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A New Look at the >70 MeV Cosmic Ray Radial Gradients in the Heliosphere Measured by the IMP, Voyager and Pioneer Spacecraft

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Abstract

We re-examine the interplanetary cosmic ray radial gradients (G_r) of >70 MeV cosmic rays as obtained from the IMP, Voyager and Pioneer spacecraft between 1978 and 1998. We separate out three distinct effects on the magnitude of G_r. These are due to; (1) intensity changes, (2) changes in the radial distance (radial dependence) and (3) the influence of the solar magnetic field polarity. We have found the following; (1) the value of G_r depends strongly on the cosmic ray intensity in periods of negative solar magnetic polarity, but is only weakly dependent in periods of positive polarity. (2) The radial dependence of G_r depends strongly on the solar magnetic field polarity. In the positive polarity cycle the gradient beyond ~40 AU, starting in 1992, actually increases with increasing r. The behavior of these gradients from 1992 to 1998 including the onset of the new modulation cycle will be discussed.

1. Introduction

A measurement of the radial gradient of cosmic rays is important to our understanding of global flow patterns of cosmic rays in the heliosphere. Furthermore, measurements of this gradient simultaneously in the inner and outer heliosphere during periods of varying cosmic ray intensities and different solar magnetic field polarities provide an important key to our understanding of the solar modulation process. The >70 MeV/nuc cosmic ray intensities from the IMP, Voyager 1 & 2 and Pioneer 10 spacecraft are useful in making such measurements because of their excellent statistics.

With the spacecraft data currently available we can now compute the value of G_r for >70 MeV cosmic rays in both the inner and outer heliosphere for the entire time interval from 1978 to 1996, covering about two 11-year solar activity cycles. After 1996 when data are no longer available from P10 we can estimate the behavior G_r in the outer heliosphere using V1 and V2. We can separate out three distinct effects which change the value of G_r: 1) intensity changes, 2) changes in radial distance, and 3) the influence of the solar magnetic field polarity. This means that to carefully compare the radial dependence of this gradient, periods of different magnetic polarity must be examined separately and changes in this gradient due to intensity changes must be taken into account.

2. The Data and Calculation of G_r

Previous studies (Webber and Lockwood, 1986; Lockwood and Webber, 1988, and references therein) have shown that the spacecraft data for >70 MeV cosmic rays provide an excellent measure of the cosmic ray flux with a median energy of ~1 GeV (or rigidity of ~1.7 GV). Considerable care must be taken in the normalization of the different spacecraft data, otherwise uncertainties can be introduced in the calculated gradients. This normalization has been periodically re-examined and the original normalization verified (Webber and Lockwood, 1999).

In practice cosmic ray measurements in the heliosphere are made at two or more widely separated spacecraft and only the non-local G_r between the spacecraft can be calculated. If only two spacecraft are available, the instantaneous integral radial gradient is given by:

$$1)\qquad G_r = [1/(r_2 - r_1)] \ln J_2/J_1 ,$$

where J_1 and J_2 are the cosmic ray intensities at r_1 and r_2 respectively.

Since we have >70 MeV cosmic ray data available from IMP as well as V2 and P10 from 1978-1994 when the latitude of all of these spacecraft was close to zero, we can use equation 1 to determine both G_r (V2, IMP) and G_r (P10, V2) at these times.

3. Results

As noted earlier, all three effects: 1) the cosmic ray intensity, 2) the radial distance, and 3) the solar magnetic field polarity, play an important role in the determination of the value of G_r and its temporal variation. These effects must be examined separately and in as independent a manner as possible to evaluate their role in the temporal dependence of the gradient. Even the order in which these effects are separated is important, as we shall see. We start out by examining the dependence of G_r on cosmic ray intensity.

In Figure 1 we show G_r as determined between P10 and V2 throughout the 18 year period from 1978 to 1996, plotted as a function of the reference intensity at IMP. Note that during this time P10 andV2 moved outward in the heliosphere between an average radius from 8.5 to ~58 AU always with a radial separation of 17±1 AU. The average radial distances for selected times are indicated on the figure. The dependence of G_r that results from the radial dependence itself is essentially de-emphasized in this type of G_r versus J plot. What remains is the combination of G_r versus intensity and the solar polarity effects.

During the period from 1978.5 to 1981.5 it can be seen that the average value of G_r remained nearly constant while the intensity at IMP decreased by a factor of ~3. This almost complete independence of G_r on intensity changes was noted originally Webber and Lockwood (1981) and later confirmed in Webber and Lockwood (1999).

In a simple force field approximation to the modulation, cosmic ray intensity changes can be related to changes in the integrated value of the diffusion coefficient between the observer and the modulation boundary if the Compton-Getting factor and the solar wind speed remain approximately constant. Since the value of G_r doesn't change during the 1978.5-1981.5 time period, the overall modulation (intensity) to a first approximation wouldn't be expected to change either. The fact that the intensity does change in this period suggests that other effects not included in this simple force field modulation picture might be occurring. Even though the average radial distance of P10 and V2 increased from ~8.5 to 17 AU during this time period, G_r remained constant which implies that there was little radial dependence of G_r during this period when A>0.

After 1983, when A<0, there is now a noticeable correlation of G_r with J. This inverse correlation of G_r with J is exactly what would be expected in the force field model when $G_r \propto CV/K$. Therefore, during this entire negative solar magnetic polarity period, the increasing and decreasing intensity changes can essentially be described by the force field model. At the two periods of high solar modulation (low intensity) in 1983 and 1989 there must also be a weak radial dependence of G_r as indicated by the fact that the value of the gradient returns to nearly its same value (2.5-3%AU) even though the radial distance changes from ~20 to 35 AU.

Later between 1992.5 and 1996.0, when A>0, the value of G_r shows only a weak dependence on the intensity in Figure 1. This is similar to the behavior in the earlier positive cycle from 1978.5 to 1981.5.

In Figure 2 we have determined the 6 month average instantaneous values of G_r measured between V2 and IMP and P10 and V2 plotted at the average radial distances of the two pairs of spacecraft and connected by solid lines to show how the instantaneous G_r changes with distance and time after 1992.

After mid 1996 when data are no longer available from P10, we can use the ratios of V1 and V2 to estimate the magnitude of G_r in the outer heliosphere. These values are shown in Figure 2. Clearly G_r is not increasing beyond 65 AU which might be expected if the Voyager spacecraft were approaching the modulation boundary. Instead G_r decreased continuously from 1993 to 1998 in the outer heliosphere. In the inner heliosphere the gradient also decreases from 1993 to 1996 but then begins to increase as solar activity reduces the cosmic ray intensity in the inner heliosphere.

4. Summary and Conclusions

In summary we find that:

1) The value of G_r depends strongly on the cosmic ray intensity, e.g., $G_r \propto 1/J$, in periods of negative solar magnetic polarity. This dependence is only weakly evident in periods of positive polarity. During these A<0 periods this is the dominant effect changing the gradients with only a weak radial dependence of G_r.
2) The values of G_r show a strong solar magnetic polarity cycle dependence. This is manifested in a much

more rapid radial falloff of G_r inside of ~10-20 AU in the 1978 and 1996 A>0 periods as compared with 1987 (A<0). Beyond 10-20 AU the average gradient when A>0 is only ~0.5 %/AU or about 1/3 of that (1.5%/AU) of that in the A<0 cycles in 1987.

3) During the period from 1993 to 1998 the value of G_r continuously decreases in the outer heliosphere, however in the inner heliosphere the gradient decreases from 1993 to 1996 but then begins to increase as solar activity reduces the intensity in the inner heliosphere.

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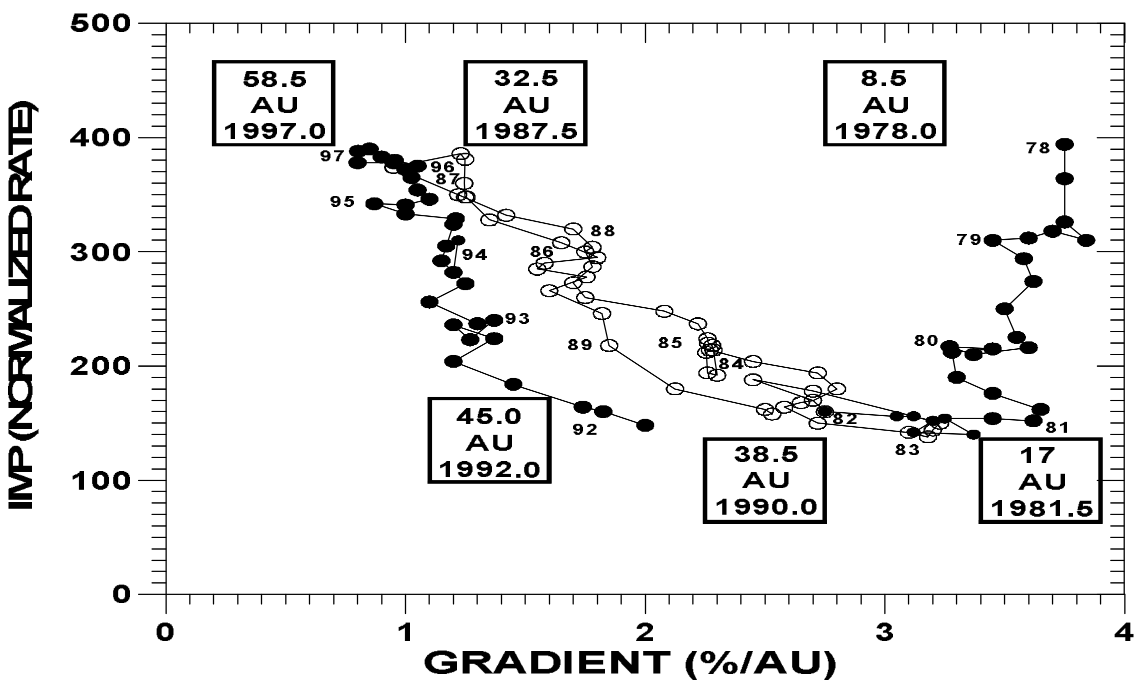

Figure 1: The 52-day average of the >70 MeV intensity at IMP versus G_r (P10/V2) from 1978 to mid 1996. When A>0 the data are shown as solid circles and when A<0 the data are shown as open circles. The average radial distance of the P10 and V2 pair is shown for various times.

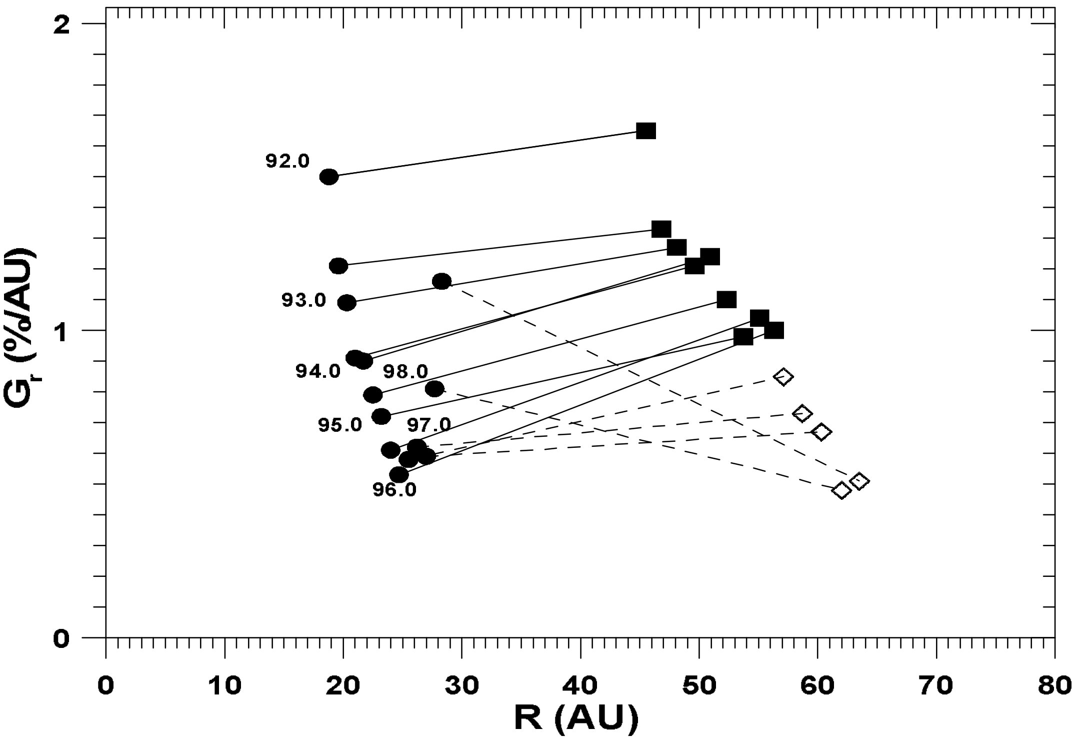

Figure 2: Six monthly average radial gradients of >70 MeV cosmic rays in the inner heliosphere (V2/IMP shown as solid circles) and outer heliosphere (P10/V2, solid squares, or V1/V2, open diamonds) from 1992.0 to 1998.5. Thin solid and dashed lines connect these inner and outer heliosphere gradient values before and after 1996.5.