Cosmic Ray Modulation Observed by the Princess Sirindhorn Neutron Monitor at High Rigidity Cutoff

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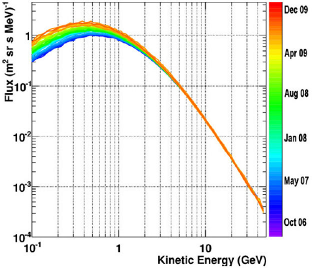
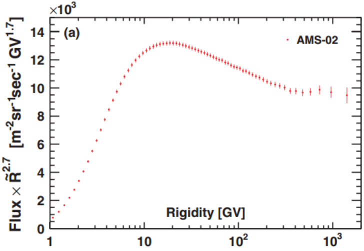
Overview

Introduction



Adriani et al. (2013)

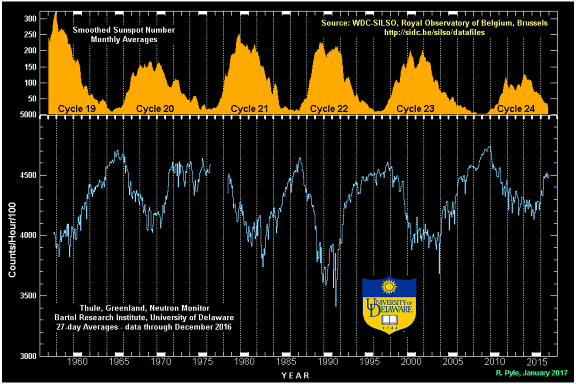


Aguilar et al. (2015)

- PAMELA and AMS-02 provide the first long term, direct and precise measurements of cosmic rays (CRs) at the TOA
- Neutron monitor (NM) are ground-based detectors. NMs don't provide a spectrum but we can take advantage of the high statistic to study time dependence (SEP, FD)
- This talk will focus on the CR modulation above $\sim$17 GV.

Solar Modulation Observed With a Fixed NM

http://neutronm.bartol.udel.edu/



- Flat ($qA > 0$) or peaked ($qA < 0$) modulation patterns
- Including effects of drifts in the modulation process can produce such patterns (Jokipii et al. series, 70's-80's)

Solar Modulation Observed with Latitude Surveys

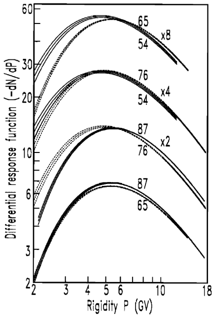


Fig. 7. Differential response functions with the numbers N_0 (for 1954, 1965C, 1976, 1987AVV) in Table 2 multiplied with 0.968, 1.000, 0.952, 0.986. This brings the N_0 values in the ratio 99.5, 100.0, 98.5, 100.1, as suggested by *Webber and Lockwood* [1988].

Moraal et al. (1989)

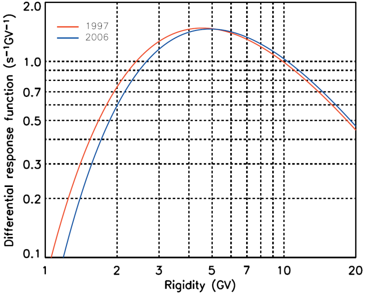
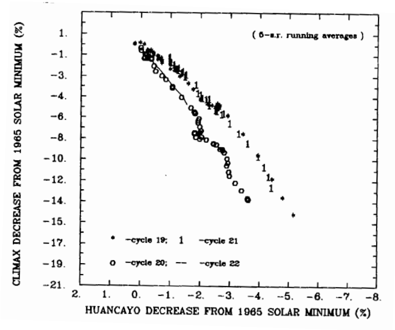


Figure 8. Differential response functions for two survey years, near solar minimum, of opposite polarity and similar modulation level. A crossover is apparent near 5 GV.

Nuntiyakul et al. (2014)

- Spectral crossover of the DRF between periods of $qA < 0$ and $qA > 0$ with similar modulation level.
- Bieber, Evenson and Matthaeus (1987) pointed out that magnetic helicity could change diffusion coefficients.

Solar Modulation Observed with multiple NMs



Popielawska and Simpson (1991)

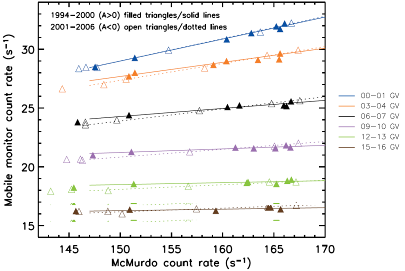
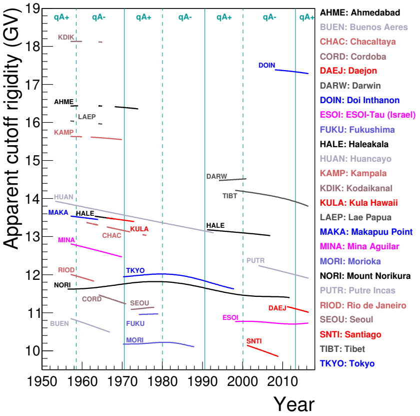


Figure 10. Alternative presentation of the data in Figure 9 using every third rigidity bin for clarity and superimposing the data for different solar magnetic polarities. Filled triangles are used to indicate positive ($A > 0$) solar magnetic polarity with solid lines showing the linear fits. Open triangles indicate data for negative ($A < 0$) solar magnetic polarity while the dotted lines are linear fits to these data. There are clear differences in cosmic ray modulation before and after the solar magnetic polarity reversal.

Nuntiyakul et al. (2014)

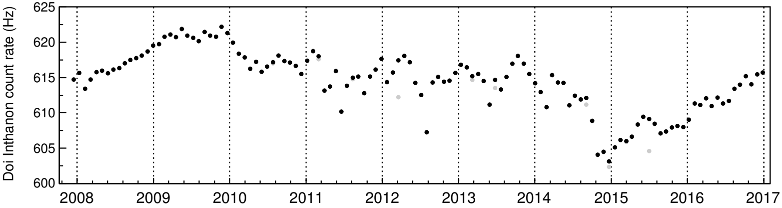
- Linear trends are predicted by the force-field model but not the change of slope after a solar magnetic polarity reversal.

History of NMs at High Rigidity Cutoff



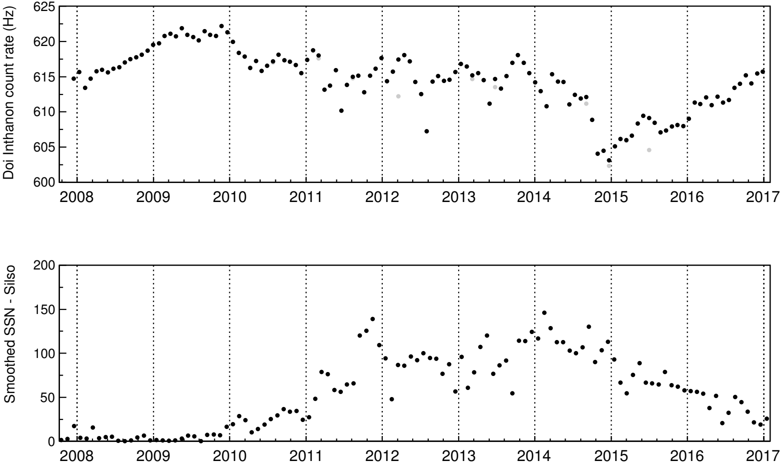
- Only few long-term NM stations recorded multiple cycles
- A gap of $\sim$ 30 years above 15 GV
- PSNM located at Doi Inthanon (DOIN), Thailand extends the sensitivity of the NM network to higher rigidity

Observation by PSNM



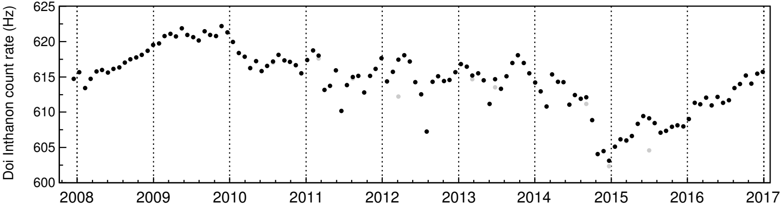
- Count rates averaged per Carrington rotation.
- The variations of the rigidity cutoff are assumed negligible.
- Tropical climate: correction for variations of the water vapor pressure at the surface.
- Grey: All data. Black: Main Forbush decreases were removed.
- Note dips of 1-2 months, even with Forbush decreases removed.

Observation by PSNM

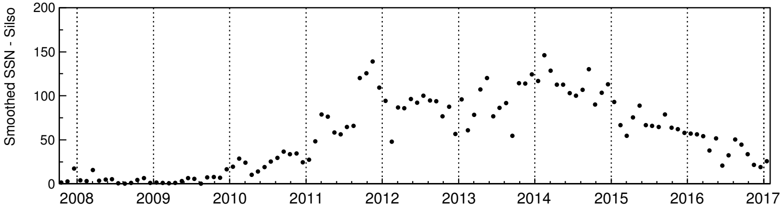


Data V2.0 from `http://www.sidc.be/silso/datafiles`

Observation by PSNM



Solar minimum



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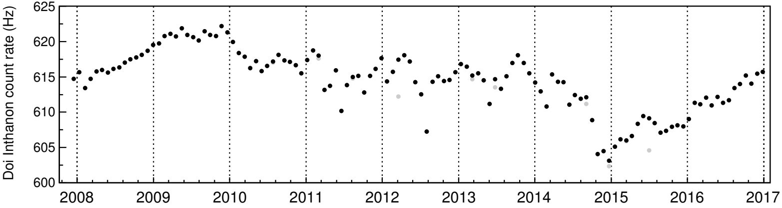
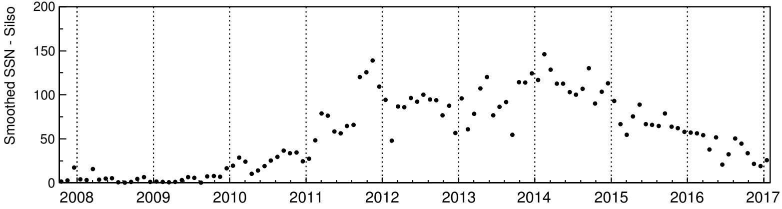
Observation by PSNM

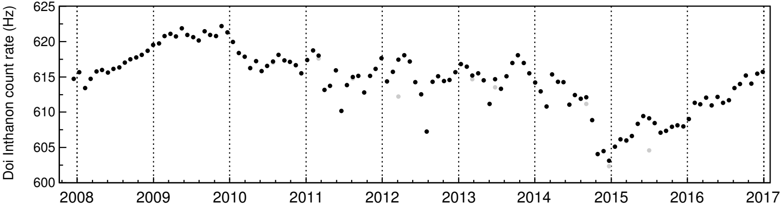


Solar minimum maximum

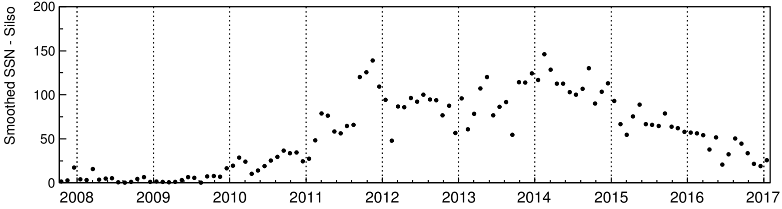


Data V2.0 from `http://www.sidc.be/silso/datafiles`

Observation by PSNM

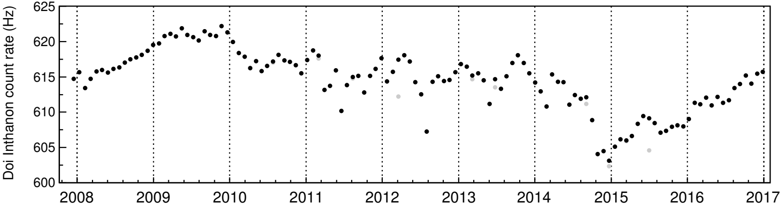


Solar minimum maximum min?



Data V2.0 from `http://www.sidc.be/silso/datafiles`

Observation by PSNM



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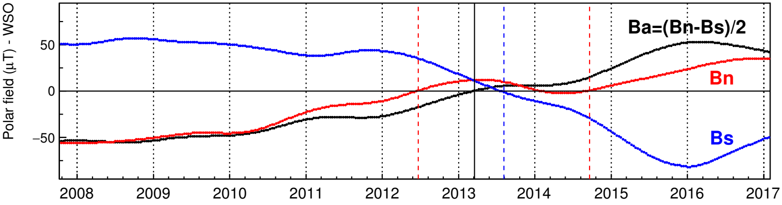
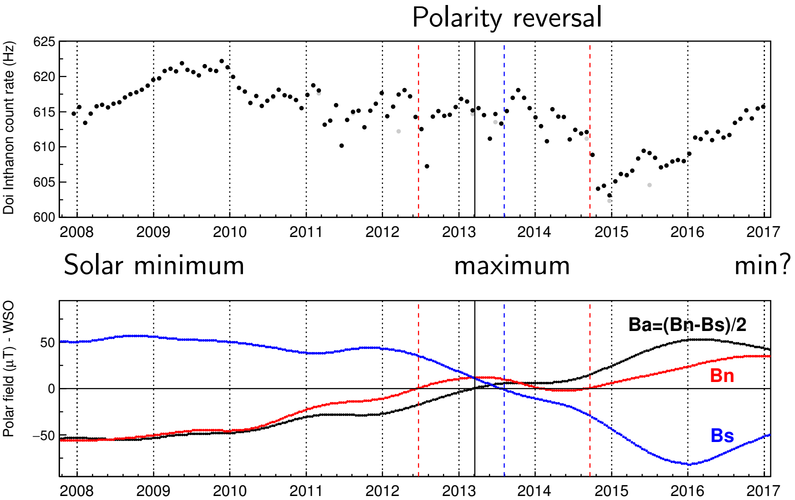


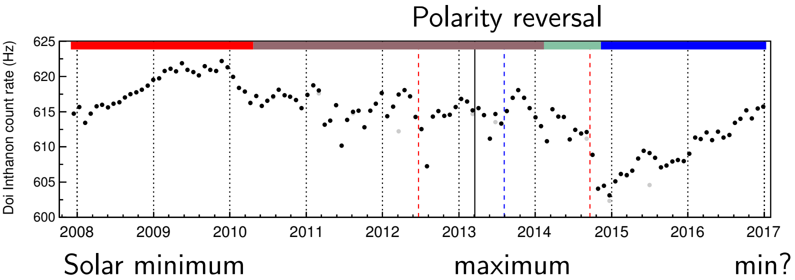
Data from `http://wso.stanford.edu/Polar.html`

Observation by PSNM



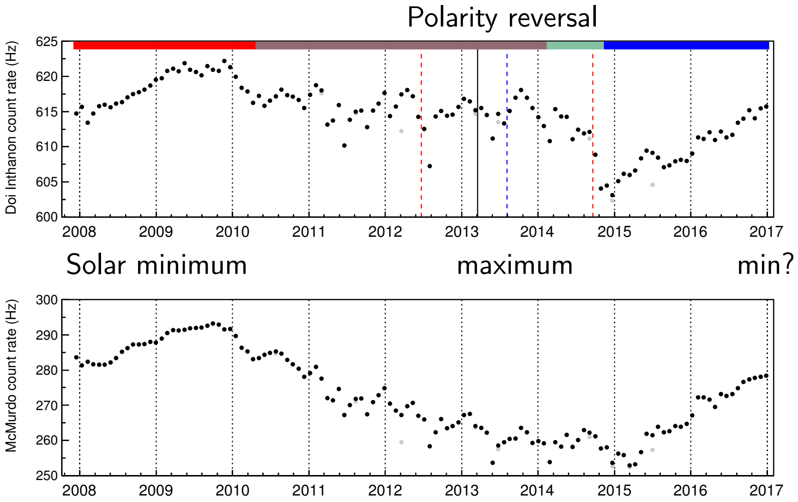
Data from `http://wso.stanford.edu/Polar.html`

Observation by PSNM



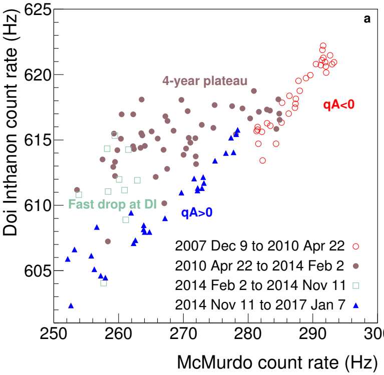
1. Solar polarity $qA < 0$ with low solar activity (RED)
2. 4-year plateau with full recoveries (BROWN)
3. Fast decrease of the count rate: $\sim$50% of the total modulation (GREEN)
4. Solar polarity $qA > 0$ after the fast decrease (BLUE)

Comparison With McMurdo Data (1)



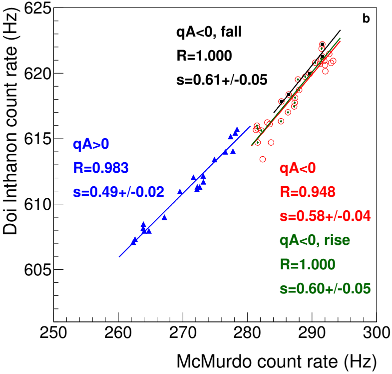
Distinct pattern during the period of high solar activity

Comparison With McMurdo Data (2)



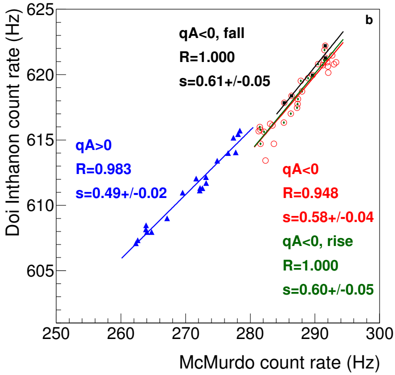
- Linear trends during low solar activity. Is there a change of slope after the solar polarity reversal?
- Spectral hysteresis is observed
- The fast decrease at DI is actually observed at McMurdo...
- Loss of linearity for $\sim$ 4 years. This was only during $\sim$1 year ($\sim$2000) for the previous solar maximum (Nuntiyakul et al. (2014)).

Comparison With McMurdo Data (3)



- Scatter plot for low solar activity only
- The linear trend between count rates of NMs at different cutoff is now observed at ∼17 GV
- The change of slope after the solar magnetic polarity reversal confirms the observation from the latitude surveys (Nuntiyakul et al. (2014))

Comparison With McMurdo Data (3)



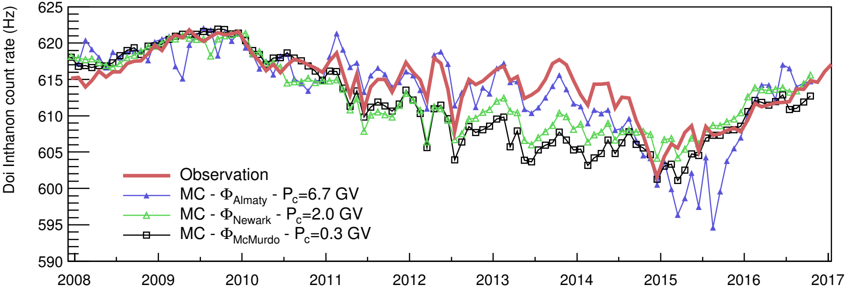
- Scatter plot for low solar activity only
- The linear trend between count rates of NMs at different cutoff is now observed at ∼17 GV
- The change of slope after the solar magnetic polarity reversal confirms the observation from the latitude surveys (Nuntiyakul et al. (2014))

- What about the crossover? We need more NMs at different rigidity cutoffs

Inadequacy of Modulation Parameter Derived From Low-Cutoff NM Data (1)

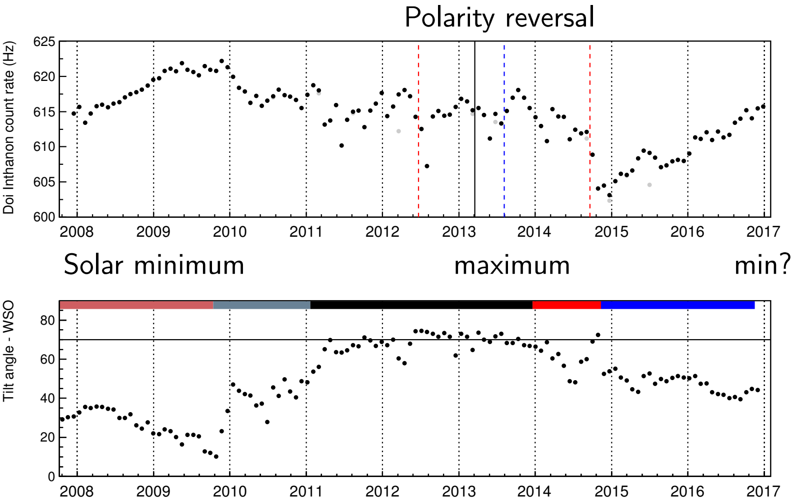
- TOA spectra were estimated from the NMs from Almaty, McMurdo, and Newark using the method presented in Ghelfi et al. (2016a, 2016b). (See talk of David Maurin).
- MC yield functions of PSNM from Mangeard et al. (2016a).
- The simulated count rates were normalized to that of PSNM at the solar minimum (December 2009).
- We compared the simulated modulations with the real data.

Inadequacy of Modulation Parameter Derived From Low-Cutoff NM Data (2)



- A single modulation parameter doesn't allow one to reproduce the variations over the whole period at all cutoffs.
- Observed modulation at 6.7 GV is much more similar to that observed at DI than that at McMurdo
- Compatible with a crossover at 5-6 GV

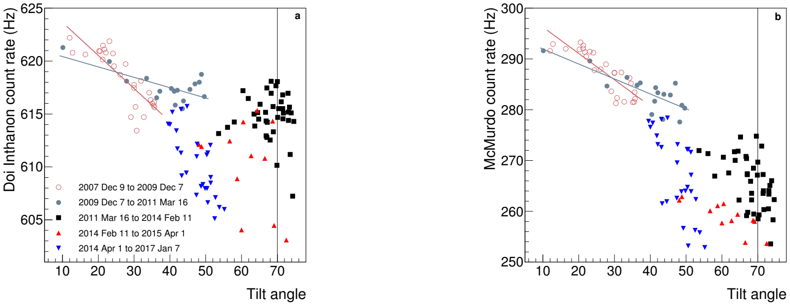
Comparison With Tilt Angle From WSO (1)



Data from http://wso.stanford.edu/Tilts.html

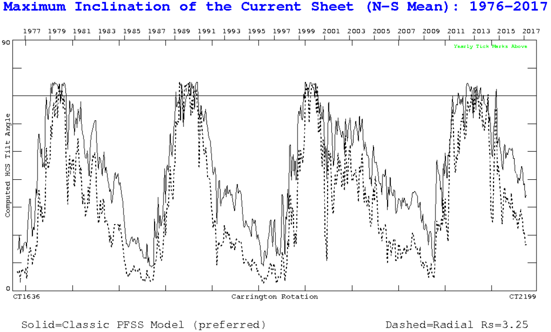
Comparison With Tilt Angle From WSO (2)

- A delay of two Carrington rotations is applied.



- At $qA < 0$, low tilt angles ($<\sim 40^{\circ}$) were well correlated with variations at both stations as expected from drift calculations.
- About 4 years of data with very high tilt angle ($>\sim 65^{\circ}$)
- We have a 4-year plateau at DI with the loss of linearity...

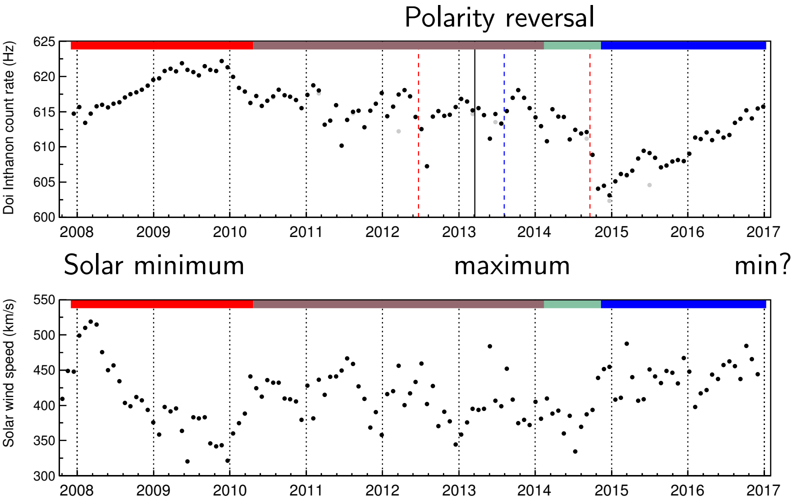
Loss of Linearity at Very High Tilt Angle



http://wso.stanford.edu/gifs/Tilts.gif

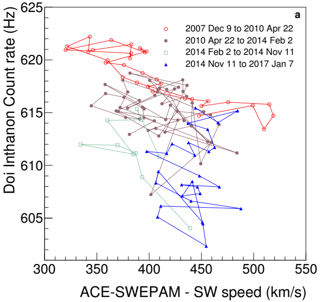
- ∼1 year near 2000: loss of linearity in the latitude surveys
- ∼4 years 2011-2014: loss of linearity between DI and McMurdo
- Could be related to duration at high tilt angle, $> 65^\circ$.

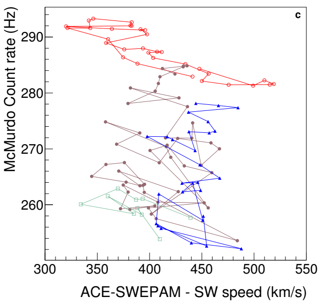
Comparison With the Solar Wind (ACE)



Data from `http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_SWEPAM.html`

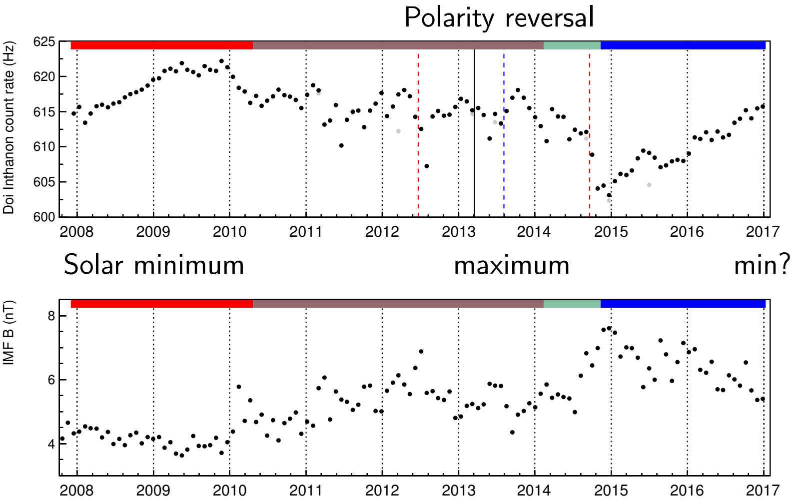
Comparison With the Solar Wind (ACE) (2)





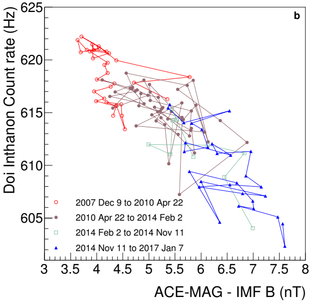
- At $qA < 0$ with low solar activity, variations in the count rates are well correlated with the solar wind.
- At $qA > 0$ no correlation is observed.
- During the transition, the correlation with variations at DI is not that great

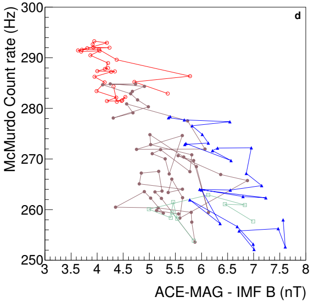
Comparison With the Interplanetary Magnetic Field (ACE)



Data from `http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html`

Comparison With the IMF (ACE) (2)





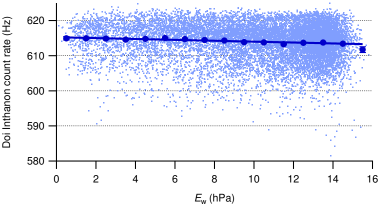
- Variations at DI are very well correlated with the IMF at $qA < 0$ with a very tilted HCS and at $qA > 0$.
- Variations at McMurdo are correlated with the IMF at $qA > 0$.
- 4 year plateau at DI is consistent with an increase in diffusion at high rigidity that short-circuits the effects of drifts and HCS during $qA < 0$.

Conclusions

- Observations at Doi Inthanon confirm the results from the latitude surveys and extend them to higher cutoff rigidity
- Low tilt angle: Linear relation between count rates of NMs at different cutoff.
  - Dependence of the slope on solar magnetic polarity
  - Compatible with the spectral crossover at 5-6 GV.
  - Distinct modulation patterns at high and low rigidity cutoff during periods with a very high tilt angle.
- High tilt angle: Distinct modulation patterns at high and low rigidity cutoff
  - The 4-year plateau and count rate minimum at DI can be explained by the variations of the IMF

BACKUP

Correction for water vapor pressure



$$C_{\mathrm{WVcor}} = C_{\mathrm{Pcor}} \frac{1 - aE_{\mathrm{w},0}}{1 - aE_{\mathrm{w}}} \quad (1)$$

$$a = (2.05 \pm 0.19) \times 10^{-4}\ \mathrm{hPa}^{-1}$$

- Dots: pressure-corrected count rate at DI, averaged in 6-h intervals, versus water vapor pressure, E_{w}, interpolated from GDAS data;
- circles: mean values of count rate for 1-hPa intervals in E_{w};
- line: linear fit to mean values.
- $E_{\mathrm{w},0} = 6.3$ hPa is chosen as in Ruffolo et al.(2016).

The PSNM station

- BP-28 neutron counter tubes with BF_3
  - Neutron Monitor 18-NM64
  - 3 bares
- Located at Doi Inthanon, Thailand, ∼2560 m
- Operation started in 2007
- Highest rigidity cutoff for a fixed station: $P_c = 16.8$ GV
- $P_{med} \sim 35$ GV
- Data available at `http://www.thaispaceweather.com`