in Fig. 2. Characteristic scales go from 11.4 to 365 days. Here we can clearly see the periods in which the data present gaps, but we also see structure in the data that seem to repeat itself at different scales, that is to say, they seem to present a fractal character. In fact, we notice that the behaviour of the function changes with time, so that as we corroborate below, the data can be said to be multi-fractal. In order to corroborate this and to obtain quantitative information on the corresponding fractal dimensions, we performed a power spectrum analysis of the same period, where we have eliminated the data gaps. The results are shown in Fig. 3. We notice that all four spectra are rather noisy but a clear power law tendency can be observed, at least for years 1991, 1992, and 1994. The power spectral indexes obtained are 1.036 ± 0.110,

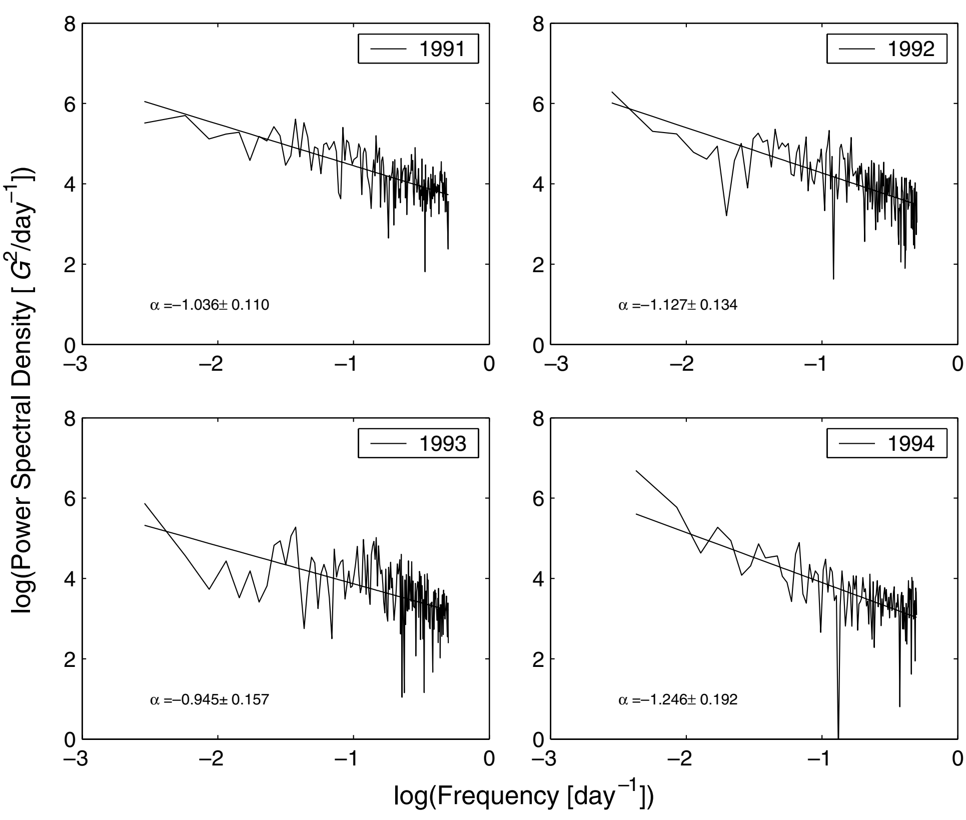

Fig. 3. Power spectra of G index of IPS, for the years 1991–1994, where the data gaps were eliminated. For 1991 the power spectrum was calculated with 174 data, and the spectral index obtained was 1.036 ± 0.110; for 1992 the data points used were 177, and the spectral index obtained was 1.127 ± 0.134; for 1993 the data points used were 173, and the spectral index obtained was 0.945 ± 0.157; and for 1994 the data points used were 117, and the spectral index obtained was 1.246 ± 0.192.

for 174 data points in 1991; 1.127 ± 0.134, for 177 data points in 1992; 0.945 ± 0.157, for 177 data points in 1993, and 1.246 ± 0.192, for 117 data points in 1994. The uncertainties in the spectral indexes were calculated with a *t*-student at 90% level of confidence. We notice that the uncertainties are rather high, perhaps because of the presence of CMEs or secondary scintillation in the magnetosphere or ionosphere. However, the tendency toward a power law behavior is clear.

4. Discussion and conclusions

The technique of interplanetary scintillation (IPS) is a powerful tool that can be used to study the three-dimensional structure of the heliosphere, for it can monitor the presence of large scale perturbations in the interplanetary medium originating at the Sun, such as coronal mass ejections. In this paper, we have analyzed IPS daily *G* index from Cambridge for the period 1991–1994, as we consider that it may contain valuable information of both the presence of coronal mass ejections as well as small-scale structure of the inner heliosphere. In fact, in this study we have found evidence of self-organization in the data. Indeed, the power spectra have a clear power law behavior, with no characteristic scales involved. However, we have also found that the power spectra are rather noisy. We assume that this noise is related to the presence of large scale structures such as CMEs in the interplanetary medium. Thus, in the case of the inner heliosphere, our results suggest that in the absence of coronal mass ejections the interplanetary medium is fractal, multi-fractal really, because the power spectral index is not constant. Furthermore, the spectral index is close to one, which may be indicative of a case of self-organized criticality. This is somewhat similar to the magnetosphere where evidence of self-organization has been found (see for instance Haken, 1975; Sitnov et al., 2000). There seems to be two regimes, one which is produced by solar activity, and one which is internally produced by the self-organization phenomenon.

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