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THE G INDEX OF INTERPLANETARY SCINTILLATION DATA AND ITS RELATION TO FORBUSH DECREASES DURING 1991–1994

R. PÉREZ-ENRÍQUEZ
Centro de Geociencias, UNAM, Juriquilla, Qro. Apdo. 1-742, México
(e-mail: roman@geociencias.unam.mx)

A. CARRILLO
Instituto de Geofísica, UNAM, Coyoacán, México D. F. 04510, México

and

A. KOTSARENKO and J. A. L. CRUZ ABEYRO
Centro de Geociencias, UNAM, Juriquilla, Qro. Apdo. 1-742, México

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Abstract. The purpose of this work is to analyze a global index of interplanetary scintillation, G, obtained from the g-maps of Cambridge Observatory, UK, and associate it with the occurrence of sudden decreases of the cosmic radiation, known as Forbush decreases (Fds), to determine their possible relation. For this purpose we perform a superposed epoch analysis of the G index, with respect to the occurrence of Forbush decreases, registered at Oulu Station, Finland, for the period 1991–1994. We found an increase in the value of G coinciding with the occurrence of the Forbush decrease, especially for those events with a fall greater than 10%. We conclude that the G index is a macroscopic parameter representative of the inner structure of the heliosphere, and has bearings on phenomena affecting the Earth's environment, as shown by Forbush decreases and possibly geomagnetic activities.

1. Introduction

Cosmic ray modulation in the interplanetary medium is a phenomenon being studied for several decades mainly by ground-based observations. Important are also results obtained from distant missions, like *Pioneers*, *Voyagers*, and *Ulysses*. 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 (Hewish, Scott, and Wills, 1964; Gapper *et al.*, 1978). The interplanetary scintillation is a very useful technique for the study of the three-dimensional structure of the heliosphere and to probe the presence of large-scale perturbations in the interplanetary medium, that originate at the Sun. The technique of 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.

Forbush decreases (Fds), defined as the sudden fall in the cosmic ray counting (measured in percent) that accompany interplanetary shocks arriving to Earth are, however, the most conspicuous proof that large-scale perturbations in the interplanetary medium strongly modulate the arrival of cosmic rays to the inner heliosphere. Therefore, the purpose of this paper is to study the relation between the occurrence of Fds and the state of the inner heliosphere for a particular period, 1991–1994, when daily maps of IPS were made at Cambridge Radio Telescope array. In order to do this we used the calculations of a new index, called G, obtained from the integration of all sources of scintillation used to construct the scintillation maps of Cambridge, as described later. We then performed a superposed epoch analysis of the G index with respect to Forbush decrease occurrences.

In the next section, we first obtain a list of Forbush decreases detected at the Cosmic ray station of Oulu, Finland, for the period 1991–1994, together with their percentage of fall. It is well known that this is related to the presence of geomagnetic storms (see for instance Kudela *et al.*, 2000). We then use the computation of the daily g index of interplanetary scintillation, that is used to calculate the g-maps from the Cambridge Array, for the years 1991–1994, to obtain G (see later). We then perform a superposed epoch analysis of G index, with respect to the beginning of Fds. After analysing the results obtained, we make a discussion related with the possibility of using IPS to study both the cosmic ray modulation by magnetic large-scale irregularities in the interplanetary medium. We end the paper with our conclusions.

2. The Inner Heliospheric Index G

The G index of interplanetary scintillation is based on another index, g, which corresponds to the scintillation degree of a radio source, observed at a frequency of 89 MHz with the radio telescope of Cambridge, UK. 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 denoted by "$I_{\rm rms}$." The 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

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

As seen from this equation, the basic operation 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

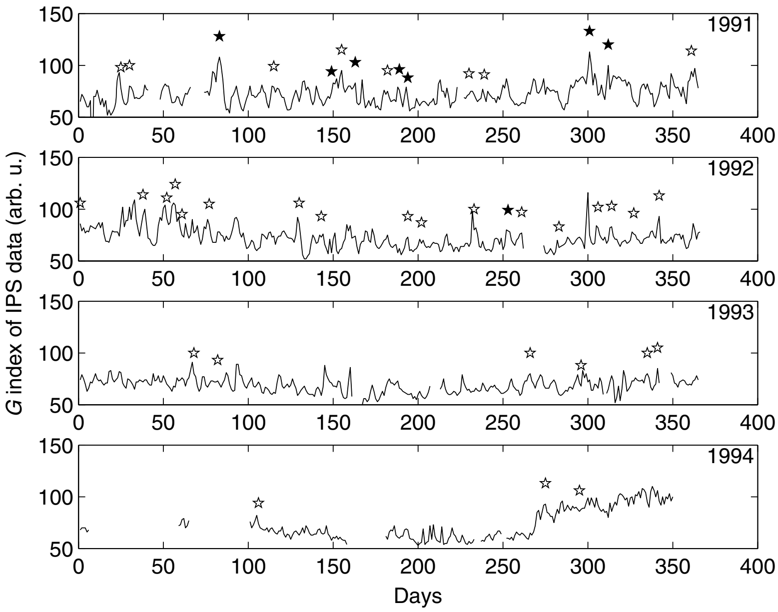

Figure 1. G index of IPS data from Cambridge, UK. The units are arbitrary. In the graph, the Forbush decreases are marked; in *black stars*, those with a percentage fall of the Forbush greater or equal to 10%, and in *white stars* those with a percentage fall of less than 10%.

ϵ, as $g = 0.06\lambda(\sin\epsilon)^{-1.6}$. Readhead, Kemp and Hewish (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 Equation (1) should change so that we obtain a relative value for g as

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

where ΔS represents the normal scintillation for a specific source at a certain elongation, which has been observed through several years. The g index of IPS contains the everyday measure of the comparison that is made for each source observed with a calibrated value obtained with the same instrument. The g values measure the scintillation level of all sources that lie in a part of the sky extending between 10° and 75° in declination, and between 40° and 110° in elongation. These g values represent a matrix of values corresponding to real sources, which change their position continuously along the year. The definition of G is then, operationally,

$$G = \int_{40}^{110} g(\epsilon)\,\mathrm{d}\epsilon, \tag{3}$$

where the value $g(\epsilon)$ depends on the instrument of observation. For a given ϵ, the maximum dispersion occurs for a specific region of interplanetary medium where

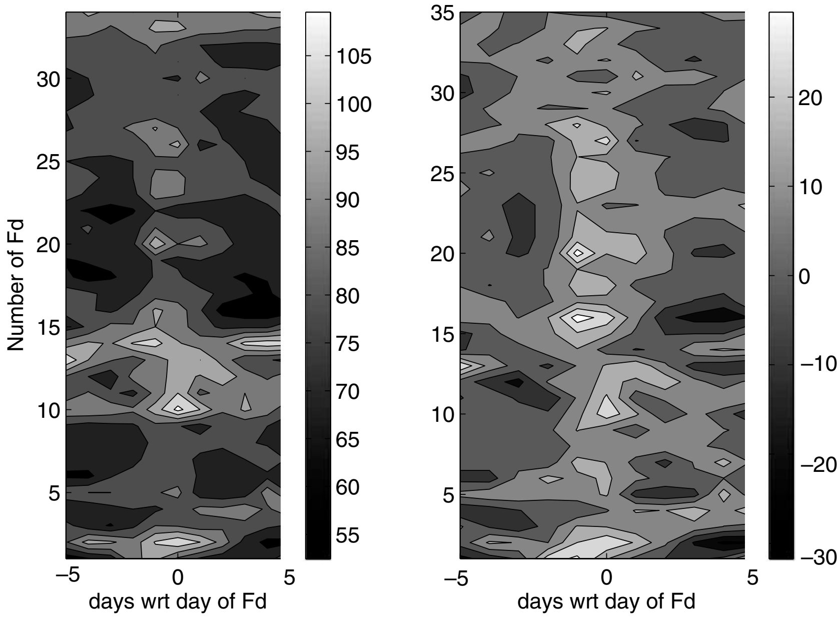

Figure 2. Map showing the time series of G for each of the 34 different events that occurred in the period. The plots go from 5 days before the Fd occurrence to 5 days after it, the day of occurrence of the Fd being the day 0. In the *left panel* the actual values of G are shown, and in the *right panel*, the normalized values in percent for the time of the events are shown.

the line of sight to the source lies in its maximum aproach to the Sun, at a distance $p = \sin \epsilon$. For a source out of the ecliptic, the point of maximum aproach will cover very high heliographic latitudes as the line of sight of the source moves toward the Sun. Therefore, the matrix of values g, that is, G, gives us three-dimensional information about the turbulence of the interplanetary medium, or density structure of the inner heliosphere, evaluated at the above-mentioned point p. This makes it possible to obtain local correlations of fluctuations at different scales of the plasma close to the Sun, on a daily basis. In order to do that, we have assumed that the g corresponds to a value in a plane perpendicular to the Sun–Earth line. The g data from which we have calculated G were obtained with the dipole array of Cambridge, UK, for the period 1991–1994 as provided to us by Thomas Detman from NOAA.

3. Superposed Epoch Analysis of G Index of IPS with Respect to Forbush Decreases

The time series of the daily G index of IPS data from Cambridge for the period 1991–1994 is shown in Figure 1, together with the Fds that occurred during this

TABLE I
Forbush decreases from Oulu Cosmic Ray Station for 1991–1994.

Number of Fd	Date	Fall (%)
1	25/01/91	4
2	24/03/91	17
3	25/04/91	9
4	29/05/91	11
5	12/06/91	18
6	01/07/91	12
7	08/07/91	6
8	18/08/91	7
9	27/08/91	4
10	28/10/91	16
11	08/11/91	10
12	27/12/91	4
13	07/02/92	5
14	21/02/92	5
15	17/03/92	6
16	09/05/92	8
17	22/05/92	4
18	12/07/92	3
19	20/07/92	4
20	20/08/92	8
21	09/09/92	10
22	09/10/92	3
23	01/11/92	6
24	09/11/92	6
25	22/11/92	4
26	07/12/92	3
27	09/03/93	4
28	23/03/93	4
29	23/09/93	7
30	23/10/93	5
31	01/12/93	4
32	16/04/94	5
33	01/10/94	4
34	22/10/94	5

period. As we can see there are some gaps in the data and at times, when the solar activity is stronger, the data look very noisy. The Fds correspond to those observed at Oulu Cosmic Ray Station, Finland (2005, web page). The events list is given in Table I.

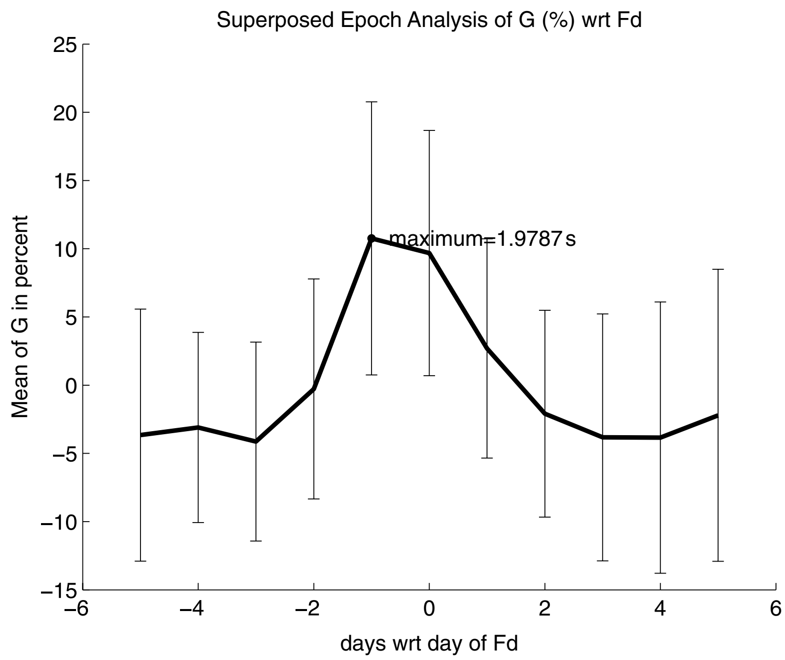

Figure 3. Superposed epoch analysis of G index of IPS with respect to the day of occurrence of a Forbush decrease. The mean value is shown together with the values $\pm\sigma$. There seems to be a significant increase of the index starting 2 days before the time of the Forbush and reaching its maximum on the day of the Forbush. The maximum value lies at 1.98σ from the mean.

Forbush decreases are caused by interplanetary shocks (either originated from a flare or driven by a CME) passing by Earth. Therefore, they are related to the presence of large-scale structures in interplanetary space, and we believe that a superposed epoch analysis of the G index, which contain information about such structures, might be of some value when performed around the time of Fd occurrences. In fact, according to Prager and Hoenig (1989), since the statistical significance of associations between one event and its possible consequences is determined by a randomized test, this method of analysis does not rely on the usual assumption of parametric testing.

The superposed epoch analysis was performed over the basis of 5 days before until 5 days after the beginning of the Fd. Figure 2 shows a map of G for all the 34 Forbush decreases, detected at Oulu, and shown in the table. In this figure, both the G values and the normalized ones in percent for each event are given with respect to Fd occurrence. The latter values are obtained as the difference between the value and the mean for that event, divided by the same mean. The reason of obtaining this value is that the background of G for each event varies from event to event. The epochs considered go from 5 days before the Fd occurrence to 5 days after it. The

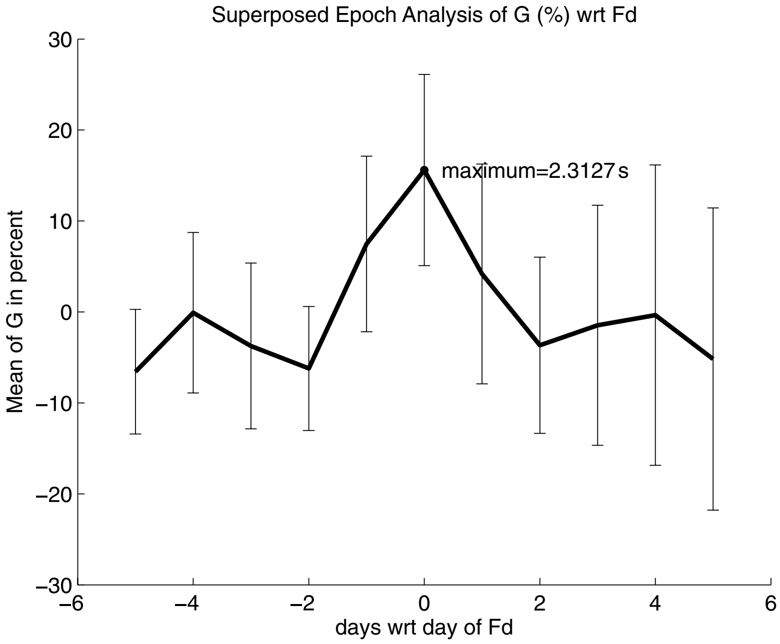

Figure 4. Superposed epoch analysis of G index of IPS with respect to the day of occurrence of a Forbush decrease for all events with a fall greater than 10%. There is also a significant rise of the index but starting 1 day before the Fd, and the peak of the distribution lies on the day of the Fd occurrence. The maximum value lies at 2.31σ from the mean.

amount of data is important to the composition of the time series for each event, but unfortunately we have only one value per day. In comparing both panels we notice that the normalized values show a clearer tendency for the series to increase towards day 0.

The superposed epoch analysis was made with the normalized values in percent, which were averaged for each box. The plot is shown in Figure 3 where the error bars are depicted and the s value of the maximum was found to be 1.98σ. There is a marked increased in the G value starting 2 days before the occurrence of the Forbush, reaching its maximum 1 day before the Fd. A 1-day time shift between IPS index and Fd is understandable taking into account that this is the time it takes for a CME to reach 1 AU and cause a Forbush decrease. However, we notice a large dispersion in the data.

To examine this problem, we analyzed the events considering their magnitude; in this case the percent fall. There were seven events with a fall greater or equal to 10%. For those events, the superposed epoch analysis is plotted in Figure 4. Here, the rise starts only one day before the occurrence of the Fd, and the peak in the distribution lies at day 0. The s value of the maximum is now 2.31σ, and the error bars are smaller.

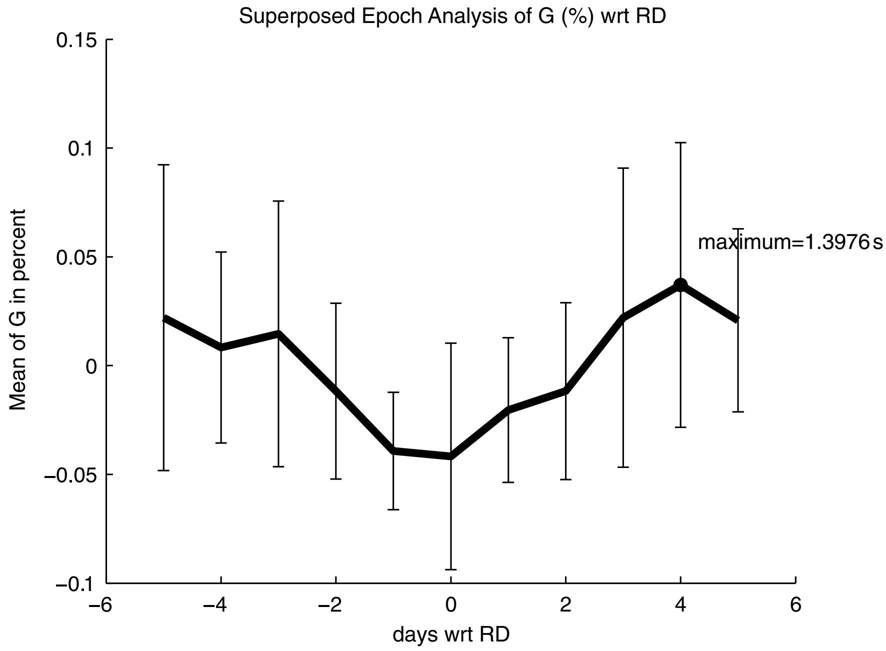

Figure 5. Superposed epoch analysis of G index of IPS with respect to the eight chosen days with no Forbush decrease present. The mean value is shown together with the values $\pm\sigma$. There is no significant increase of the index.

In order to see if these results are robust, we perform a random test, similar to the one described and repeating it 100 times, each time randomly selecting eight 10-day intervals. The number of cases with a peak or dip going beyond 1.98σ and 2.31σ, divided by 100, gives the significance of the found effect, for the analysis of all events and those with a fall greater or equal to 10%, respectively. We found that 28% go beyond 1.98, whereas only 7% go beyond 2.31. Therefore, according to the significance test, the result, based on all the analyzed Fds, is not significant (the significance level of 72% can be considered, at most, only marginally significant). The result for the strong Fds, though, are significant at a 93% level. To emphazise this, we performed a superposed epoch analysis but with respect to eight randomly chosen days, two per year during 1991–1994, for which no Forbush decrease was detected. The actual periods are 30/01/91 to 9/02/91, 16/09/91 to 26/09/91, 10/04/92 to 20/04/92, 9/06/92 to 19/06/92, 9/04/93 to 19/04/93, 31/07/93 to 10/08/93, 29/04/94 to 9/05/94, and 15/11/94 to 25/11/94. The results are shown in Figure 5, where we notice that there are no significative peaks in the epochs.

4. Discussion and Conclusions

In this paper we have used the calculations of a new index, called G, obtained from the integration of all sources of scintillation used to construct the scintillation maps of Cambridge, in order to perform a superposed epoch analysis of *G* index, with respect to Forbush decrease occurrences. We have done this with the purpose of studying the relation between the occurrence of Fds and the state of the inner heliosphere for a particular period, 1991–1994. We have shown that there is a tendency for the *G* index to peak around the time of the Forbush decrease occurrence, particularly for those events in which the cosmic ray fall is greater or equal to 10%. As Fds are an indication of effects taking place close to the Earth, and *G* is an index related to perturbations of all scales close to the Sun, our results emphazise the importance of IPS studies in those involving large-scale phenomena affecting the Earth's environment.

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References

Gapper, G. R., Hewish, A., Purvis, A., and Duffet-Smith, P. J.: 1982, *Nature* **296**, 633.
Hewish, A., Scott, P. F., and Wills, D.: 1964, *Nature* **203**, 1214.
Kudela, K., Storini, M., Hofer, M. Y., and Belov, A.: 2000, *Space Sci. Rev.* **93**, 153.
Oulu Cosmic Ray Station: 2005, *http://spaceweb.oulu.fi/projects/crs.*
Prager, M. H. and Hoenig, J. M.: 1989, *Trans. Am. Fish. Soc.* **118**, 608.
Readhead, A. C. S., Kemp, M. C., and Hewish, A.: 1978, *Mon. Not. R. Astr. Soc.* **185**, 207.
Rickett, A.: 1973, *J. Geophys. Res.* **78**, 1543.