Understanding Cosmic Ray Solar Modulation for cycle 20

H.S. Ahluwalia
Dept of Physics and Astronomy, Univ. of New Mexico, Albuquerque, NM 87131-1156, USA

Abstract

It is well known that time variations of galactic cosmic rays for cycle 20 (1964–1976) present a challenge to our understanding of the heliospheric dynamics and the physical processes involved in causing the observed modulation. Several interesting questions have been raised. We attempt to provide some plausible answers based on our analysis of cosmic ray data obtained with the detectors on ground, as well as on board the balloons and satellites; they respond to a wide range of cosmic ray rigidity spectrum.

1. Introduction

The dominant role played by the solar wind in causing modulation of galactic cosmic rays (GCR) is now quite apparent [1, 3]. This understanding has come very slowly. When solar wind parameters (bulk speed V and IMF intensity B) became available in the sixties, the folks studying modulations were shocked to find that there was no correlation between the time variations of GCR intensity recorded by the neutron monitor (NM) at Deep River (DR) and V or the measured power spectral levels of IMF at 1 a.u. for 1963 to 1969; Jokipii [10] had predicted that in the rigidity range 1 to 10 GV the diffusion coefficient (K) is directly proportional to the total power spectral density in IMF fluctuations, the median rigidity of response (Rm) to GCR spectrum is 16 GV for the DR/NM. The stark choices facing the researchers at that time is well described by Mathews et al [13] and Hedgecock et al [8]. Regrettably, the understanding of modulation has not advanced much since then [4], although several new ideas have been proposed.

Stoker and Carmichael [15] drew attention to the existence of the steplike long-lasting changes between successive segments of the counting rates of DR/NM and Kula NM during 1967 and 1969 (ascending phase of solar cycle 20); three distinct steps were identified (see their Fig. 4), step 3 being the largest. They interpreted the steps as a proof that GCR modulation function in the heliosphere is not independent of time. Lockwood et al [12] studied the regression between the counting rates of Pioneer 8 telescope and Mt. Washington NM for 1968–1971. They concluded that as a result of the June 8 Forbush decrease the rigidity

pp. 4035–4040

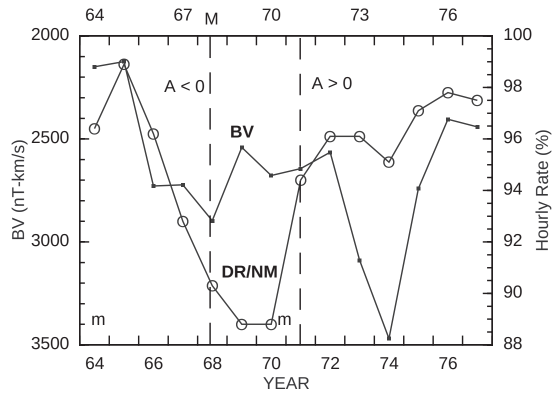

Fig. 1.

dependence of the 11-year modulation was drastically altered; this epoch coincides with step 3 observed by Stoker and Carmichael. Lockwood et al concluded that a change in the functional form of the diffusion coefficient (K) is needed to explain their result. Iucci et al [9] ascribed Lockwood et al's finding to a sharp decrease of solar activity at the middle heliolatitudes ($\sim 30°$), given by the coronal green line (5303°) intensity; they noted that the frequency of Forbush decreases is sharply reduced after June 1969.

Ahluwalia [1] emphasizes that convective removal of GCR from the inner heliosphere (by the solar wind) is the main cause of the observed modulations over three solar cycles (20, 21, 22). He points to the dominant role of the solar wind electric field ($\mathbf{E} = \mathbf{B} \times \mathbf{V}$) in promoting this process via $\mathbf{E} \times \mathbf{B}$ drift. Here we explore further the merit of his suggestion with respect to solar cycle 20 data for a wide range (1 to 70 GV) of GCR rigidities.

2. Observed GCR modulation

Figure 1 shows a plot of the annual mean hourly DR/NM rate for 1964–1977, normalized to 100% in May 1965. Also plotted are the annual mean hourly values of BV data obtained from the OMNItape (inverted scale on theleft). The cycle minima (m), maxima (M) and the epoch of the solar polar field reversal (vertical dashed lines) are shown too. The correspondence between the two time sets is quite good, except that BV data points for 1969 and 1970 (at the height of GCR modulation) are embarrassingly out of place. Except for them, there is no phase difference between the corresponding features of the two series. For example, there is a phase difference of one year with respect to cycle minimum (m) and maximum (M); they do line up pretty well in 1976 but so does BV. Also note that in an approach to minimum (1973–1975) a larger change in BV yields a smaller inverse change of GCR intensity. This period corresponds to the epoch of

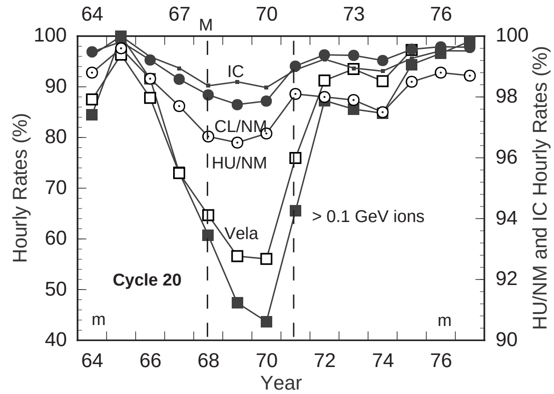

Fig. 2.

high speed solar wind streams (HSSWS) and A > 0. This indicates that either E in HSSWS is not as effective for the convective removal of GCR at 1 a.u. or else its efficiency is impaired by the drift of GCR protons from the higher heliolatitudes towards the heliospheric current sheet as proposed by Kota and Jokipii [11].

3. Rigidity dependence of modulation

Figure 2 shows a plot of the annual mean hourly rates of worldwide network of detectors with different median rigidities of response (Rm) to GCR spectrum. They include, NMs at Climax (CL), and Huancayo (HU) with values of Rm equal to 11 GV and 33 GV respectively, Forbush ion chamber (IC) at Cheltenham/Fredericksberg (Rm = 67 GV), the ions (> 0.1 GeV) at high latitude balloon altitudes (Rm = 2.3 GV). Also plotted are the neutron data obtained aboard VELA satellites by John R. Asbridge; neutrons are produced in the satellite skin by GCR protons with an energy > 25 MeV (Rm $\sim$ 4 GV). Neutrons rates are normalized to 100% in May 1965 and those of IC and ions to 100% for the year 1965. The vertical dashed lines mark the epoch of the solar polar field reversal (SPFR). The general behavior is similar for all detectors; maximum modulation is nearly complete at rigidities above 3 GV in 1969 but for ions a significant additional decrease occurs between 1969 and 1970.

Figure 3 shows a plot of the amplitude of GCR modulation for 1965–1969, as a function of Rm, on a log-log graph. The fitted line represents a power law dependence of modulation on rigidity R. The data also indicate that modulation depends inversely on B [1, 5]. These dependences must define the form of the effective diffusion coefficient in the heliosphere.

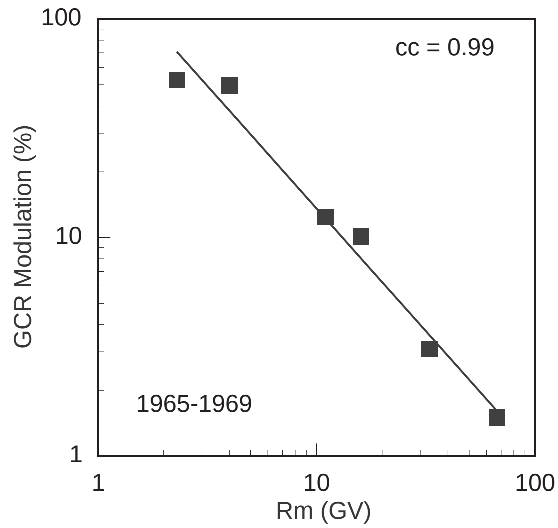

Fig. 3.

4. Steplike changes in modulation

Figure 4 shows a plot of 27-day averages of CL/NM and available BV data for the Bartel rotation numbers (BRNs) 1800 (3 Feb 1965) to 1906 (5 Dec 1972); the scale for BV is inverted. A three point moving average is shown for BV data to reduce noise. Vertical dashed lines demarcate the SPFR epoch. The Stoker-Carmichael steps are indicated by upward pointing arrows labeled 1, 2, 3 respectively. They coincide with steplike changes in BV data; step 3 corresponds to the largest discontinuous change in BV. Thus we may have identified the physical signature of the observed steps in GCR modulation, or at least the data are strongly suggestive of a relationship between the two time series. This may mean that the causal connection is influenced by the dynamics of the souce regions of B and V on the sun rather than by something happening in the outer heliosphere as proposed by Stoker and Moraal [16].

5. Discussion

We have related several observed features of GCR modulation for cycle 20 to the corresponding time variations of the parameter BV, indicating that convection caused by the solar wind electric field (via electric drift) is the primary driver of the observed modulation in the heliosphere. Several important questions are still unanswered. If E is weakened during SPFR epoch what drives the modulation to maximum amplitude in 1968–1970? It is plausible that significant contributions are made by the propagating heliocentric barriers formed in the outer heliosphere by the fast CMEs [6] as well as the shielding of the heliosphere

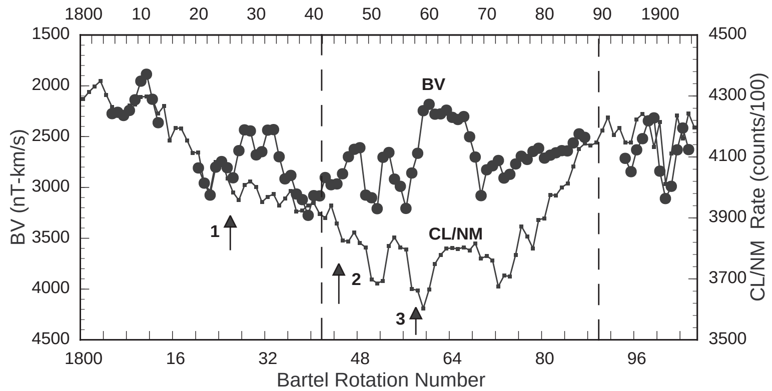

Fig. 4.

by the magnetic field at the termination shock [7]; these contributions need to be sorted out. Also, we need to understand the role of the garden hose angle (between **B** and **V**) for the observed correlation; for example, if **B** is radial the electric field is zero even though BV may be large. A spherical symmetry solution of Parker [14] equation is often invoked to understand GCR modulation in terms of the modulation parameter ϕ introduced by Urch and Gleason [17] but it does not depend on R and BV explicitly. We urge the modelers to consider choosing a proper functional form of the effective diffusion coefficient (K) to incorporate an explicit dependence on R and BV. Clearly, cycle 20 modulation has surprised us with unexpected puzzling features but we do not agree that it is anomalous as suggested by Wibberenz et al [18].

6. Acknowledgements

Supported by NSF grant ATM-9904989. I thank all PIs for the data used here, to Michael Fikani for technical support, to George Skadron for helpful comments.

7. References

1. Ahluwalia, H. S., 2000a, Geophys. Res. Lett., 27, 1603
2. Ahluwalia, H. S., 2000b, J. Geophys. Res., 105, 27481
3. Ahluwalia, H. S., 2003, Geophys. Res. Lett., 30(3), 1133, doi: 10.1029/2002GL016017
4. Bieber, J. W., et al, 1993, J. Geophys. Res., 98, 3585
5. Burlaga, L. F., et al. 1985, J. Geophys. Res., 90, 12027
6. Burlaga, L. F., F. B. McDonald, N. F. Ness, 1993, J. Geophys. Res., 98, 1
7. Exarhos, G., X. Moussas, 1999, Solar Phys., 187, 157

8. Hedgecock, P. C., J. J. Quenby, S. Webb, 1972, Nature, 240, 173
9. Iuuci, N., M. Parisi, G. Villoresi, 1974, J. Geophys. Res., 79, 659
10. Jokipii, J. R., 1967, Astrophys. J., 149, 405
11. Kota, J., J. R. Jokipii, 1983, Astrophys. J., 265, 573
12. Lockwood, J. A., J. A. Lezniak, W. R. Webber, 1972, J. Geophys. Res., 77, 4839
13. Mathews, T., J. Quenby, J. Sears, 1971, Nature, 229, 246
14. Parker, E. N., 1965, Planet. Space Sci., 13, 9
15. Stoker, P. H., H. Carmichael, 1971, Astrophys. J., 169, 357
16. Stoker, P. H., H. Moraal, 1986, J. Geophys. Res., 91, 1355
17. Urch, I. H., L. J. Gleeson, 1972, Astrophys. Space Sci., 17, 426
18. Wibberenz, G., I. G. Richardson, H. V. Cane, 2002, J. Geophys. Res., 107, 1353