Solar modulation during unusual minimum of solar cycle 23: Comparison with past three solar minima

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Abstract: We study the modulation of cosmic rays during the solar minimum, including declining phase, of solar cycle 23 and compare the results of this unusual period with the results obtained during the similar phases of previous solar cycles 20, 21 and 22. These periods consist of two $A < 0$ and two $A > 0$ polarity epochs of the heliospheric magnetic field. In addition to current sheet tilt, we utilize simultaneous solar and interplanetary plasma/field data. We study the relation between simultaneous variations in cosmic ray intensity and solar/interplanetary parameters during minimum, including declining phase of cycle 23. We compare these relations with those obtained for three previous solar cycles minima and declining phases. We observe certain peculiar features in cosmic ray modulation during this deep minimum of solar cycle 23. We discuss these results and some of their implications.

Keywords: Cosmic ray modulation, solar minimum, solar wind, heliospheric current sheet

1 Introduction

Cosmic ray particles in solar wind plasma flow and magnetic field of the heliosphere are subjected to four distinct transport effects; convection, diffusion, adiabatic cooling and drifts. The diffusion and convection components of cosmic ray transport equation are independent of the solar polarity and will only vary with the solar activity cycle. Conversely, the drift components will have opposite effect in each activity cycle following the field reversal around each solar maximum. Cosmic rays would essentially enter the heliosphere along the helio-equator and exit via the poles in the $A < 0$ polarity state. In the $A > 0$ polarity state the flow would be reversal, with particles entering over the poles and existing along the equator [1-3]

The recent solar minimum of cycle 23 has been unusually long and deep. In comparison with the previous three minima, this solar minimum has smallest sunspot number, the lowest solar wind speed, and the weakest solar and interplanetary magnetic field. However, in contrast to previous minimum, there are more stream interaction regions and more shocks and CME. But the SIRs, ICMEs and shocks during this minimum are generally weaker than during the previous minimum [4]. However, the heliospheric current sheet (HCS) during this minimum was less flat (more warped) than previous two minima. All these peculiar solar and heliospheric conditions make this recent minimum an interesting period to study, in particular, from the cosmic ray modulation point of view.

Cosmic ray modulation during recent unusual solar minimum of cycle 23 was studied using cosmic ray neutron monitor data and by utilizing both the anomalous and galactic cosmic ray data. However, the physical processes suggested by different authors, responsible for record intensity observed during this minimum, are in some cases quite different [see, 5-10]. For example, record GCR intensities observed during cycle 23 solar minimum, where explained by considering, during this period, only higher diffusion coefficient [5]; larger diffusion coefficient and the structure of the heliosphere [10]; increased GCR parallel mean free path and drift velocities [9]; and without any significant role of drifts [7]. Thus, further study is needed to understand the physical processes responsible for the record GCR intensity during recent solar minimum.

2 Results and Discussion

Fig. 1(a) shows the 27-day solar rotation average sunspot numbers for four solar cycles 20, 21, 22 and 23. The shaded portions highlight decreasing and minimum phases of solar cycles. Simultaneous variations in cosmic ray intensity are also shown in Fig. 1 (b). It is clear that the cosmic ray intensity reached the highest level during the latest minimum of cycle 23.

A comparison of sunspot numbers (SSN) during declining and minimum phases of four solar cycles 20, 21, 22 and 23 is shown in Fig. 2 (a). Time zero in this figure corresponds to the end of minimum of a solar cycle, after which the solar activity starts increasing for the next solar cycle.
As compared to previous three cycles, the cycle 23 is the largest and weakest one. Solar wind velocity (V) variations for the same periods are plotted in Fig. 2(b). Although solar wind speed variations do not strictly follow the sunspots variation, the speed is slowest during the latest minimum of cycle 23, in comparison to previous three minima.

When compared during decreasing and minimum phases of four solar cycles (see Fig. 2(c)), the interplanetary magnetic field (IMF) shows a decline trend at least during cycles 21, 22 and 23, some what similar to sunspot number; however such a trend is not clearly apparent in the IMF during cycle 20. Further, the magnetic field (B) is weakest during the cycle 23 minimum. These parameters, and many more, are nicely summarized during the deep minima of solar cycle 23 by Jian et al. [4]. However, in contrast to sunspot number, solar wind velocity and magnetic field, the heliospheric current sheet (HCS) tilt (Λ) is not the smallest during cycle 23, but larger than that during previous two minima of cycle 21 and 22 for which tilt data is available (WSO website). Further, in contrast during minima of cycle 21 and 22, the tilt angle during the deep minimum of cycle 23 changes very fast by about 25° in a span of about 20 solar rotations (see Fig. 2(d)), during a period when sunspots were almost absent.

These differences in solar/heliospheric parameters (sunspot number, solar wind velocity, interplanetary magnetic field strength and tilt of the heliospheric current sheet) during this peculiar minimum is expected to throw some light as regards the cosmic ray modulation models. Thus, we have plotted the neutron monitor data as observed at Oulu station, during the decreasing and minimum solar activity phases of cycles 20, 21, 22 and 23 (Fig. 2(e)). These periods correspond to recovery of cosmic ray modulation cycles. In addition to differences in cosmic ray recovery during odd cycles (21, 23) as compared to even cycles (20, 22), we can see that during the deep minimum of cycle 23, the cosmic ray intensity reached the highest level, never recorded earlier in neutron monitor records (see Figs. 1 and 2(e)).

Figs. 2 (a-e) compare the variability of various solar and interplanetary parameters, and cosmic ray intensity during declining, including minimum phases of solar cycles 20, 21, 22 and 23. However, in order to understand the cosmic ray modulation mechanism, one needs to study the relationship between the variability of cosmic ray intensity with solar and interplanetary parameters (e.g., sunspot number, solar plasma speed, interplanetary field strength, tilt of the heliospheric current sheet) during different polarity states of the heliosphere (A>0 and A<0). For this purpose we have considered the solar rotation average values of various parameters plotted in Fig. 2 (a-e), and studied the cross correlation plots of CRI with different parameters SSN, V, B and Λ during declining and minimum phases of solar cycle 20 (A>0), 21 (A<0), 22 (A>0) and 23 (A<0). The correlations and slopes obtained from a linear fit during (a) declining and (b) minimum phases of these four solar activity cycles are tabulated (see Table-1). Looking at the rate of change of CRI with different parameters (∆I/∆P) and correlation coefficients (R), we conclude that the CRI decreases at a faster rate with increase in IMF and HCS tilt in A<0 epoch. This trend is more clearly evident during minimum phases of solar cycles. Similar trends in CRI decrease rate is also seen with solar wind velocity, although the correlations in this case are poor. Further, there are stronger correlations between CRI and HCS tilt during A<0 epochs. Another observation of special mention (see Table-1) is that correlations of CRI with magnetic field strength, solar wind speed and tilt angle of the HCS are the best during cycle 23 (A<0) compared to all other previous cycles, both during declining and minimum phase of solar cycles.

Since the recent peculiar solar minimum of cycle 23 has been unusually long and deep, we study this minimum in more detail. In Fig. 3, we have plotted the solar rotation averaged parameters (SSN, V, B, Λ and CRI) during this minimum. The duration shaded between two vertical lines by dots indicates the duration of sunspot minimum. During most of this period, sunspots are almost absent and essentially there is little or no variability in solar activity as seen from sunspot numbers. As regards the interplanetary parameters V and B, although they reached a record low level during this period, they are variable in time, particularly the solar plasma speed. For the cosmic ray modulation point of view, it is interesting to note that, although the intensity of solar polar field is very low and almost constant [4], the tilt of HCS is fast changing, a decrease of about 25° during this peculiar minimum itself. Moreover, the tilt angle is not at its minimum as compared to tilt during minima of cycles 21 and 22. However, the cosmic ray intensity reached the record highest level in the whole era of neutron monitor observations.

Figure 1: Solar-rotation averaged sunspot number and cosmic ray intensity for four solar cycles 20, 21, 22 and 23. The highlighted periods between vertical lines are the declining and minimum periods of different solar cycles.
Figure 2: Comparison of different parameters (27 day average) during declining and minimum phases of solar cycles 20, 21, 22 and 23. On the time axis '0' corresponds to the time of last rotation in each solar cycle, after which the solar activity (as seen in sunspots) starts raising, marking the beginning of next cycle.

In Fig. 4, we have plotted the scatter diagram, and best fit linear curve, in order to study the cosmic ray modulation, particularly during recent minimum. We find that, during this particular minimum CRI shows poor correlation with sunspot number (R = -0.24), a better correlation with magnetic field (R = -0.66), still better with solar wind speed (R = -0.80) and it is the best with tilt angle of HCS (R = -0.92) among all the parameters considered.

3 Conclusions

The GCR intensity decreases at a faster rate with increase in all three interplanetary parameters B, V and Λ during A<0 as compared to A>0 epoch. This difference in rates is particularly high during solar minimum conditions (see, Table-1).

As compared to previous solar cycles minimum, the correlations of GCR with parameters B, V and Λ are stronger during the deep minimum of cycle 23.

During the last five rotations of cycle 23 when GCR intensity was at its record highest level, SSN was increasing after a record low number, field B was almost constant at a low value, solar wind velocity decreased to a very low value, and tilt angle decreased in initial two rotations in continuation to preceding trend, but it increased very fast during the next three solar rotations.

High speed streams were more frequently observed during this peculiar minimum [4]. It has been reported [7] that GCR intensity is weakly anti-correlated with the contribution of high speed stream to magnetic field B. GCR intensity is highly (anti) correlated (R = -0.80) with the velocity of solar wind during deep minimum of cycle 23 only; correlations are poor during minimum of previous three solar cycles, 20 (R=-0.37), 21 (R=-0.41) and 22 (R=-0.21) [see Table-1]. Thus, in our view, it is not the diffusion or drifts alone but the solar wind convection is an additional effect responsible for record GCR intensity during unusual minimum of cycle 23.
<table>
<thead>
<tr>
<th>Solar Cycle</th>
<th>Phase</th>
<th>SSN</th>
<th>Magnetic Field</th>
<th>Plasma Speed</th>
<th>Tilt angle</th>
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<tr>
<td></td>
<td></td>
<td>ΔI/ΔP</td>
<td>R</td>
<td>ΔI/ΔP</td>
<td>R</td>
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<td>20</td>
<td>A &gt; 0</td>
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<td>-0.69</td>
<td>-93.4 ± 45.9</td>
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<td></td>
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<td>-0.06</td>
<td>-33.6 ± 9.5</td>
<td>-0.57</td>
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<td>A &lt; 0</td>
<td>Decreasing</td>
<td>-3.08 ± 0.73</td>
<td>-0.58</td>
<td>-119.6 ± 27.9</td>
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<tr>
<td></td>
<td>minimum</td>
<td>-5.4 ± 3.8</td>
<td>-0.27</td>
<td>-120.8 ± 50.4</td>
<td>-0.43</td>
</tr>
<tr>
<td>22</td>
<td>A &gt; 0</td>
<td>Decreasing</td>
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<td>-0.88</td>
<td>-123 ± 13.6</td>
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<tr>
<td></td>
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<td>-69.9 ± 22.9</td>
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<tr>
<td>23</td>
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<td>Decreasing</td>
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<td>-0.82</td>
<td>-230.2 ± 11.5</td>
</tr>
<tr>
<td></td>
<td>minimum</td>
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<td>-0.24</td>
<td>-164.7 ± 36.3</td>
<td>-0.66</td>
</tr>
</tbody>
</table>

Table 1: Rate of cosmic ray intensity decrease with various parameters (ΔI/ΔP) and correlation coefficient (R) during decreasing and minimum phases of solar cycles 20, 21, 22 and 23.

Figure 3: Solar rotation averaged parameters (Sunspot numbers, Interplanetary magnetic field, Solar Plasma velocity, Tilt angle of the heliospheric current sheet and Galactic cosmic ray intensity) during minimum phase of solar cycle 23 (shaded area by dots). Five solar rotation periods after the end of minimum ‘0’ are marked (slanted lines) highlighting the period when the cosmic ray intensity is at highest level.

4 Acknowledgements

We acknowledge the use of plasma/field data available through NASA/NGDC OMNI Web interface. We thank Ilya Usoskin for making available Oulu Neutron monitor data and Todd Hoeksema for the HCS inclination data.

References