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Intensity Gradients of Anomalous Cosmic Rays Between 1 AU and Voyager During Solar Cycle 23

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Using ACE/SIS data we obtain measurements of the variation of the anomalous cosmic ray (ACR) O intensity at 1 AU throughout the solar cycle, including periods near solar maximum. After being suppressed by a factor of ∼100 or more from 2001 through 2003 during solar maximum, ACR intensities are once again recovering at 1 AU, but their intensities are lower relative to higher rigidity galactic cosmic rays (GCRs) than they were during entry into solar maximum in 1998-2000. Comparison of the 1 AU ACR and GCR time variations with those measured by both Voyager spacecraft in the outer heliosphere shows that both ACR and GCR large-scale radial gradients are greater at solar maximum than at solar minimum, and that the ACR radial gradients are much larger than those of the GCRs, becoming very large inside of ∼5 AU.

1. Introduction

Measurements of anomalous cosmic ray (ACR) and galactic cosmic ray (GCR) intensities throughout the heliosphere during the solar cycle can be used to study the effects of solar modulation on cosmic ray transport. Many studies have shown that ACR and GCR intensities and their gradients vary with radial distance (e.g., [1]), heliographic latitude [2], phase [3] and polarity [4] of the solar cycle, and particle rigidity [5]. Most previous ACR gradient studies that used a 1 AU baseline were not done under solar maximum conditions, since at 1 AU near solar maximum ACR intensities are severely reduced and suffer contamination from frequent solar energetic particle (SEP) events. To define quiet time periods for this study, we use a ratio of He intensities from SIS on ACE [6] as illustrated in Figure 1. Large SEP events produce elevated intensities at both the higher and lower energies (horizontal and vertical axes), while smaller events affect only the lower-energy rate, most often when the higher energy rate is low (heavily modulated) near solar maximum. The line shown (low energy rate = high energy rate / 0.6) indicates the data cut adopted here to select days regarded as quiet. This cut is essentially equivalent to requiring that "quiet" days have a daily average He spectrum from 6-30 MeV/nucleon with an index harder than about -0.55, independent of phase of the solar cycle.

Shown in the right panel of Figure 1 are oxygen spectra accumulated over the resulting quiet days during three time periods: solar minimum, near solar maximum, and the recent initial ACR recovery (see Figure 3). Our solar maximum ACR oxygen intensity is almost a factor of 2 lower than that reported at the same time and energy using Wind data [7]. Their quiet selection criteria (2.0-3.7 MeV/nuc He $<2\times10^{-4}$ (cm^2 sr s MeV/nuc)$^{-1}$) may be less stringent and may have subjected their results to SEP contamination.

2. Discussion

Our quiet time oxygen intensities are shown in Figure 2 along with earlier data going back 3 solar cycles. When plotted as shown in the figure, the Climax neutron monitor rate matches the ACR oxygen data during the A>0 magnetic polarity cycle of the 1970's and during the decline of the last A>0 cycle; differences in the ACR and

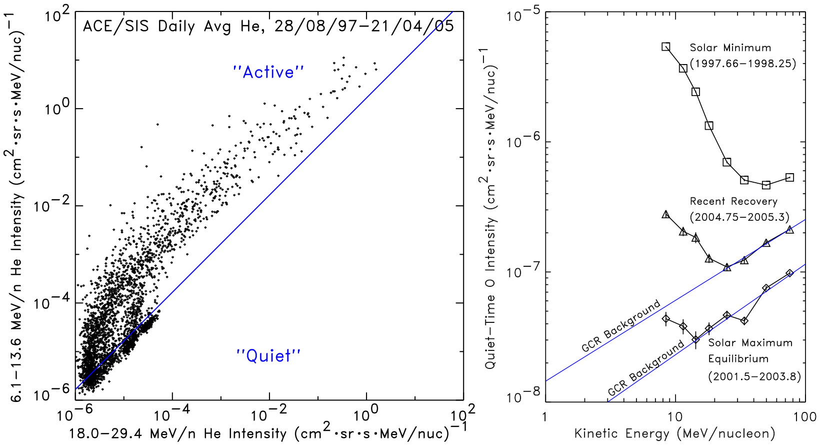

Figure 1. *Left panel:* Daily-averaged 6.1-13.6 MeV/nucleon He intensity vs. 18.0-29.4 MeV/nucleon He. *Right panel:* Oxygen spectra accumulated over quiet days in the 3 time periods indicated.

GCR recovery during 1992-1994 led to the conclusion that much of the GCR modulation occurs beyond the termination shock [9]. The ACR oxygen fell short of the scaled neutron monitor during the last A<0 cycle, apparently due to the effects of particle drifts [10], and is doing so again during the initial ACR recovery in the present cycle which has clearly begun. The lag in the ACR recovery relative to that of the neutron monitor is seen more clearly in the hysteresis plot in the right panel of Figure 2. The 108-day averages are connected by a line which starts at the upper right during the 1997 solar minimum period, runs to the lower left along the upper trace, and starts back up along the lower trace. So far the recovery appears to be following the same slope as the last decline, with the ACR O intensity scaling as the neutron monitor rate to the ∼25th power, but with a significant offset between the decline and recovery tracks.

During the period of the ACE measurements at 1 AU, the Voyager spacecraft were probing the outer heliosphere at distances of ∼50-95 AU. Figure 3 compares oxygen time profiles from the CRS instruments on Voyagers 1 & 2 [11] and ACE/SIS. Although the oxygen intensities at 1 AU dropped by a factor of ∼100 between solar

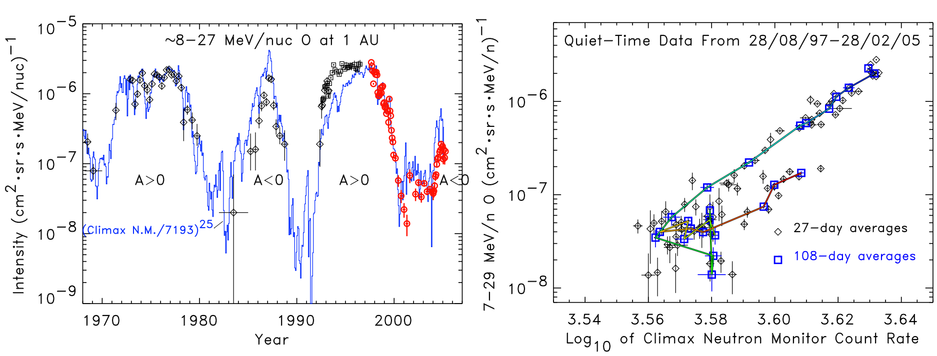

Figure 2. *Left panel:* Quiet time intensities of ∼8-27 MeV/nuc oxygen from ACE/SIS (*circles*), SAMPEX (*squares*), and earlier missions (OGO-5, IMP 6, 7, 8; *diamonds*) (see [8] for references) compared with the scaled Climax neutron monitor rate (*histogram*). *Right panel:* 7-29 MeV/nuc oxygen intensity vs. the Climax neutron monitor count rate.

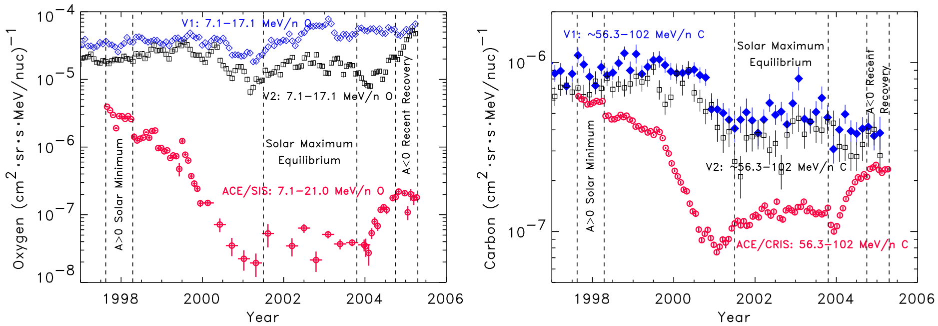

Figure 3. Oxygen intensity (*left*) (mostly ACRs during solar minimum, but with no GCR background subtraction) and GCR carbon (*right*) vs. time from ACE (*circles*), Voyager 1 (*diamonds*), and Voyager 2 (*squares*). The three time periods used for the gradient study are indicated between vertical dashed lines.

minimum and maximum, there was hardly any change in the outer heliosphere; at Voyager 1 the intensities actually increased near solar maximum (largely due to Voyager 1's increased radial distance compared with solar minimum). At solar maximum, the ACR intensities at Voyager 1 were ∼1000 times greater than those at 1 AU, while at solar minimum the rates in the two locations were within a factor of ∼10 of each other. The start of the ACR recovery at 1 AU is followed ∼6 months later at Voyager 2, while almost no residual ACR modulation exists at Voyager 1 so there is no recovery. Unlike ACR O, at solar minimum the GCR carbon intensities are practically the same at 1 AU as in the outer heliosphere, and even during solar maximum the rates are only a factor of ∼5 higher at the Voyagers than at ACE. As noted before for GCR He [12], the intensity decline of GCR C from 1999-2001 moves out through the heliosphere as it first appears at ACE and then ∼1 year later at Voyager 2 and finally Voyager 1. The recent recovery in GCR intensities at 1 AU does not seem to have reached either Voyager 1 or Voyager 2, indicating that the recovery at 1 AU was effective only inside 75 AU and that most of the GCR modulation at Voyager 1 occurs in the heliosheath.

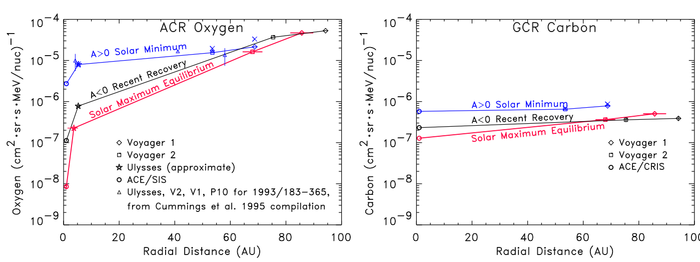

Figure 4. Intensity versus radial distance for ACR oxygen (*left*) and GCR carbon (*right*) from ACE (*circles*), Voyager 1 (*diamonds*), Voyager 2 (*squares*), and Ulysses (*stars*; see text) during the three time periods of interest. For solar minimum, values from an earlier study [4] (*triangles*) and without latitudinal gradient corrections (*crosses*) are also shown.

The "solar minimum" and "solar maximum equilibrium" periods we select are indicated in Figure 3. Both ACR and GCR intensities at 1 AU were somewhat higher during our "solar maximum equilibrium" period than during intervals on either side of it, but during the period we chose the intensities seem to have stabilized throughout the heliosphere. Also, the inferred mean free paths for ACR He and O in the outer heliosphere more nearly resemble solar maximum values during this period than they did during late 2000/early 2001 [13].

Summing over the selected periods and, for the ACRs, subtracting the GCR O background indicated in Figure 1, results in the intensities shown versus radial distance from the Sun in Figure 4. To help cover the wide gap between 1 and >50 AU, online rate data from COSPIN/LET on Ulysses were obtained. Using COSPIN/LET H and He daily-averaged intensities, quiet days were selected in a manner analogous to that illustrated in Figure 1 and the accumulated 7.1-39 MeV/nucleon CNO intensities in our 3 time intervals were calculated. Estimated background due to GCR O, N, and C as well as ACR N was subtracted and a correction applied to account for the different energy intervals in the Ulysses and ACE data. For the A>0 solar minimum we corrected all the data shown for a latitudinal gradient (+1.3%/° for ACRs, +0.3%/° for GCRs). Although a larger negative gradient is expected during A<0, the recovery is far from complete and it is uncertain whether this gradient is established yet or not; so far we have not corrected the recent recovery data.

3. Conclusions

Throughout the heliosphere, the ACR radial gradients are found to be greater at solar maximum than solar minimum, with the initial stages of the recent recovery falling somewhere in between. The ACR radial gradients between ∼5 and ∼95 AU are nearly independent of radial distance in all 3 periods, and become much greater inside of 5 AU [3]. While the intensity of ACR oxygen varies by nearly 4 orders of magnitude between 1 AU at solar maximum and the outer heliosphere at solar minimum, GCR carbon varies by less than a factor of 10, and the steep increase in ACR radial gradients in the inner heliosphere is not seen in the GCR gradients. Like the ACR gradient, the GCR radial gradient is greater during solar maximum than during solar minimum [14]. The lack of recovery so far in the outer heliosphere GCR C intensities suggests that the heliosheath has not yet recovered towards solar minimum conditions.

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