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The Level of Solar Modulation of Galactic Cosmic Rays from 1997 to 2005 as Derived from ACE Measurements of Elemental Energy Spectra

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1. Introduction

In the inner heliosphere, intensities of cosmic-ray nuclei with energies below a GeV/nucleon are strongly modulated by the interaction with the magnetic field carried by the expanding solar wind. Consequently these particle intensities undergo a sizable variation over the solar cycle. In order to predict the radiation environment in interplanetary space, which can present a serious hazard to astronauts on long-duration missions, it is important to quantify and ultimately to understand these variations.

The Cosmic-Ray Isotope Spectrometer (CRIS) [1] on the Advanced Composition Explorer (ACE) mission makes statistically precise measurements of elements from Li ($Z = 3$) through Zn ($Z = 30$) in the energy range ~ 50 to ~ 500 MeV/nuc close to the peak of the cosmic-ray energy spectrum. We have used CRIS data collected from September 1997 to June 2005 to investigate cosmic-ray time variations from solar minimum to solar maximum and into the declining phase of solar cycle 23. This work extends our previous investigations of interplanetary cosmic-ray intensities as observed with CRIS [2, 3, 4].

2. Data Analysis and Results

Elemental energy spectra from CRIS are available from the ACE Science Center web site [5] on various time bases. For this study we have used data averaged over 27-day Bartels rotations. Figure 1 shows the oxygen intensities measured at 8 different energies during 3 different Bartels rotations (filled symbols). Also plotted are a family of model curves produced by combining a leaky-box model of interstellar propagation with a simple, spherically-symmetric model of solar modulation. Parameters of the propagation model [6] were adjusted to reproduce secondary-to-primary ratios (B/C, Sc+Ti+V/Fe) measured with CRIS and the high-energy spectra measured with the HEAO-C2 experiment [9] (open points in Fig. 1). The solar modulation calculation includes convection, diffusion (diffusion coefficient $\propto \beta R^1$ where R is magnetic rigidity), and adiabatic deceleration under steady-state conditions and is performed numerically using the technique of Fisk [7]. We follow the common practice of characterizing the modulation level by the modulation parameter ϕ (MV) [8]. Varying the value of ϕ changes the rate of low-energy roll-off of the calculated spectra at 1 AU. For each value of ϕ we calculate the χ^2 deviation of the measured spectral points from the curve. Starting from a grid of ϕ values with a resolution of 10 MV, a ϕ value is assigned to each Bartels rotation by choosing the value that minimizes χ^2.

Figure 2 shows the time dependence of the resulting ϕ values obtained from Bartels rotations 2241 through 2345 (September 1997 to June 2005). Values of ϕ derived using spectra of three abundant elements, C, O, and Fe, are shown (values obtained from Mg and Si lie between those obtained from O and Fe). Starting from a

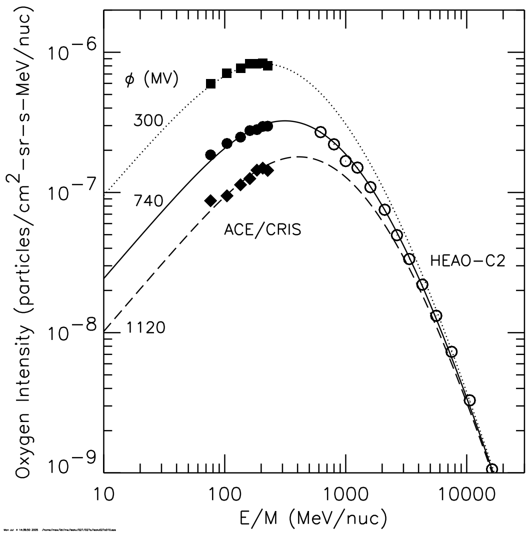

Figure 1. Cosmic-ray oxygen energy spectra measured during various Bartels rotations using CRIS: filled squares–rotation 2241 (Sept. 1997), filled circles–rotation 2274 (Feb. 2000), filled diamonds–rotation 2286 (Jan. 2001). Open points were obtained by HEAO-C2 [9] during a period in 1979-80 with modulation level $\sim$ 740 MV comparable to that during Bartels rotation 2274. Curves show results of the cosmic-ray propagation and solar modulation calculations for the indicated values of the modulation parameter, ϕ. Rotations 2241 and 2286 had the lowest and highest modulation levels, respectively, since the launch of ACE.

solar minimum value of $\sim$325 MV in 1997, ϕ briefly peaked at a value of approximately 1100 MV in early 2001 and then declined to $\sim$900 MV where it remained until early 2004. Since that time ϕ has been decreasing with the approach of a new solar minimum and in early 2005 had a value of $\sim$600 MV.

3. Discussion

ACE has provided an essentially-continuous monitor of cosmic-ray intensity in interplanetary space that now extends over nearly 8 years. The ACE spacecraft and the CRIS instrument are in good health and should be capable of extending the data set well into the next solar cycle and beyond. However for purposes of obtaining a measure of the cosmic-ray modulation parameter covering times prior to the ACE launch it is of interest to investigate correlations with neutron monitor counting rates. Neutron monitor data records from a number of stations cover the past 4+ solar cycles and should be continuing into the future. The left-hand panel in Figure 3 shows the correlation between the ϕ values derived from the CRIS data and the counting rate from the Climax neutron monitor [10] averaged over full Bartels rotations. Although the general correlation is evident, there is a clear hysteresis. Over the past year as ϕ has decreased from $\sim$900 MV to $\sim$600 MV, the neutron monitor counting rate has been at a level $\sim$4% higher than during the period when ϕ had comparable values during rising phase of solar cycle 23. If the overall correlation with the neutron monitor rate were to be used to derive the modulation level, one would have an uncertainty of at least $\pm$100 MV unless the hysteresis could be properly taken into account.

A similar hysteresis is observed in the CRIS data set alone, as illustrated in the right-hand panel in Figure 3. Here the particle intensities from the lowest- and highest-energy intervals measured with CRIS are plotted

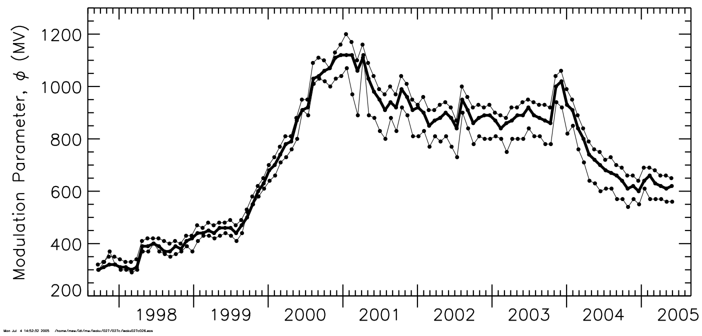

Figure 2. Time dependence of the solar modulation parameter, ϕ, derived from the energy spectra of the elements carbon (upper light curve), oxygen (heavy curve), and iron (lower light curve).

versus one another for the elements C and O. In both cases the recovery of the higher-energy intensity has been leading that of the lower-energy intensity.

In Figure 4 we put the observed time dependence of the cosmic-ray modulation parameter in the context of other familiar solar-cycle dependent quantities. The panels show: (a) smoothed sunspot number, (b) Climax neutron monitor counting rate [10], (c) the modulation parameter derived using the CRIS galactic cosmic-ray (GCR) oxygen spectra, (d) the occurrence of solar energetic particle (SEP) events as indicated by the intensity of 21–29 MeV/nuc oxygen from the Solar Isotope spectrometer (SIS) on ACE, and (e) the anomalous cosmic-ray (ACR) intensity as indicated by the 7–10 MeV/nuc oxygen intensity restricted to solar quite times (an ACR contribution is also seen in the time variation of the baseline in the SEP panel). When the ACR intensity is at its lowest level the oxygen intensity shown includes significant contamination from GCR oxygen that has been decelerated while penetrating into the inner heliosphere. The singly-charged ACR oxygen (panel e) had a magnetic rigidity ∼2.0 GV, which less than that of the particles measured by the Climax neutron monitor

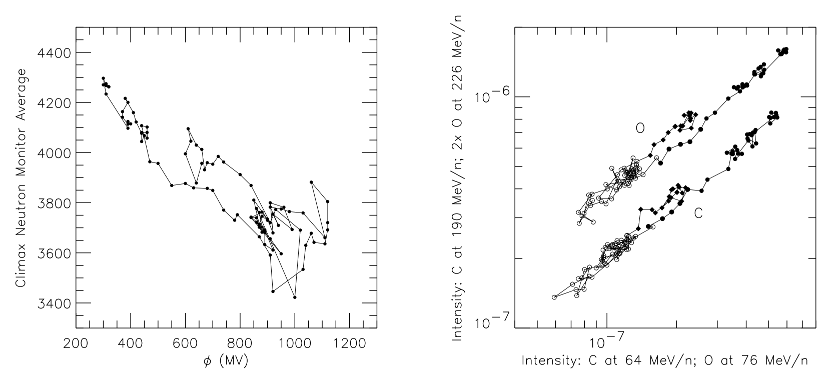

Figure 3. Left panel: correlation between modulation parameter and Climax neutron monitor counting rate [10] averaged over full Bartels rotations. Right panel: correlation between lowest- and highest-energy intensity points measured by CRIS for the elements C and O. The O intensity on the vertical scale has been multiplied by 2 to separate the two curves. Symbols distinguish time periods: filled circles–Bartels rotations 2241 to 2275 (Sept. 1997 to Apr. 2000); open circles–rotations 2276 to 2328 (Apr. 2000 to Mar. 2004); filled diamonds–rotations 2329 to 2345 (Marx. 2004 to Jun. 2005).

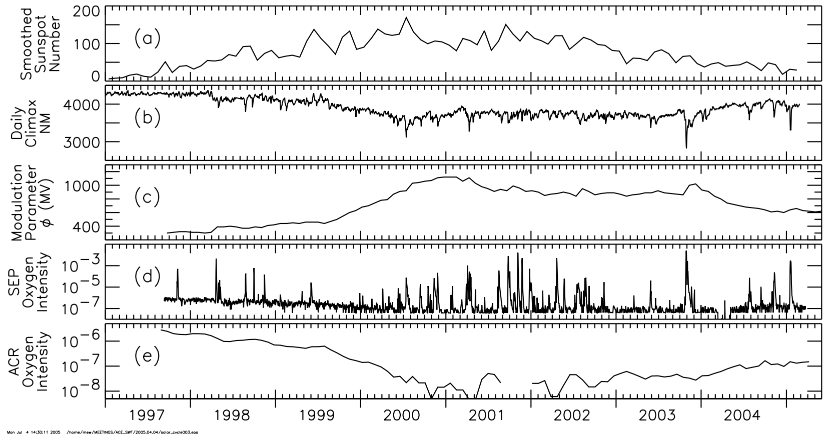

Figure 4. Comparison of the solar cycle dependences of: (a) sunspot number; (b) Climax neutron monitor; (c) modulation parameter, ϕ; (d) SEP event occurrence; and (e) ACR oxygen intensity. See text for details.

($\gtrsim$3 GV) but greater than that of the highest-energy (fully-striped) GCR oxygen used in deriving the modulation parameter ($\sim$1.4 GV).

The familiar delay between the sunspot cycle (panel a) and the related energetic particle signatures (panels b through e) both during the rising and declining phases of the cycle is evident. Between the sunspot number and the cosmic-ray modulation parameter this delay is $\sim$12–15 months. Following some of the large SEP events, which are associated with fast coronal mass ejections (CMEs), one sees Forbush decreases in the neutron monitor rate and also accompanying increases in the modulation parameter indicating that the 50–500 MeV/nuc GCR intensity measured by CRIS also decreased. The most evident instances of the cosmic-ray intensity responding after a large SEP events are in April 1998, October/November 2003, and January 2005. During the period from mid-2001 through 2002 when there was a high rate of large SEP events, the cosmic-ray modulation level remained relatively constant rather than undergoing a further increase. The ACR intensity modulation, although of a much larger amplitude that of the GCRs, tracks the large-scale time variation of the modulation parameter rather closely, with the ACR response possibly leading by a month or two.

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