Proceedings of ICRC 2001: 3843 © Copernicus Gesellschaft 2001

ICRC 2001

Step-like variations of cosmic rays and their relation to an inclination of the heliospheric current sheet

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Abstract. The large and fast step-like variations in the GCR intensity are examined during both the descending and recovery phases of the 20–23 solar cycles. The cosmic ray intensity data sets obtained in the stratospheric measurements in Murmansk, Mirny (Antarctica) and Moscow are used. At present the global merged interaction regions (GMIRs) are considered as a natural explanation of step-like intensity decreases. But the GMIRs are not suitable to explain the rapid intensity recovery that was as fast as the step-like decreases, for example in 1962, 1971, and 1991. According to the ULYSSES measurements, the IMF was much more disturbed within the sector zones. It means that the diffusion coefficient is smaller within the sector zone (just as inside the GMIR) than one beyond the sector zones. The changes of the heliospheric current sheet inclination cause the changes in the angular sizes of sector zones and due to that the fast decreases or increases of the GCR intensity. It is also shown that the intensity changes immediately after the step-decreases depend upon the IMF polarity. The cosmic ray intensity after the step-decrease tends to recover at $A>0$ and continues to decrease slowly at $A<0$.

1 Introduction

In the very beginning of regular cosmic ray (CR) measurements it was established that the CR intensity did not change continuously during a solar cycle. Analyzing the Mount Washington neutron monitor data at the descending phase of the solar cycle (1955–1959) Lockwood (1960) noticed that the intensity change occurred in a few step-like decreases after which the intensity tended to recover. Using the data on CR fluxes in the atmosphere during the recovery phase (1960–1964) T.N. and A.N. Charakhchyans (1966) noted that the intensity rise had also occurred in a few steps and that the solar activity (Wolf's number R_Z) had decreased in the same manner. Burlaga et al. (1991) associated step-like CR variations with formation of extended (to 10 AU in width) long-lived shells with the enhanced strength and disturbance of magnetic field – the GMIRs. On the base of the steady state spherically symmetric transport equation Fujii and McDonald (1995) have shown that the formation of the GMIR at the distance of ~25 AU from the Sun within of which the diffusion coefficient is smaller by a factor of 1.5 in comparison with that outside of the shell resulted in the fast CR intensity decrease consistent with the CR observations at 1 AU and in the distant heliosphere. McDonald et al. (1993) have argued that CR intensity changes during the 22-year cycle could be described in the model including drifts and step decreases induced by GMIRs formation.

The CR intensity variations at the descending phase of a solar cycle were considered by McDonald et al. (1993), Fujii and McDonald (1995). Fast CR intensity increases at the recovery phase can be associated with the decrease of the heliospheric current sheet (HCS) inclination. The inclination of the HCS α determines the angular size of a sector zone – the part of the heliosphere where there are the magnetic fields B of the opposite polarities. Within the boundaries of the sector zone the IMF B is more disturbed and the diffusion coefficient k is smaller than that outside of the sector zone. In that aspect the sector zone differs from the GMIR only by its shape. The increase of the HCS tilt α could cause the CR intensity decrease due to the depressed diffusion in the same way as it was shown by Fujii and McDonald (1995) for GMIRs. The fast reduction of the sector zone angular size due to decrease of the HCS inclination α could cause the fast intensity increase.

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2 Experimental data

In analysis we have used the data obtained at the stratospheric stations Murmansk (R_c =0.6 GV), Moscow (R_c =2.4 GV) and Mirny, Antarctica (R_c =0.03 GV) in the years 1957–1999. We have also used the Wilcox Solar Observatory data on the inclination of the HCS taken from the http://quake.stanford.edu/~wso/tilts.html. Data on the IMF and the solar wind velocity were obtained from the http://solarsystem.estec.esa.nl/ulysses/. The monthly averaged count rates at the atmospheric depth interval x =30–60 g/cm^2, included the Pfotzer's maximum, are shown in Fig. 1 for Murmansk station. Two peaks in early sixties are due to nuclear tests in the atmosphere. The fast CR intensity decreases were observed after all four solar activity minima. The similar fast intensity increases took place in the years 1971–1972 and 1991–1992, and in several more short periods in 1960–1965 and 1982–1987. The step increases in 1960–1965 and their correlations with R_Z were considered by Charakhchyan and Charakhchyan (1966).

The CR intensity changes immediately after the steps show the 22-year periodicity. After the 1965 and 1987 solar activity minima the count rates after the step decreases continued to drop only more slowly or formed the plateau for a few months. After the 1976 and 1996 solar minima the count rates after the decreases tended to recover until the next step decrease started. The 22-year periodicity is observed during the recovery phases too. In the years 1971–1972 and 1991–1992 the smooth rises of the CR intensity were observed, while the count rate curve in 1980–1987 had the deep rifts. One can explain qualitatively the observed features of the CR intensity changes within the scope of Fujii and McDonald (1995) suggestions about the GMIRs importance for the long-term modulation. The diffusion flux of particles becomes weaken for a long while after the GMIR formation and that causes the CR intensity step decrease. An arisen barrier effectively prevents the GCR penetrations both into the inner heliosphere and out of it. Now suppose that the drift flux of particles over the GMIR is also depressed. When the polarity of the solar magnetic field is away in the northern hemisphere (N^+S^- or $A > 0$) the drift particle flux from the high heliospheric latitudes inward to the ecliptic plane tries to recover the CR intensity after the step decrease. In the case of N^-S^+ ($A < 0$) field polarity the drift particle flux is out from the ecliptic and the CR intensity after the step decrease continues to decrease.

In Fig. 1 the HCS tilt α is also presented. Similarity in the shapes of the count rate and tilt inclination curves is impressive and not accidental. In the eighties the GCR recovery was delayed as well as the HCS tilt α decrease. The fast (step) CR intensity increase in 1991–1992 was in agreement with the fast HCS tilt decrease.

3 Correlation between the CR count rates and the HCS inclination

In the drift models with the wavy HCS the CR intensity is inversely proportional to the HCS tilt α (Jokipii and Thomas, 1981). The tilt α is not important by itself but because it determines the length of the particles path along the wavy current sheet and the more long is the path the less is the CR intensity deep in the heliosphere.

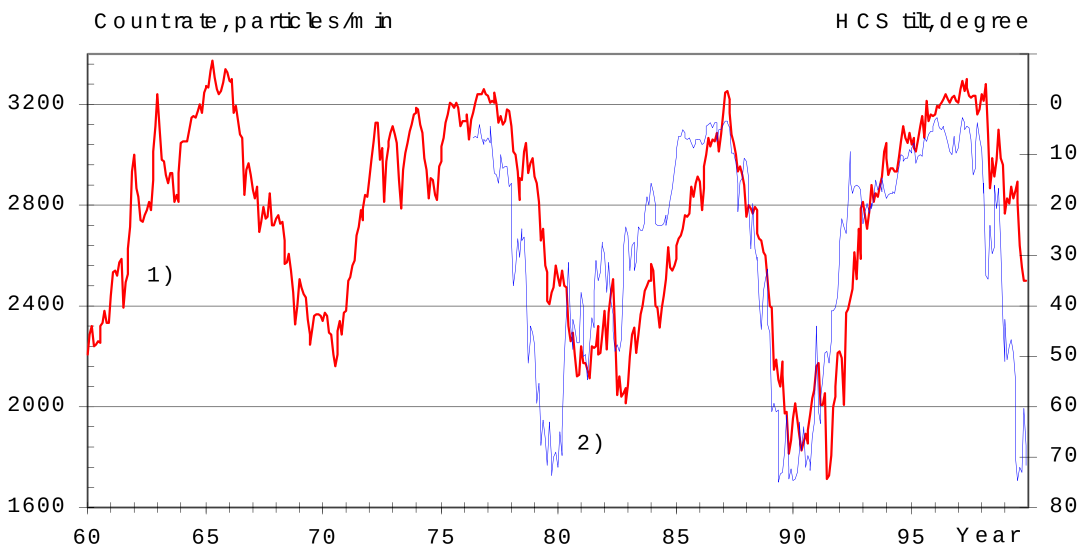

Fig. 1. Monthly averaged count rate at the stratospheric station Murmansk in the interval of atmospheric depths x =30–60 g/cm^2 (1 – heavy line) and the heliospheric current sheet tilt (2 – light line) versus time.

Relationship between the HCS tilt and the CR intensity is strong in the case of $A<0$ when the GCRs propagate inward along the HCS. In the case of $A>0$ the drift fluxes of particles come to the observer at 1 AU from the heliospheric poles and they do not have to depend on the length of the wavy current sheet along of which they will propagate in the future. As it is clear from Fig. 2 in the case of $A>0$ there exists the relation between the HCS tilt and the CR intensity as well.

During the descending phases of solar cycles (Fig. 2a) there exist the linear relations between the CR intensities and the HCS tilts. During the recovery phases these relations are nonlinear. In both cases of the recovery (Fig. 2b) one can select time periods when the CR intensity rises and the tilt α does not change. In the years 1991–1996 ($A>0$) such period was since 1992.5 to 1994.5. The relation between the CR intensity and the HCS tilt was not weak but complex in 1991–1996.

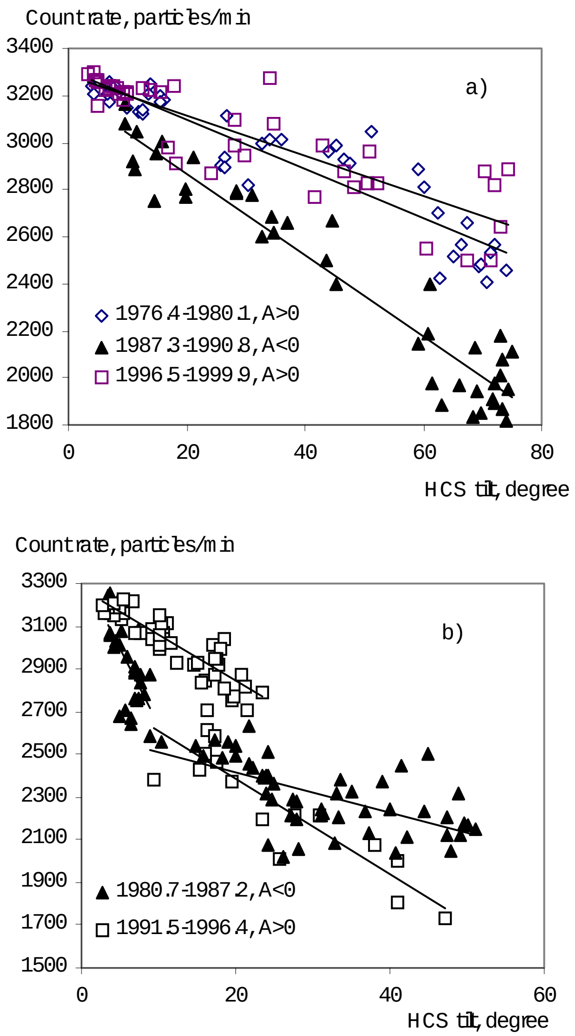

Fig. 2. The correlation between the CR intensity and the HCS tilt: a) during the descending phases of the solar cycles; b) during the recovery phases. The straight lines were calculated with least square method.

We have estimated the IMF $B_1(t)$ and its fluctuations $(\delta B)^2$ in the sector zone and outside of it using the hourly ULYSSES data on the magnetic field $B(R,t,\theta)$ and solar wind velocity $V(R,t,\theta)$ in 1995. Firstly, the magnetic field $B_1(t)$ at 1 AU was calculated according to Burlaga et al. (1998). Then the δB value was obtained as $\delta B = B_1(t) - <B_1(t)>$, where $<B_1(t)>$ is the magnetic field averaged over 10 day periods to eliminate time trends. The $(\delta B)^2$ values are shown in Fig. 3. The solar wind velocity $V(R,t,\theta)$ is also shown in Fig. 3 to determine the time when ULYSSES had crossed the sector zone. Within the sector zone the fluctuations $(\delta B)^2$ were larger than outside of it. The $(\delta B)^2$ values were obtained from the low time resolution data on magnetic fields. Nevertheless the differences in the $(\delta B)^2$ values in the sector zone and outside of it enable us to consider the sector zones as regions with more turbulent magnetic fields and smaller diffusion coefficients.

The average magnetic field $<B_1(t)>$ was weaker in the sector zone.

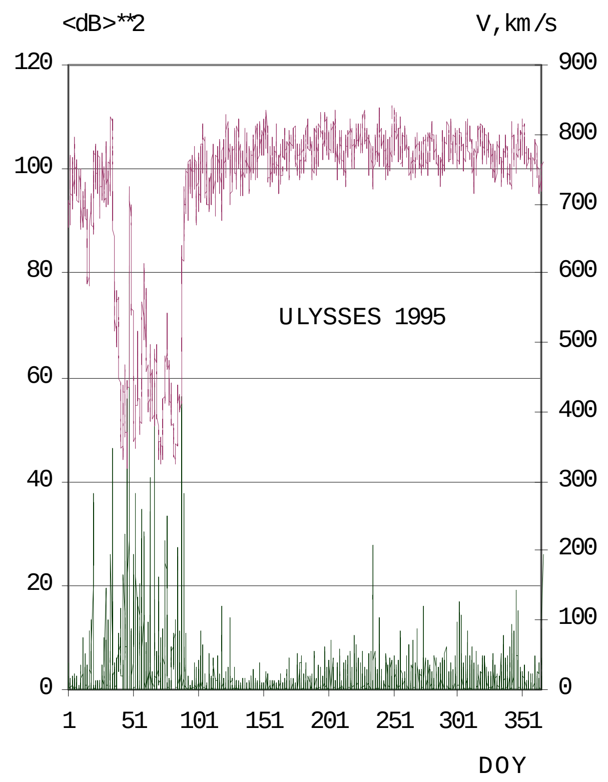

Fig. 3. The magnetic field fluctuations $(\delta B)^2$ and the solar wind velocity $V(R,t,\theta)$ versus time in 1995 when ULYSSES have crossed the sector zone.

4 Conclusion

During the 11-year solar cycle not only the step CR intensity decreases are observed but the fast intensity increases as well. The GMIRs formation explains successfully the step decreases. Fast intensity increases during the recovery phase of the cycle could be involved by fast HCS tilt α decreases. The decrease of the tilt α causes the decrease of the angular size of sector zone within of which the magnetic field is more disturbed and the diffusion coefficient is smaller.

Acknowledgements. We thank our colleagues participating in the LPI stratospheric experiment. We thank the ULYSSES scientific groups for providing the magnetic field and solar wind velocity data taken from http://solarsystem.estec.esa.nl/ulysses/. We are grateful to Wilcox Solar Observatory group for providing the HCS inclination data taken from http://quake.stanford.edu/˜wso/tilts.html. The Russian Foundation for Basic Research supported this work, grants no. 01–02–31005 and no. 01–02–16131.

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