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Response of IMP 8 penetrating proton channel to galactic cosmic ray modulation

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Abstract: At the 29th ICRC, Pune, India, we presented a new methodology for investigating the rigidity dependence of galactic cosmic ray (GCR) modulation. It uses the median rigidity of response (Rm) of cosmic ray detectors deployed at global sites; we define Rm as the GCR rigidity below which lies 50% of the detector counting rate. We pointed out that Rm values of neutron monitors of the global network reported in the literature are underestimated. Since then we have discovered that mean energy of response for IMP-8 penetrating proton channel reported in the literature is also underestimated. We present our computations of the mean energies of response for the IMP-8 Cosmic Ray Nuclear Composition instrument to GCR protons for 1973 - 1998, encompassing two solar cycles (21 and 22). We find that the mean energy of response changes by a factor of two over this period whereas the corresponding change for Climax neutron monitor is only 21%.

Introduction

The Climax neutron monitor (CL/NM) was established in 1950. It is the oldest continuously operating neutron monitor in the world. It is located at an altitude of 11,400 ft (3400 m). It is an International Geophysical Year (IGY) design instrument, with two sections of six tubes each. Great care has been taken to maintain the stability of atmospheric pressure measurements. The pressure-corrected hourly count rates have been used in numerous galactic cosmic ray modulation studies. Although its geomagnetic vertical cut-off rigidity is 3 GV, CL/NM is 16 % more sensitive to the 11-year intensity variations than the sea level neutron monitor at Deep River (DR/NM) with an (atmospheric) cut-off rigidity of 1.1 GV; see Fig. 2 in Ahluwalia and Wilson [1], the reader may also refer to Pyle [2] for a detailed discussion of CL/NM sensitivity related issues and comparison with other NMs. In the past, we have used 11 GV as the median rigidity of response for CL/NM [3, 4, 1]; it corresponds to a mean energy of about 10 GeV.

IMP-8 (Explorer 50) satellite was launched into earth's orbit on 26 October 1973 to measure the magnetic fields, plasmas, and energetic charged particles of near earth solar wind, among other things. It operated till October 2006 in its near circular, 35 earth radii, 12-day orbit (private communication from Bruce McKibben). Therefore, any perturbations due to atmosphere and geomagnetic field are negligible. The spacecraft carries an apparatus designed by the University of Chicago called the Cosmic Ray Nuclear Composition (CRNC) instrument [5]. In this paper we are concerned only with the penetrating proton (> 100 MeV) channel on IMP 8. The median rigidity of response for the proton channel is reported at 2.3 GV [6], corresponding to a mean energy of ≤ 1.5 GeV. A proton of momentum p, charge e, has a rigidity $R = cp/e$, c is the speed of light.

We present calculations of the long-term variations of the mean energies of response of CL/NM and the penetrating proton channel of CRNC for Bartel rotation number (BRN) 1919 (10 / 25 / 1973) to 2258 (12/13/1998). This period encompasses two solar cycles (21 and 22). We show that mean energy for the penetrating proton channel on IMP 8 varies from 3 to 6.5 GeV during this period. This is surprising because it implies that some of the energy dependence studies (of the past) of transport parameters using spacecraft data (Pioneers, Voyagers, IMP and Ulysses) are now questionable. This is a preliminary report on work in progress.

Methodology

The integral energy spectrum of GCR, with energies exceeding a specified lower limit E, is represented by a power-law given by: $j(>E) = K E^{-\gamma}$, where K and γ are constants; for E > 1 GeV, the value of γ varies around 1.6 up to about 10^{15} eV. The differential energy spectrum D(E) = dj(E)/dE indicates how the intensity of particles in a range between E and E + dE varies with energy. It is given by,

$$D(E) = -K\gamma E^{-(\gamma+1)} \qquad (1)$$

The mean energy E(av) of GCR measured with a detector, with a threshold at Eo, is given by,

$$E(av) = \int_{Eo}^{\infty} E D(E) dE \Big/ \int_{Eo}^{\infty} D(E) dE \qquad (2)$$

It can be shown that for Eo = 1 GeV,

$$E(av) = (\gamma / \gamma - 1) Eo \qquad (3)$$

The mean energy of response of IMP 8 CRNC penetrating proton (>100 MeV) channel has been calculated as a function of time from 1973 to 1998, for two solar cycles (21 and 22).

Mean energy computation

Figure 1 depicts a plot of our computed 27-day values of the mean energy for penetrating proton channel on IMP 8 as well as for CL/NM for Bartel rotation number (BRN) 1919 (10 / 25 / 1973) to 2096 (12/ 22 /1986); also displayed are the corresponding values of the modulation parameter for the best-fit spectra at 1 AU [7]. The vertical dashed line is drawn through the epoch of solar polar field reversal, separating the epochs of positive (A >0) and negative (A<0) polarities in the northern hemisphere of the sun. The scale for the computed IMP mean energies and modulation function (MeV) is on the left and for CL/NM is on the right.

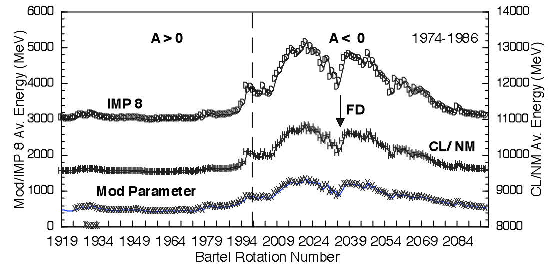

Figure 1

The following features are easily noted.

1. The computed mean energy for IMP 8 channel remains at a value of about 3 GeV until just before the solar polar field reversal. Afterwards it reaches a high value of 5.2 GeV for BRN 2021 (6/6/1981) and starts to decrease, reaching a value of 3.9 GeV for BRN 2034 (5/23/1982). It increases sharply afterwards to about 4.8 GeV for BRN 2039 (10/5/1982); in between a large Forbush decrease (FD) occurred on 14 July 1982 [8]. Fillius and Axford [9] note that the FD reduced GCR intensity to the lowest level for cycle 21, three years away from sunspot maximum, well past the epoch of solar polar field reversal in 1980 [10]. Thereafter, the mean energy declines to ~ 3 GeV by the end of 1986 when solar activity reaches a minimum value for cycle 21.
2. The computed mean energy for CL/NM follows a course similar to that of the mean energy for the IMP-8 channel. It starts off with a value of about 9.5 GeV, attaining a value of about 11 GeV for BRN 2021, decreasing to about 10 GeV for BRN 2034, rising to about 10.5 GeV for BRN 2039 at the time of FD and declining to a value of about 9.6 at the end of 1986. So, over solar cycle 21 the mean energy of CL/NM changes by about 1.5 GeV (~ 16 %). We obtained similar results for solar cycle variations of the median rigidity of response for CL/NM using coupling functions derived by Nagashima et al. [11]; the reader may refer to Ahluwalia and Fikani [8].
3. The modulation function [7] also undergoes similar variations. It starts off with a value of about 490 MeV, attaining a value of about 1.33 GeV for BRN 2021, decreasing to about 900 MeV for BRN 2034 and rising to about 1.2 GeV at the time of the FD and declining to 550 MeV at the end of 1986.

Figure 2 describes the time variations of the three parameters discussed above but for the case of solar cycle 22, starting with BRN 2097

(1/18/1987) through BRN 2258 (12/13/1998); GCR intensity reached the lowest level ever observed in June 1991 since continuous monitoring began in 1950 [12]. As such it is not surprising to note that all three parameters vary over a larger range than during solar cycle 21. For example, IMP 8 mean energy starts off at 3 GeV for BRN 2097 reaching 6.5 GeV for BRN 2146 (9/2/1990) after the polar field reversal in 1990.

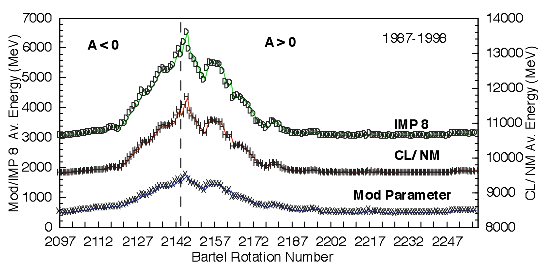

Figure 2

The corresponding extreme value for CL/NM is 11.7 GeV and for the modulation function 1.74 GeV. Thereafter, the values decline to 3 GeV for IMP 8 mean energy, 9.6 GeV for CL/NM mean energy, and 565 MeV for the modulation function at the end of 1998.

Summary

We have shown that the mean energy for the penetrating proton channel on IMP 8 spacecraft reported in the literature is highly underestimated. Even at the solar minima the value should be 3 GeV rather than 1.5 GeV reported by Lopate and Simpson [6]. Furthermore, the value changes by a factor of more than two over a solar cycle. This calls into question a number of studies involving energy dependence of modulation parameters based on data obtained with detectors on board the spacecrafts and balloons in conjunction with data obtained with neutron monitors and underground muon telescopes at global locations. As an example, let us consider the Forbush decrease (FD) of 14 July 1982; it reduced the GCR intensity measured by neutron monitors to the lowest level for cycle 21, three years away from the epoch of sunspot maximum in 1979 [9], well past the epoch of solar polar field reversal in 1980 [10]. The date for the FD lies near the start of BRN 2036. From Figure 1 we note that the mean energy of response for the IMP 8 detector is 4.5 GeV for BRN 2036 corresponding to a rigidity of 5.4 GV instead of 2.3 GV reported by Lopate and Simpson [6].

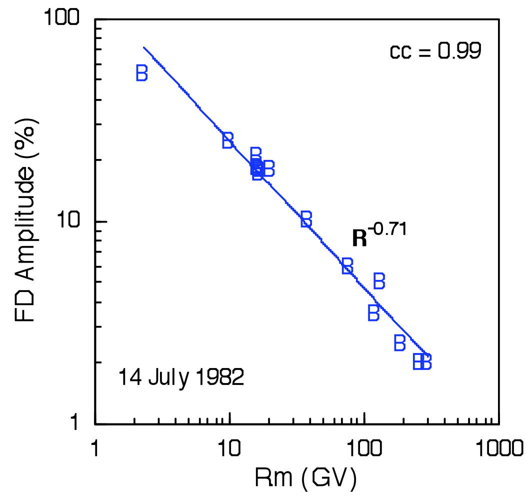

Figure 3a

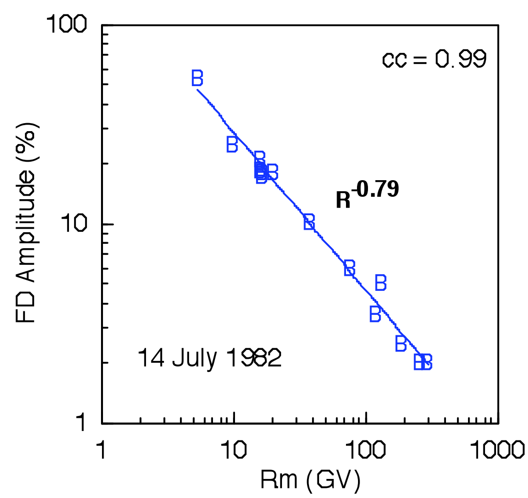

Figure 3b

Figure 3a shows the plot of the amplitude of the FD as a function of Rm for a variety of detectors, using Rm = 2.3 GV for IMP detector, see Ahluwalia and Fikani [8] for details. Figure 3b shows the same data except that we have used Rm = 5.4 GV for IMP detector. The data are plotted on a log-log graph and the best-fit lines are drawn across the plots, indicating an inverse power-law dependence on GCR rigidity. Clearly, the line in Figure 3b, with a slope of – 0.79, represents a better fit to the data.

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