# Cosmic Ray Spectra and the Solar Magnetic Polarity: Preliminary Results from 1994-2002

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**Abstract.** Each year, beginning in 1994, a U.S./Australia collaboration has conducted a neutron monitor latitude survey from the United States to McMurdo, Antarctica and back over a ~6-month period. This experiment permits us to observe the high-energy cosmic ray spectrum as it evolves from the last solar activity minimum, through the recent maximum and magnetic polarity reversal, and into the early stages of the new polarity epoch. In this work, we focus on the controversial issue of whether a high-energy (~8 GeV) "cross-over" exists in spectra observed during opposite magnetic polarities. We report on a preliminary analysis of the data and discuss our findings. In particular, we investigate the sensitivity of the modulated cosmic ray spectrum to the sign of the Sun's magnetic field.

## 1. INTRODUCTION.

Over the past eight years we have conducted an annual latitude survey which traversed the Pacific Ocean from Seattle, USA to McMurdo, Antarctica and return during a ~6-month interval each year. The monitor, a standard 3-NM64 design, is carried aboard one of two U.S. Coast Guard icebreakers, the *Polar Sea* or the *Polar Star*. The data from the surveys cover a wide range of cutoff rigidities, from ~0 GV at McMurdo to over 14 GV in the mid-Pacific. The survey technique ([1, 2] and references therein) has been used for many years to improve our knowledge of the neutron monitor response function and to test geomagnetic cutoff models. Differentiating the curve relating counting rate and cutoff rigidity produces the neutron monitor "differential response," which is a measure of the cosmic ray spectrum. There have been recent reports of one or more 'crossovers' in the spectral forms from two opposite magnetic polarity epochs (e.g. [1, 3, 4]. One of the major goals of this series of surveys is to try to observe such a crossover by deriving a series of cosmic ray spectra through a solar magnetic polarity change (as occurred in 1999/2000). We believe that this is the first set of observations which span the entire period from solar minimum to solar maximum at semi-regular intervals. Data reported in this paper extend through the first half of the 2001/2002 survey.

## 2. DATA AND METHODS.

Data were taken on eight separate trips from Seattle to McMurdo and return. These voyages are plotted in Fig. 1.; also shown are selected 1980 vertical geomagnetic cutoff contours. Counts from the three counter tubes are recorded once a second, together with data from pitch and roll inclinometers. Once a minute, pressure data and the GPS-derived latitude, longitude and time are recorded. In this preliminary study, we have not yet corrected for any possible effects resulting from non-level operation; however, the data we are utilizing in this paper are from regions where the geomagnetic cutoff is greater than 2 GV, which eliminates most periods of rough seas, especially near Antarctica.

We have calculated the effective geomagnetic cutoff for each hour of the surveys, at the exact time and location of the measurement, taking into account the applicable DGRF magnetic field model, geomagnetic activity level and tilt angle of the geomagnetic dipole (using the Tsyganenko model magnetosphere); [5, 6, 7, 2, 8].

During each survey, the monitor spent several weeks in the harbor at McMurdo, near the McMurdo neutron monitor. We used this period to normalize the total counting rate to the McMurdo monitor. This compensates for any instrumental changes which may have occurred from year to year. In December 2001 we installed the monitor in a new shipping container

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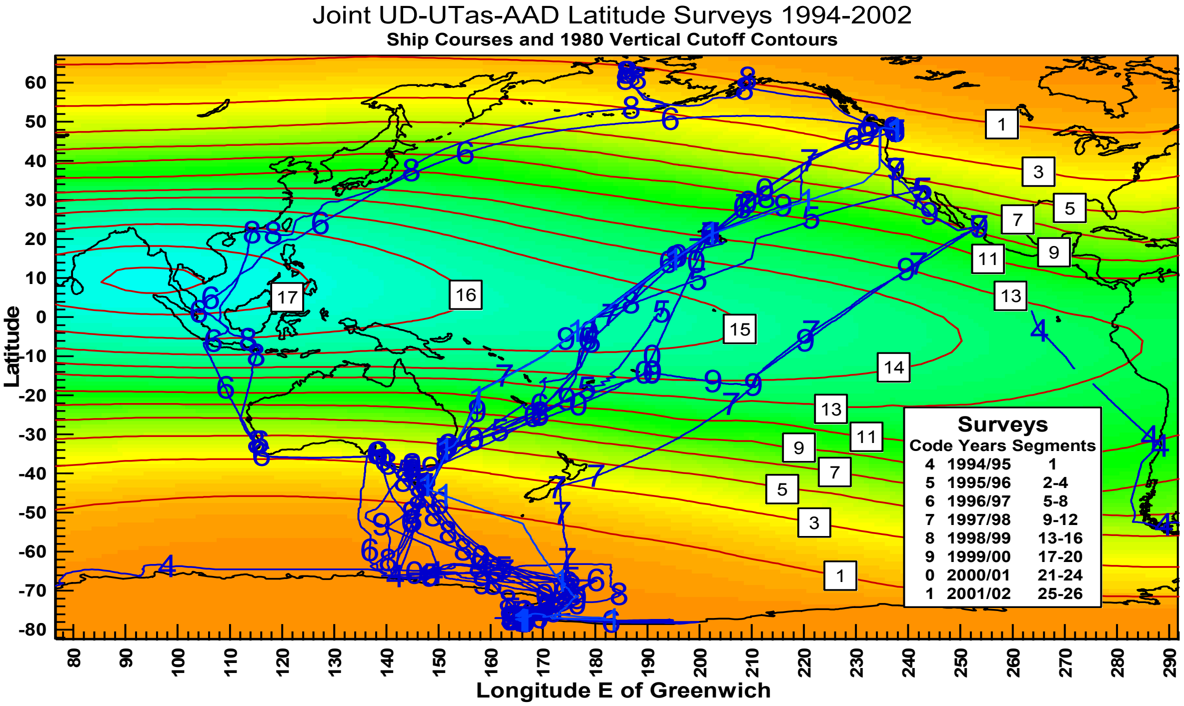

**FIGURE 1.** Course plots for the 8 surveys used in this paper. Each is labeled at 5-day intervals by the start year of the survey (e.g. 7 for 1997/98). "Segment" codes are given in the inset. Selected vertical cutoff contours are labeled.

during a port call in Hobart, Australia, and used the nearby Kingston neutron monitor to renormalize the data. Otherwise, during each survey year (approximately November-May), care was taken not to make any instrumental changes which might have affected the normalization.

In order to remove various noise problems encountered during the trips, the counting rate data were corrected on a minute-by-minute basis, time-corrected using onboard GPS clock data, and then pressure-corrected to 760 $\mathrm{mm_{Hg}}$ using a pressure coefficient varying with cutoff rigidity as follows: $\beta = 0.983515 - 0.00698286 * \mathrm{Pc}$, where $\beta$ is in percent per $\mathrm{mm_{Hg}}$ and Pc is in GV [8]. Since this series of observations was conducted during a period of frequent and often extreme changes in modulation level, we have organized the data to yield the highest time resolution possible, consistent with a significant sweep over a large range of cutoff rigidities. Therefore, we have divided the 8 surveys into 26 segments, with each traverse to and from the Magnetic Equator (or highest vertical cutoff value) treated separately. Some segments were adjusted to avoid the inclusion of major Forbush decreases. Each voyage, therefore, would be expected to yield 4 data segments, but equipment failures, etc, result in four of the possible segments not being available. For each segment, the hourly data points were plotted against the effective vertical cutoff rigidity at the center of the hour. A least-square fit to a three-parameter Dorman function, (e.g. [1]) was performed for all data above 2 GV. The resulting fit was then differentiated to give the differen-

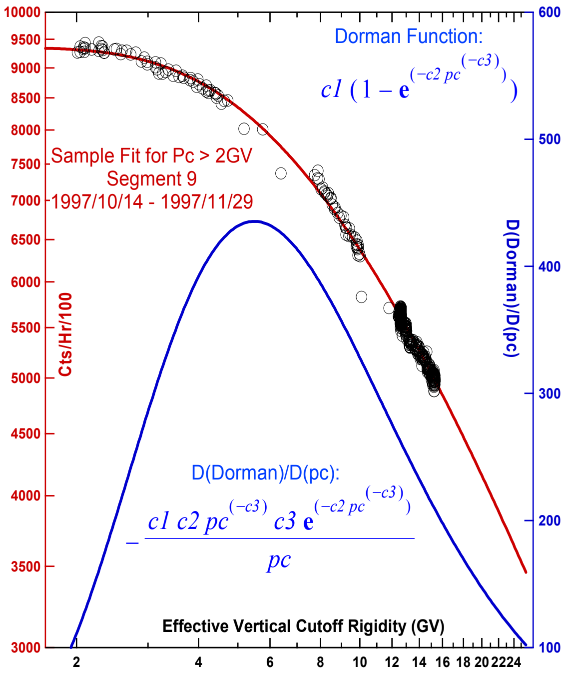

**FIGURE 2.** Sample fit of a segment's data to a Dorman function, along with the corresponding derivative.

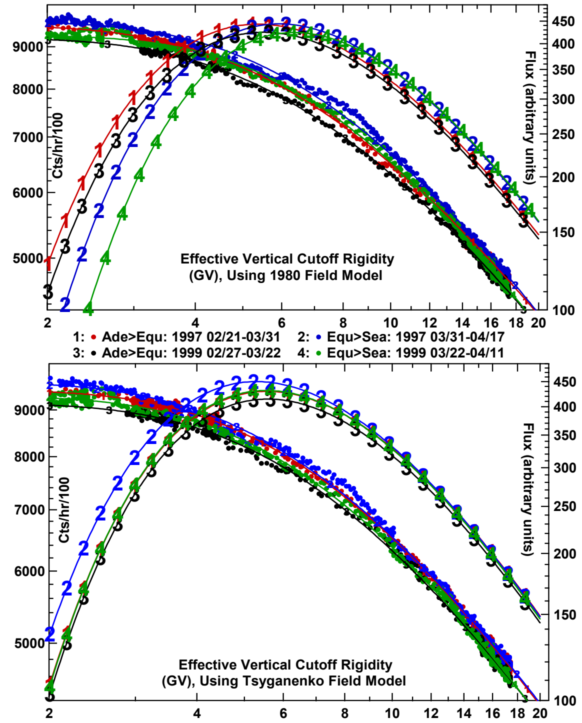

**FIGURE 3.** Western Pacific Segments: using 1980 Cutoffs (top) *vs* Tsyganenko Cutoffs (bottom).

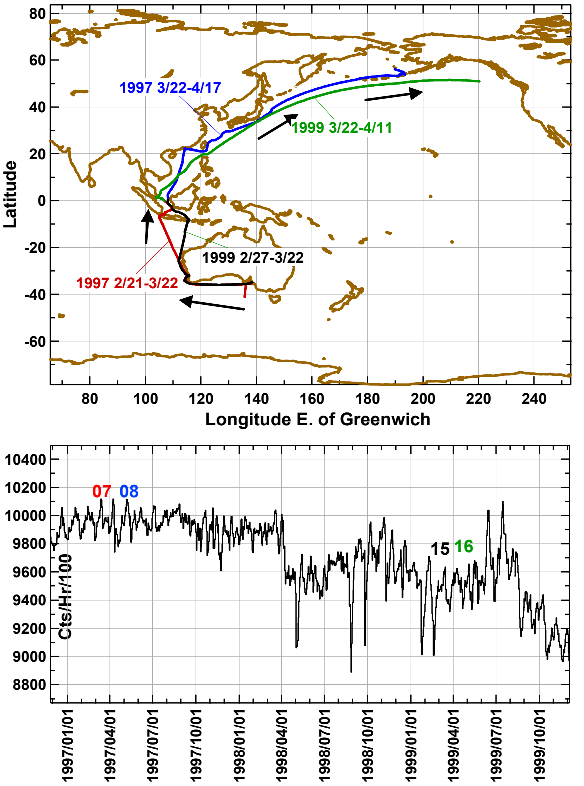

**FIGURE 4.** Course plots for the 4 western Pacific segments (top). Times of the segments on a plot of the McMurdo counting rate (bottom).

tial response. For one segment, a sample set of results is shown in Fig. 2.

## 3. RESULTS.

In our previous analysis of these data [9], we used constant 1980 vertical cutoff values. We found that all 4 segments which went west of Australia and through the western Pacific (segments 7, 8, 15, 16 from the 1996/7 and 1998/9 surveys - see Fig. 1) formed a separate and distinct set from those segments east of Australia and in the mid-Pacific. These four spectra did not agree among themselves, even at high cutoff rigidities (>10 GV). We attributed this difference to the secular drift of the earth's geomagnetic field and/or changes in the overall level of geomagnetic activity, in combination with our use of a simple vertical cutoff.

With the use of the new cutoff calculations, this discrepancy has been resolved. In Figure 3 we depict the results from our earlier paper (based on the 1980 effective cutoffs with a static field model) as well as the same spectra analyzed using the Tsyganenko model magnetosphere. Figure 4 displays the two surveys (segments 7, 8, 15, and 16) together with a plot of the McMurdo counting rate with the times of the segments indicated.

The key point is that the differential response curves should converge at high rigidity, where solar modulation becomes weak. This convergence was not obtained with the 1980 cutoffs (top panel of Figure 3), but it does occur with the new Tsyganenko cutoffs (bottom panel).

In Figure 5, the rigidity of the response function

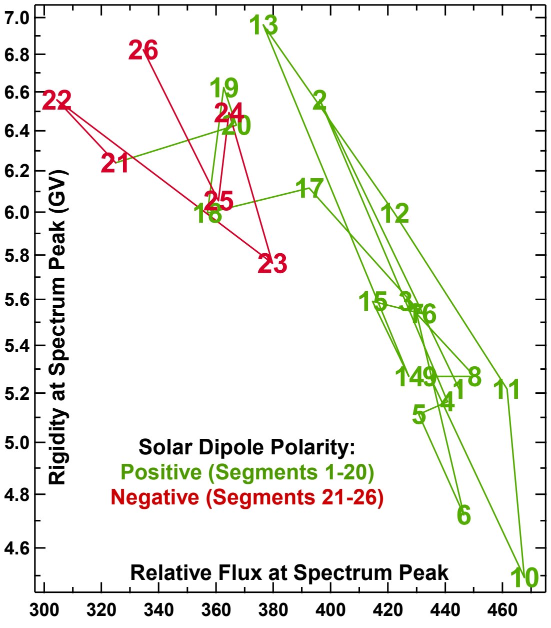

**FIGURE 5.** Rigidity at the spectrum maximum is plotted versus relative flux at the maximum for each of the 26 segments.

maximum is plotted versus the relative flux at the maximum for each of the 26 segments. As solar activity increased from 1994 to 2000, the points move towards upper left. With increased modulation, the spectrum peak is lower, but it occurs at a higher rigidity. The more recent surveys occurred during negative solar magnetic polarity (shown red in the plot), and they appear to have moved off the trend line established during positive magnetic polarity (shown green). The results are suggestive of a nascent "hysteresis loop." If confirmed by further analysis, this hysteresis effect would be evidence for effects of drift and/or magnetic helicity in solar modulation.

Moraal et al. [1] previously reported evidence of an 8 GeV spectrum cross-over between positive and negative solar polarity, with harder spectra in negative polarity. If the negative (red) polarity points in Figure 5 continue to stay to the left of the positive (green) polarity points as solar activity decreases, this would however be consistent with harder spectra in positive polarity (i.e., for a fixed peak flux, the rigidity of the peak is higher in positive polarity), which is in the opposite direction of the effect reported by Moraal et al.

## 4. DISCUSSION.

The existence of a 22-year hysteresis loop or of a spectrum cross-over at 8 GeV would indicate the influence of transport effects sensitive to magnetic polarity. Only two such transport mechanisms are known: drift and scattering by turbulence containing nonzero magnetic helicity. Drift models of solar modulation can rather easily produce a spectrum cross-over near 400 MeV, but have difficulty producing one as high as 8 GeV [4]. On the other hand, the low-frequency turbulence responsible for scattering > 10 GeV cosmic rays has been shown to possess finite magnetic helicity with a definite dominant sign [10]. However quantitative modeling of this effect has yet to be performed.

In the near future we will be incorporating additional (small) corrections in the analysis by taking into account 1) the tilt of the monitor, especially important during periods of rough seas; 2) corrections due to anisotropy (by fitting the Spaceship Earth data to measure the first-order anisotropy [11]) and the effects of spectral variations (by using a network of stations at various cutoff rigidities); 3) examination of the contribution of off-vertical directions to the calculated cosmic ray cutoffs .

We plan to continue these yearly surveys at least until the next solar minimum, so that a complete 11-year modulation cycle can be studied in detail.

## 5. ACKNOWLEDGMENTS.

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