Characteristics of the 22-year modulation of cosmic ray intensity*
N K Sharma & R S Yadav
Cosmic Rays & Space Physics Group, Department of Physics, Aligarh Muslim University, Aligarh 202 002
Received 12 April 1993; revised 13 August 1993; accepted 4 October 1993

Using the neutron monitor data for the period 1954-89, several new features in the 22-year modulation cycle as well as in the well known 11-year cycles have been observed. Systematic differences and similarities in the shape of two successive 11-year cycles (viz. even and odd) and alternate 11-year cycles (viz. even-even or odd-odd) are observed, which seem to be related with the 22-year magnetic cycle. These observed features need to be explained on the basis of the drift model, taking into account the effect of the equatorial current sheet.

1 Introduction
Cosmic ray modulation has been known to have various time scales. Though time scales of various modulation effects may differ from each other, the basic process may be common, which is, the interaction between the cosmic ray particles and interplanetary magnetic field. The transport equation for cosmic rays has received considerable attention over the last 26 years, with different terms emphasized in order to account for various physical phenomena. Three physical effects which have traditionally been emphasized are the outward convection of the cosmic rays by the supersonic solar wind, the diffusion of cosmic rays in the ever present irregularities in the solar heliospheric magnetic field and adiabatic energy changes. Recently, a fourth term has been emphasized and re-examined which represents the drift of cosmic rays in the large-scale magnetic field and especially in the vicinity of the current sheet which divides the heliosphere into two hemispheres containing oppositely directed fields, namely, along the Parker spiral toward the sun in the north and away from the sun in the south.

Now the cosmic ray modulation is an experimental fact, but we do not yet understand exactly how and where this modulation occurs. To understand this riddle, we have studied the long-term cosmic ray intensity variations (11-year/22-year) along with the polarity reversal of the solar polar magnetic field. For this purpose it is essential to study the behaviour/nature of the long-term variation of cosmic ray intensity during different solar activity cycles and observe the significant changes from one solar sunspot cycle to another.

The anticorrelation between the sunspot number and cosmic ray intensity was first shown by Forbush and it has been studied extensively at the earth and beyond up to 75-100 AU for more than three decades by various investigators (Fig. 1). The long-term variations in cosmic ray intensity have been studied by various investigators by utilizing different parameters as representatives of solar activity. It has been known that cosmic rays in the heliosphere show dependence on the polarity of the solar magnetic field. Nagashima and Morishita and Sharma and Yadav suggested that the nature of the long-term vari-

*This paper was presented at the National Space Science Symposium held during 11-14 March 1992 at Physical Research Laboratory, Ahmedabad 380 009.
tion of cosmic ray intensity depends upon the polarity of the solar polar magnetic field, in addition to the sunspot and other solar activities. This aspect has been discussed extensively in literature\textsuperscript{21-23}.

This paper reports the results of an analysis intended to observe the various features of 22-year modulation of cosmic rays. The observed features are explained on the basis of drift current sheet model. The present results are obtained from the study of pressure-corrected data of neutron monitors situated at different latitudes on the surface of the earth (Deep-River: cut of rigidity $R_c = 1.02$ GV and latitude $\lambda = 46.10^\circ$N; Alert: cut of rigidity $R_c = 0.00$ GV and $\lambda = 82.50^\circ$N). The stress has been put on the data recorded by Deep-River because it is a well-maintained station.

2 Analysis

To observe the characteristic features of the 22-year modulation of cosmic rays, the pressure corrected yearly average data of Deep-River and Alert neutron monitors have been analyzed for the periods 1954-89 (Deep-River) and 1965-87 (Alert), which include the solar activity cycles 19, 20, 21 and a part of cycle 22. The counting rate has been arbitrarily normalized to 100 for the maximum cosmic ray intensity associated with the year 1965, the year of minimum solar activity.

The magnitude of cosmic ray modulation is calculated for different solar activity cycles and for their decreasing and increasing phases by the following formula.

$$\text{Magnitude of cosmic ray modulation (\%)} = \frac{I_{\text{max}} - I_{\text{min}}}{\left( I_{\text{max}} + I_{\text{min}} \right) / 2} \times 100$$

where $I_{\text{max}}$ and $I_{\text{min}}$ are maximum and minimum cosmic ray intensities respectively.

The results obtained from the present analysis are given in Tables 1 and 2.

3 Results and discussion

To study the 11-year/22-year variation of cosmic ray intensity, we have plotted the annual average of the pressure corrected neutron monitor data during the solar activity cycles 18, 19, 20 and 21 along with the polarity of the solar polar magnetic field (Fig. 2). The purpose of this plot is to identify the differences/similarities in the nature of the cosmic ray intensity variations from one solar sunspot cycle to another, particularly in the average time profile of cosmic ray intensity and the magnitude of variations recorded by two stations plotted in Fig. 2.

Figure 2 indicates that minimum (or maximum) of cosmic ray intensity occurs after every 11 years, but the time profile of the variations of cosmic ray intensity is significantly different from one solar cycle to another. Several features of the individual 11-year solar modulation cycles and 22-year modulation cycle are indicated in the figure. First there is a sharply peaked maximum of cosmic ray intensity in 1987 (cycle 21) in contrast to the flatter maxima noted during 1972-77 (cycle 20) and earlier during 1952-54 (cycle 18) (Ref. 24) after 22 years. Second, the neutron monitor intensity is 1.87% higher at the time of 1987 and 1965 maxima as compared to the flat maxima of 1972-77 period. Figure 2 also indicates humps during the maxima of cycles 18 and 20. These results summarized in Table 1 clearly indicate systematic differences/similarities in the overall shape of successive/alternate 11-year modulation cycles.

<table>
<thead>
<tr>
<th>Period of solar activity minimum</th>
<th>Solar field polarity at solar activity minimum</th>
<th>Polar field changes over</th>
<th>Cosmic ray intensity at solar activity minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952-54 (cycle 18)</td>
<td>N$^+$, S$^-$: qA$&gt;$0</td>
<td>-</td>
<td>Flat maximum intensity</td>
</tr>
<tr>
<td>1965 (cycle 19)</td>
<td>N$^-$, S$^+$: qA$&lt;$0</td>
<td>1957-58, (± to $\mp$)</td>
<td>Peaked maximum intensity</td>
</tr>
<tr>
<td>1972-77 (cycle 20)</td>
<td>N$^+$, S$^-$: qA$&gt;$0</td>
<td>1969-71, (± to $\mp$)</td>
<td>Flat maximum intensity</td>
</tr>
<tr>
<td>1987 (cycle 21)</td>
<td>N$^-$, S$^+$: qA$&lt;$0</td>
<td>1980</td>
<td>Peaked maximum intensity</td>
</tr>
</tbody>
</table>

qA$>$0 Drift notation for outward field of the sun
qA$<$0 Drift notation for inward field of the sun
Table 2 – Observed features of the modulation during solar activity cycles 19, 20 and 21

<table>
<thead>
<tr>
<th>Station</th>
<th>Parameter</th>
<th>Cycle 19</th>
<th>Cycle 20</th>
<th>Cycle 21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Decreasing</td>
<td>Increasing</td>
<td>Decreasing</td>
</tr>
<tr>
<td>Deep-River</td>
<td>Magnitude of cosmic ray modulation</td>
<td>22.11%</td>
<td>17.11%</td>
<td>10.97%</td>
</tr>
<tr>
<td></td>
<td>$R$</td>
<td>179</td>
<td>179</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>$T$</td>
<td>~ 6 to 7 years</td>
<td>~ 2 years</td>
<td>~ 5 years</td>
</tr>
<tr>
<td>Alert</td>
<td>Magnitude of cosmic ray modulation</td>
<td>14.03%</td>
<td>11.78%</td>
<td>14.64%</td>
</tr>
<tr>
<td></td>
<td>$R$</td>
<td>96</td>
<td>96</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>$T$</td>
<td>~ 2 to 3 years</td>
<td>~ 5 to 6 years</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Sunspot number</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Recovery time</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 – Plots of the yearly average of cosmic ray muon intensity for a shielded ion chamber during the period 1944-53 (solar sunspot cycle 18) (○–○), and for Deep-River (DR) neutron monitor during 1954-89 (includes solar sunspot cycles 19, 20 and 21) (×–×) along with the polarity of the solar polar magnetic field. To record the magnitude of variation and average time profile at high latitudes, Alert yearly rate is also plotted for the period 1965-87 (●–●).

The data plotted in Fig. 2 and summarized in Table 2 also reveal that the cosmic ray intensity recovers very slowly (~ 6-7 years) during the odd solar cycles (19 and 21) while its recovery is quite fast (~ 2 years) for the even solar cycle 20. The magnitude of the cosmic ray modulation is large during odd solar cycles (19 and 21) as compared to the even solar cycles. The observed even and odd solar cycles asymmetry and the various features of the modulation are probably related to solar poloidal field reversal and the difference in the solar magnetic field configuration. The polarity of the solar field reverses sign about every 11 years near the time of maximum sunspot activity (or minimum cosmic ray intensity). Thus successive activity minima are characterized by a different solar field polarity, which are visible in cosmic ray modulation cycle (see Table 1).

Production of the specific features of the modulation during odd and even solar activity cycles indicate that a modulation process sensitive to the particle sign is operating in the interplanetary medium, which are the drifts due to gradient and curvature in the interplanetary field as proposed by Jokipii and coworkers (see Kota and Jokipii25 and references therein). To understand fully how cosmic rays move in the heliosphere under the influence of drifts, one needs to recognize the importance of the current sheet which divides the heliosphere into two hemispheres containing oppositely directed magnetic fields. Thus the role played by the drift current sheet model is that the time dependence of the cosmic ray intensity during two halves of the 22-year magnetic cycle must have a very different shape25. This model also predicts a relatively sharp peak during the semi-cycle in which drifts bring positive particles from the equator to the heliosphere poles and a rather broad plateau during the semi-cycle in which the drifts run in the opposite directions. Our observational results presented in Table 1 are in good agreement with the theoretical results of Kota and Jokipii25. According to the drift current sheet...
model, during the solar activity minimum in 1965 (cycle 19) and 1987 (cycle 21), when the north polar magnetic field was inward (±; qA<0), positive particles drifted along the equator from the outer boundary of the heliosphere. At this time the current sheet tilt played an important role in the arrival of cosmic rays in the inner heliosphere and shaping the modulation peak during solar activity minimum in 1965 and 1987. For the periods 1952-54 (cycle 18) and 1972-77 (cycle 20), when the north polar field was outward (±; qA>0), positive particles drifted to the inner heliosphere from the polar region and then drifted outward along the current sheet. Therefore during these periods current sheet tilt is not important in modulating the cosmic ray intensity in the heliosphere21,26.

At present it is possible to understand the slow and fast recoveries during odd and even solar activity cycles in terms of this model. The slow recoveries, which occurred during 1959-65 (cycle 19) and again during 1981-87 (cycle 21), happened just after the change of magnetic field configuration from ± to ± in 1957-58 and 1980 (Table 1). At this time the flow of particles into the inner heliosphere is controlled by the current sheet tilt because galactic protons move down along the outer boundary of the heliosphere to the current sheet and then inward along the neutral sheet to the earth. The situation is different for the fast recovery which occurred during 1972-73 (cycle 20) just after the change of magnetic field polarity from ± to ± during 1969-71. At this time the flow of particles into the inner heliosphere is not controlled by the current sheet tilt because the positive particles drift to the inner heliosphere from the polar regions and then drift outward along the current sheet.

The above discussions describe qualitatively how the drift current sheet model and the 22-year solar magnetic cycle can explain some of the most significant features of the 22-year cosmic ray modulation as seen by neutron monitors.

4 Conclusions

The conclusions which emerge from the present study are as follows:

1. Systematic differences in the overall shape of successive 11-year modulation cycles (odd and even) and similarities in the shape of alternate 11-year modulation cycles (even-even or odd-odd) are observed. These indicate a 22-year periodicity in cosmic ray intensity variations, which seem to be related to the 22-year solar magnetic cycle.

2. Observed differences in the two solar activity cycles (odd and even) are attributable to the rapid drift of cosmic rays along the current sheet.

3. The changing inclination of current sheet and the reversal in polarity of the solar polar magnetic field play an important role in explaining the various observed features of modulation during different solar activity cycles (odd and even).

Acknowledgements

The authors wish to thank Prof. B N Khanna for providing necessary facilities for conducting this work in the department. They are also thankful to various investigators for supplying the cosmic ray intensity data. One of the authors (NKS) is grateful to Prof. M Z R Khan, Co-ordinator DSA-UGC research programme for the financial support during the course of this study. Finally, the authors are thankful to the referees for their useful suggestions for the improvement of the paper.

References


