Cosmic-Ray Modulation and Solar LDE-Type Flares

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Cross-correlation analyses between galactic cosmic-ray intensities from Calgary neutron monitor and several solar-activity parameters, on daily basis, have been undertaken. We report here results connected with the unresolved full-solar X-Ray background and the occurrence of solar LDE-type flares (both from GOES-satellite data) in the time interval July 1988–June 1989 (i.e. the last part of the ascending phase of sunspot cycle 22). Our findings do not support the hypothesis that LDE-type flare occurrence is the best parameter to describe the medium-term modulation of galactic cosmic rays; however, it could be a good indicator of sudden but stable coronal variations occurring along the solar-activity cycle, i.e. a proxy data set to include peculiar transient-induced effects on the long-term cosmic-ray modulation studies.

1. Introduction

The understanding of the solar modulation of galactic cosmic rays is still far from complete. Efforts are made to identify good “predictors” for forecasting models. In this frame of research cross-correlation analyses between cosmic ray intensities and several solar-activity parameters have been undertaken. Some results were reported in the Part I of the Proceedings of the 8th International Symposium on Solar Terrestrial Physics (Antalova et al., 1994; Sykora and Storini, 1994). Here we discuss in more detail the possible role of solar flares accompanied by a long-lasting soft X-ray flux.

The appreciation of the importance of coronal mass ejections (CMEs) for Solar-Terrestrial Physics has increased in recent years (e.g. Sheeley et al., 1985; Gosling et al., 1990, 1991; Harrison et al., 1990; Kahler, 1992; Gosling, 1993; Hundhausen, 1993; Tsurutani and Gonzalez, 1993; Dryer, 1994; Feynman and Hundhausen, 1994; among others). Attempts to correlate the appearance of CMEs with other more easily observed manifestations of solar activity have been extensively made. In particular:

- Sheeley et al. (1983) found that the probability of observing a CME increases with the duration of 1–8 Å X-ray flares;
- Kahler et al. (1989), after a survey of CMEs associated with ≥M1 X-ray flares, revealed a good correlation between the flare duration and the CME angular width;
- St. Cyr and Webb (1991) remarked that “eruptive prominences and soft X-ray events (especially long-decay events) were the most likely forms of activity to accompany the appearance of mass ejections”;
- Kahler and Hundhausen (1992) noticed a possible relationship between CME structures and the occurrence of long-lasting X-ray flares (i.e., LDE-type flares).

Therefore, it is reasonable to test if in the periods characterized by a high frequency of LDE-type flares (i.e. those with a possible increased number of CMEs travelling in the interplanetary medium) there is a good correlation between LDEs and cosmic ray intensity. The necessity of further work in this field was underlined by Potgieter (1994). We choose for our investigation the last part of the rising phase of sunspot-number cycle 22.
2. Data Sets: An Overview

The following parameters have been used in our study:

(i) the daily pressure-corrected data from the Calgary neutron monitor (N 51.1 W 114.1; height: 1128 m; cutoff-rigidity: about 1 GV; Venkatesan et al., 1989) covering July 1988–June 1989. Values are normalized to the 100% level of May 1965 (i.e. about 285554 counts/h). The data series is shown in Fig. 1 together with its 15-day running mean, while the insert reports the monthly intensities of the nucleonic component of the galactic cosmic rays derived from the Climax (N 39.4 W 106.2; height: 3400 m; cutoff-rigidity: about 3 GV), Deep River (N 46.1 W 77.5; height: 145 m; cutoff-rigidity: about 1 GV) and Huancayo (S 12.0 W 75.3; height: 3400 m, cutoff-rigidity: about 13 GV; from 1992 on data from Haleakala detector—N 20 W 156, height: 3030 m—have been used to update the series) neutron monitors (SGD, 1994) to illustrate the ascending phase of the present sunspot-number cycle. We notice that during the investigated period (marked by an horizontal bar) the cosmic-ray modulation increases by about 12% (on monthly basis), which is nearly two-third of the total modulation induced by solar activity during this rising phase. In this period polar coronal holes cover small areas of the solar external region and equatorial holes are not long-lived features. Moreover, during the ascending phase of cycle 22 no ground-level enhancements (GLEs), ascribed to solar cosmic rays were recorded by the world-wide network of cosmic-ray detectors (see, for instance, Gentile, 1993). In other words, the particles recorded by the ground-based detectors are related to the galactic ones. Hence, the magnitude of the observed cosmic-ray modulation during the analysed 365 days should be primarily associated with the transient solar activity and the induced phenomena in the heliospheric domain (e.g., Burlaga et al., 1984, 1993).

Fig. 1. Daily and 15-day running averages for the nucleonic intensity (I, in % of the May 1965 average), as derived from Calgary neutron monitor, in the period July 1988 to June 1989. The inserted panel shows the monthly cosmic-ray intensities during solar cycle 22 for three charged-particle energies, while the horizontal bar denotes the investigated period.
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(ii) the daily average of the unresolved full-sun X-ray (SXR) flux from GOES 7 satellite. The preliminary SXR-background (SGD, 1994) is given by the XBG intensity (XBG-I), which, we believe, represents the density of the quiet corona structures over the whole solar disk. We recall that the letters A, B, C, M, and X in the SGD tables stand for powers of ten, where A denotes $10^{-8}$, B the power $10^{-7}$, C the power $10^{-6}$, and so on, and digits from 1.0 to 9.9 following above letters act as multipliers (e.g., C3.5 means B35 or A350). All the daily values has been transformed to the A level ($10^{-8}$ Watts/square meter). The left upper panel of Fig. 2 reports the XBG-I parameter. Several XBG-I peaks are emerging with the minimum values strengthened for data numbers greater than 160.

(iii) the daily index for SXR long-lasting solar flares (LDE-type flares, i.e., those accompanied by a SXR-flux of long-duration: >2 hours). This index (TF-Index) is built up weighting the SXR-GOES classes reported in the SGD, as discussed by Antalová and Viktorinová (1991). We notice that the importance of a flare in X-ray wavelengths is the “peak flux” measured at the Earth in the 1 to 8 Å range in units of Watts/square meter. For example, when an X-ray burst with a maximum flux of C7.9 (M2.5, X6.7) is reported it was ascribed to the event with a TF-Index = 8 (25, 670). The daily TF-Index is shown in the right upper panel of Fig. 2: there is an increase in the occurrence of LDE-type flares during the second

![Fig. 2. Time behaviour of four daily solar-activity indices in the July 1988-June 1989 period: XBG-I (solar X-ray background, left upper panel), TF-Index (occurrence of LDE-type flares weighted according their X burst importance, right upper panel), EF-Index (as the previous one but only for eastern flares), WF-Index (index for western flares).](image-url)
half of the data set.

Moreover, two subsets are derived from the TF-Index taking into account the heliographic longitude of the LDE-type flares: the EF-Index for those located to the east of the central meridian (left lower panel of Fig. 2) and the WF-Index for the western ones (right lower panel of Fig. 2).

3. Cosmic-Ray versus SXR Parameters

We have employed the method of least squares to evaluate the linear correlation coefficient between the cosmic ray intensities and each of the logarithmic transformed SXR-parameters. When no lag between the correlated data sets is introduced we found that the SXR-parameters are anticorrelated with the cosmic ray intensities, as expected from the solar activity-induced phenomena in the interplanetary medium. However, Pearson’s coefficient is not high: -0.60 for CR-XBG, -0.40 for CR-TF, -0.20 for CR-EF and -0.34 for CR-WF. To go deeper into the matter, we have prepared new correlation plots introducing a timelag between the correlated data-sets. The lag was increased up to the value +/-24 days. Figure 3 shows the obtained results. The best correlation coefficients are: -0.62 (-3-day lag), -0.43 (-4-day lag), -0.34 (-6-day lag) and -0.34 (-1-day lag), respectively (see filled triangles in Fig. 3).

We conclude that the correlation coefficients between cosmic-ray data and LDE-type flares are lesser than -0.45, which is in agreement with results obtained for a longer period (1969–1991) on half-monthly basis (Antalová et al., 1993). However, they are nearly a factor two lower than those obtained by Storini et al. (1995) correlating cosmic-ray data with sunspot numbers on monthly basis (ascending and descending phases of cycles 19 to 22). In fact, when we compare the TF-Index moved +4 days (to take into account the best time-lag for correlations) with the modulated levels of the nucleonic intensity, several of them have missing LDE-type flares, while others are in close coincidence (see Fig. 4, where days with negative difference between pressure-corrected intensities and 15-day smoothed values are reported).

Finally, we notice that the best lag for the EF-Index is about -7 to -5 days and for the WF-Index it is about -1 day, in agreement with past findings, particularly when the fact that not all the LDEs are accompanied by type-IV radioemission is considered (e.g., Iucci et al., 1979, 1984; Storini 1990 and references therein). Moreover, with this second type of predictors (type-IV flares) transient cosmic-ray modulation is forecasted with a higher confidence level. For example, energetic events (i.e., the B and GB classes defined by Iucci et al., 1979) occurring in the period 1957–69 are associated with the 90% of the

Fig. 3. Correlation coefficients obtained from correlation plots between the cosmic ray intensities and the solar activity indices reported in Fig. 2. A time-lag ranging from -24 to +24 days has been included to evaluate the best correlation coefficients.
Fig. 4. The subset of the negative difference between pressure-corrected cosmic-ray intensities and 15-day smoothed values (left scale, filled areas) and the TF-index moved +4 days to take into account the delayed answer of cosmic-ray modulation (right scale, unfilled areas) in the near-Earth environment.

Fig. 5. Running averages of the soft X-Ray parameters from July 1988 to June 1989. Dotted segments remark base-line levels for XBG-I, while full segments periods with strong LDEs.
recorded Forbush decreases.

Comparing Fig. 1 with the left upper panel of Fig. 2 we understand why there is a better correlation between the cosmic rays and the XBG-I values (when no LDE-type flares are observed the CR-XBG correlation increases to \(-0.68\), Antalová et al., 1994). In fact, the SXR flux for the whole quiet corona, as described by this index, has itself a nearly 1 1-year cycle. Moreover, this parameter has been found, on monthly basis, to be well correlated with the H-alpha solar-flare counts by Pearce et al. (1992). They conclude that “there is a remarkably close relationship between flare rate and X-ray luminosity which suggests that not only do these parameters vary in sympathy with the solar cycle but also they are intimately related on shorter timescales” (see also Wilson, 1993). What is the role of LDEs in this context? In Fig. 5 we show the 15-day running values of the solar parameters here investigated. We observe the progressive increase of the base-line level (B1 to B2 to B3) of XBG-I after the series of LDE-type flares (A1, A2). We conclude that the XBG-I parameter reflects the large-scale coronal variations occurring during the on-going solar-activity cycle and that the LDE-type flares should be the signatures of some transient but stable changes over wide regions of solar corona. However, it seems that by using only LDEs the medium-term modulation of galactic cosmic rays cannot be forecasted (e.g., Storini, 1990, Potgieter, 1994 and references therein; Ahluwalia, 1994; Storini, 1995a, b). Nevertheless, they should be useful for studies on long-term cosmic-ray modulation, as an “ingredient” for long-lived effects induced by solar transient activity. More work is needed to solve the CME-flare controversy (see, for instance, Harrison, 1991; Harrison and Sime, 1992; Gosling, 1993; Crooker, 1994; Dryer, 1994).

4. Conclusions

The last 365 days of the ascending phase of sunspot-number cycle 22 were characterized by a strong cosmic-ray modulation, with high particle depletions in the second half of the investigated period (Fig. 1). Several of them are well correlated with LDE-type flares (Fig. 4), however over the entire period the correlation between both phenomena is low (Fig. 3). The flare East-West distribution has been considered (Fig. 2) because, in general, western events from extreme heliolongitudes, due to the Sun’s rotation, are less effective on the cosmic-ray modulation observed in the near-Earth environment (see, Fig. 4 reported by Iucci et al., 1979). However, as it is shown in Fig. 3, the magnitude of the obtained correlations is the same in both data subsets, suggesting again that the LDE-flare occurrence is not the best parameter to describe the medium-term cosmic-ray modulation. If they are connected with CME occurrence, it is hardly to believe in a CME primary role on forecasting work for solar-terrestrial phenomena. Nevertheless, the number of CMEs is larger than the one for LDE-type flares. The latter could only be a proxy data subset (see also Harrison, 1991). For completeness, we add that this preliminary analysis is based on the X-ray flare peak without taking into account the changing background level. It should be interesting to evaluate the weight of this level in our results.

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