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A 22-Year Variation in the Size of Corotating Cosmic Ray Depressions at 1 AU

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Abstract

We point out a 22-year cycle in the amplitude of recurrent cosmic ray modulations observed during solar activity minima in the 1950s-1990s. These modulations are ~50% larger in **A** > 0 epochs than when **A** < 0 (where **A** is the direction of the solar global magnetic field) and are evident in all the data examined, extending from ~100 MeV to >13 GV. Although particle interactions with low-latitude structures might be expected to be more important in **A** < 0 epochs, when particle drifts are sunward along the equatorial current sheet, the observations suggest otherwise. An epoch-dependence in the particle transport parameters, such as the particle diffusion coefficient, may account for the observations.

1 Introduction:

Numerous studies have been made of recurrent GCR depressions, most using superposed-epoch analyses of daily-averaged neutron monitor (NM) data (see the references in Richardson et al., 1996). In recent studies (Richardson and Cane, 1995; Richardson et al., 1996), we have used data from anti-coincidence guards on the IMP 7/8 and Helios 1/2 spacecraft, which detect > 60 MeV particles and are dominated by GCRs at times of low solar activity, to examine such events at high time resolution. Richardson and Cane (1995) noted that corotating depressions observed by the IMP 8 guard were ~50% larger in 1974-77 than during the subsequent solar minimum (1984-87). The reason for this was unclear. Among the possibilities were a difference in the typical solar wind stream speeds in each minima (studies having suggested that size of corotating events is correlated with the speed of the related stream (Iucci et al, 1979; Richardson et al., 1996)), or an effect arising from the integral response of the guard to the changing GCR spectrum in successive minima (Lockwood and Webber, 1996). To understand this phenomenon further, we have extended our study to include GCR observations which extend over a wide energy range and, in some cases, encompass five solar minima. A more extensive report on this work will be published elsewhere (Richardson et al., 1999).

2 Observations:

Figure 1 summarizes the GCR intensity observed by various instruments during two year intervals around the 1950s to 1990s solar minima. Left- (right-) hand panels display data for **A** < (>) 0 epochs, respectively, where **A** is the direction of the solar global magnetic field. Each panel shows: 121-230 MeV ("150 MeV") proton intensity from the GSFC instrument on IMP 8; IMP 8 guard counting rate (>60 MeV); Climax NM (cut-off rigidity 2.99 GV); and Huancayo or Haleakala NMs (>12.9 GV). (The NM data are courtesy of the University of Chicago.) In some cases, data are not available for a particular minimum period. In order to emphasize the ~27 day modulations which are the subject of this paper, the underlying long-term modulation has been removed from the data in this figure by subtraction of a 3-solar rotation running average. The variations are expressed as a percentage of this mean. Inspection of Figure 1 shows that the periodic fluctuations are more prominent around the minima of **A** > 0 epochs in all of these data sets. To quantify these variations, we have fitted a 27-day (~solar rotation) period Fourier series centered on each data point. The first and second harmonics (A_1 and A_2) give the amplitudes of the ~whole-and half-solar rotation period components of the GCR variations. Figure 2 summarizes the mean values of A_1 and A_2

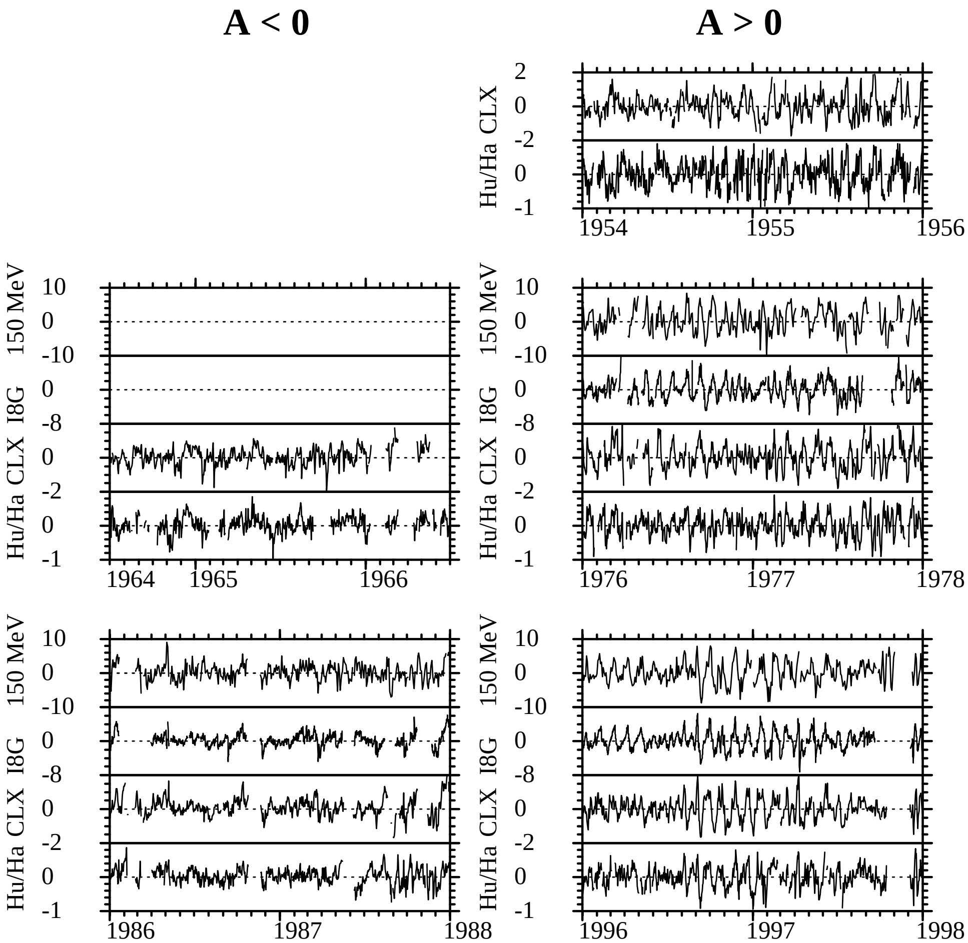

Figure 1: Detrended cosmic ray data (% variation from running average) for 2-year periods around five solar minima. The data shown are ~IMP 8 150 MeV protons and GME anti-coincidence guard (> 60 MeV), and the Climax and Huancayo/Haleakala neutron monitors. Recurrent modulations are more prominent when **A** > 0.

during the periods in Figure 1. For both components, the depressions are ~50% larger when **A** > 0 in the 1950s, 1970s and 1990s. The depression amplitudes decrease with increasing particle energy/rigidity, from A_1 ~2-3% at 121-230 MeV to ~0.2-0.3% for the Huancayo and Haleakala NMs. Figure 2 also includes the results of analyses of data from the Mount Wellington and Deep River NMs, which have similar responses to Climax. Consistent with this, they show similar variations in the amplitude. Thus, Figure 2 indicates that the difference in the size of corotating depressions noted by Richardson and Cane (1995) is part of a 22-year variation which is evident over a wide range of cosmic ray energies, and by various instruments, as well as the IMP 8 guard.

To compare the observations in another way, the top three panels of Figure 3 show periodgrams obtained by Lomb frequency analysis (Lomb, 1976) of a subset of the data in Figure 1. Results for the **A** > 0 minima are displaced above those for the **A** < 0 minima. Consistent with the above conclusions, the ~whole- and half-solar rotation period components are more evident in the **A** > 0 intervals.

3 Discussion:

The observations presented above indicate that there is a 22-year variation in the size of recurrent GCR modulations near the ecliptic at 1 AU. There are several factors which might be involved. For example, there may be a change in the solar wind structure in successive epochs. The different particle drifts in **A** > 0 and < 0 epochs may play a role, or the cosmic ray transport coefficients may vary in a 22-year cycle. The difference in the cosmic ray spectrum in successive epochs is unlikely to be important since the variations in the modulation size are observed over a wide range of energies and, in particular, in the IMP 8 differential energy data. Also, the effect in the 1970s-1980s minima observed by Richardson and Cane (1995) is not an artifact of the IMP 8 guard response. Figure 4 shows 2-day averages of the IMP 8 guard counting rate vs. the IMP 8 121-230 MeV proton intensity (which has been carefully corrected for instrumental drifts in order to provide a baseline for long-term cosmic ray studies) for the IMP 8 mission from 1973 to present.

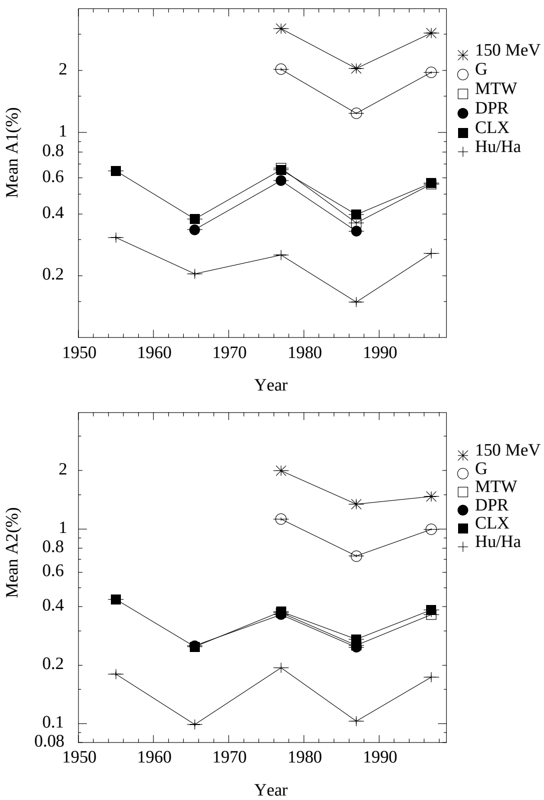

Figure 2: Mean values of A_1 and A_2 (corresponding to the sizes of ~one- and half-solar rotation period variations) during each solar minimum in various data sets.

Evidently, the guard response has been remarkably stable, changing by < 2% and showing little dependence on **A**.

Considering the solar wind stream structure, in the force-free model, the size of corotating depressions will be related to the stream speed, assuming the radial diffusion coefficient is kept constant. We have examined the near-Earth solar wind data for evidence of a 22-year variation in the speed of corotating streams. Figure 5 shows the solar wind speed and Climax data for the last four solar minima. Unfortunately, the data are intermittent during both **A** < 0 solar minima for which data are available, so that a conclusive answer cannot be obtained. Note however, that while there are more dominant streams in the 1970s than in the 1980s, the 1990s period also shows a preponderance of modest streams. Also, there are clear streams in the 1980s which are accompanied by weak GCR variations, whereas modest streams are associated with strong modulations in the 1990s. The bottom panel of Figure 3 shows Lomb periodgrams of the solar wind speed during the 1960s-1990s minima (note that the Lomb technique is ideal for analyzing intermittent data) which suggest that similar ~one- and half-solar rotation periodicities were present in the solar wind during each epoch. This then implies that GCRs have a weaker response to solar wind speed variations in **A** < 0 epochs. For the guard data, we estimate that the mean depression varies from ~1.5%/(100 km/s) when **A** > 0 to ~1.0%/(100 km/s) when **A** < 0. In terms of the steady-state model, a change in response suggests that an epoch dependence in the radial diffusion coefficient may play a role, such as that suggested by the observations of Chen and Bieber (1993) and the modeling of Reinecke et al. (1996). Figure 5 of Wibberenz et al. (1998), adapted from Chen and Bieber (1993), suggests that the parallel mean free path for cosmic rays may be a factor of two smaller around solar minimum when **A** > 0. A variation in the radial mean free path in the same sense would be qualitatively consistent with our observations.

Most reviews suggest that diffusion is the more dominant than drift effects in short-term modulations (e.g. Wibberenz et al., 1998). Thus, all other parameters being equal, the depressions are similar for both polarities of **A**. Kóta and Jokipii [1991] find a similar result when modeling corotating depressions, with the depressions being only slightly larger when **A** < 0. This is the situation where particles enter the inner heliosphere along the current sheet at low latitudes where the effect of low-latitude solar wind structures is expected to be more significant. However this is evidently inconsistent with the observations presented in this paper, which show that the larger modulations occur in epochs when particle drifts are directed inward from over the poles of the Sun.

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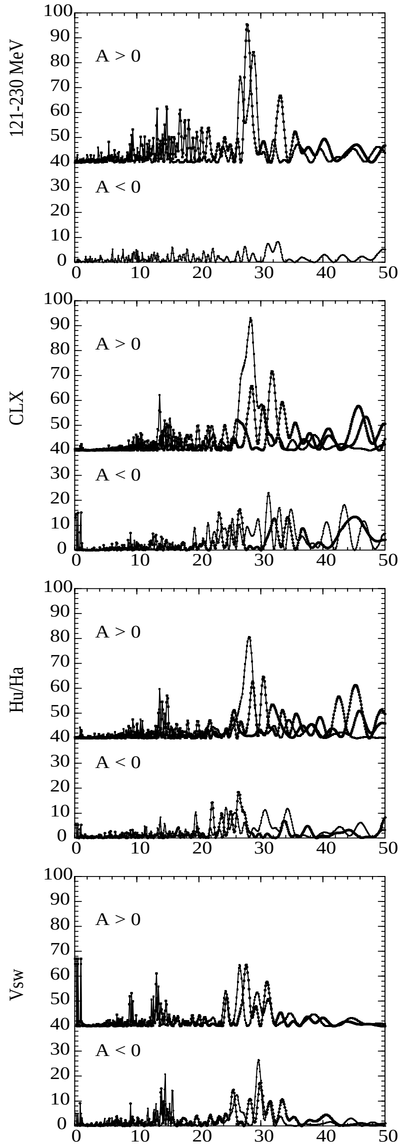

Figure 3: Lomb periodgrams for the cosmic ray data in Figure 1 and the solar wind speed.

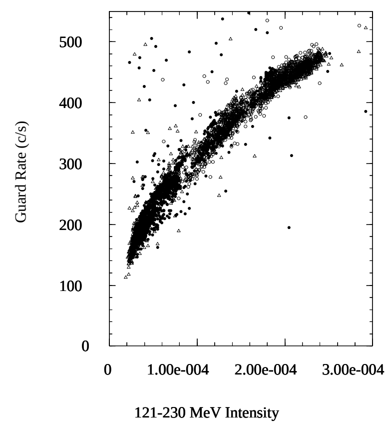

Figure 4: 2-day averages of the IMP 8 guard rate in 1973-1998 vs. 121-230 MeV proton intensity.

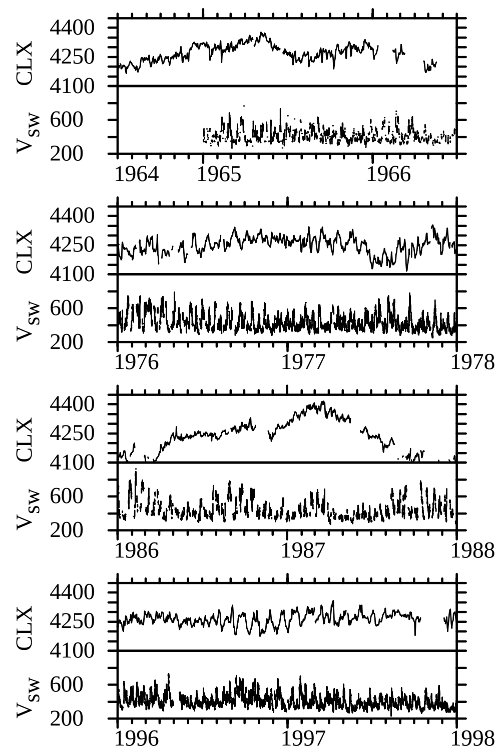

Figure 5: Climax NM rate and the solar wind speed for the last four solar minimum periods.