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Onset of solar modulation in the outer heliosphere as seen in anomalous cosmic rays

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Abstract. We examine intensities and gradients of anomalous cosmic rays determined from observations on the Voyager 1 and 2 spacecraft to study the rapid increase in solar modulation that begins near mid-2000. We suggest that these effects are due to the arrival in the region of the spacecraft of complex magnetic field topologies associated with the reversal of the Sun's magnetic field.

1   Introduction

The 22-year solar magnetic cycle is characterized by two roughly equal periods when the Sun's field is either predominantly positive in the northern hemisphere (A>0) or negative (A<0). During the A<0 cycle (last complete was ∼1980-1990), positively charged anomalous cosmic rays (ACRs) are thought to arrive at spacecraft in the outer heliosphere from their source at the solar wind termination shock by rapidly drifting along the heliospheric current sheet and then drifting upwards towards the poles of the heliosphere (Jokipii and Thomas, 1981). The changing tilt or warp of the current sheet causes significant changes in the gradients and intensities of ACRs during this portion of the cycle (Stone and Cummings, 1999). During the A>0 cycle (e.g., 1990-2000), the drift patterns are reversed and ACRs drift down from the polar regions to the lower latitudes where spacecraft in the outer heliosphere are located. ACR intensities are observed to be relatively insensitive to the tilt of the current sheet in this portion of the cycle.

The onset of solar modulation effects, signalling the end of solar minimum, is typically ascribed to Global Merged Interaction Regions (GMIRs) (Burlaga et al., 1984, 1993; McDonald and Burlaga, 1997) that are created during solar active times when shocks from coronal mass ejections merge, creating long-lived Forbush decreases. A series of GMIRs lead to step-like decreases in the intensity-time profiles (McDonald et al., 1981). A recent study (McDonald et al., 2000)

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identifies the modulation onset at V2 at ∼1999.5 and at V1 at perhaps ∼1999.85. In this study we investigate a subsequent rapid increase in modulation that occurs with the arrival of the increasingly complex magnetic field topology associated with the reversal of the Sun's magnetic field. We suggest that large scale drifts are disrupted by the complex topology, leading to deeper levels of modulation at that time.

2   Observations and Analysis

Figure 1 shows the intensity of 7.1-17.1 MeV/nuc O and 5-7.8 MeV/nuc He at Voyager 2 (V2) from 1993 to 2001/104. At these energies and during the period shown in Figure 1 the intensities are almost entirely due to ACRs. The bottom panel shows the tilt of the current sheet from the Wilcox Solar Observatory shifted to the position of V2 using solar wind speeds from IMP-8 and ACE. The insensitivity of the ACR intensities to the tilt can be seen by examining the period from 1994 through 1999.5. The tilt varies from ∼30° down to ∼10° in 1996 and back up to ∼40° at 1999.5. During this time the ACR O intensities exhibited a rather steady increase by a factor of ∼2 and the ACR He intensities increased steadily by a larger factor. A downward change in the intensity of ACR He occurs at ∼1999.5, marking the onset of modulation at V2 (McDonald et al., 2000). However, there is a transient increase that occurs in early 2000 that brings the intensity back to the highest levels observed in 1998 and 1999.

Up through mid-1999, the current sheet is well described by a simple warped sheet as can be seen from coronal source surface maps from the Wilcox Solar Observatory. The current sheet tilt is a good indication of the topology of a simply-warped current sheet. However, as the current sheet tilt continues to increase in the latter half of 1999 into 2000, the topology of the sheet becomes increasingly complex, and by the end of that year there may be more than one current sheet present as the solar magnetic field begins reversing.

In order to portray this increased topological complexity,
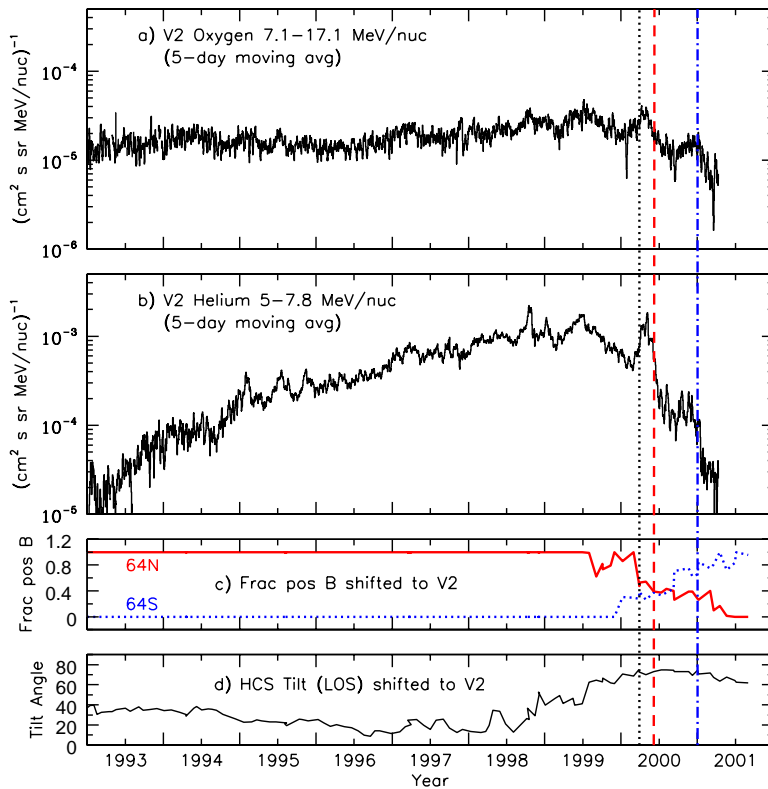
Fig. 1. a) Intensity of ACR O vs. time observed at Voyager 2. b) Same as a) except for ACR He. c) Magnetic field topology indices 64N and 64S (defined in the text) shifted to the location of V2 using solar wind speeds from IMP-8 and ACE. The vertical dotted, dashed, and dot-dashed lines mark the arrival time at V2 of the magnetic toplogy structures shown in the computed coronal field maps (Wilcox Solar Observatory, classic, line-of-sight method) from Carrington rotations 1952, 1955, and 1961, respectively. d) Tilt of the heliospheric current sheet (classic, line-of-sight method) from the Wilcox Solar Observatory shifted to the location of V2.

we have computed for each Carrington rotation (CR) the fraction of positive magnetic field at latitudes of 64°N and 64°S, based on the Wilcox Solar Observatory coronal field maps (classic, line-of-sight method). This polarity fraction is then time shifted to the location of V2 using Carrington rotation averaged solar wind velocities measured at 1 AU. As shown in Figure 1, the field at 64°N is predominantly positive at all longitudes on the Sun, and hence the "64N" index is 1.0 from 1993 to mid-1999. Similarly the field at 64°S is predominantly negative during solar minimum in this A>0 period, and so the "64S" index is 0.0 from 1993 to late 1999. The arrival of the increasingly complex current sheet is indicated by departures from these nominal values.

It is interesting to note that the significant increase in ACR flux beginning around 2000.2 occurs at about the time that there is significant positive and negative flux in both polar regions. By August 1999 (CR1952), the coronal map shows two sectors extending from one polar region to the other, a topology that arrives at V2 around 2000.24 (vertical dotted line in Figure 1). The current sheet topology continues to evolve rapidly with a second current sheet appearing in the solar model by late October, 1999 (CR1955). This would arrive at V2 around 2000.43 as shown in Figure 1 by the vertical dashed line. By April, 2000 (CR1961), the solar current sheet topology again resembles a tilted sheet with a very large tilt, but with the field now reversed. This topology would arrive at V2 by 2001.0. As seen in Figure 1, this corresponds to the onset of the minimum flux seen up to that

time (vertical dot-dashed line).

The comparison of these transitions in topology with Voyager 1 (V1) observations is shown in Figure 2. The same averaged solar wind velocities were used for this initial comparison, although V1 is at ~34°N while V2 is at ~22°S. Thus the timing is somewhat more uncertain. Even so, there seems to be a correlation between significant changes in the flux and transitions in the topology.

3 Discussion

Thomas et al. (1986) explored modulation during solar maximum with two models, one involving a highly inclined planar current sheet rotating through 90° tilt and a second involving multiple current sheets. Although highly simplified, both models qualitatively illustrated that either larger tilts or greater topological complexity could result in increased modulation. The level of modulation in the tilt model does depend on the tilt angle in a manner similar to that deduced by Stone and Cummings (1999). However, as the field reverses and the tilt angle rotates through 90°, the Thomas et al. model exhibits a modest recovery in the intensity.

As expected from such drift models, there was no significant change in the ACR flux at V2 as the tilt of the current sheet increased steadily to ~40° from mid-1998 to mid-1999, indicating the continuing presence of the large scale drifts expected during the A>0 cycle. When the flux of 5-7.8 MeV/nuc ACR He began decreasing in mid-1999, the tilt had
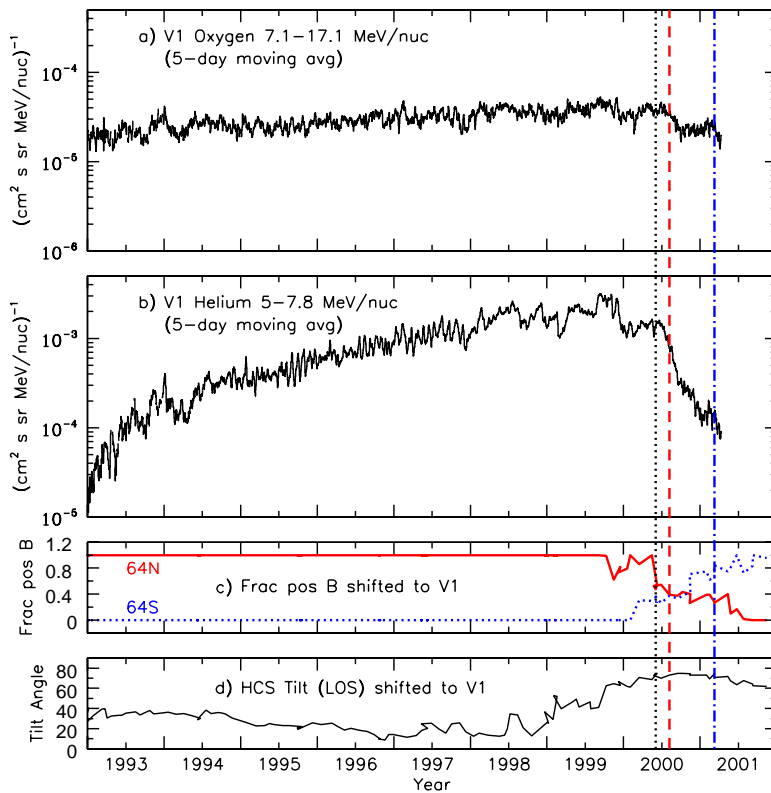
**Fig. 2.** Same as Figure 1 except for Voyager 1 instead of Voyager 2.

increased to $\sim 60°$. The flux subsequently decreased a factor of ~ 50 over the next 18 months, suggesting the disruption of the A>0 drift pattern due to the increasing topological complexity of the current sheet in the coronal field as the solar magnetic field reversed. This suggestion is further supported by the correlation of some of the topological transitions in the coronal field with the transitions in the ACR intensities and the lack of any significant corresponding changes in the tilt angle during this time.

In the absence of large scale drifts, diffusion will dominate particle propagation during periods of maximum modulation. We have recently investigated the diffusion mean free path of ACRs in the outer heliosphere for this time period (Cummings and Stone, 2001). The mean free paths are estimated using the force-field solution of cosmic ray modulation (Gleeson and Axford, 1968) in which $\lambda = 3 < r >< C > V/(c\beta A)$ where $< r >$ is the average radial position of V1 and V2, $< C >$ is the average Compton-Getting factor for V1 and V2 energy spectra, and $A = \ln(j_1/j_2)/\ln(r_1/r_2)$, which is determined from the V1 and V2 ACR energy spectra. Since the method does not account for the small positive latitudinal gradients expected during the A>0 portion of the cycle, the inferred values of λ are somewhat underestimated by this technique. The results for the period 1990 through 2001/104 are shown in Figure 3.

From 1992 to mid-2000, the gradients at 1.5 GV were small and $\lambda > 1$ AU. As discussed by Cummings and Stone (2001), these larger mean free paths are expected at higher

latitudes and the resulting smaller gradients are mapped onto lower latitudes by drifts. However, when drifts are disrupted, the particles must then diffuse inward at lower latitudes where increased turbulence results in much shorter mean free paths. As shown in Figure 3, the larger gradients and smaller mean free paths appear at about the time that the complex current sheet topology associated with CR1955 reaches V2 and the two polarity indices crossover.

As noted above, in CR1961 (April 2000 at the Sun), the current sheet once again resembled a tilted sheet with a large tilt, but with the polarity (A<0) of the new cycle. This reached V1 by 2001.2 and would have reached a termination shock at 90 AU by 2000.3. Thus the topological conditions should now allow the inward drift along the current sheet to be re-established as the amplitude of the current sheet tilt decreases. During the last solar cycle with A<0, Stone and Cummings (1999) found that at ~ 33 AU the tilt has to drop below $\sim 25°$ before inward drifts dominate diffusion and the radial gradient becomes proportional to the tilt angle. Voyager 1 and 2 are now much closer to the shock, so the onset of drifts may be observable at a different tilt angle. In January, 2002, V1 and V2 will be at 83 AU and 67 AU, respectively, and the tilt should be below 50°. When drifts again dominate, the dependence of the gradient on tilt should allow a determination of the remaining distance to the termination shock as was done for the last cycle with A<0 (Stone and Cummings, 1999).
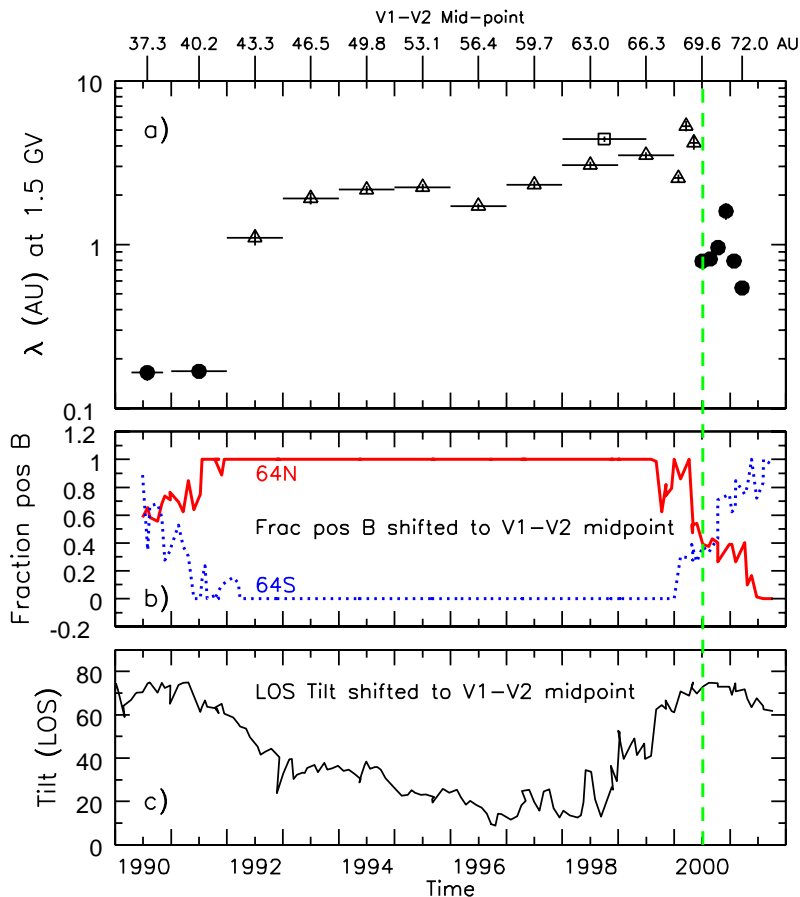
Fig. 3. a) Mean free path at 1.5 GV vs. time from Cummings and Stone (2001). The symbols beginning in 2000 are for 52-day periods. b) Magnetic field topology indices 64N and 64S (defined in the text) shifted to the V1-V2 mipoint location using solar wind speeds from IMP-8 and ACE. The vertical dashed line marks the arrival at the V1-V2 midpoint of the magnetic topology structures shown in the computed coronal field map (Wilcox Solar Observatory, classic, line-of-sight method) from CR1955. c) Tilt of the heliospheric current sheet (classic, line-of-sight method) from the Wilcox Solar Observatory shifted to the V1-V2 mipoint location.

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