Time Dependence of Solar Modulation throughout Solar Cycle 23 as Inferred from ACE Measurements of Cosmic-Ray Energy Spectra

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***Abstract*. Since the launch of the Advanced Composition Explorer (ACE) in August 1997, the Cosmic Ray Isotope Spectrometer (CRIS) has been providing measurements of cosmic-ray energy spectra between ∼50 and ∼500 MeV/nuc for a wide range of elements. The shape of these low-energy spectra, which are measured with good statistical precision on time scales as short as a solar rotation, are strongly influenced by modulation in the heliosphere. By combining calculated local interstellar spectra from a leaky-box propagation model with a spherically-symmetric, steady-state model of solar modulation, we have derived the time dependence of the modulation strength throughout solar cycle 23. In addition, we have investigated hysteresis effects in the modulation by comparing time dependences at different energies in two ways. First, we have compared values of the modulation parameter, ϕ, calculated based on CRIS spectral measurements with published values derived from neutron monitor data. Second, we have studied effects over relatively small energy ranges by comparing CRIS intensity measurements at different energies. We report the ACE/CRIS observations, discuss the trends in the data, and compare with previous results on the variations of the solar modulation level over the solar cycle.**

***Keywords*: cosmic-ray modulation, energy spectra**

I. Introduction

The near-Earth intensity of galactic cosmic rays (GCRs) with energies of a few hundred MeV/nuc varies by up to an order of magnitude over the course of an 11-year solar cycle. These variations are of interest both as probes of the modulation process and because of the radiation hazard these particles present for astronauts and space instrumentation. The Cosmic Ray Isotope Spectrometer (CRIS) on NASA's Advanced Composition Explorer (ACE) mission has been making high-statistical-accuracy measurements of the energy spectra of cosmic ray heavy elements with $Z \leq 28$ since the launch of ACE in August 1997. CRIS measurements of composition and spectra obtained under solar minimum (August 1997 to April 1998) and solar maximum (May 2001 to September 2003) conditions have recently been reported [1].

Galactic cosmic ray spectra near Earth have maxima near ∼500 MeV/nuc as the result of solar modulation (including adiabatic energy losses) occurring between the local interstellar medium and the inner heliosphere. The energy range covered by CRIS, extending a factor of ∼5–10 below this maximum, is particularly useful for monitoring changes in solar modulation conditions. For the more abundant elements such as C, O, Ne, Mg, Si, and Fe, CRIS precisely determines the shape of the spectra on time scales as short as a solar rotation (27 days). We have been monitoring the evolution of these spectra over the past 11+ years and using them to infer the strength of solar modulation by comparing with calculated spectra. Results extending to June 2005 have previously been reported [2]. Over the subsequent ∼4 years, cosmic-ray modulation continued to decrease, reaching the lowest level since the launch of ACE, and possibly the lowest since cosmic rays have been measured in space. In this paper we update the results of [2] to cover a full solar cycle.

II. Cosmic-Ray Variations

Bartels rotation averages of the CRIS cosmic-ray intensity measurements obtained from the ACE Science Center[1] were used for this study. Intensities at seven energies (corresponding to particles stopping at seven different depths in the silicon detector stack used by CRIS for measuring energy losses [3]) are available. The spectral points for a given element were compared with the results of a calculation involving a leaky-box model of interstellar propagation effects followed by a spherically symmetric solar modulation model based on the method of Fisk [4]. These calculations were constrained using primary and secondary GCRs measured with ACE and with the HEAO-C2 instrument at higher energies [5], as discussed in [6] and [2]. For the solar modulation

[1] http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_CRIS.html

calculation, which includes the effects of adiabatic deceleration as well as diffusion and convection, a diffusion coefficient of the form $\kappa(r,R) = \kappa_0\,\beta\,R^1$ was assumed, where β and R is the particles' velocity (in units of the speed of light) and rigidity, respectively. Thus, κ was taken to be independent of radius in the heliosphere (r) out to an outer boundary of the modulation region. The strength of the modulation was adjusted by varying κ_0, the magnitude of the interplanetary diffusion coefficient, while holding fixed these assumed rigidity and radial dependences, the solar wind speed ($V_{\rm SW}$), and the outer boundary distance (D). We find it convenient to express the strength of the modulation in terms of the parameter ϕ (MV):

$$\phi \equiv \frac{R}{3}\int_{1\,\rm AU}^{D} \frac{V_{\rm SW}(r)}{\kappa(r,R)/\beta}\,dr. \quad (1)$$

Although this modulation parameter was introduced in connection with the force field approximation [7], we are not making that approximation.

The lower panel of Figure 1 shows the time variation of ϕ over the course of solar cycle 23, as derived from the CRIS measurements of the C energy spectrum. Similar curves can be derived from measured spectra of other elements and should yield similar values if the model adequately describes the modulation. The upper panel of Figure 1 shows the differences between ϕ values derived for other major elements and those obtained for C. The largest differences are $\sim$50–75 MV at solar minimum and $\sim$200 MV at solar maximum. Furthermore, the values derived from different elements have a consistent ordering, with ϕ decreasing with increasing Z. A possible source for such an ordering could be the fact that the energies covered by the CRIS measurements increase with increasing Z, so if the rigidity dependence of ϕ is actually stronger than the assumed R^1, the strength of the modulation would appear weaker for the heavier elements.

Usoskin et al. [8] have used data from the worldwide neutron monitor network to derive monthly values of ϕ going back to 1951. We will denote these values as ϕ_{NM} to distinguish them from the CRIS-derived values. The neutron monitor counting rates include contributions from all cosmic-ray elements, but are dominated by the H and He intensities. In addition, these data are most sensitive to energies in the GeV/nuc range, somewhat higher than the CRIS data. The force field approximation was used in [8] for deriving $\phi_{\rm NM}$, but at these high energies little difference is expected from the value obtained using Fisk's method. In Figure 2 we compare Usoskin et al. [8] $\phi_{\rm NM}$ values for times since the ACE launch with those we obtain from CRIS. The modulation parameters derived using these different data sets have very similar time profiles and are also in rather good quantitative agreement through much of the 11+ years. One extended period where there is a sizeable difference between the two ϕ values extends from the later part of 2000 through mid-2001, following the strong increase

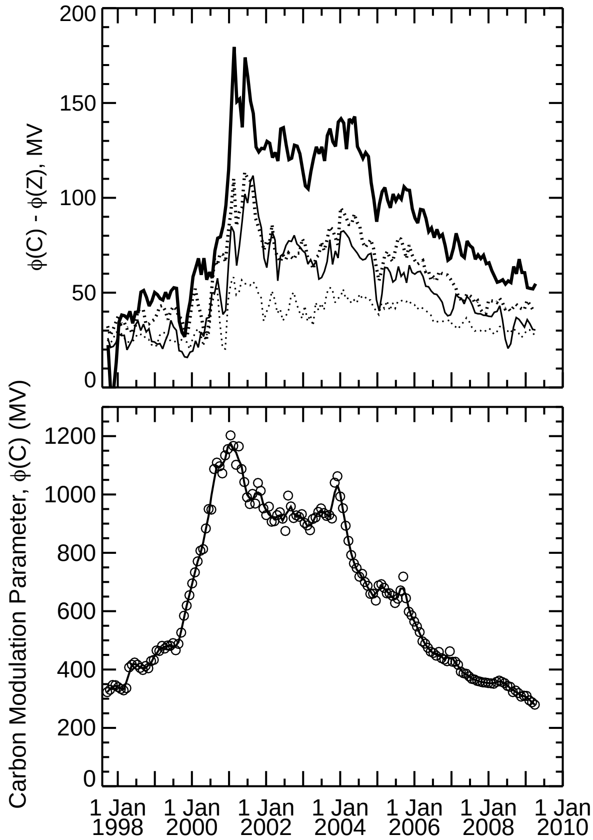

Fig. 1: Bottom panel: Time dependence of the solar modulation parameter, ϕ, derived from ACE/CRIS measurements of the carbon spectrum. Points show values for individual Bartels rotations, curve shows a 3-rotation smoothing of these values. Top panel: Difference between ϕ values derived from the carbon spectrum and those derived from other elements (thin dotted line: O; thick dotted line: Mg, thin solid line: Si, thick solid line: Fe). Curves are based on 3-rotation smoothed ϕ values.

in modulation after the major solar activity associated with the Bastille Day 2000 event. There is a similar period, starting a few months later, when the agreement among ϕ values derived from the CRIS energy spectra of different elements is the poorest (Fig. 1). Given that solar modulation is being modeled as a quasi-steady-state process while large-scale magnetic structures in the solar wind take $\sim$1 year to be transported to the outer heliosphere at the solar wind speed, it perhaps should not be surprising that discrepancies of this duration are found after major disturbances in the interplanetary field cause significant changes in the modulation level.

The changes in $\phi_{\rm NM}$ tend to lead those in the ϕ derived from CRIS data by several months. In addition to being delayed, the short-term variations seen in $\phi_{\rm NM}$ tend to be smoothed out and reduced in amplitude in the ϕ obtained from the CRIS spectra. This behavior suggests that there is a longer characteristic time constant for the heliosphere to adjust to cosmic-ray-modulating disturbances at low energies than there is at

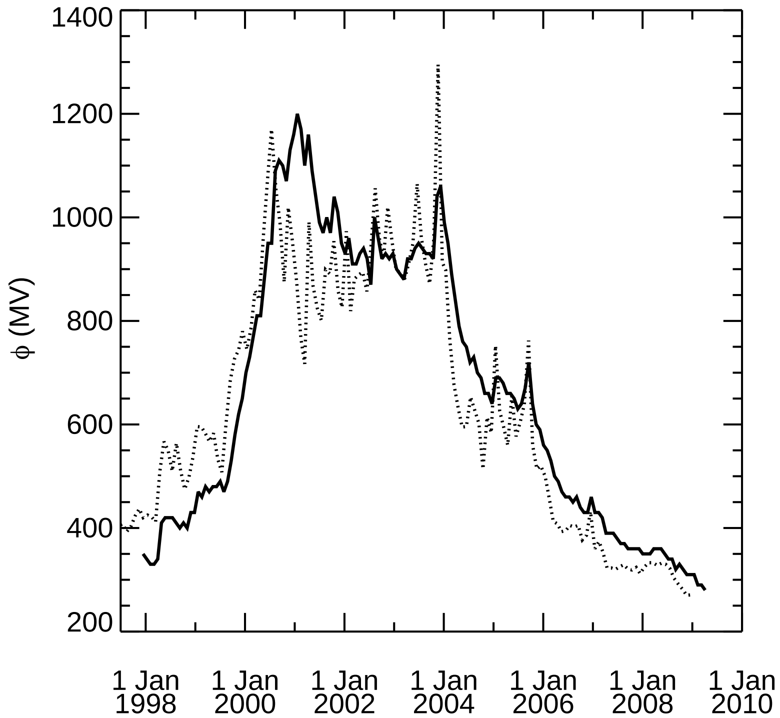

Fig. 2: Comparison of solar modulation parameters derived from ACE/CRIS carbon spectrum (ϕ, solid line) and from neutron monitor data [8] ($\phi_{\rm NM}$, dotted line).

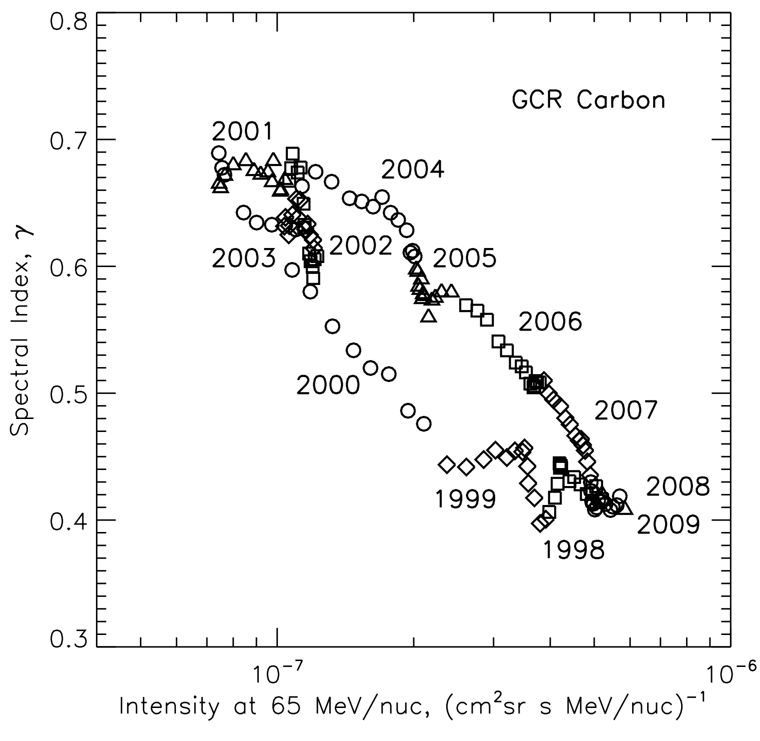

Fig. 3: Hysteresis in the response of the GCR carbon spectrum to changing solar modulation. The ordinate displays the spectral slope, $\Delta \ln J / \Delta \ln E$, calculated between the energies of 65 and 190 MeV/nuc. Data from different years are indicated with different symbols to show the time sequence of the points: 1998, 2002, and 2006, squares; 1999, 2003, and 2007, diamonds; 2000, 2004, and 2008, circles; 2001, 2005, and 2009, triangles. Each data point is an average over 7 consecutive Bartels rotations.

high energies. This may be associated with the increase of the heliospheric diffusion coefficient with increasing rigidity.

The more-rapid response of the higher-energy cosmic rays to changing modulation conditions, which was noted in [2], results in a “hysteresis curve” when plotting cosmic ray intensities at two different energies versus one another. Hysteresis effects are evident even over the energy range of the CRIS measurements, which typically span a factor ~ 3 in energy for a particular element [2]. An alternative way of displaying this effect is shown in Figure 3, which compares CRIS carbon intensities at 65 and 190 MeV/nuc by plotting the average spectral slope between these two points versus the intensity at the lower of the two energies. Points for each Bartels rotation are shown as a running average of 7 successive rotations in order to smooth the relatively large rotation-to-rotation fluctuations. At a given value of the 65 MeV/nuc carbon intensity, the energy spectrum was flatter during the transition from solar minimum to solar maximum (1998–2000) than during the return from solar maximum to solar minimum (2004–2007), reflecting the more rapid response of the higher energy particles to changing modulation conditions.

III. Conclusions

The availability of essentially uninterrupted time series of cosmic-ray intensity measurements extending over a full solar cycle or more and covering a range of magnetic rigidities can provide new constraints on models of cosmic-ray solar modulation. By applying models that go beyond the quasi-steady-state analysis of the type used in this work and taking into account dynamical aspects of the response of cosmic rays to changing heliospheric conditions (e.g., [9]), it should be possible to gain insights into questions related, for example, to the radial and rigidity dependences of the interplanetary diffusion coefficient and the size of the modulation region.

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