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Long term residual modulation of lower energy galactic cosmic rays

H. S. Ahluwalia[1] **and C. Lopate**[2]

[1]Physics & Astronomy Dept., University of New Mexico, Albuquerque, NM 87131-1156, USA
[2]Enrico Fermi Inst., Lab for Astrophys. & Space Res., University of Chicago, Chicago, IL 60637, USA

Abstract. Galactic cosmic ray (GCR) intensity data have been analyzed by Stozhkov et al (2000), and by Ahluwalia (2000) for 4 consecutive solar activity minima for the period 1963 to 1998. Data obtained with a variety of detectors located at the global sites as well as the balloon altitudes are used in both analyses. A systematic decrease is observed in all data sets, near solar minimum epochs for the 1965 to 1987 period. The median rigidity of response (Rm) for these detectors to GCR spectrum lies in the range: 1 GV < Rm < 67 GV. The observed decrease (residual GCR modulation) is ascribed to a supernova explosion in the near interstellar medium by Stozhkov et al. This is disputed by Ahluwalia's analysis. He ascribes it to the long-term modulation of GCR flux within the heliosphere by the solar wind. Additional data (not presented before), obtained on board the IMP spacecrafts, are presented in support of the heliosphereic modulation hypothesis.

1. Introduction

A study of the modulation of galactic cosmic rays (GCR) is important because of its potential for revealing the subtle features of energetic charged particle transport in the tangled fields that permeate the heliosphere and in part as a means of remotely probing the heliosphere, as well as for learning about the physics of the processes operating on the Sun. Eleven-year GCR modulation has been studied quite aggressively since the work of Forbush (1954). He discovered an anti-correlation between GCR intensity and the sunspot numbers (SSNs). We know now that sunspots are the sites of intense magnetic fields on the Sun's photosphere. The outer reaches of these fields (in the solar corona) are drawn into space by the solar wind. Recent modeling results obtained by Potgieter et al (1993) suggest that drifts are responsible for the long term GCR modulation during low to moderate solar activity and the global merged interaction regions become progressively more important to eventually dominate during maximum solar activity. However, this generalization seems to be incomplete in light of the fact that a significant fraction of the observed modulation in cycle 20 (1964-76), near maximum solar activity (1967-70), is attributable to the magnetic fields at the termination shack (Ahluwalia, 2000). Moreover, a case has been made that the local value of the interplanetary magnetic field (B) plays a significant role in controlling GCR modulation at an observing site (Perko and Burlaga, 1992; Burlaga and Ness, 1998; Belov et al, 1999; Ahluwalia, 2000).

We have shown (Ahluwalia, 2000) that one observes a systematic annual mean GCR flux decrease at its recovery from 11 year modulation from 1965 to 1987, while the flux near the solar minimum in 1997 is higher than the 1986-87 level. A corresponding inverse trend is observed in the annual mean values of B; it undergoes a monotonic increase near SSN minima from 1965 to 1986, while the measured value of B in 1996 is lower than the values observed in 1976 and 1987, i.e. the anti-correlation between the two data sets remains valid but the long term trends change in 1997. The systematic decrease in GCR flux (for the period 1965 to 1987) was observed in the data obtained with a variety of detectors located at global sites at sea level as well as at mountain location and balloon altitudes. The median rigidity of response (Rm) for these detectors covers the range from a few GV to 67 GV. Stozhkov et al (2000) analyzed a similar set of data in a different manner and concluded that the observed decrease in GCR flux from 1965 to 1987 may be ascribed to a supernova explosion that may have occurred about 50,000 years ago at a distance between 10 to 150 parsecs from our solar system. Their analysis did not reveal the crucial change in the long-term trend of GCR flux near the solar minimum of 1996. It is important to settle this controversy (Ahluwalia, 2001). In

Correspondence to: H. S. Ahluwalia
Physics & Astronomy Department
University of New Mexico
Albuquerque, NM 87131-1156, USA

this paper, we present additional data from IMP detectors in support of our heliospheric modulation hypothesis.

2. New Data

We present one set of the long term measurements obtained with the University of Chicago cosmic ray telescopes on board the IMP-7 (Explorer 47) and IMP-8 (Explorer 50) satellites. They were launched in low eccentricity orbits whose closest approach to Earth is about 29 Earth radii; as such the measurements are free of the perturbation due to the atmosphere or the geomagnetic field. The main purpose of these precision telescopes was to separate different chemical species and isotopes using the dE/dx versus residual energy technique (Comstock, et al, 1966). The measurements are characterized by high instrument stability (Garcia-Munoz, et al, 1977). In this paper we present the annual mean counting rates per second for the penetrating protons, with threshold at 95 MeV and mean energy ~ 1.5 GeV (which corresponds to a rigidity of about 2.3 GV). The measurements cover the 1972 to 2000 period.

For comparison purposes, we also use low energy (> 0.1 GeV) GCR measurements, made with Geiger counter telescopes on board the high altitude balloons. These measurements were carried out at high latitude locations in the USSR, for over three decades (1957-89). The transition curve data have been carefully corrected for the albedo effect by Bazilevskaya et al (1991) and the annual mean values (1958-89) of GCR flux are summarized in Table 2 of their paper. For details pertaining to the instruments and calibration techniques, the reader is referred to the review paper by Bazilevskaya and Svirzhevskaya (1998). Together, the two data strings comprise a continuous record of the time variations of the low energy GCR from IGY period to date, an epoch spanning five solar activity cycles (19 to 23).

3. Results

Figure 1 shows a plot of the two data strings normalized in a suitable manner so that they are juxtaposed to represent the continuous temporal variations of low energy GCR over more than three decades (1964-2000). The process involved in carrying out the normalizations is as follows. First, the balloon measurements are normalized to 100% in 1965. This leads to the low energy GCR level of 99% in 1997. The IMP penetration proton measurements are then normalized to 99% in 1977 and the two measurements are thereby superposed. The two curves track each other in an impressive manner, where they overlap; a major discrepancy is seen for the two-year period 1972 and 1973. This needs to be explained. The epochs of solar minimum (m), maximum (M), and solar polar field reversals (vertical dashed lines) are also shown in Fig. 1. The close tracking between the two data strings is not surprising since a large fraction of GCR nuclei (>90%) are protons. Extended data sets are also available for alpha particle fluxes measured on board the IMP spacecrafts. Our study of their long-term variations will be reported elsewhere. The following characteristic features of the low energy GCR temporal variations may be noted.

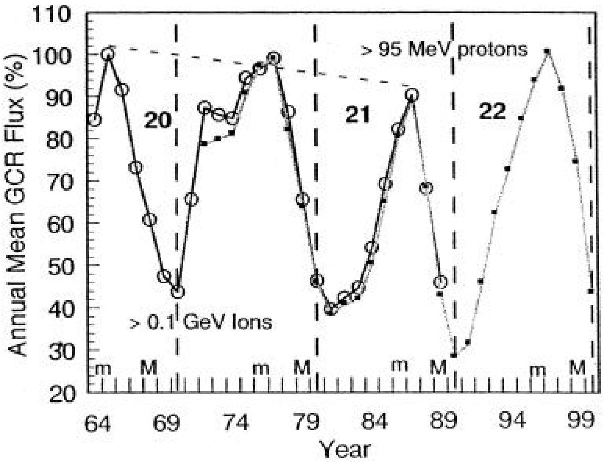

Fig. 1. Annual mean GCR flux, 1964-2000

1. There is an inverse correlation between GCR flux and solar activity measured by SSNs, as one would expect from Forbush's original analysis. However, the maximum of GCR flux modulation does not always occur at the M epochs. For example, during cycle 21 a significant fraction of modulation (>25%) occurs 2 years after M epoch. Similarly, for cycle 22 about 15% of modulation occurs one year after M. epoch. This behavior was noted previously for the neutron monitor (NM) counting rates (Ahluwalia, 1994).
2. The recovery from 11 year modulation always begins after the epoch of the solar polar field reversal, as noted earlier for NM and ion chamber (IC) data (Ahluwalia, 1994). The polar field for cycle 23 reversed in 2000. So a recovery should follow in 2001.
3. The progressive increase of residual modulation for the 1965 to 1987 period is highlighted by the dashed line at m epochs near the top of Fig. 1. This phenomena was discussed in detail by Ahluwalia (2000) for a variety of data, obtained with different detectors, at several different global sites. Clearly, IMP-8 protons subscribe to this behavior also. The decreasing trend is clearly disrupted following the m epoch in 1996; the low energy GCR flux is significantly higher in 1997 than the 1987 level. This constitutes another independent confirmation of the heliospheric modulation hypothesis. It also provides another crucial piece of evidence against the supernova hypothesis proposed by Stozhkov et al (2000). If they are right the decreasing trend should have continued in 1997. But it did not. Alpha particle data, to be reported elsewhere, are in accord with this inference also. Previously, we have shown that GCR flux for > 0.1 GeV ions is well correlated with climax NM rate (Fig. 3, in Ahluwalia, 2000).

Figure 2 shows the linear inverse correlation between the flux of the penetrating protons (1972-2000) and B. The fit parameters are given by, GF = -17.9 B + 189, %

The correlation coefficient (cc) is 0.84, at a confidence level (cl) > 99%. The reader is referred to Fig. 1 in the paper by Ahluwalia (2000), for a plot of the long term temporal changes in the value of B. The observed time variations of B are representative of changes in the flux of the open field lines of the solar dipole moment.

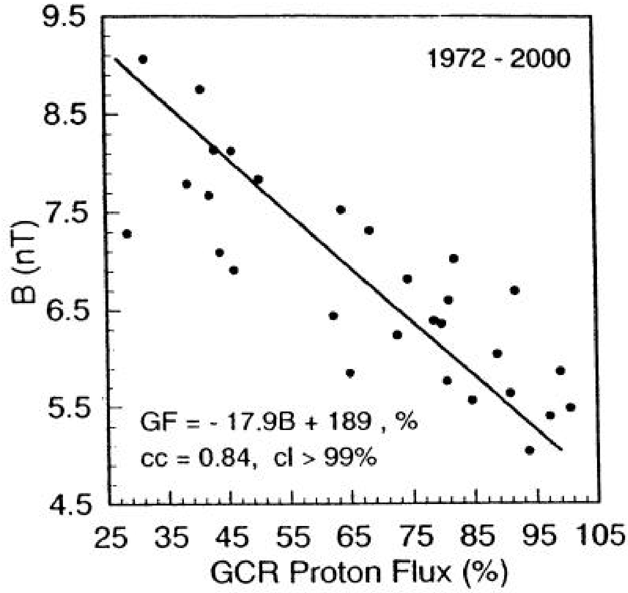

Fig. 2. Inverse correlation between protons and B

4. Rigidity Dependence

Figure 3 depicts the annual mean time variations of GCR intensity at three global sites covered by the neutron monitors (NMs). The rigidity dependence of the 11 year modulation is brought out by the fact that the median rigidity of response (Rm) of these NMs covers a decent range; For Huancayo (HU) Rm = 33 GV, for Kiel (KL) Rm = 17 GV, For Deep River (DR) Rm = 16 GV, and for Climax (CL) Rm = 11 GV. The NMs have a track record of stable operation since the IGY epoch. As such they provide the most homogeneous data sets for our analysis. The plots are for the period 1964 to 2000 which covers four epochs each of solar minimum (m), maximum (M) and solar polar field reversals (vertical dashed lines). A preliminary discussion of the characteristic features of the modulation during three solar cycles (20, 21, 22) has been presented elsewhere (Ahluwalia, 2001a). Also, it is noted that all NMs exhibit an increase in the residual modulation during the 1965 to 1987 period (Ahluwalia, 2001b). However, the change in trend in 1997 is only indicated by three NMs; namely KL/NM, DR/NM and CL/NM. For HU/NM the level in 1997 is not above that for 1987. Two possible explanations are offered. The increase in 1997 may only be confined to lower GCR rigidities (Rm < 30 GV). So more work needs to be done to define the rigidity dependence for this phenomenon. However we also note that the vertical cut off rigidity (Ro) applicable to the HU/NM is subject to a downward drift arising from a decrease in the total geomagnetic field intensity (Shea, 1971). We have not studied this effect yet with respect to HU/NM for cycle 22. So the rigidity dependence of the residual modulation in 1997 is still an open question. It should be emphasized that this effect (change in Ro) is not important for the other three NMs.

5. Summary

New data comprising of the penetrating GCR protons (> 95 MeV), recorded on board the IMP spacecrafts for the 1972 to 2000 period are presented and discussed in this paper.

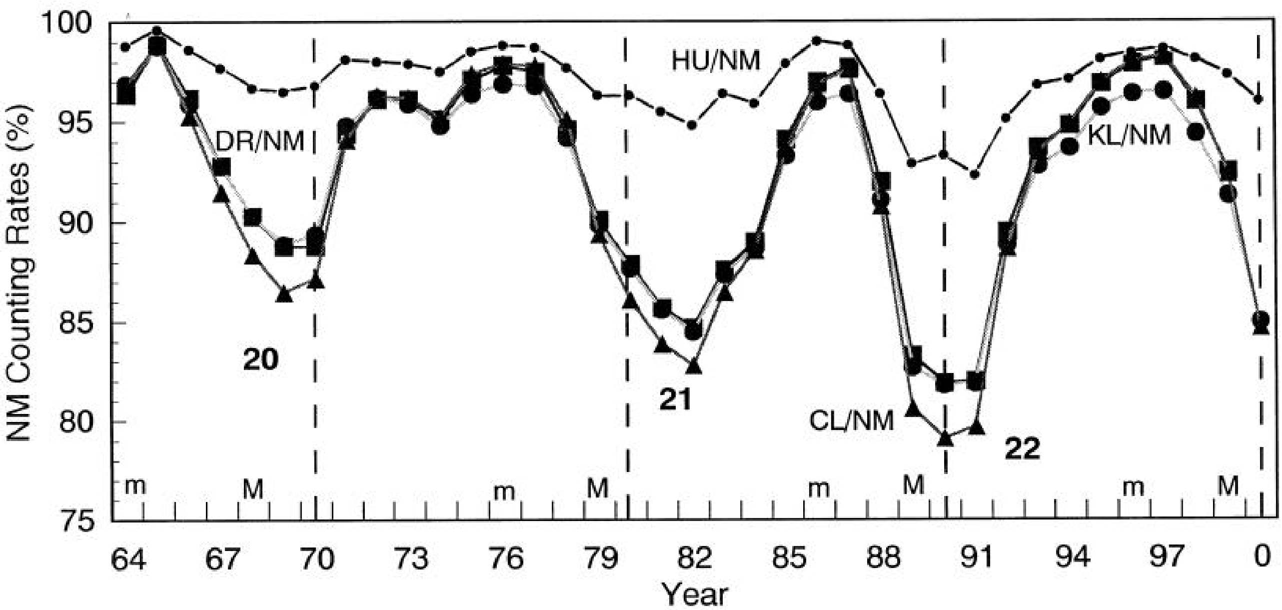

Fig. 3. Annual mean hourly rates for four neutron monitors, 1964 - 2000

The following inferences may be drawn from our careful study.

1. The IMP data smoothly blend in with the balloon measurements of > 0.1 GeV ions incident on the top of the atmosphere. Thereby, we obtain a homogeneous, continuous data string over the period 1958 to 2000, to study the temporal variations of the lower energy GCR, over more than four decades. The data are also important for the study of the long-term changes in Earth's climate (Svensmark, 1988).
2. The IMP data support the observed change in the trend of the GCR residual modulation by high- and mid-latitude neutron monitors in 1997, when the observed value of the interplanetary magnetic field intensity (B) has a lower value than that in the previous two solar minima (1976, 1986). Thereby, we confirm that the cause of the observed residual modulation during 1965 to 1997 period lies within the heliosphere.
3. The level of GCR intensity at Huancayo (as recorded by the neutron monitor) is not higher than that observed in 1987. This may imply that the residual modulation in 1997 is confined to lower rigidities. Alternate explanations cannot be ruled out at this stage.

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References

Ahluwalia, H. S., 1994. *J. Geophys. Res., 99*, 11561.

Ahluwalia, H. S., 2000. *Geophys. Res. Lett., 27*, 1602.

Ahluwalia, H. S., 2001. *Geophys. Res. Lett., 28*, 949.

Ahluwalia, H. S., 2001a. *Adv. Space Sci.*, in press.

Ahluwalia, H. S., 2001b. *Adv. Space Sci.*, in press.

Bazilevskaya, G. A., Krainev, M. B., Stozhkov, V. I., Svirzhevskaya, A. K., and Svirzhevsky, N. S., 1991. *J. Geomag.Geoelectr., 43*, 893.

Bazilevskaya, G. A., and Svirzhevskaya, A. K., 1998. *Space Sci. Rev., 85*, 431.

Belov., A. V., Guschina, R. T. , and Yanke, V. G., 1999. 26th Int. Cosmic Ray Conf. Pap., 7, 175.

Burlaga, L. F. and Ness, N. F., 1998. *J. Geophys. Res., 103*, 29719.

Comstock, G. M., Fan, C. Y., and Simpson, J. A., 1966. *Ap. J. 146*, 51.

Forbush, S. E., 1954. *J. Geophys. Res., 59*, 525.

Garcia-Munoz, M., Mason, G. M., and Simpson, J. A., 1977. *Ap. J., 217*, 859.

Perko, J. S. and Burlaga, L. F., 1992. *J. Geophys. Res., 97*, 4305.

Potgieter, M. S., le Roux, J. A., McDonald, F. B., and Burlaga, L. F., 1993. 23rd Int. Cosmic Ray Conf. Pap., *3*, 525.

Shea, M. A., 1971. 12th Int. Cosmic Ray Conf. Pap., 3, 859.

Stozhkov, Y. I., Pokrevsky, P. E., and Okhlophov, V. P., 2000. *J. Geophys. Res., 105*, 9.

Svensmark, H., 1998. *Phys. Rev. Lett., 81*, 5027.