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Galactic cosmic ray modulations for four solar activity cycles

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Abstract. The cosmic ray (CR) particles are affected by the electromagnetic disturbances while transporting from galactic space to the Earth. The data obtained with a variety of detectors on Earth and located at different global sites, are examined. We discuss the solar cycle 22 in comparison with previous cycles. Principle characteristics of CR variations as given by ground-based observations were examined. Very similar of CR intensity modulations observed at different neutron monitors. The solar activity cycle 22 is the second most active cycle.

1. Introduction

It has been known that the cosmic ray intensities (CRIs) and their energy spectrum are modulated by solar activity cycle (SAC) from one to another. Usoskin et al (1998) performed a correlation study of sunspot numbers and CRI for the last four solar cycles. Their analysis of the running cross correlation between the monthly series showed that the two cycles 21 and 22 coincided with each other, at least to the time available of the study. The region of cosmic ray modulation has changed according to the solar cycle (even or odd cycle). The magnitudes of modulation region for cycles 21 and 22 are significantly larger than for cycles 19 and 20 (Dorman et al., 1999a; 1999b). Ahluwalia (1997a) showed that there did not appear to be any striking correspondence between the amplitudes and durations of solar activity cycles and observed cosmic ray modulation over six cycles. Also, he found a three SAC periodicity may be present in the CRI data and geomagnetic activity (Ap), expecting the amplitude of CR modulation for SAC 23 may be further smaller than for cycles 21 and 22. On the other hand, the spectra of long-term CR modulations displayed a clear dependence on the global solar magnetic field (GSMF) sign with harding spectra for qA<0 epochs.

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The transition of GSMF polarity to negative state led to increasing in CR modulation (Belov et al, 1997).

Studies by Shea and Smart (1990a; 1999) have revealed that the number of solar proton events increased during the maximum solar activity years than the remaining portions of the solar cycle (except the solar cycle 21) and significant solar proton events can occur at any time of the solar cycle.

The present work discusses the main characteristics of SC 22nd in comparison with cycles 21st, 20th, and 19th. The starting of each SC was selected as the month after the minimum sunspot number; 19th (May 54 - Oct. 64), 20th (Nov. 64 - Jun 76), 21st (Jul. 76 - Sep. 86), and 22nd (Oct. 86 - end 95). In this work, when speaking of CR particles, we mean particles detected by ground-based monitors.

2. Some features of the SAC 22 in comparison with previous cycles

2.1 Solar and geomagnetic activity indices

The even solar cycle 22 began in 1986, which has some different features in comparison with the cycles 19th, 20th, and 21st. The fact is, the shape of the sunspot number cycle changes from cycle to another around the 11-year periodicity. It is interesting to note that the cycle # 19 is the most active cycle ever, cycle 22 the second most active and cycle # 21 the third most active cycle (Ahluwalia, 1997b; Usoskin et al., 1998). The cycles of solar activity represented by the Zurich (from 1964 to the end of 1980) and International sunspot numbers (1981-95) and plotted in Fig. 1a, to illustrate the changes in the solar activity. Monthly mean sunspot numbers are shown for the 20th, 21st, and 22nd solar cycles. Circles are the yearly averages. Figure 1b shows the monthly *Kp* values, the measure number of geomagnetically disturbed. Arrows on the bottom plot indicate the duration of the considered cycles. The pattern of the *Kp* is considerably more complicated than that of the sunspot number changes. It is clearly seen that R_z reveals a single peak denoting the 11-year cycle,

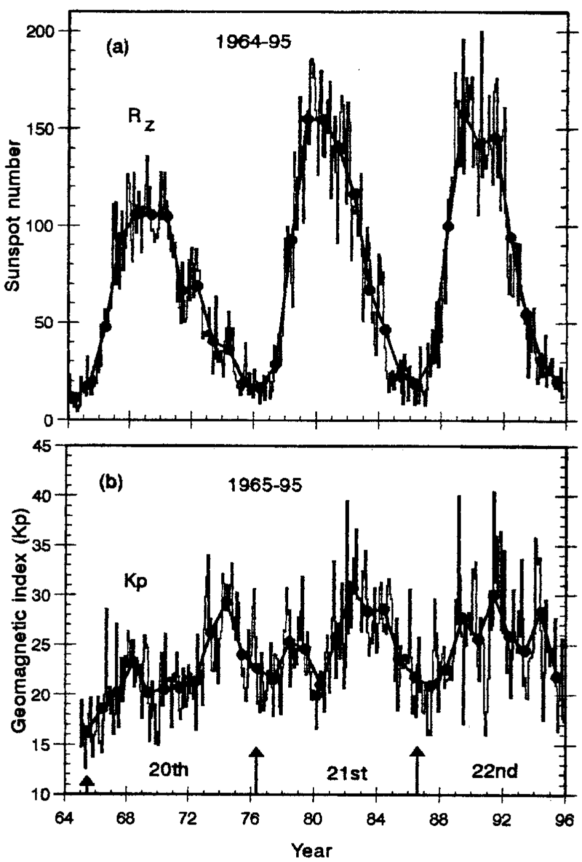

Fig. 1. Monthly sunspot numbers (R_z) from 1964 to 1995 (upper plot), as well as the geomagnetic index values from 1965 to 1995 (bottom plot). Circles represent the yearly mean values. Arrows mark the solar minima epochs.

whereas the *Kp* is basically cyclic with two separate peaks. At least one peak occurred during the declining period of the solar cycles and the second was at the board of the maximum solar activity epoch. These two discrete components attributed to; the former represents the amount of geomagnetic perturbation caused by the coronal mass ejections and the latter the contribution from the corotating streams of high speed solar wind streams (Venkatesan et al., 1991; Ahluwalia, 1999). Three close peaks in *Kp* are observed in the solar cycle 22nd (occurred in Mar. 1989, Jun. 1991, and Feb.-Mar. 1994). Two peaks happened in the solar maximum years (1989-91) of the 22nd cycle. In cycles 20th and 21st the two peaks quite separated and the latter (occurred during the declining activity phase of solar cycle) is the larger than the first one. In contrast, during the cycle 22 nearly three equal and close peaks have been measured. The time separation between the two *Kp* peaks changed according to the cycle (odd or even one).

The monthly values of R_z and *Kp* both are peaked in 1989 (with a little lag time between them), dropped in 1990 (35% and 25% below the yearly average for each parameters, respectively), and peaked again in 1991. The pattern of previous cycles did not follow such as the behavior of the solar cycle 22. R_z for the 22nd solar cycle exceeds than those for the solar cycle 20, and is a little less during the 21st solar cycle. Also, the sunspot number evolution of SACs 21 and 22 are very similar to each other.

2.2. The ground level enhancements

Figure 2 shows the magnitudes of GLE (vertical lines) for the solar cosmic rays during the period 1952-95. The magnitudes of GLE from 1952 to the end of 1989 are tabulated by Nagashima et al. (1991), while from 1990 to 1995 are taken from Shea et al., (1995). We added the sunspot numbers (crosses) for each event for comparison. Most ground level events that occurred during the solar cycles 20th and 21st are relatively short lived with the high energy particles flux passing the Earth within a few hours. Some of these events had a duration of just over an hour (the event on 7 May 1978). In contrast, the event on 29 Sep. 1989 had the highest increase for all relativistic solar proton events in the 22nd solar cycle with a recorded increase of ≈ 340.4 %, and it had longer duration than similar events of the previous solar cycle. Most of events of long duration often had an enhanced particle flux in conjunction with the arrival of the interplanetary shock at the Earth (Shea and Smart, 1990a; 1990b). Also, they indicated that the proton effect of solar cycle 22 has already exceeded that for either cycle 20 or 21 and it was approximately half the value for cycle 19. From the Fig 2, we noticed that, during the 20th and 21st solar cycles, the GLEs were considerably smaller than happened in cycles 19 and 22. The GLEs had the larger increase with a recorded of 17.6 % in 28 Jan. 1967 and 12.8 % in 1 Sep. 1971 during the solar cycle 20th; and 15.2 % in 22 Nov. 1977 and 18.5 % in 7 Dec. 1982 during the solar cycle 21st. These increases, above the background CRI at high latitude stations, are generally smaller than the major events of the 19th and 22nd SACs. In 1989, seven GLEs were recorded and never had the same number in one year.

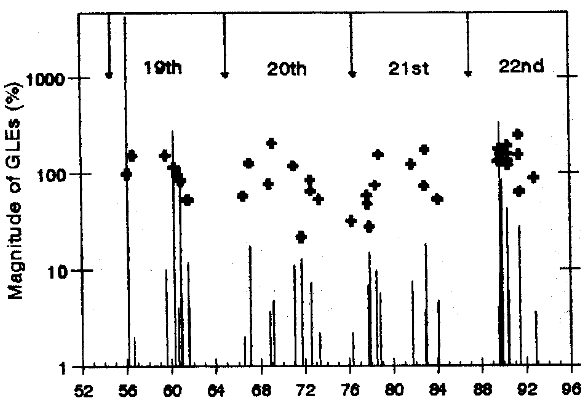

Fig. 2. The magnitudes of GLE (vertical lines) for the solar cosmic rays during the 1952-95 period. Crosses show the corresponding sunspot number for each event.

It is clearly seen that the GLEs occur near the maximum solar years and toward to the end of the cycle. Large GLEs were not necessary associated with high sunspot numbers. We found no consistent changes in R_z related to the large GLEs. In addition, the interval time between the beginning of cycle 22 and the first GLE observed is the longest ever. It was 32 months for cycle 22 (Oct. 86-Jul. 89), 13 months for cycle 21 (Jul. 76-Sep. 77), 19 months for cycle 20 (Nov. 64-Jul. 66), and 20 months for cycle # 19 (May 54- Feb. 56).

2.3. Cosmic ray intensities

The variations of CRs near the Earth are an integral results of numerous solar and heliospheric factors. So, it is not easy to confirm that any parameter alone can determining the behavior of cosmic ray modulations in the heliosphere (El-Borie, 2001). The considered cycle started in Oct. 1986 and the maximum cosmic ray intensity was recorded in Feb.-Mar. 1987. Neither the GLEs were observed (from Feb. 1984 to July 1989) nor great Forbush decreases at the beginning of the cycle. So, the CR distribution was quieter at the starting of cycle 22 than in other cycles.

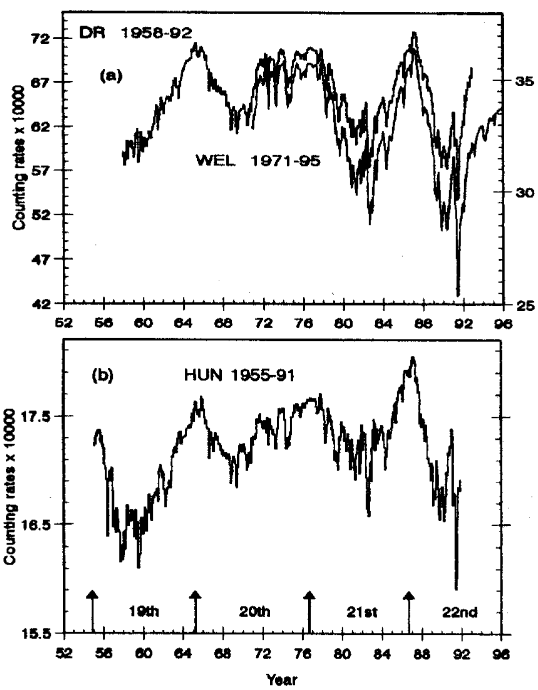

Fig. 3. In upper panel, we plotted the monthly mean counting rates detected at Deep River (1958-92) and Mt. Wellington (1971-95). In bottom panel we plotted the monthly rates at Huancayo (1955-91). The scale of counts detected at Mt Wellington is in the left hand side. Arrows illustrate the start of each solar cycle from 19th to 22nd.

Figure 3 (panels a and b) shows the monthly mean of the counting rates detected at Deep River (DR), Mt. Wellington (WEL), and Huancayo (HUN) throughout the 1955-95 period. The median galactic cosmic ray rigidity for these detectors ranges from 16 GV to 33 GV. Note that, the scale of the left side of plot 3a corresponds the counting rates measured at Mt. Wellington. Arrows indicate the periods of minima solar activity. The string extends four cycles (19, 20, 21, and 22). As seen from Fig. 3, the CRI maximum of cycle 22 was much higher than the beginning of the solar cycle 21 but it close to the starting of the cycle 20th. We notice different levels at the 1985-87 solar minimum. This is probably due to that the lower energy particles recover more slowly than particle of high energy. It didn't reach the maximum intensity before the new cycle sets it. On the other hand, within the energy range of neutron monitors sensitivity, our results indicate that there is no a remarkable change in the CR behaviors even the modulation changed with the solar cycle phase. This gave us a well opportunity to examine the possible differences in CR modulation between the odd and even cycles.

From May 1987, the CRI started to decrease more rapidly than it did in all previous cycles. The rate of decrease was a rigidity dependent (21 % for DR and 8 % for HUN). The same behavior (or the shape) of decrease was observed in cycle # 19 (from Aug.-Sep. 1955 to Nov. 1957) with a less rates of decrease. During the 1989-91 period the CR intensities were very distributed. Obridko et al. (1992) reported that, five major Forbush decreases (Fds) of magnitudes larger than 10 %, about 30 Fds of magnitude > 5 % were recorded during the distributed period.

The CRI began to drop again in mid-1990 and reached to the smallest counting rate in June 1991. This minimum count was never recorded before for the whole history of ground-based observations. In contrast, nearly the same behavior of decrease was observed in the previous cycle from # 19 to # 22 with different degrees in the rate of decrease. For a comparison, in HUN the rate of decrease was 12 % in cycle # 22, 5 % in cycle # 21, 1.2 % in cycle # 20, and 3 % in cycle # 19. In July 1991, the CRI started to a new significant increase. So, we can say that the net rate of cosmic ray modulation in cycle # 22 exceeded anything seen before. This implies that the perturbation of the heliosphere was stronger and much widely spread during cycle 22 than during other cycles. The most striking events in solar cycle 22 are that, throughout the period from Mar. 1956 to 1995 (~ 40 years) we observed the largest GLE in Sep. 29, 1989, the lowest cosmic ray intensities in June 1991 and the shorter time in reversal of the polarity of the interplanetary magnetic field (~ 6 months). Also, the 22 cosmic ray modulation cycle had relatively short and sharp minimum. The high solar activity of cycle 22 was not responsible alone for the unusual behaviors found.

It is well known that the records of CRI follow the inverse time profile of SA. From the two Figs 1 and 3, we note a time lag between the SA and CRI series. It varies by the cycle and its solar activity phases. The time lag was longer for cycle 21 than those for even cycles 20 and 22. The observed delay is more pronounced at high galactic cosmic ray rigidity (HUN monitor in our case). It is clearly seen that the CRIs of cycle 22 is quite different in shape and magnitude than observed before. This is a further evidence how much the reversal of the global magnetic field polarity in 1979-80 epoch played an essential role in the CR modulation observed in the heliosphere.

3. Summary and conclusions

Previously, we studied the long-term of CR modulations and its association with solar and geomagnetic activity (e.g., El-Borie et al., 1997; 1998; El-Borie, 1998; 2001). This work discusses the solar cycle 22nd, which it is extremely magnificence. We summarize the most interesting features of the solar cycle 22 as the following:

1- An unprecedented number of GLEs in the cycle (15 events), in comparison with previous cycles, solar cycle 19th (11 events), 20th (10 events), and 21st (9 events). Major events occurred during the maximum SA period from July 1989 to Jun 1991. In previous cycles, large events were observed during the descending or ascending phases of the cycle.

2- Six of fifteen events in the solar cycle 22 occurred at high latitudes larger than 30° and four events were generated by impulsive flares (Shea et al., 1995).

3- The largest solar proton event, on 29 Sep. 1989, since 23 Feb. 1956 happened during the considered cycle with nearly two maxima according to the particle rigidities.

4- The 22nd solar cycle is reminiscent of consecutive large events, three in Oct. 1989 (7 were recorded in 1989) and four in May 1990. This effect was detected before in Nov. 1960 (four events). The occurrence a GLE as observed by a cosmic ray neutron monitor was interpreted as evidence of high energy of protons.

5- The event of 24 May 1990 was detected prior to the arrival of the relativistic solar particles and it was extremely anisotropic (Shea et al., 1995). This event was the largest of all neutron enhancements observed before.

6- Some of GLEs happened in cycle 22 had longer duration time and never seen before.

7- The time separation between the start of cycle 22 and the first GLE observed was longer ever (Oct. 86 to Jul. 89).

8- A higher activity in the southern than in northern hemisphere, which was a continuation of the process that started in Nov. 1980 (Obridko et al., 1992). In addition, an unprecedented number of large flaring sunspot groups at latitudes larger than 25 in both hemispheres.

9- Although the solar activity cycles 21 and 22 nearly have the same pattern, the cosmic ray modulation of SAC 22 is quite different in shape and magnitude than observed before, depicting the different modulation for odd and even SACs, and implying an important role of the 1979-80 epoch reversal of the solar polar magnetic field polarity.

10- Three close peaks in *Kp* were observed in the solar cycle 22nd (occurred in Mar. 1989, Jun. 1991, and Feb.-Mar. 1994). In contrast, two peaks with considerable separation (4-5 years) were observed in cycles 20 and 21.

11- The net of cosmic ray modulation of cycle 22 exceeded anything seen before. At the beginning of the considered cycle the cosmic ray distribution was quite small and quieter than in other cycles.

12- The minimum CR counted in June 1991 was never recorded before for the whole history of ground-based observations. Also, a shorter time is observed in reversal of the polarities of the interplanetary magnetic field (6 months). This implies that the perturbation of the heliosphere was stronger and much widely spread during cycle 22 than during other cycles.

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