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A continuing yearly neutron monitor latitude survey: Preliminary results from 1994-2001

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Abstract. Each year, beginning in 1994, a Bartol Research Institute—University of Tasmania—Australian Antarctic Division collaboration has conducted a neutron monitor latitude survey from the United States to McMurdo, Antarctica and back over a ~6-month period. 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; this series of surveys covers the period from the end of the previous solar activity cycle through the recent solar magnetic polarity change, which occurred in 1999 or 2000.

1. Introduction.

Over the past seven years we have conducted an annual latitude survey which traversed the Pacific Ocean from Seattle, USA to McMurdo, Antarctica, over 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 (Moraal et al., 1989; Bieber et al., 1997, 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.* Moraal et al. 1989; Lockwood and Webber 1996; Reinecke et al. 1997). 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 or 2000). We believe that this is the first set of observations which span the entire period from solar minimum to solar maximum in semi-regular intervals.

2. Data and Methods.

Data were taken on seven separate trips from Seattle to McMurdo and return. These are plotted in Fig. 1., along with selected 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 attempted to correct 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 many of the periods of rough seas.

For this study we have interpolated a 5x15 degree 1980 vertical cutoff grid (Smart and Shea, 1985) to produce an hour-by hour set of cutoff values. As it will become apparent later in this paper, this is not an adequate measure of the actual cutoff rigidities, and we are in the process of improving the values we are using, through a series of detailed calculations of the *apparent cutoff*, obtained from the effective cutoff using different directions of incidence (Shea et al. 1965; Cooke et al. 1991; Clem et al. 1997).

During each survey, the monitor spent several weeks in the harbor at McMurdo, near the McMurdo neutron monitor. We have used this period to normalize the total counting rate to the McMurdo monitor during each visit. This compensates for any instrumental changes which may have occurred from year to year. During each survey year (approximately November-May), care was taken not to make any changes which might affect 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 mmHg

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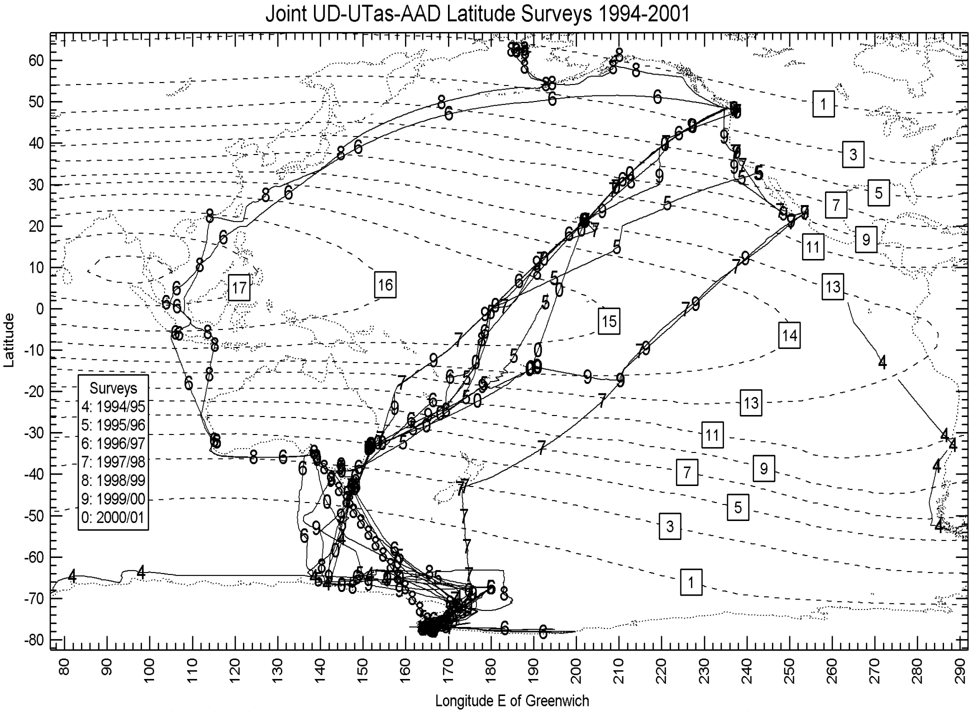

Fig. 1. Course plots for the 7 latitude surveys used in this paper. Each is labeled at one-week intervals by the start year of the survey (e.g. 7 for 1997/98). 1980 vertical cutoff rigidity contours are shown as dashed lines.

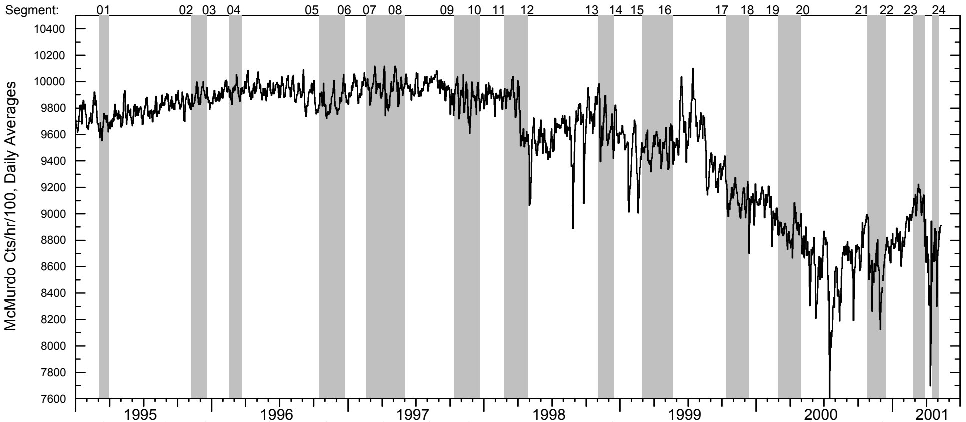

Fig. 2. The 24 time intervals used, numbered at the top. McMurdo counting rate superimposed

using a pressure coefficient α varying with cutoff rigidity as follows: $\alpha = 0.983515 - 0.00698286P_c$, where α is in percent per mmHg and P_c is in GV (Clem et al., 1997).

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 7 years of observations into 24 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. An attempt was made to lessen the effect of other, minor, modulation changes during a segment by demodulating the data using a modulation function based on the Climax and Haleakala NM-64 neutron monitor count rates. We assumed that the demodulated survey count rate can be expressed as

$$S'(t) = S(t)M(P_c,t),$$

where

$$M(P_c,t) = A(t)P_c^{-\gamma(t)}$$

(see Nagashima et al., 1989 for a similar procedure) and that the same demodulation function operated at Climax and Haleakala. We then used $P_c(Cli)=3.03$ and $P_c(Hal)=13$ and solved for $A(t)$ and $\gamma(t)$. This would appear to result in overcorrection of the survey data, since Climax and Haleakala are at mountain altitude, but examination of several Forbush effect periods showed that the data was effectively corrected to a constant level.

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. The intervals of the 24 segments utilized are shown in Fig. 2, along with the McMurdo neutron monitor count rate.

For each segment, the hourly data points were plotted against the vertical cutoff rigidity at the center of the hour. A least-square fit to a three-parameter Dorman function was performed for all data above 2 GV. The resulting fit was then differentiated to give the differential response. For one segment, a sample set of results is shown in Fig. 3.

3. Results and Discussion.

Early in our analysis, we found that all 4 segments which went west of Australia and through the western Pacific (segments 7,8,15,16—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 coincide with

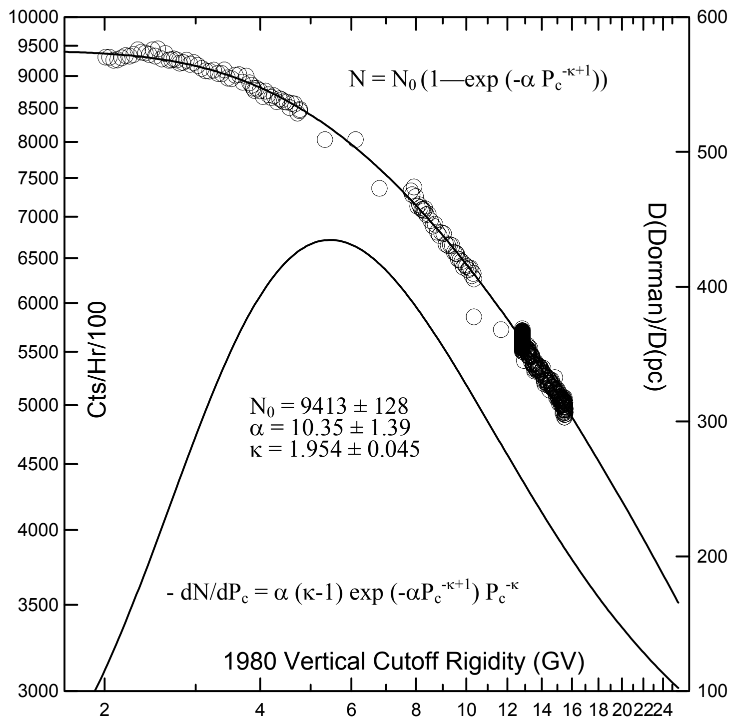

Fig. 3. A sample fit of the data (for segment 9, 14 Oct to 29 Nov 1997), showing the fit to the Dorman function, as well as the derivative. Least-square fit results are shown.

the others, even at high cutoff rigidities (>10 GV). We are tentatively attributing this difference to the secular drift of the earth's geomagnetic field, in combination with our use of a simple vertical cutoff.

We are currently investigating this by using a realistic calculation of *apparent cutoffs* (Clem et al., 1997), but since this is extremely time-consuming, even on very fast computers, this analysis will be reported in a later publication. To do this adequately, an apparent cutoff must be calculated for the midpoint of each hour using the current magnetic field model, geomagnetic conditions, and time of day (Flückiger and Kobel, 1990; Cooke et al., 1991; Bieber et al., 1997; Clem et al., 1997). We will treat these four segments separately (see Section 3.2).

3.1 Mid-Pacific Segments.

In this preliminary report, we show only a subset of the fitted spectra. In Fig. 4 are plotted spectra from a representative set of mid-Pacific segments that span the period from the approach to the last solar minimum (early 1996), through solar minimum modulation in 1997, until late April—early May, 2001.

Inspection of the spectra plotted in Fig. 4. indicates that the region beyond 12 GV shows very little modulation change, as expected, whereas the region below 10 GV forms an envelope of curves ranging from solar minimum modulation (Curves 2 and 3) to the highest modulation level (Curve 9). There is some evidence for crossing of some of the spectra (e.g. Curve 8 appears to show very strong modulation at high rigidities but a marked recovery at low rigidities). This period is characterized by a very rapid recovery in low-cutoff neutron monitors, and is typical of a dynamic modulation period..

3.2 Western Pacific Segments.

In Fig. 5 we show spectra from all 4 western Pacific segments. It is apparent that curves 2 and 4 (Equator to Seattle) form a separate group from curves 1 and 3 (Adelaide to Equator). As noted above, we expect that the use of improved apparent cutoff calculations will improve the agreement of these spectra among themselves, and with the larger set of mid-Pacific spectra.

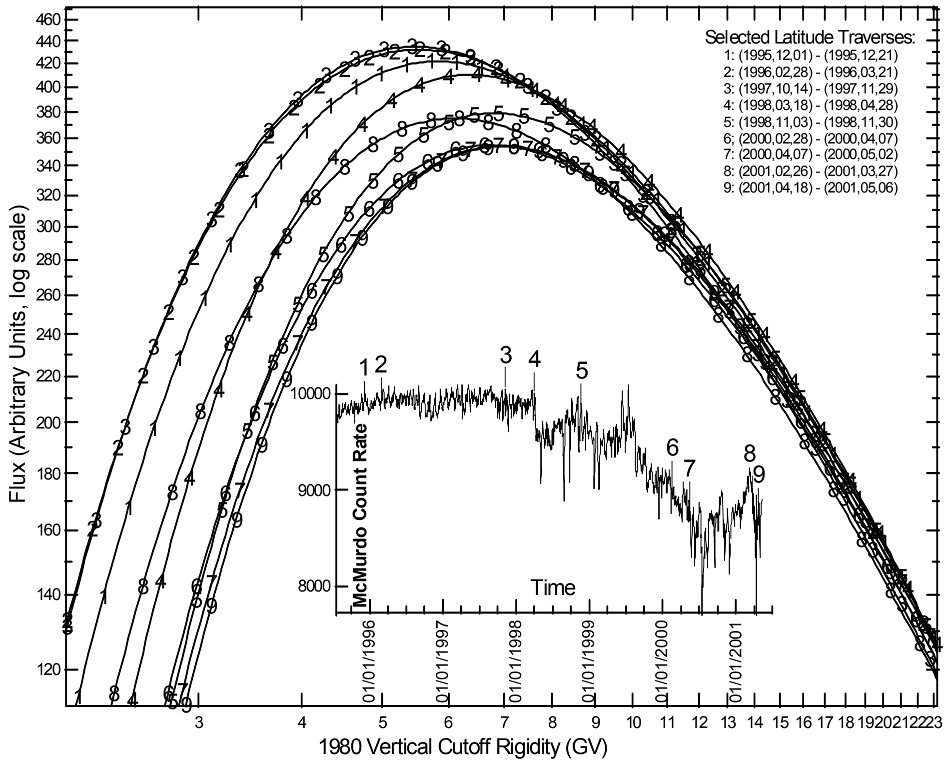

Fig. 4. Representative primary cosmic ray spectra from 1996 to 2001 for traverses of the central Pacific Ocean. The time intervals are shown in the upper right corner, together with numeric keys, which are plotted on the spectra. The inset plots the McMurdo counting rate with the key numbers at the center of the intervals used.

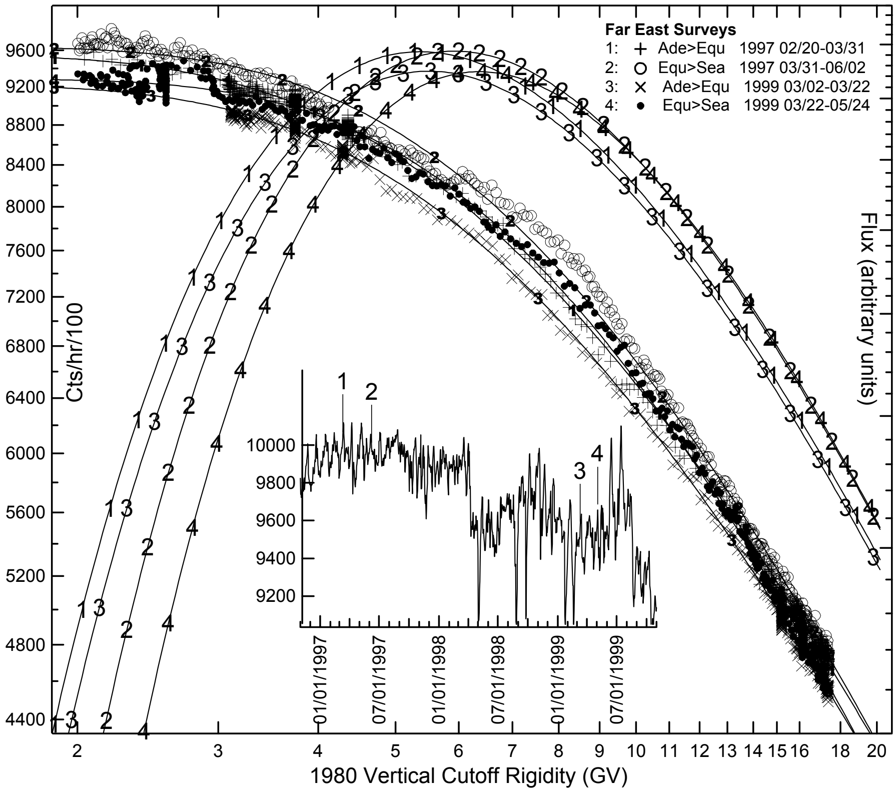

Fig. 5. Dorman function fits and derived spectra for the segments west of Australia and in the western Pacific. The southern hemisphere pair appears different, especially at high rigidities, from the northern — we attribute this to our use of a fixed 1980 cutoff grid.

4. Summary.

We have conducted a series of seven yearly neutron monitor latitude surveys from Seattle, Washington to McMurdo, Antarctica and return. These surveys began during the approach to the last solar modulation minimum and continued until the current solar maximum modulation period.

Because of the rapidly changing levels of modulation, the data were separated into 24 distinct segments, each corresponding to a single traverse from low to high or high to low cutoff rigidities.

Each segment's data was least-squares fit to a standard Dorman function above 2 GV, and the differential response was then derived by differentiating the fitted function.

We identified two separate classes of spectra, differentiated by the geographical areas which the surveys traversed. Those passing through the central Pacific (20 segments) formed one self-consistent set, which formed an envelope of curves ranging from solar minimum modulation levels to the current high level of modulation. In this analysis we did not observe any clear effect of the recent change in the solar polar magnetic field polarity (in 1999 or 2000).

Spectra derived from the four segments west of Australia and in the western Pacific are not consistent with the remainder, possibly due to secular changes in the geomagnetic field and/or our use of a simple vertical cutoff for these calculations.

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.

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