Cosmic Ray Modulation Over the 22 Year Magnetic Cycle Observed by Neutron Monitors

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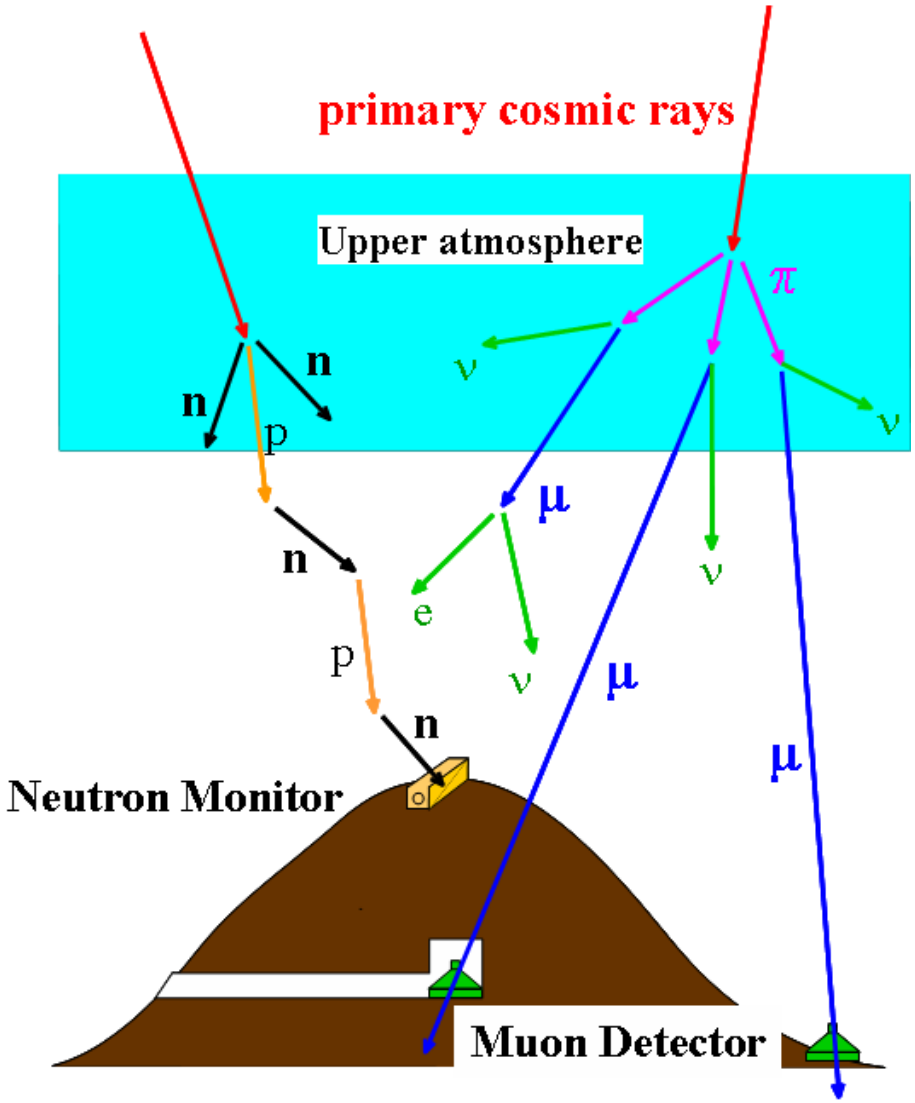
Observation Of Cosmic Rays With Ground-based Detectors



- Ground-based detectors measure byproducts of the interaction of primary cosmic rays (predominantly protons and helium nuclei) with Earth's atmosphere
- Two common types:
  - Neutron Monitor
    Typical energy of primary:
    ~1 GeV for solar cosmic rays,
    ~10 GeV for Galactic cosmic rays
  - Muon Detector / Hodoscope
    Typical energy of primary:
    ~50 GeV for Galactic cosmic rays (surface muon detector)

Neutron Monitors and AMS-02

First, let me say something about what I am not going to talk about – transient events such as solar energetic particle GLE.

AMS-02 has approximately the same collecting power as the South Pole neutron monitor.

It has massively better energy and composition sensitivity, but only “looks” is one, constantly changing, direction at a time.

The duration of one orbit is much longer than the timescale of the evolution of anisotropy in a typical solar event.

The neutron monitor network will remain a vital partner for the life of AMS-02 (if we ever see another large GLE).

Long Term Solar Modulation

So now let me turn to a topic where, if AMS-02 had been observing for the last 60 odd years, neutron monitors would not have been necessary.

With respect to the timescale of the large features of modulation, the precise AMS-02 data on composition and spectrum are clearly better than what the monitor network was able to obtain.

(This may not be fully correct, as there are rather subtle effects with small anisotropies that might be easier to see with the neutron monitors.)

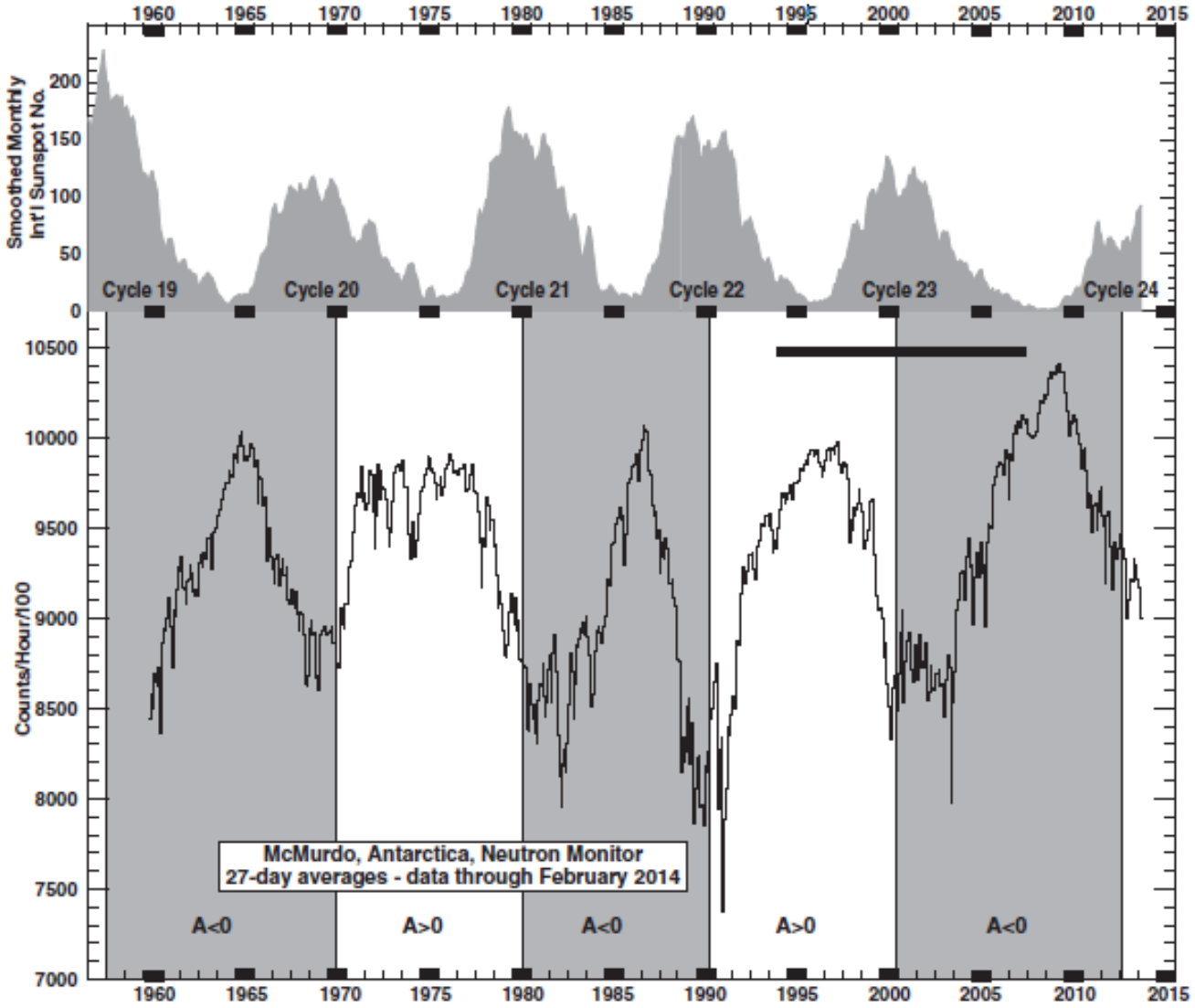
Nevertheless….

Modulation is not a simple phenomenon, and the historical record is vital to any comprehensive attempt to understand the phenomenon.

Indeed, the present modulation epoch appears significantly difficult from those that have gone before.

So now what about the solar magnetic cycle?

22 Year Solar Magnetic Cycle



- 11 year sunspot cycle
- Net polarity reverses in alternate cycles
- Flat vs peaked cosmic ray modulation
- Record high cosmic ray flux levels in 2009

The Drift Explanation

In the mid 1970's Jokipii, Levy and collaborators proposed that solar modulation is more than diffusion – namely that it also involves "gradient and curvature drifts" that make positive particle access easier in the "QA+" epochs.

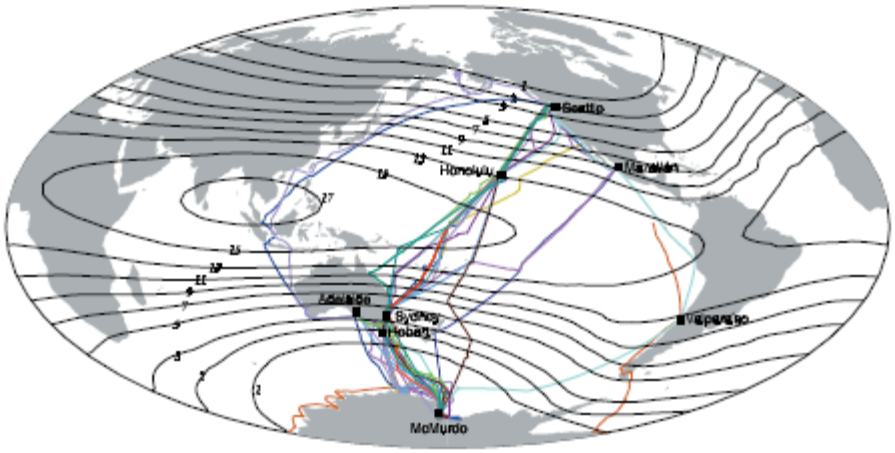
The time evolution of the drift pattern can produce the "flat" vs "peaked" pattern.

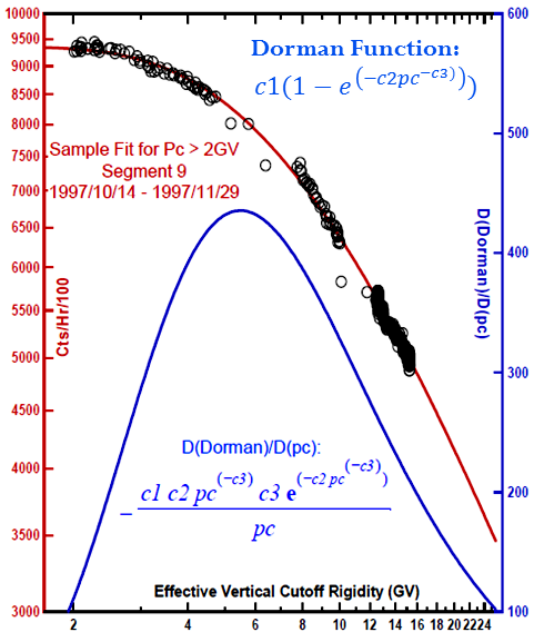
(This also produces charge sign dependent effects, but I will not comment on these here.)

However there is a problem – drifts may affect different energy particles differently, but they are always in the same direction, hence it is hard to see how they can produce the so called "spectral crossover"

By the way, what is the "spectral crossover"?

First, What is a Latitude Survey?





Spectral Crossover

Left: Moraal *et al.* 1989

Below: Nuntiyakul *et al.* 2014

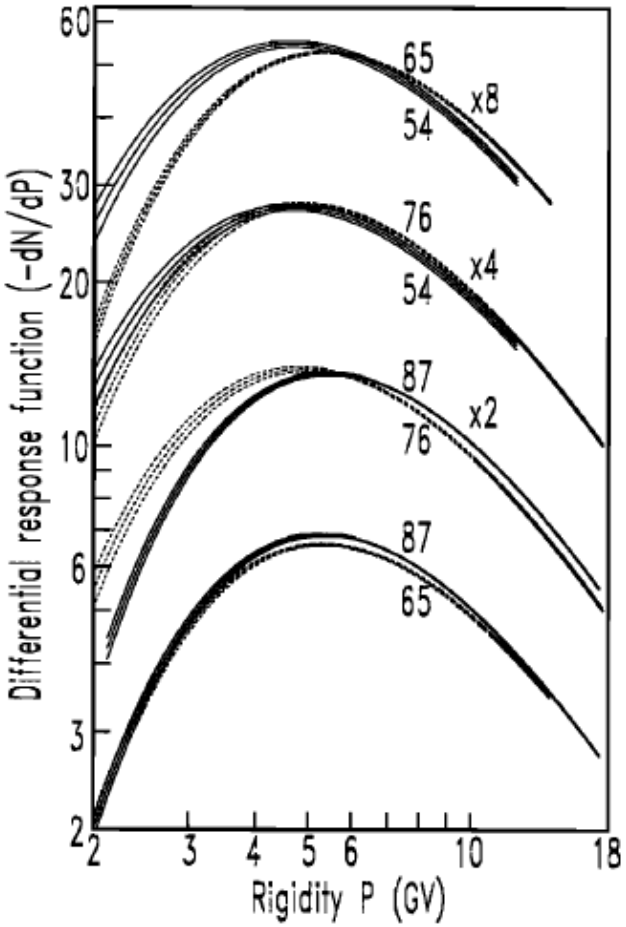


Fig. 7. Differential response functions with the numbers N_0 (for 1954, 1965C, 1976, 1987AVV) in Table 2 multiplied with 0.968, 1.000, 0.952, 0.986. This brings the N_0 values in the ratio 99.5, 100.0, 98.5, 100.1, as suggested by *Webber and Lockwood* [1988].

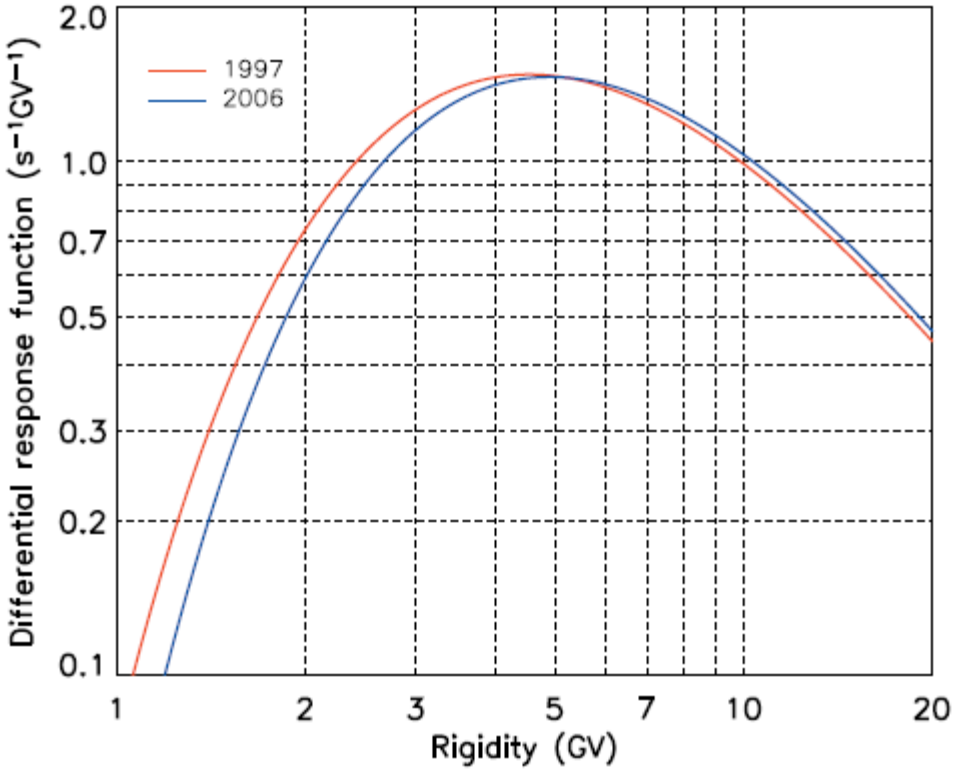
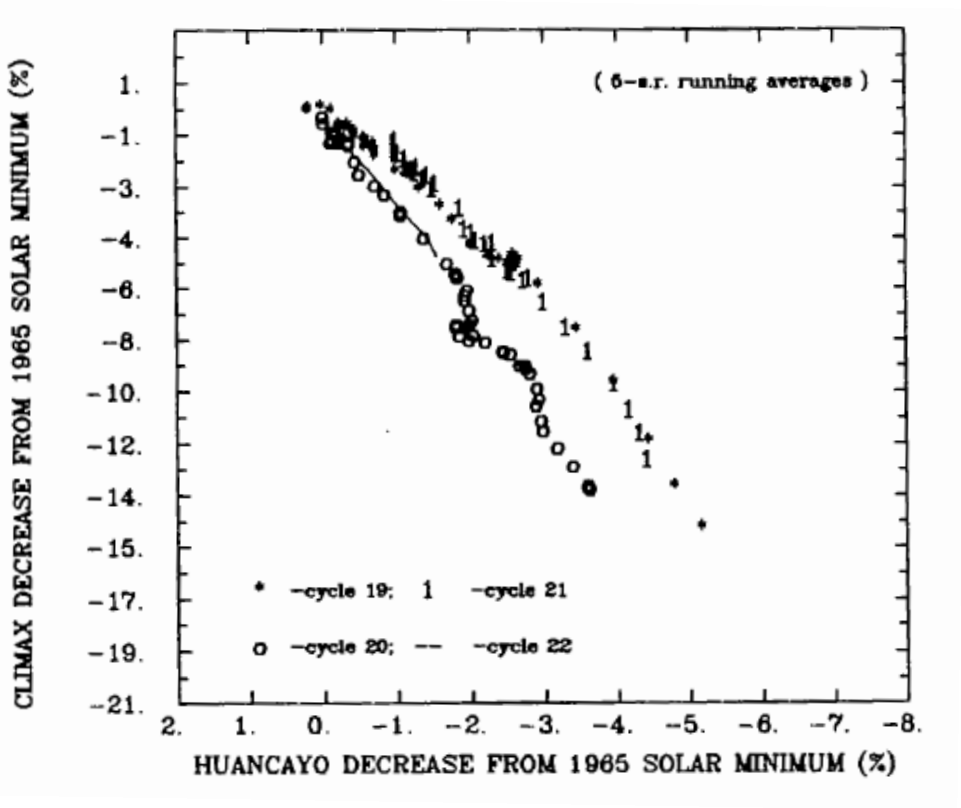


Figure 8. Differential response functions for two survey years, near solar minimum, of opposite polarity and similar modulation level. A crossover is apparent near 5 GV.

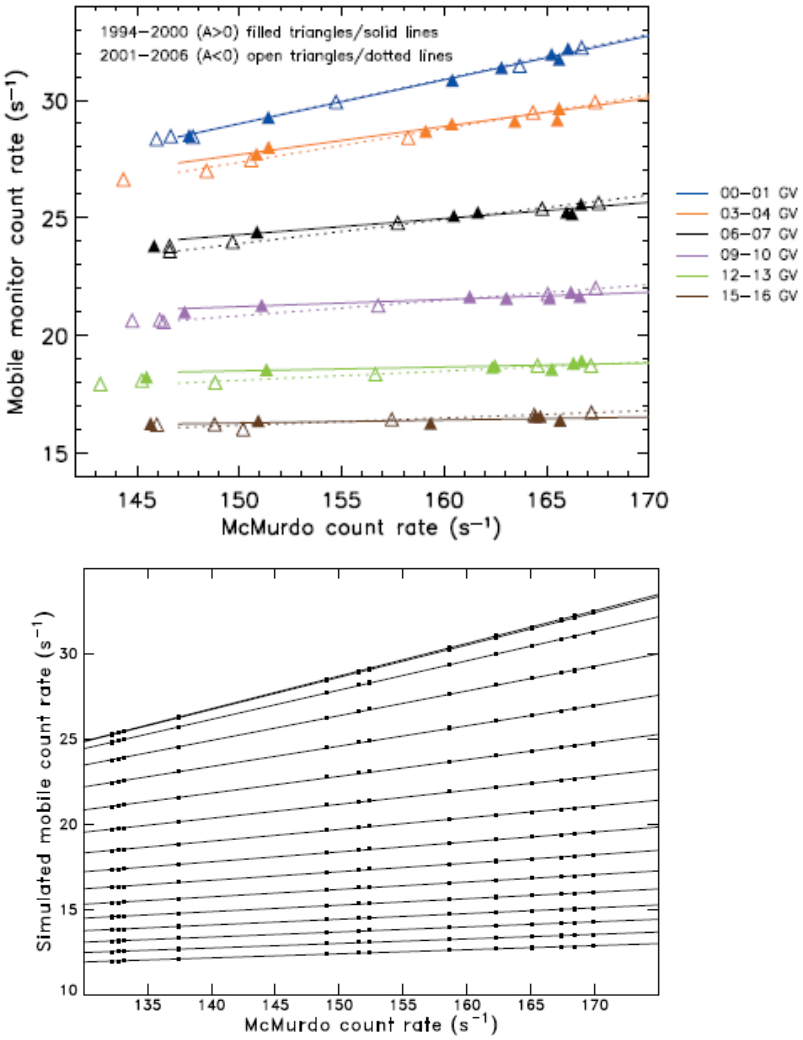
Station Correlations Agree



Popielawska and Simpson (1991) showed that Huancayo decreases more rapidly (compared to Climax) in the QA- epochs than in the QA+ epochs.

This study required a very careful correction for the rapidly changing cutoff of Huancayo.

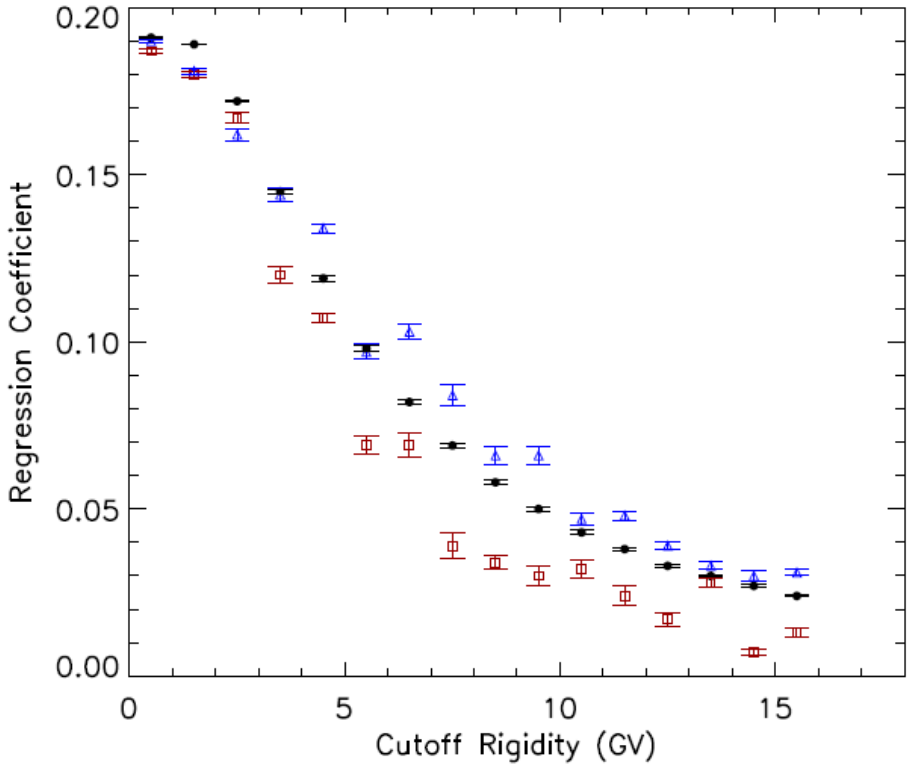
Recent Latitude Survey Summary



By binning the data in intervals of cutoff, Nuntiyakul et al. (2014) showed that the slopes of the correlations at different cutoffs vs. McMurdo are systematically different before and after the polarity reversal in 2000.

The nearly linear behavior is in fact predicted by a simple force field model of modulation.

Observations vs Force Field



Line slopes are close to those predicted by the **force field** model, but clearly smaller in the QA- epoch and larger in the QA+ epoch.

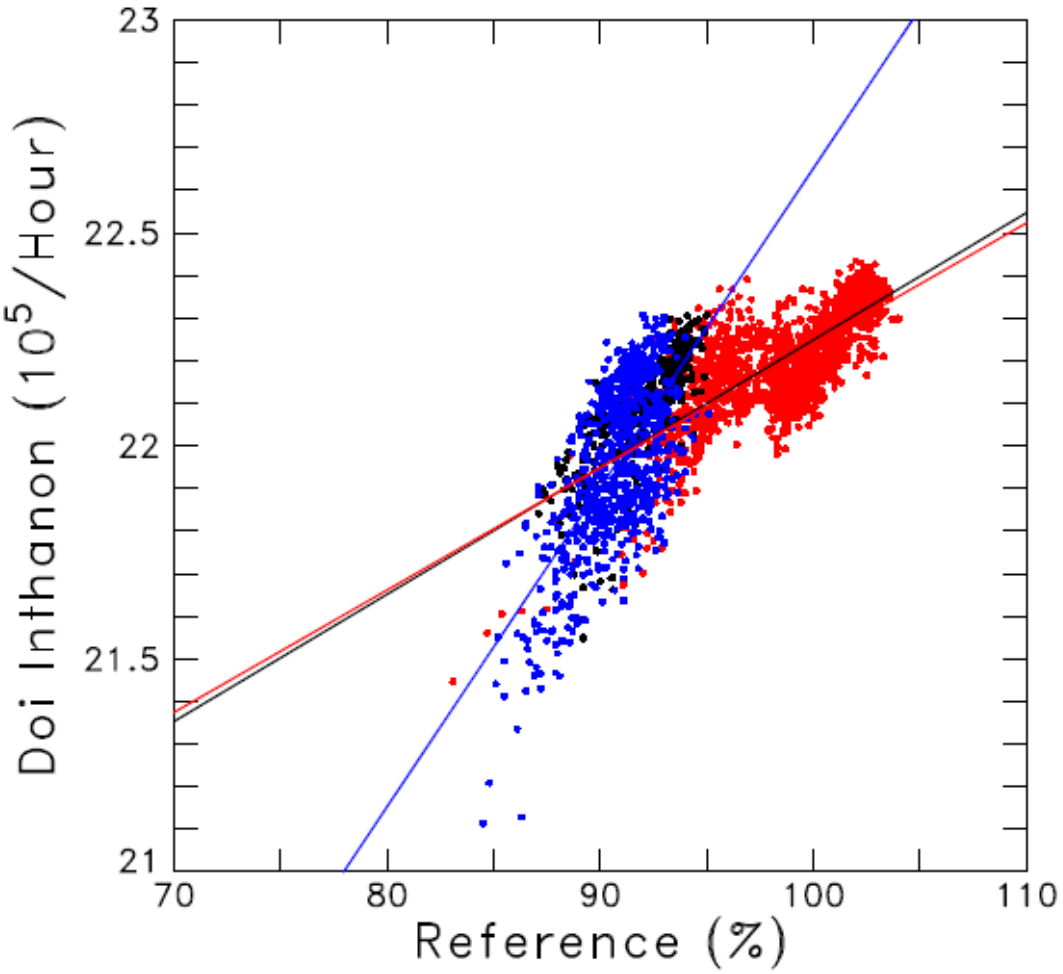
A Possible Interpretation

- The regressions say nothing about the shape of the time dependence, so the shape well can have something to do with drifts.
- Bieber Evenson and Matthaeus (1986) pointed out that magnetic helicity could change diffusion coefficients.
- The “twenty-year wave” observed in the phase angle of the cosmic ray diurnal anisotropy (Forbush 1967; Bieber & Chen 1991) has also been attributed to particle drifts by Levy (1976).
- However Chen & Bieber (1993) showed that it is a consequence of their observation that the cosmic ray scattering mean-free path is systematically larger during epochs of negative solar polarity than during epochs of positive polarity.

A Possible Interpretation

- Chen & Bieber (1993) showed that the cosmic ray scattering mean-free path is systematically larger during epochs of negative solar polarity than during epochs of positive polarity.
- Thus the increased diffusion coefficients will tend to **raise** the fluxes exactly when the drifts will operate to **lower** them.
- With competing effects, each having a different energy dependence, the "crossover" can easily appear.

The AMS-02 Era



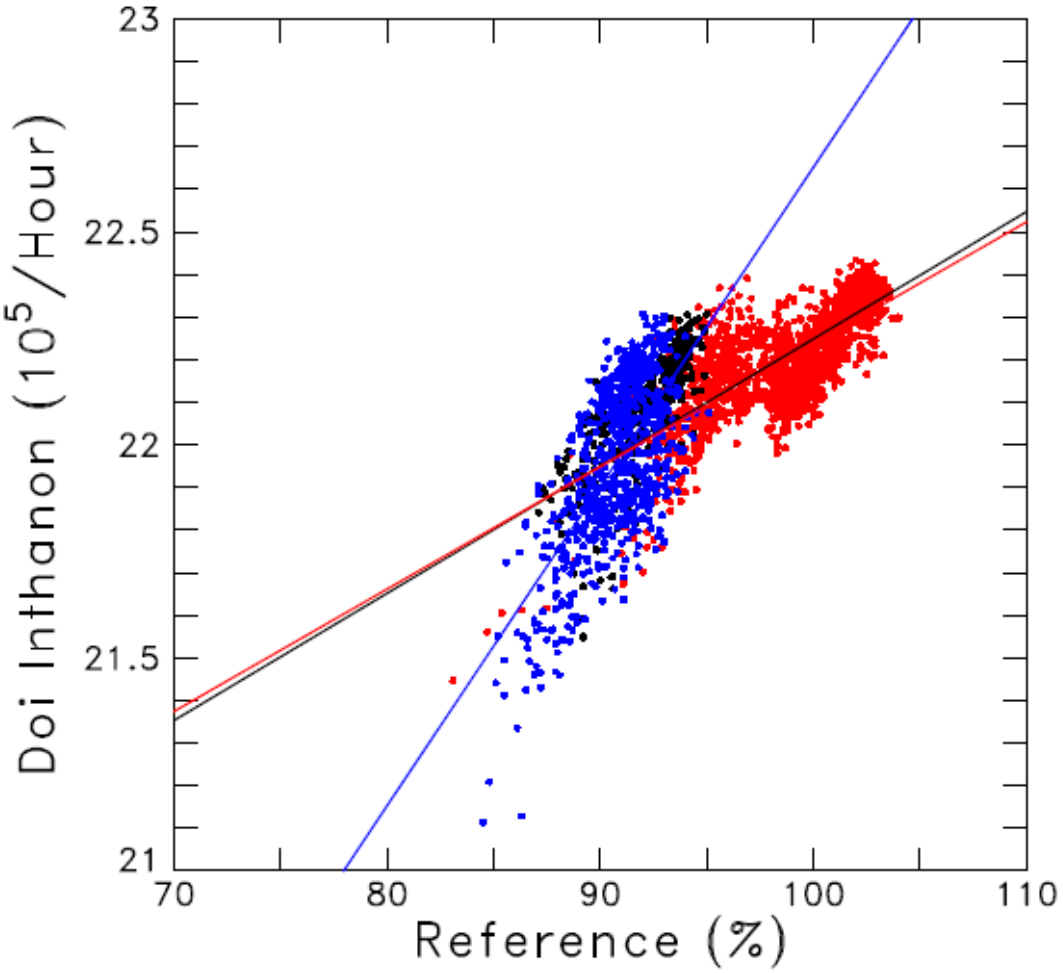
So everything is solved and there is nothing left for AMS-02 to do – right?

Well not really!

Actually, the recent record of the Princess Sirindhorn Neutron Monitor compared to McMurdo does not make a whole lot of sense.

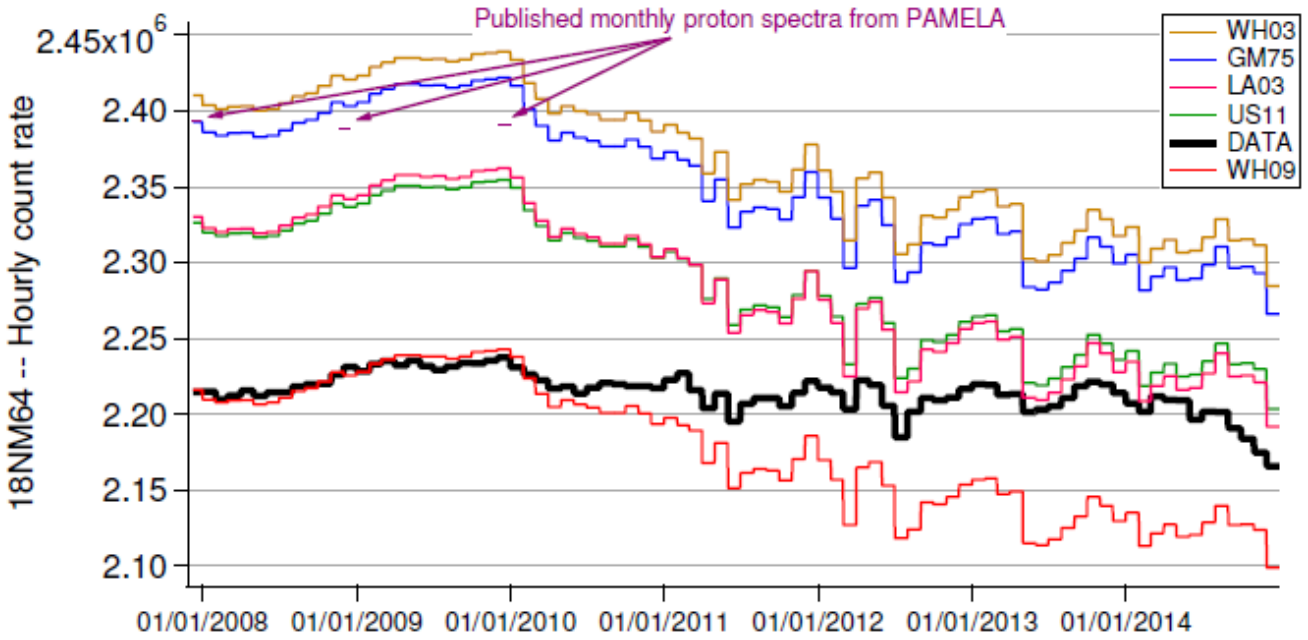
The "reference" is primarily McMurdo with some adjustments following Oh *et al.* (2013)

The AMS-02 Era



- PSNM is located at the highest cutoff rigidity in the world for a fixed station: 16.8 GV.
- If anything the slope **after** the polarity reversal is now greater than **before** the reversal.
- Something else seems to be going on.
- We really don't know what.

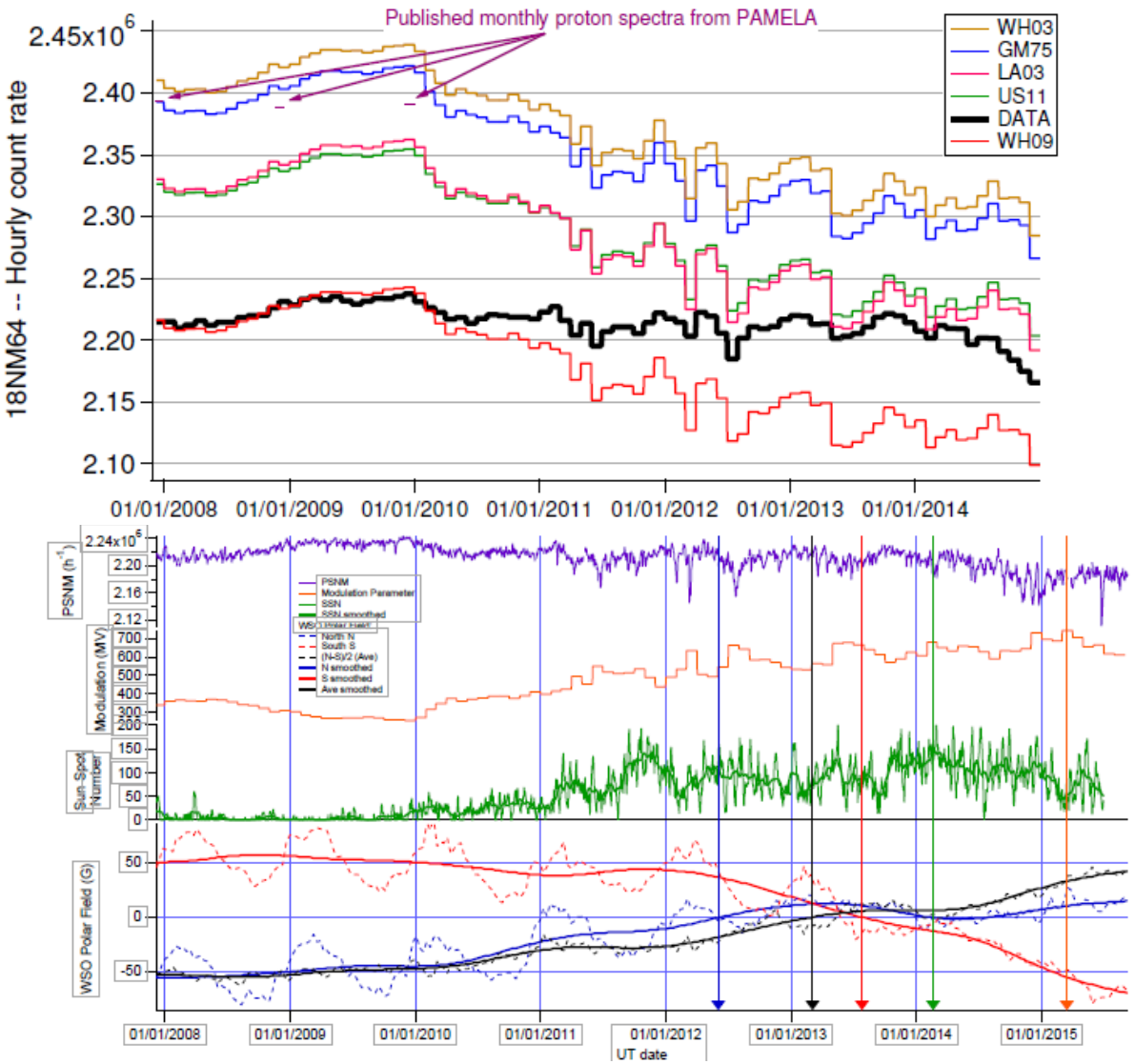
Data and Force Field Calculations Just Drift Apart



Variation of the hourly count rate (averaged monthly) of the PSNM at Doi Inthanon from December 2007 to December 2014 compared with the MC simulation results, based on input spectra from PAMELA or from the force field model of solar modulation for five different LIS models. The monthly values of the modulation parameter, as inferred from NM data at or below 6.3 GV cutoff rigidity, were taken from http://cosmicrays.oulu.fi/phi/phi.html. The simulated count rates based on the PAMELA data are shown for only 3 months. (See Mangeard et al. PoS(ICRC2015)079 for details)

The observed solar modulation at Doi Inthanon is much weaker than expected from the force-field model.

Transition Timing



- The solar magnetic transition is complicated, but the divergence of the calculation from the data seems to precede anything normally associated with the polarity transition.
- Rather, the calculation and the data appear to diverge as the sunspot number picks up.
- It is possibly just the "record maximum" that is not well described by the force field model.

Conclusion

- AMS-02 is living in exciting times.
- The old patterns seem to be changing.
- Making sense of the old data is more complicated than simply taking new data.