Observations of the Solar Modulation of Galactic and Anomalous Cosmic Rays During Solar Minimum

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Abstract

From the end of 1997 to early 1998, the relatively steady-state solar-minimum conditions provided an ideal period to study the solar modulation of anomalous cosmic rays (ACRs) and galactic cosmic rays (GCRs). Using observations of the energy spectra of the most abundant elements (H, He, C, N, O, and Ne) from an array of spacecraft and instruments, we calculate the radial gradients for ACRs and GCRs over a wide range of rigidity. The GCR radial gradient is near zero for all rigidities, out to 70 AU. The ACR radial gradient shows a strong rigidity dependence in the middle heliosphere, which is expected, but the rigidity dependence is not present in the outer heliosphere, and is not obvious in the inner heliosphere.

1 Introduction:

The measured intensity gradients of the anomalous cosmic rays (ACRs) and galactic cosmic rays (GCRs) are an important input to modeling and understanding solar modulation of cosmic rays in the heliosphere. Using five spacecraft positioned throughout the heliosphere, and multiple instruments on each spacecraft, this study includes an unprecedented range of particle species and rigidities in its calculation of the radial component of the intensity gradients.

Data are included from the CRIS, SIS, and ULEIS instruments on the Advanced Composition Explorer (ACE), the MAST and PET instruments on SAMPEX (Solar, Anomalous, Magnetospheric Particle Explorer), EPAC and COSPIN/LET on Ulysses, and CRS and LECP on Voyager 1 (V1) and Voyager 2 (V2). ACE and SAMPEX are at 1 AU, 0° heliographic latitude, Ulysses was at 5.4 AU and had an average heliographic latitude of 0°, Voyager 2 was at 54 AU, -18° lat., and Voyager 1 was at 69 AU, 33° latitude.

The time period for this study was picked so that the entire heliosphere was in a quiet, steady-state solar-minimum condition. Data was accumulated for the quiet times in Bartel's rotations 2241, 2242, 2244, 2245, 2246, and 2247 (10 Sep 1997 - 2 Nov 1997 and 30 Nov 1997 - 17 Mar 1998), where ”quiet time” was instrument dependent. The end of the period was picked because a step decrease in flux due to solar activity occured in early April 1998 (see e.g. Wiedenbeck *et al.* 1999) and this change in modulation level did not propagate out to the Voyagers until near the end of 1998. Bartel's rotation 2243 was not included due to several large flares, although this solar activity had only a small effect on the modulation level.

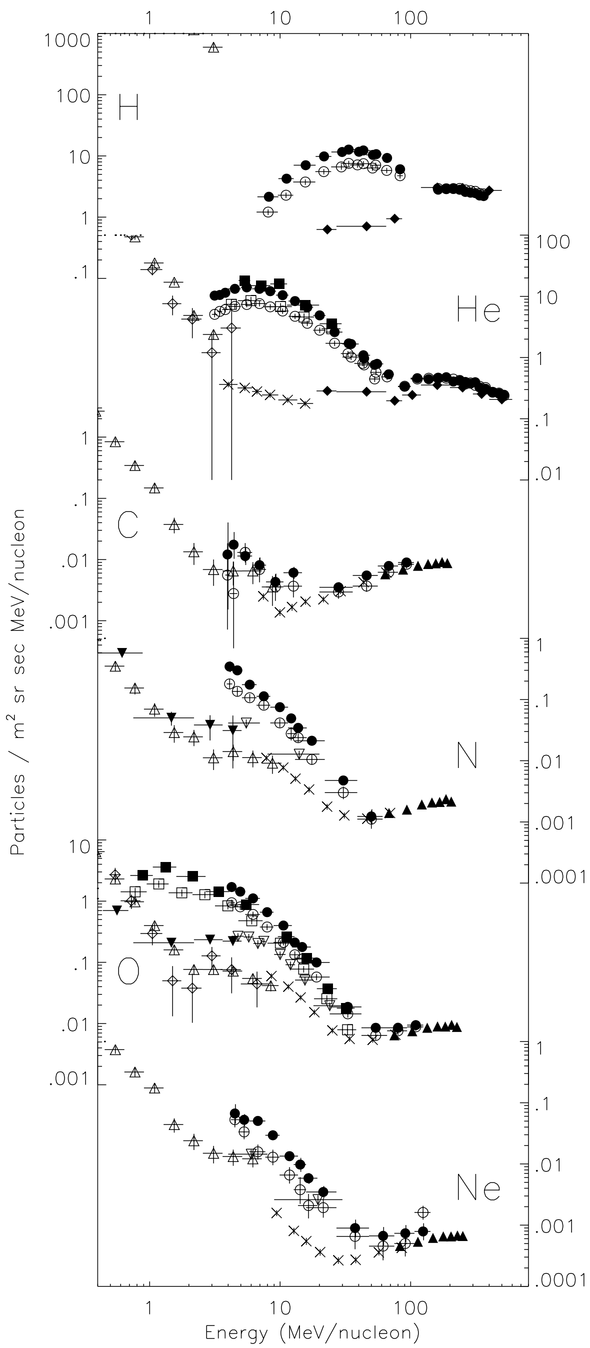

Figure 1: Energy Spectra for H, He, C, N, O, Ne. Symbols are: filled circle - V1 CRS; filled square - V1 LECP; open circle - V2 CRS; open square - V2 LECP; open downward triangle - Ulysses Cospin LET; filled downward triangle - Ulysses EPAC; filled upward triangle - ACE CRIS; X - ACE SIS; open upward triangle - ACE ULEIS; open diamond - SAMPEX LICA; filled diamond - SAMPEX PET

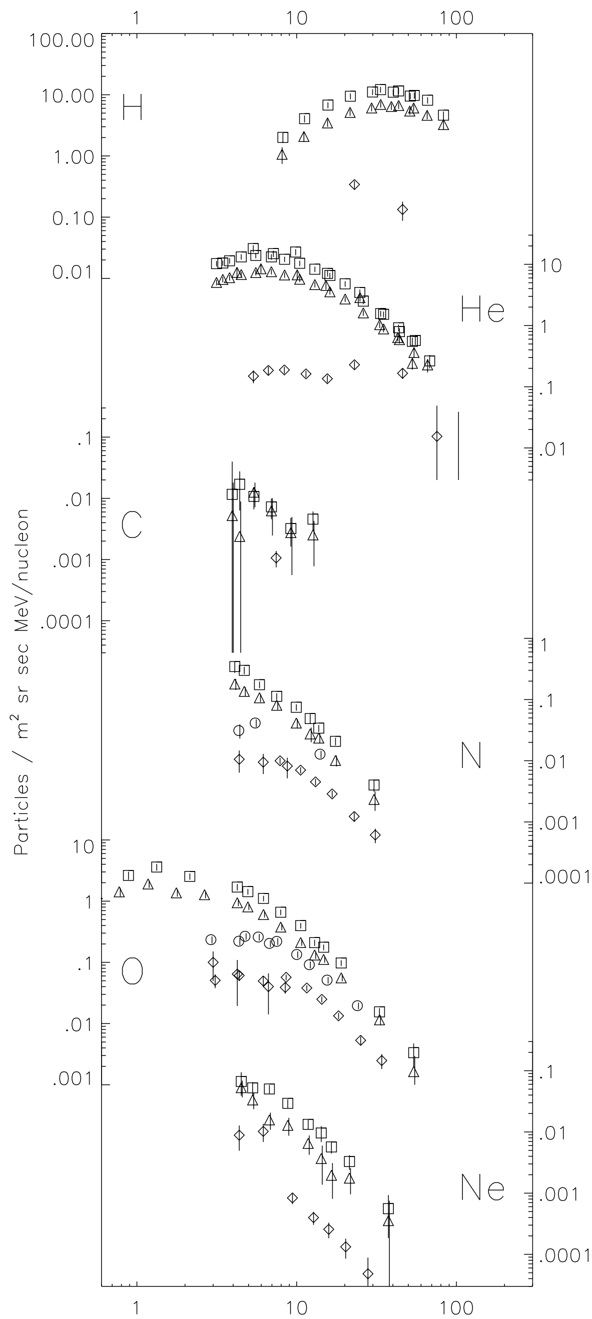

Figure 2: Energy Spectra for ACR H, He, C, N, O, Ne (SEP and GCR components subtracted). Symbols are: open square - 69 AU; open triangle - 54 AU; open circle - 5.4 AU; open diamond - 1 AU

2 Observations:

Figure 1 shows all the accumulated energy spectra at 1 AU, 54 AU, and 69 AU, and also 5.4 AU for nitrogen and oxygen. There are systematic differences in absolute fluxes measured in different instruments (see e.g. the oxygen fluxes measured in Voyager CRS and LECP). Because of this, a 10 % systematic uncertainty has been added in quadrature to the statistical uncertainty of all points.

In order to separate out the ACR energy spectra, power laws were fit to the low energy solar energetic particle components for each species and each radial position, and a J=AT power law (Rygg and Earl 1967) was fit to the two lowest energy points of the each galactic component. The resulting ACR spectra are shown in Figure 2.

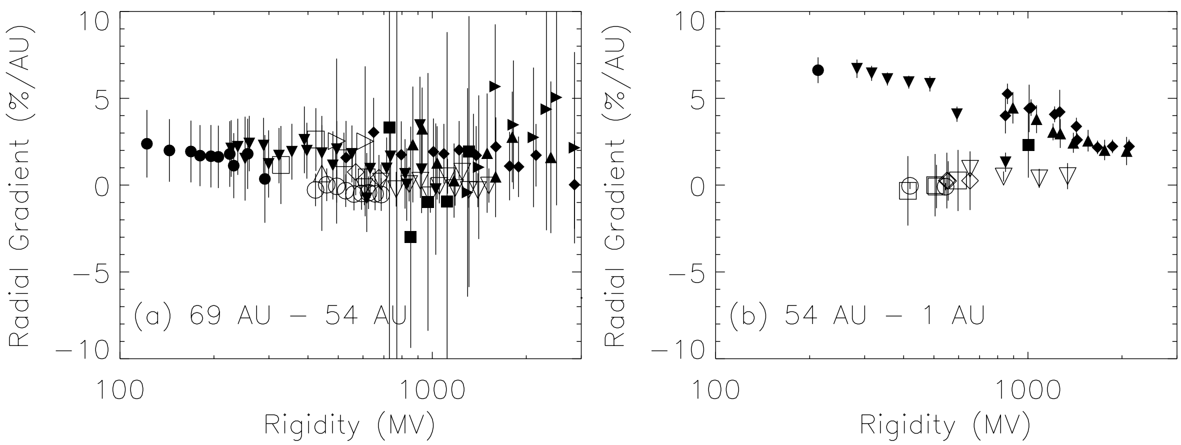

Figure 3: Radial Gradient (% per AU) vs. rigidity for both ACRs (solid points) and GCRs (open points). The symbols show the different elements: H (circle); He (downward triangle); C (square); N (upward triangle), O (diamond), and Ne (rightward triangle). (a) Gradient between 69 AU (Voyager 1) and 54 AU (Voyager 2) (b) Gradient between 54 AU (Voyager 2) and 1 AU (ACE / SAMPEX)

3 Discussion:

The non-local radial gradients, G_r, are calculated from $G_r = ln(f2/f1)/(r2 - r1)$. In addition, the V1 and V2 data has been corrected for an assumed 2 % per degree latitudinal gradient (Cummings *et al.* 1995, Trattner *et al.* 1995). Figure 3a shows the derived radial gradients in the outer heliosphere for ACRs (solid points) and GCRs (open points) vs. rigidity. The ACRs are assumed to be singly charged, and the GCRs are fully stripped of electrons. For the GCRs, the radial gradient in the outer heliosphere is consistent with zero for all rigidities studied here. The ACR gradient is small and independent of rigidity, and could be made consistent with zero if a slightly larger latitudinal gradient is assumed.

Figure 3b shows the derived radial gradients between 54 and 1 AU for ACRs (solid points) and GCRs (open points) vs. rigidity. For the GCRs the radial gradient in the heliosphere from 1 AU out to 54 AU is again consistent with zero for all rigidities. During the previous $A > 0$ solar minimum, the GCR radial gradient was small (˜1.5 % per AU) but non-zero (McKibben *et al.* 1982). The modulation that is occurring for GCRs takes place beyond 70 AU, presumably in the solar wind termination shock or in the heliopause region. For the ACRs, the correlation between G_r and rigidity is strong. Cummings *et al.* (1997) used similar data to derive a mean free path, $\lambda_\perp$, in interplanetary space. For these data, the correlation of $\lambda_\perp$ with rigidity is not as good as G_r, perhaps because we include data with energies below the peak energy, where the force field approximation that Cummings *et al.* (1997) used breaks down.

The gradient in Figure 3(b) is calculated between 54 AU and 1 AU because, at present, this work includes

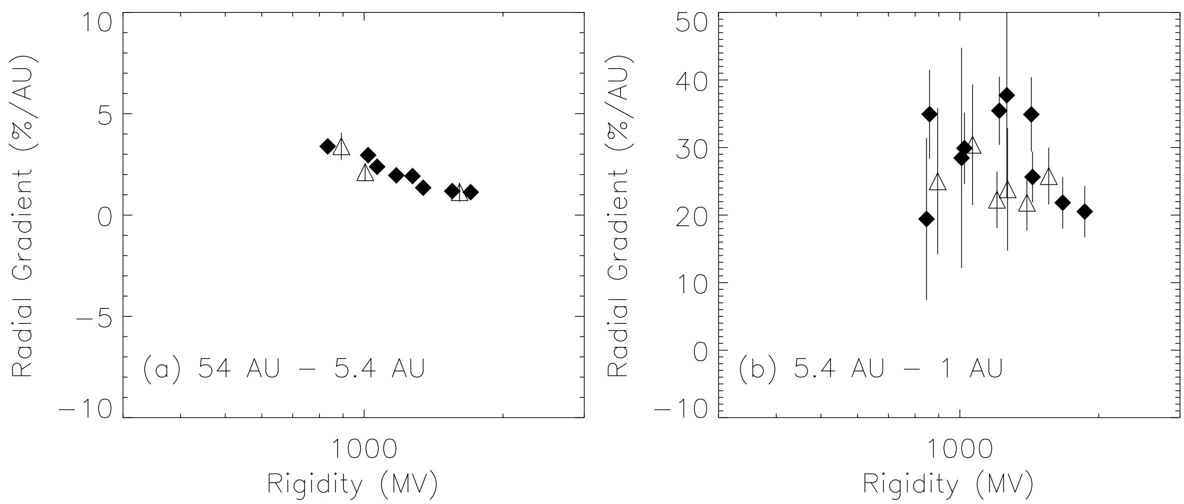

Figure 4: Radial Gradient (% per AU) vs. rigidity for ACRs. The symbols show the different elements: N (open triangle) and O (filled diamond). (a) Gradient between 54 AU (Voyager 2) and 5.4 AU (Ulysses) (b) Gradient between 5.4 AU (Ulysses) and 1 AU (ACE / SAMPEX)

only limited Ulysses data. Radial gradients over a smaller range of rigidity are shown for 54 AU - 5.4 AU and 5.4 AU - 1 AU in Figures 4(a) and 4(b) respectively. The rigidity dependence of the gradient in Figure 4(a) is obvious, but it is not clear in Figure 4(b).

4 Summary:

Clearly, more work needs to be done, and the addition of more Ulysses data will also be very useful. Several conclusions can be made, however. For this $A > 0$ solar minimum period, nearly all of the modulation of the GCRs is occuring beyond 70 AU. For the ACRs, the gradients in the outer heliosphere are small and not rigidity dependent. The ACR radial gradients increase with decreasing radial position, reaching ˜25 % per AU in the inner heliosphere, consistent with earlier measurements (Marsden *et al.* 1998). In the middle heliosphere, the radial gradient decreases with increasing rigidity, because the diffusion coefficient is increasing. Why this is not apparent in the outer heliosphere is a question for future work.

5 Acknowledgements:

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