The Radial Distribution of Galactic Cosmic Rays in the Heliosphere at Solar Minimum and Solar Maximum

F.B. McDonald[1], Z. Fujii[2], B. Heikkila[3], N. Lal[3], and R.E. McGuire[3]
(1) I.P.S.T., University of Maryland, College Park, MD 20742
(2) Solar Terrestrial Environment Laboratory, Nagoya University, Japan
(3) NASA/Goddard Space Flight Center, Greenbelt, Maryland

Abstract

The radial intensity gradients, g_r, for the qA>0 solar minimum periods of cycle 20 and 22 for 265 MeV/n galactic cosmic ray (GCR) He and 175 MeV GCR H are very small (<0.2%/AU) between 15 and 72 AU, suggesting that most of the GCR modulation at this time is occurring near the termination shock (T.S.) or in the heliosheath. The GCR latitudinal gradients (g_λ) at this time are also small ($<0.0 \pm 0.2\%/°$). For the qA<0 (1987), g_r shows a much stronger radial dependence. The increased modulation from solar minimum to solar maximum is found to occur mainly inside the T.S.. In the inner heliosphere (r<15 AU) there does not appear to be a significant change in the particle transport parameters over the last 3 cycles.

1. Introduction

The study of the temporal and spatial variations of cosmic rays in the heliosphere is important in understanding the transport of energetic particles in a large-scale, turbulent astrophysical plasma and to explore the structure and dynamics of the outer heliosphere. Over the past 30 years the cosmic ray experiments on the IMPs at 1 AU and on Pioneer 10 (P-10) and Voyagers 1 and 2 (V-1, V-2) at ever increasing heliocentric distances have constituted a unique network for observing these variations.

This flotilla of spacecraft samples a different region of space over each phase of the solar activity and 22-year heliomagnetic cycle. To separate temporal and spatial variations and to obtain a more detailed description of the radial dependence it would be highly desirable to combine the data from different solar cycles. In this study we focus on two well-defined periods of the 11-year solar activity cycle - solar minimum and solar maximum. For the cycle 20 and 22 solar minima it is found that the 1 AU, IMP 8 detailed H and He spectra and the counting rate of the Climax neutron monitor are essentially the same, suggesting that the modulation state of the heliosphere was very similar for these periods [1]. This allows the Pioneer and Voyager intensities for these times to be combined. In

pp. 3965–3968

addition, P-10 was launched near the beginning of the extended solar minimum of cycle 20, permitting a more detailed examination of the radial intensity gradients, g_r, in the inner heliosphere.

The solar maximum data are taken over the minimum in cosmic ray intensity as measured over 3-4 solar rotations. The first step in combining this data is simply to normalize the 1 AU data for the solar maxima of cycles 21, 22 and 23. Fortunately the IMP 8 solar maximum for cycles 21 and 23 are approximately the same. These 1 AU normalizing factors are then applied to the Pioneer and Voyager solar maximum data. The resulting radial dependence beyond some 15 AU fits a simple 1/r dependence.

2. Observations

The data used in these studies are the 150-380 MeV/n GCR He and 130-220 MeV GCR H data from the IMP 6, 7 and 8 Goddard Medium Energy Detector (MED) (R.E. McGuire, P.I.), the Voyager Cosmic Ray Subsystem (CRS) (E.C. Stone, P.I.) and the Pioneer 10 Cosmic Ray Telescope (CRT) (F.B. McDonald, P.I.). The Voyager GCR H intervals have a significant contribution from ACR H over the 1998.5-1999.75 solar minimum. A correction (24%) is applied for this effect assuming that the ACR spectral slope is the same as that of ACR He [2]. No P-10 data is available from the CRT experiment after May 1996 due to the declining power level on the spacecraft.

The time histories of 150-380 MeV/n (26-day averages) for the period from 1972-2002.75 from IMP, V-2 and P-10 are shown in Figure 1.

The radial distribution for the 3 solar minimum periods for 175 MeV H and 265 MeV/n He shows that for qA>0 minima there is essentially no change in their intensities between ~12 and 73 AU (Fig. 2). An estimate of the GCR intensities at the T.S. for $\lambda<34^\circ$ can be obtained by extrapolating this flat distribution out to an assumed T.S. location at 100 AU, yielding a value of 0.44 He/m^2-s-sr-MeV/n for 265 MeV/n He and 2.9 H/ m^2-s-sr-MeV/n for 175 MeV H. The 1977 P-10 measurements were made in the ecliptic plane suggesting that the latitudinal gradients for $\lambda<34^\circ$ are small. This is consistent with the 1996 measurements at 61 AU of 0.0 $\pm$ 0.2% for 265 MeV/n GCR He and 0.0 $\pm$ 0.05 for 175 MeV H [3]. The radial dependence for GCR He for the qA<0 epoch shows a stronger power law dependence out to 42 AU (Fig. 2).

The first step in the solar maximum analysis is to multiply the IMP 8 cycle 22 data by 1.6 so the solar max intensity is the same as for the two other cycles and apply this same normalization factor to the cycle 22 Voyager and Pioneer data (Fig 2). This simple normalization procedure unifies the solar maximum intensities in a remarkable way. The data in Fig. 2 show that the spatial variation of GCR He has the functional form $g_r = 1/J\ dJ/dr = G_\circ/r$ (where r is the heliocentric distance in AU) with g_r having a value of 10/r % /AU from 1- ~15 AU and g_r =

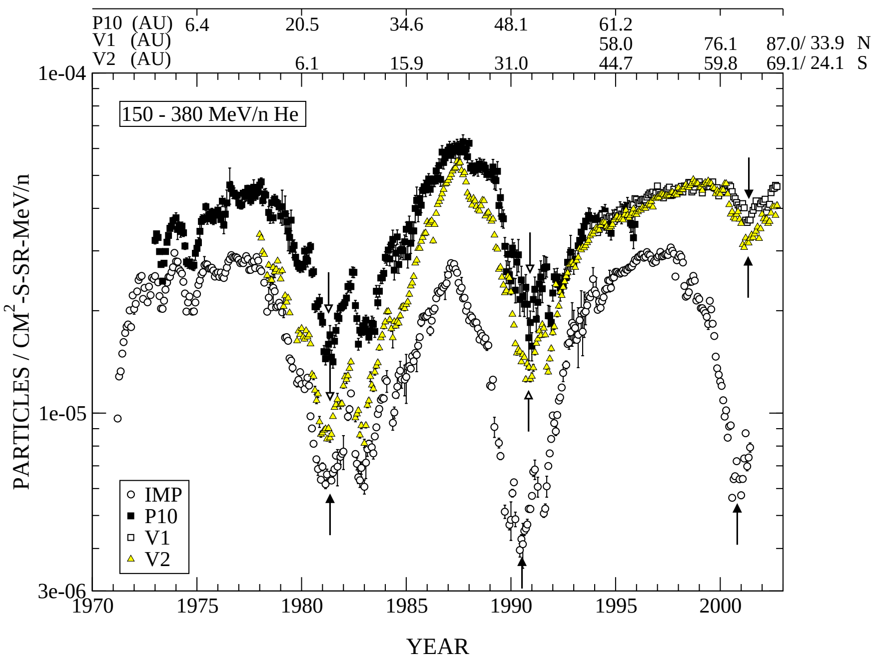

Fig. 1. Time History of 150-380 MeV/n GCR He.

73/r % /AU for r >∼15 AU. A similar pattern is found for GCR H. These changes in g_r suggest there is a fundamental difference in particle transport between the inner and outer heliosphere.

Inside 15 AU, there is not a significant change in the slope of the GCR intensity distribution as a function of r between solar maximum and solar minimum. This is consistent with previous studies using the GCR He data from the network and Ulysses [3] which found a relative constancy of g_r at 3 AU over the time span 1974-2000.

The extrapolation of the solar maximum intensities intersects that of solar minimum at 88 and 110 AU. This provides a rough estimate of the T.S. location similar to that used previously for ACR O [4].

3. Discussion

The times of solar minimum and solar maximum represent a well-defined, change of state in the modulation process. For qA>0 solar minimum, when positive ions flow into the heliosphere over the polar regions of the heliosphere, it is found that the radial distribution for 265 MeV/n GCR He and 175 GCR show there is essentially no change in their intensities between 12 and 73 AU. The GCR He intensity for these qA>0 periods is 0.295 at 1 AU, 0.43 at 14 AU and 0.44/m^2-s-sr-MeV/n at 75 AU. The expected value of the interstellar GCR He intensity at 265 MeV/n as given by Webber and Lockwood [4] is 1.2/m^2-s-sr-

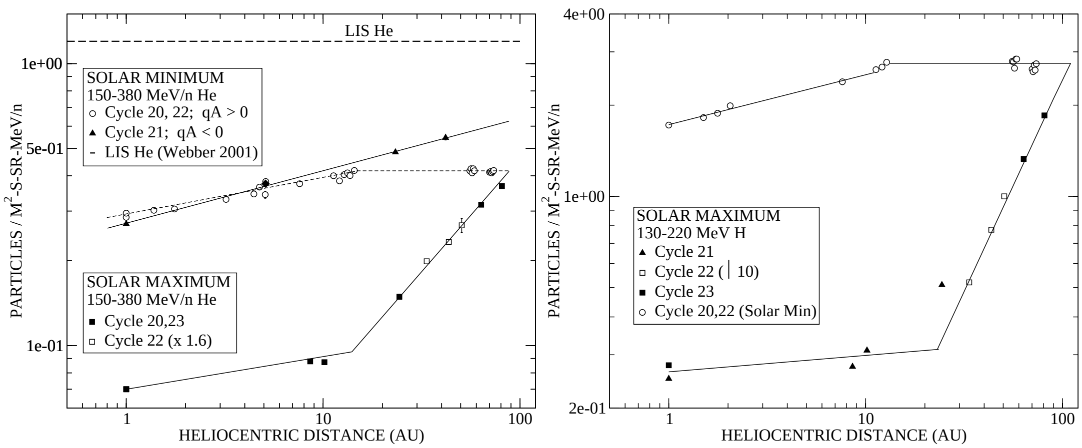

Fig. 2. Solar Maximum (norm at 1 AU) and solar minimum radial intensity distributions for GCR H and He for cycles 21, 22 and 23.

MeV/n. Based on this interstellar intensity and neglecting drift effects, some 85% of the modulation is occurring near or beyond the termination shock, consistent with the solar minimum analysis of Webber and Lockwood [5].

For cycle 21 the radial distribution GCR He is steeper and suggests larger gradients throughout the region inside the T.S.. Part of this may be the result of local reacceleration at the T.S.. Extrapolating the 1987 data to 100 AU suggests a 44% increase in intensity for cycle 23 over that of cycle 22 if latitudinal gradients are not important at ∼100 AU.

The radial intensity distributions at solar max indicates the changes that produce the 11-year modulation cycle are mainly occurring in the outer heliosphere between 15 AU and the T.S.. This conclusion is in disagreement with the solar maximum analysis of Webber and Lockwood [6]. The extrapolation of the solar max data intersects the solar minimum intensity levels at 88 AU (GCR He) and 110 AU (GCR H). These data suggest that for cycle 23 there was not a significant change in the heliosheath modulation between 1997-98 and the 2001 time of solar maximum.

4. References

1. McDonald, F.B. et al., Proc. 27th ICRC (Hamburg) 9, 3830, 2001.
2. Cummings, A.C. et al., Astrophys. J. Lett. 287, L99, 1984.
3. Stone, E.C. and A.C. Cummings, Proc. 26th ICRC (Salt Lake City) 7, 500, 1999.
4. McDonald, F.B. et al., Proc. 27th ICRC (Hamburg) 10, 3906, 2001.
5. Webber, W.R. and J.A. Lockwood, J. Geophys. Res. 106, 29,323, 2001.
6. Webber, W.R. and J.A. Lockwood, J. Geophys. Res. 106, 29,333, 2001.