Neutron monitor time-delay measurements to track cosmic ray spectral variation due to solar modulation at high and low cutoff rigidity

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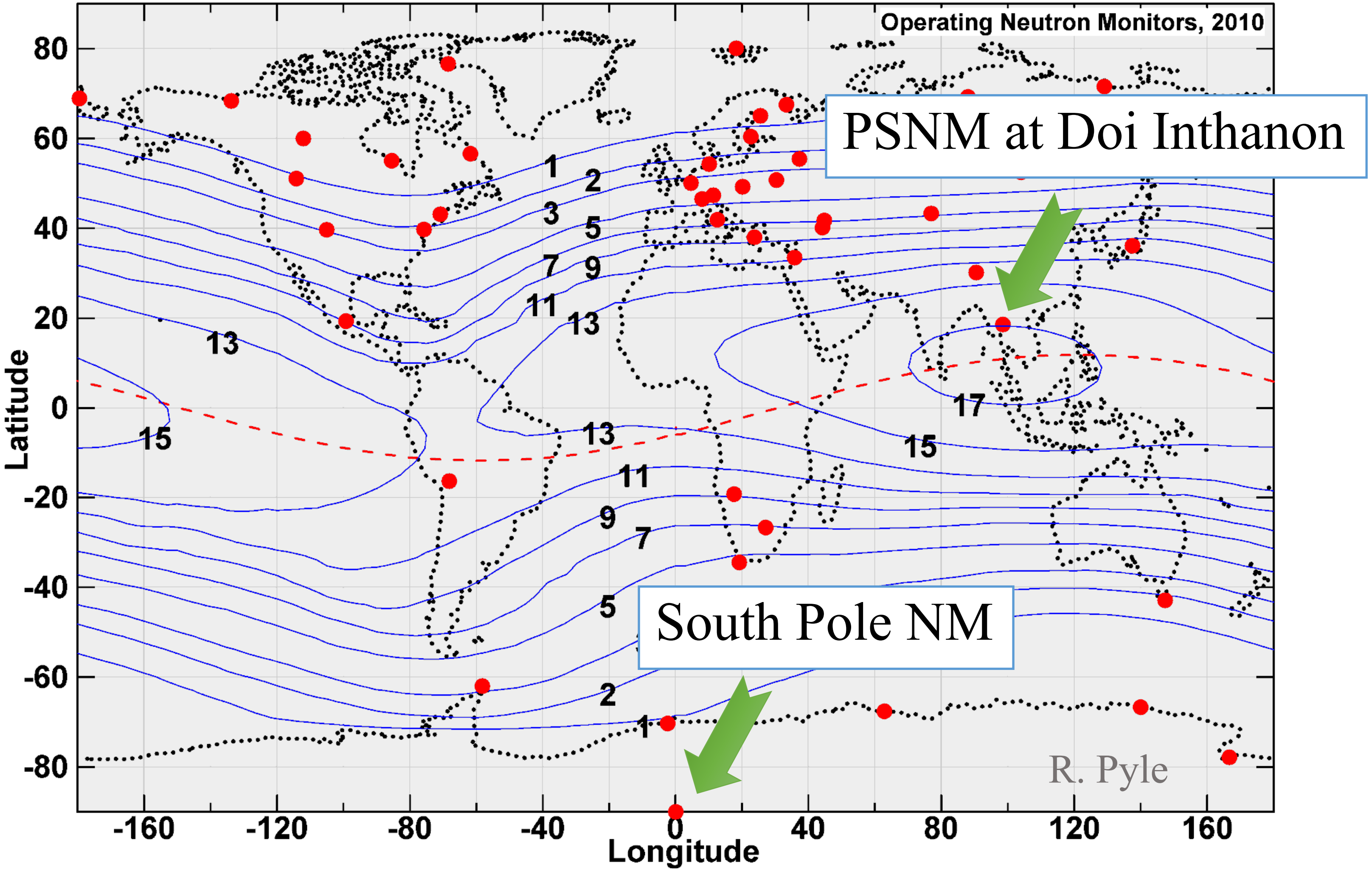
Princess Sirindhorn Neutron Monitor : PSNM



$$Rigidity: R = \frac{pc}{q}$$

p: momentum
q: charge

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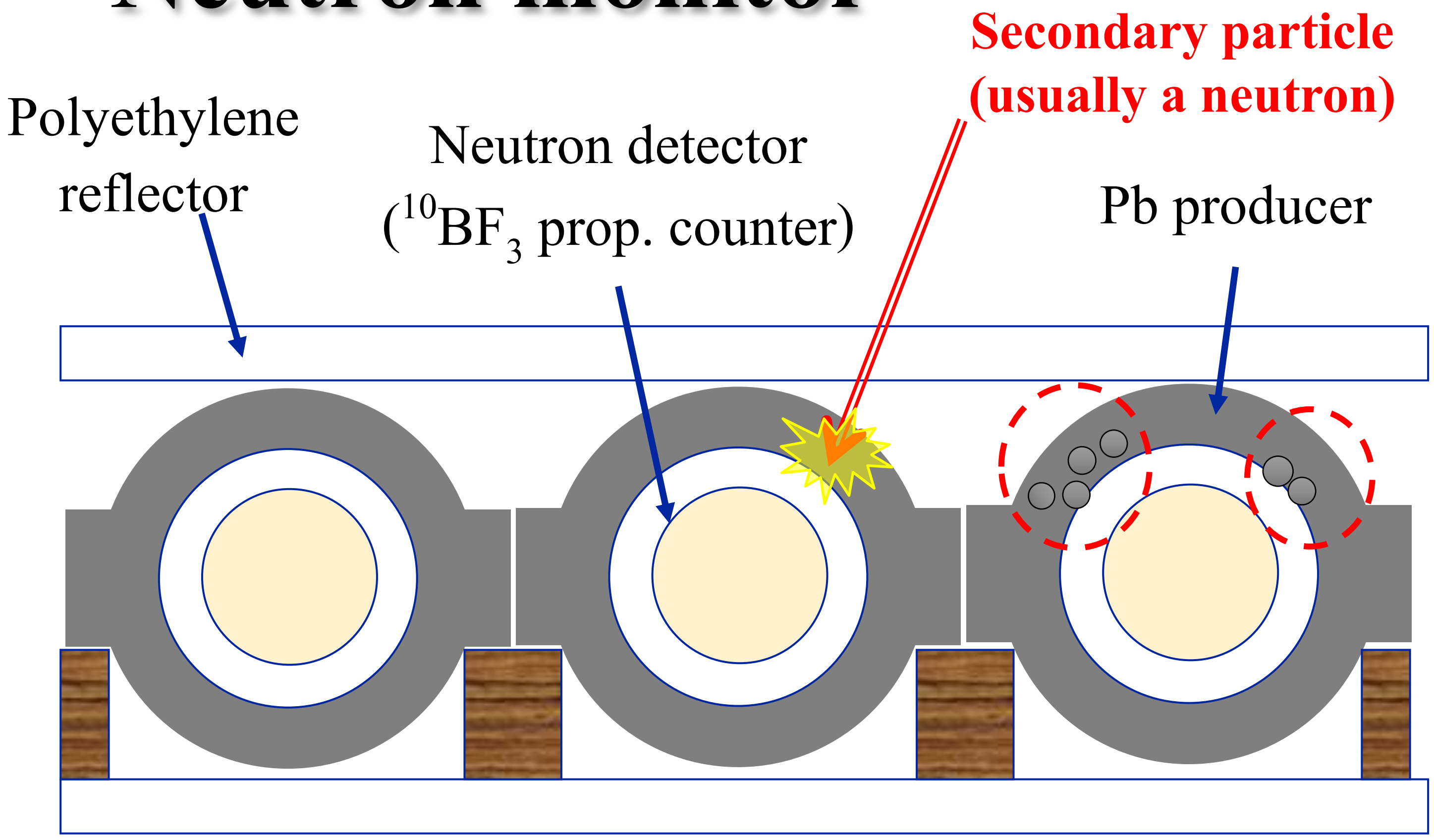
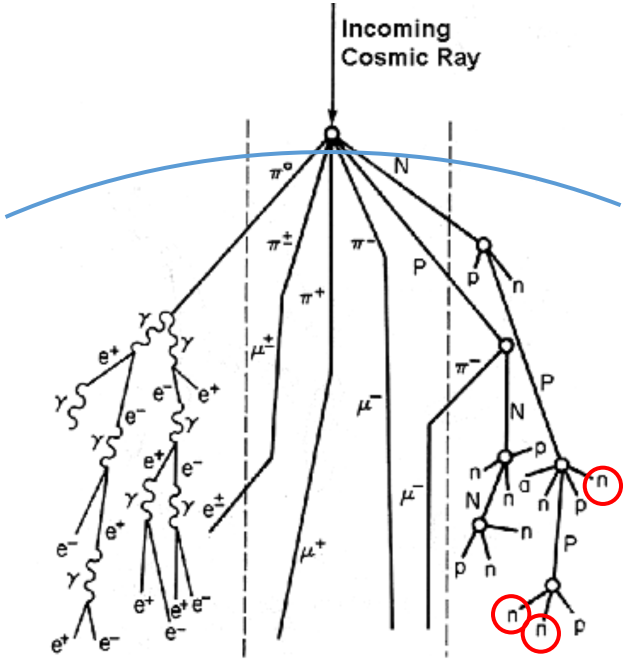
Neutron monitor





More energetic primary
More energetic secondary

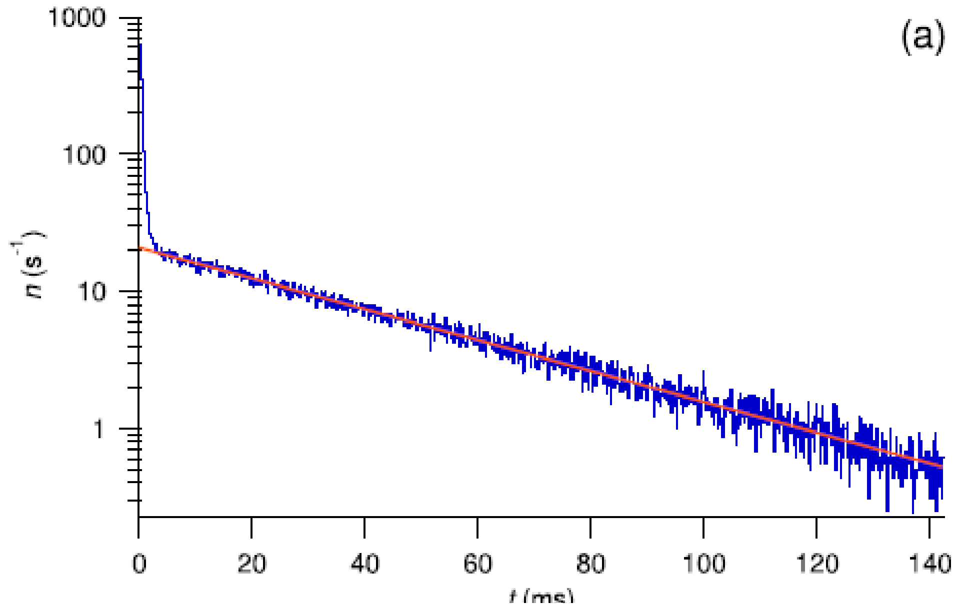
More neutrons in monitor

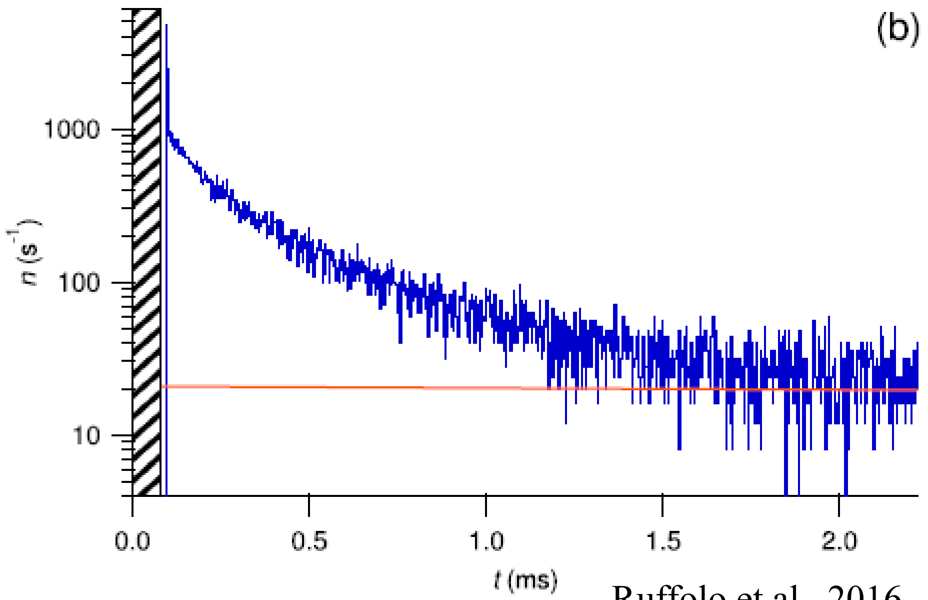
Higher multiplicity

Time-delay histograms

- Electronics record time delay, interval of time between one count to the next count.
- We statistically calculate the leader fraction from histograms of time delay, related to cosmic ray spectral index.
- Amplitude of exponential tail (red) indicates rate of "leaders" arriving by chance, not "following" in temporal association with preceding count.

L = "leader fraction" (inverse multiplicity)





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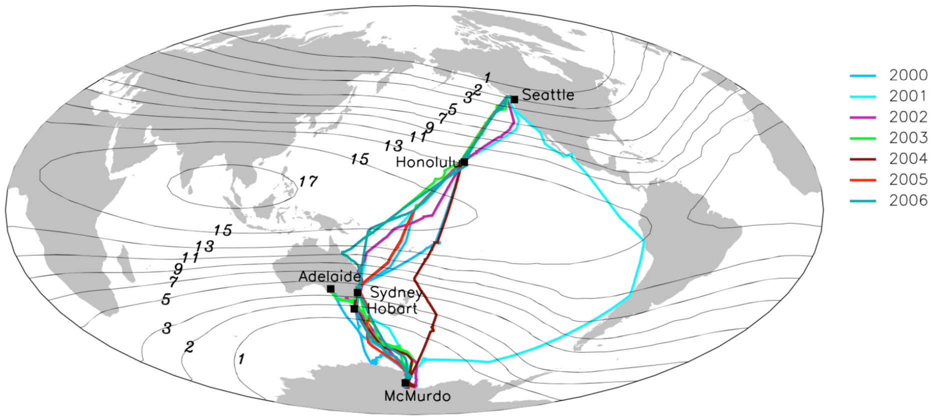
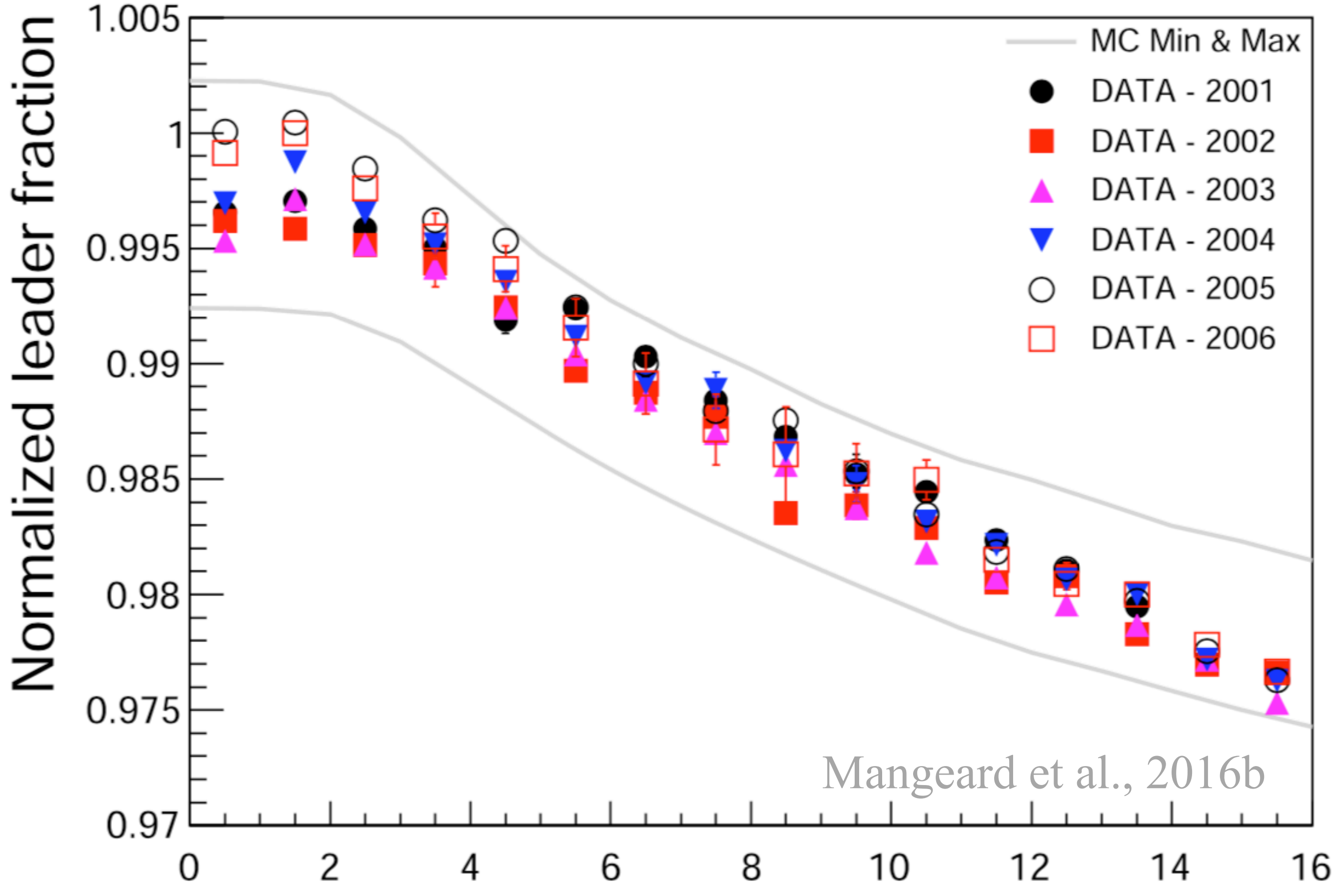
Leader fraction & cosmic ray spectrum …



… from a ship-borne latitude surveys 2000 - 2007



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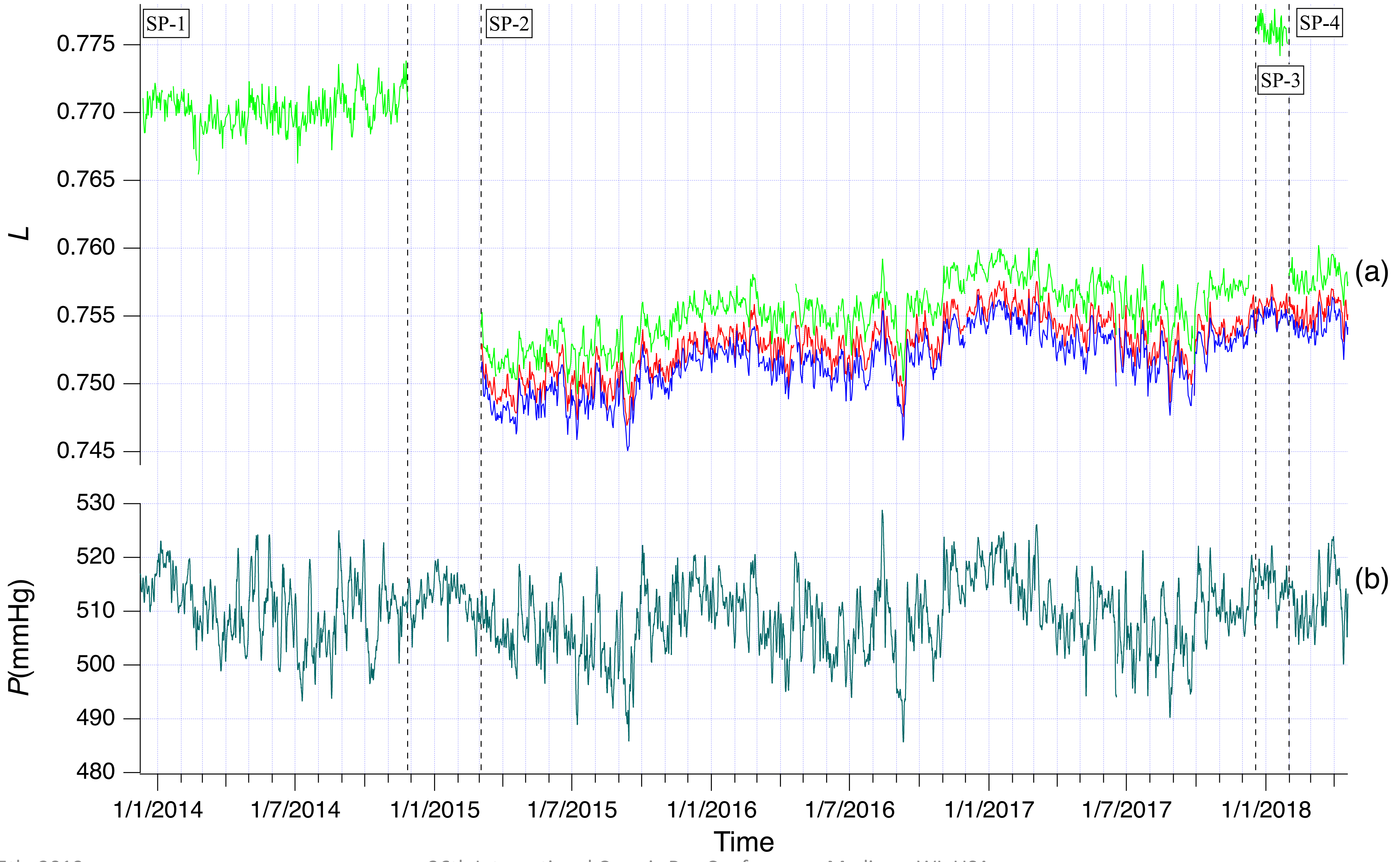
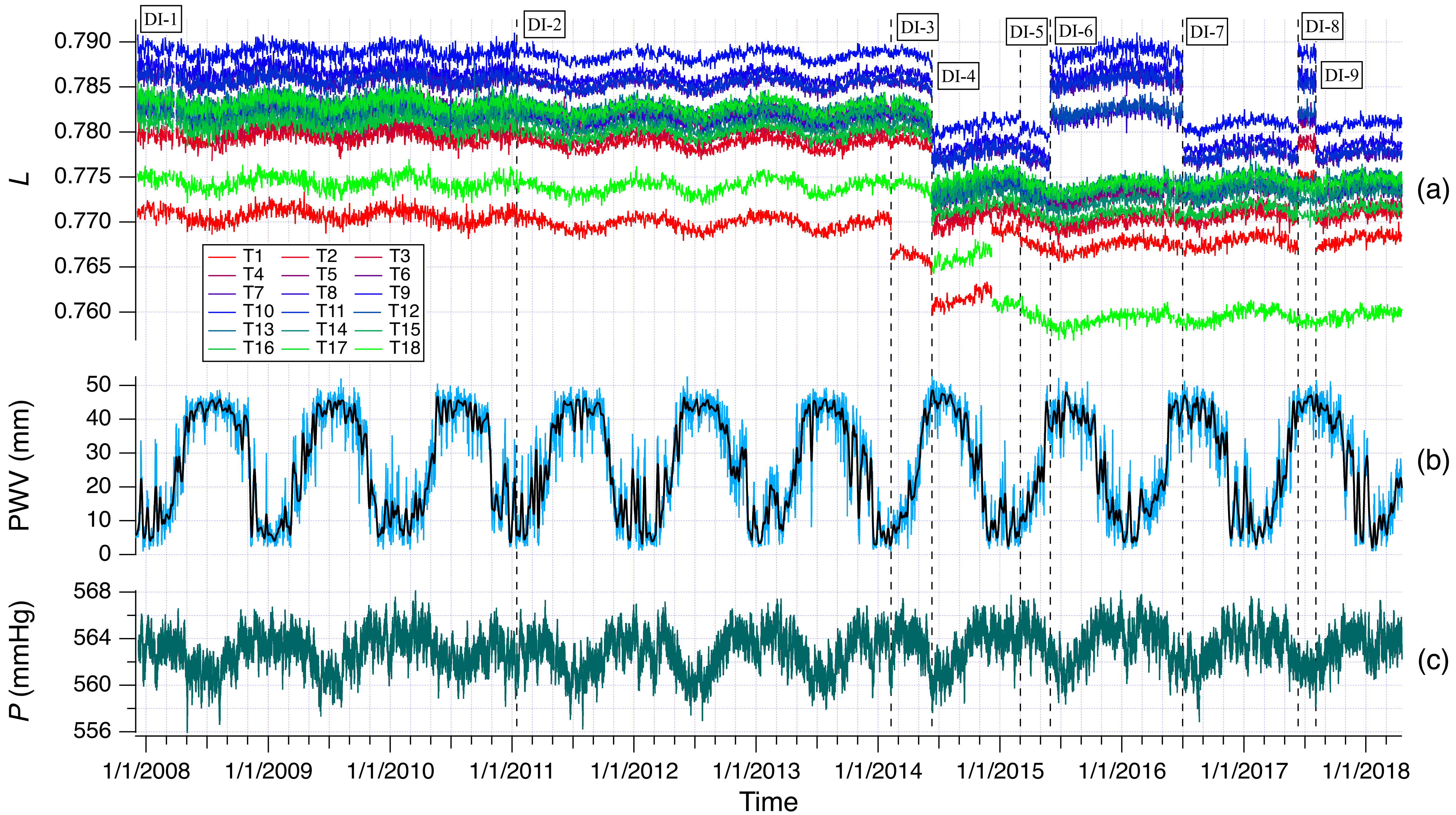
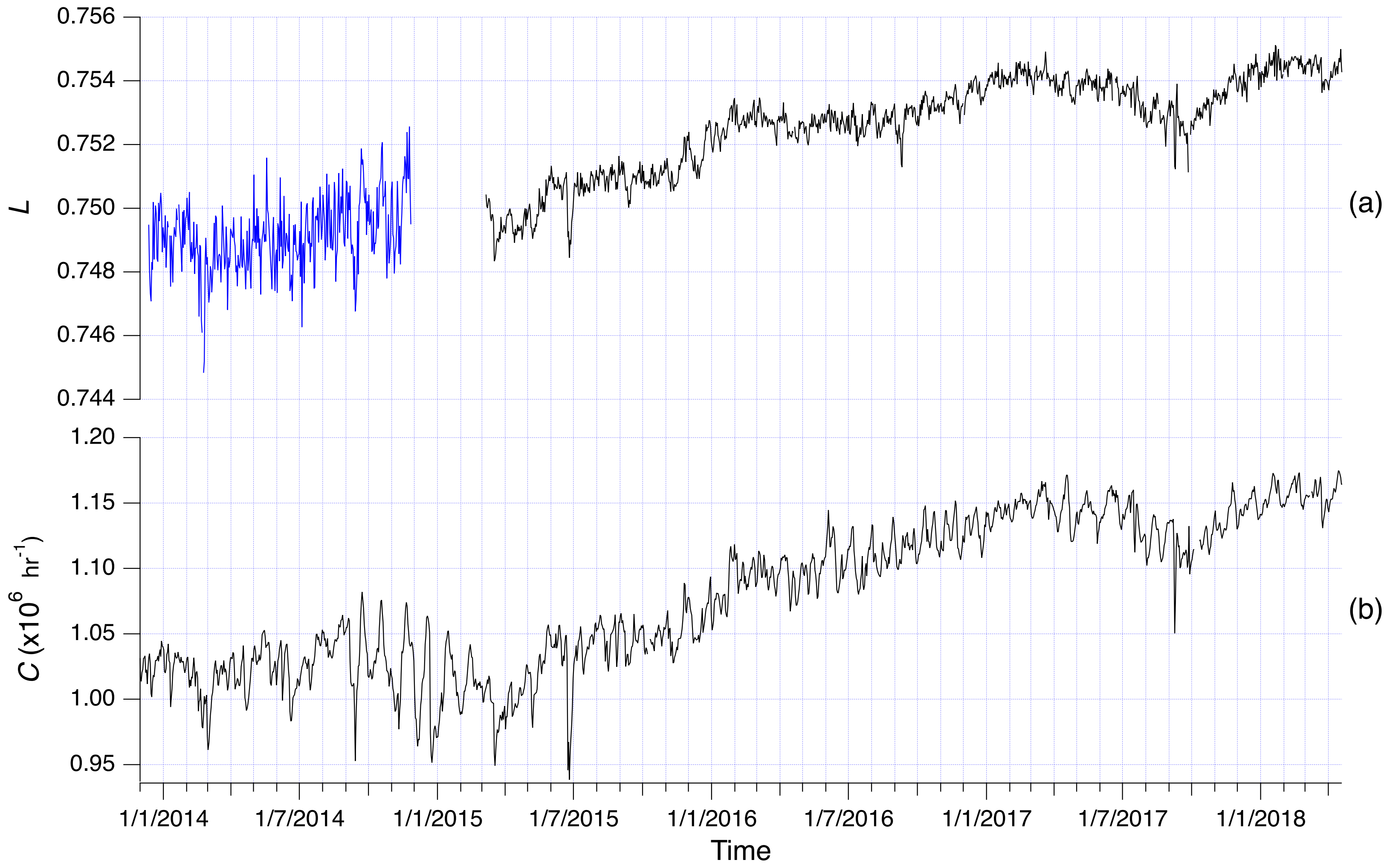
Uncorrected leader fraction at South Pole



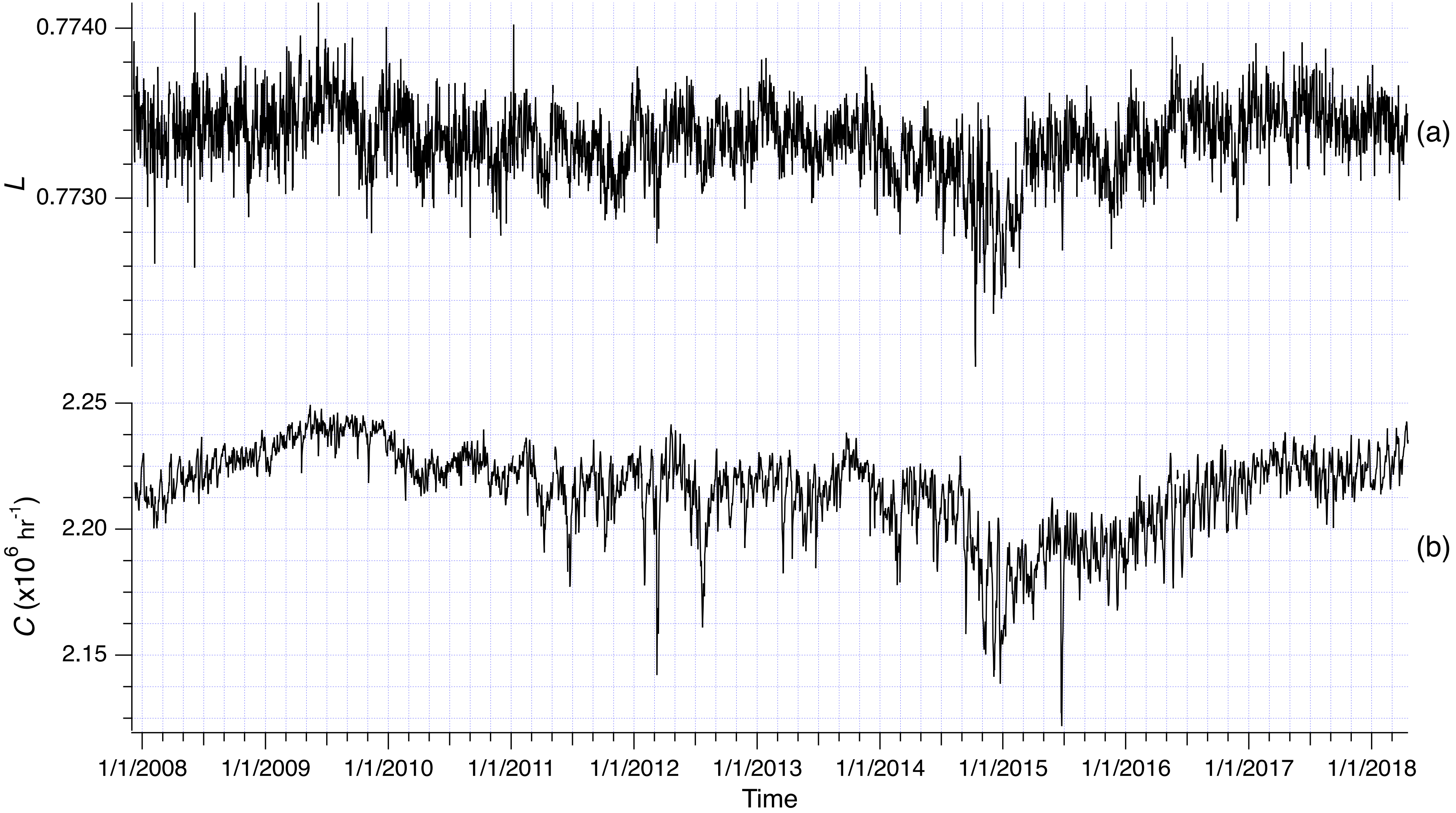
Uncorrected leader fraction at PSNM, Thailand



Leader fraction L and count rate C at South Pole

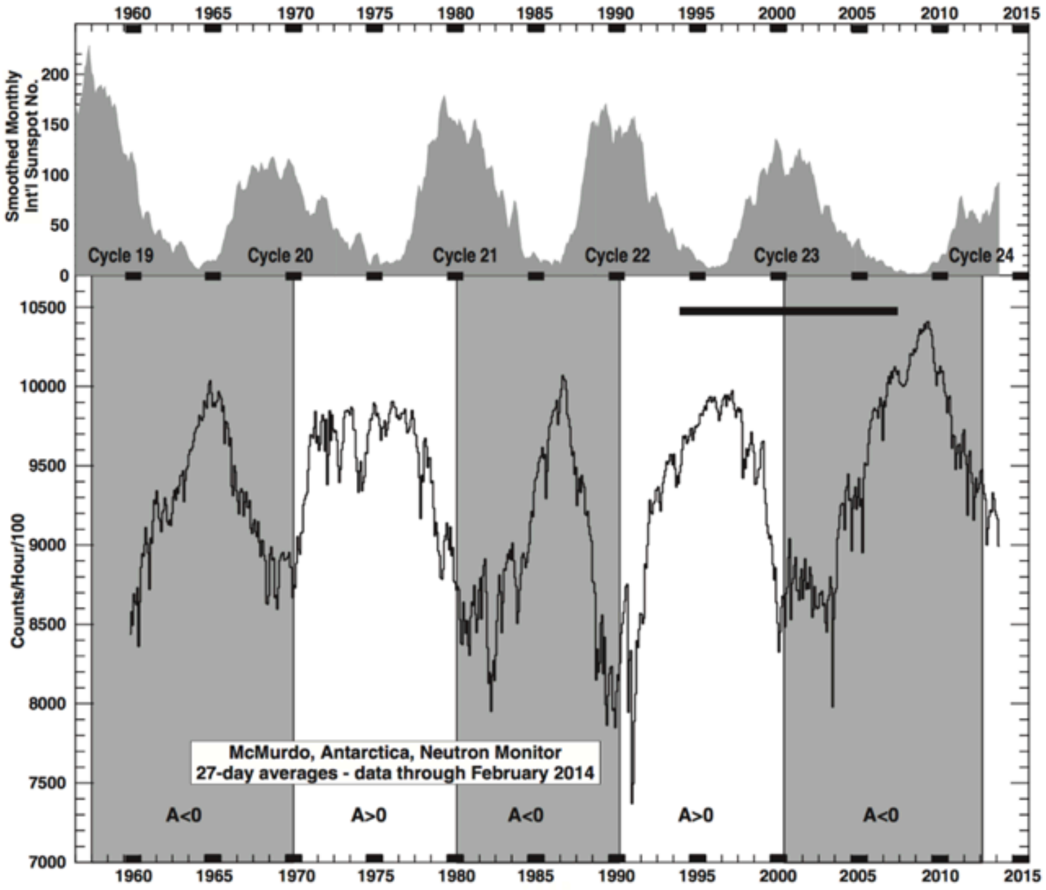


Leader fraction *L* and count rate *C* at Doi Inthanon, Thailand

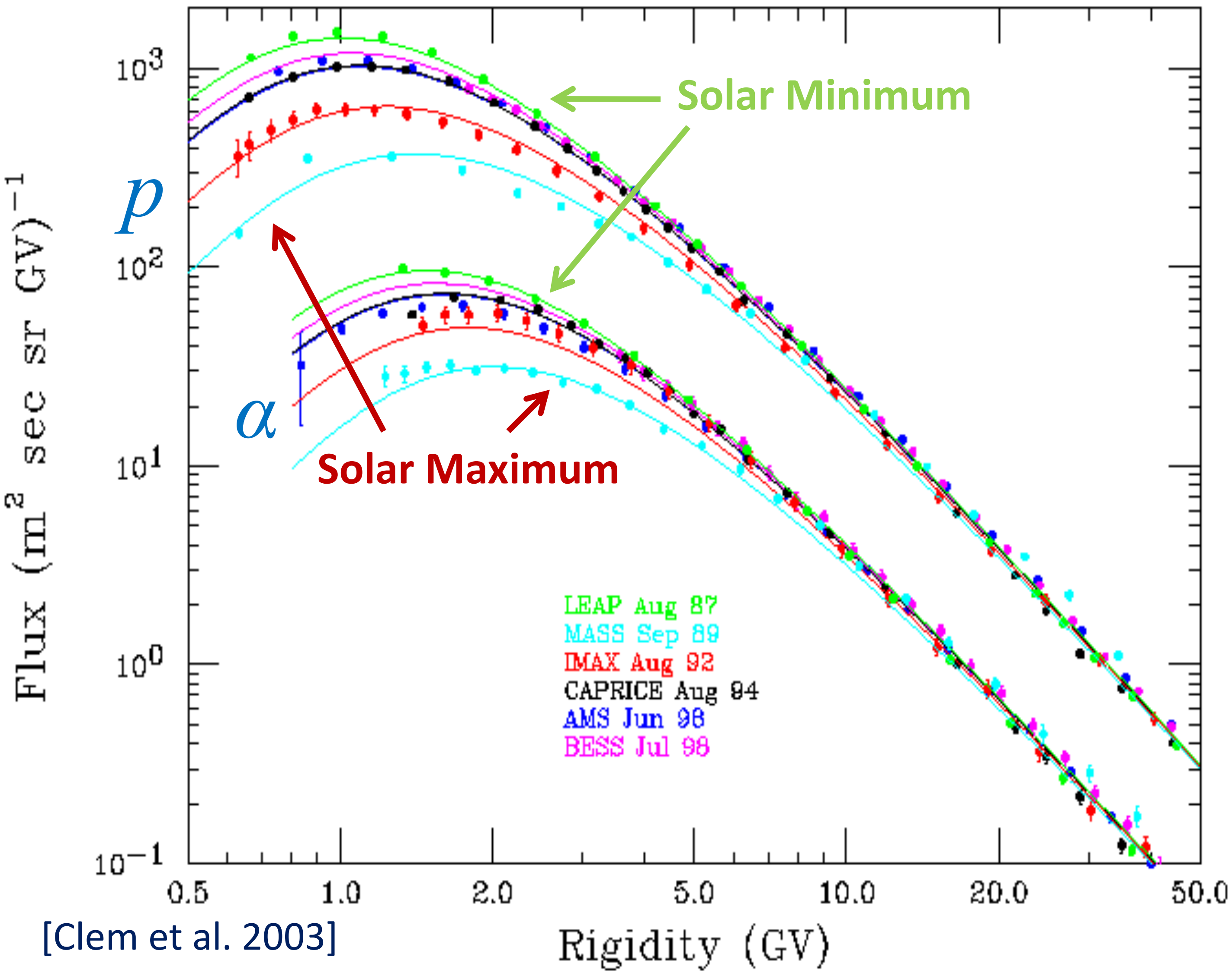


Solar modulation

The energy (or rigidity) spectrum of galactic cosmic rays varies with the solar cycle.

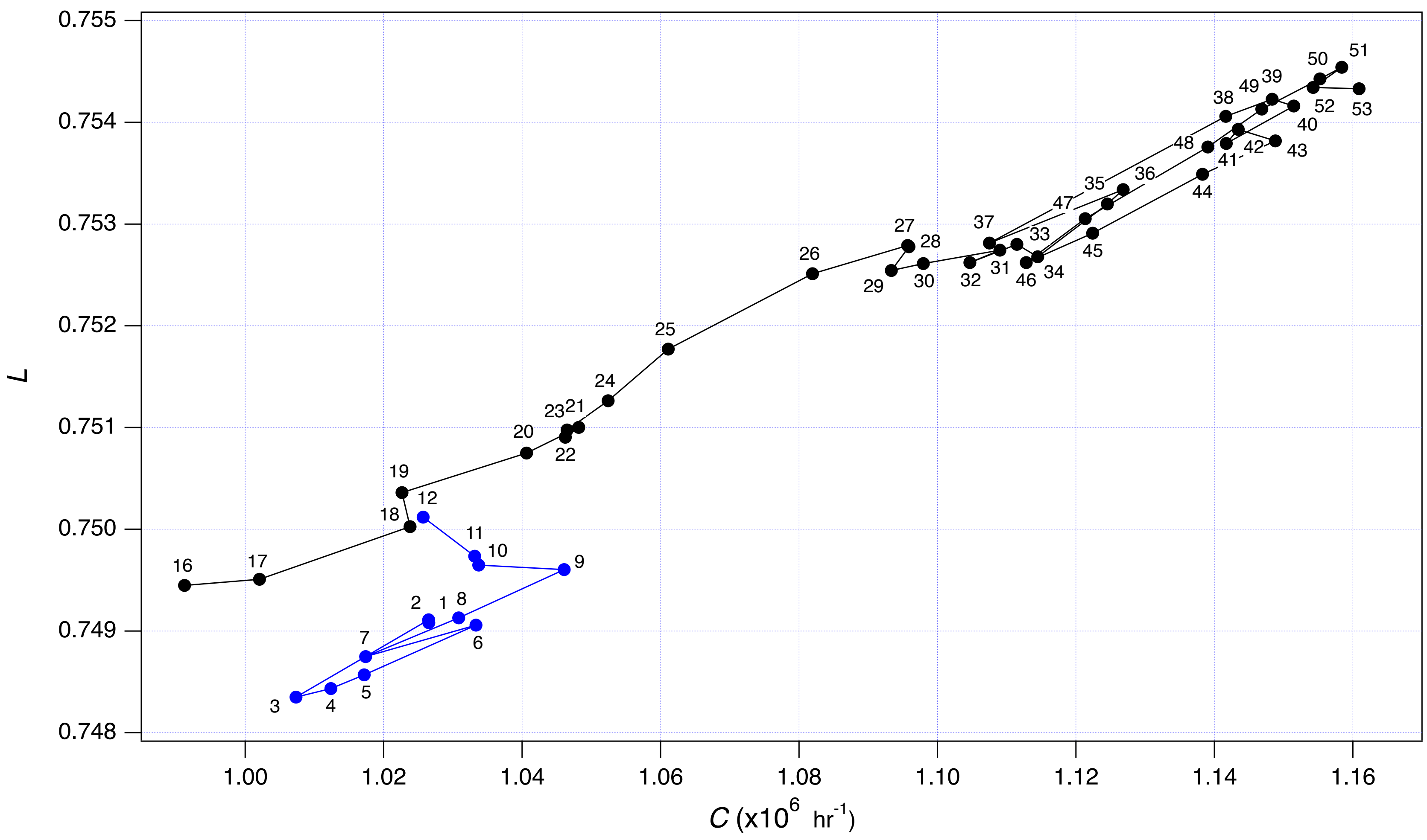


[Nuntiyakul et al., 2014]

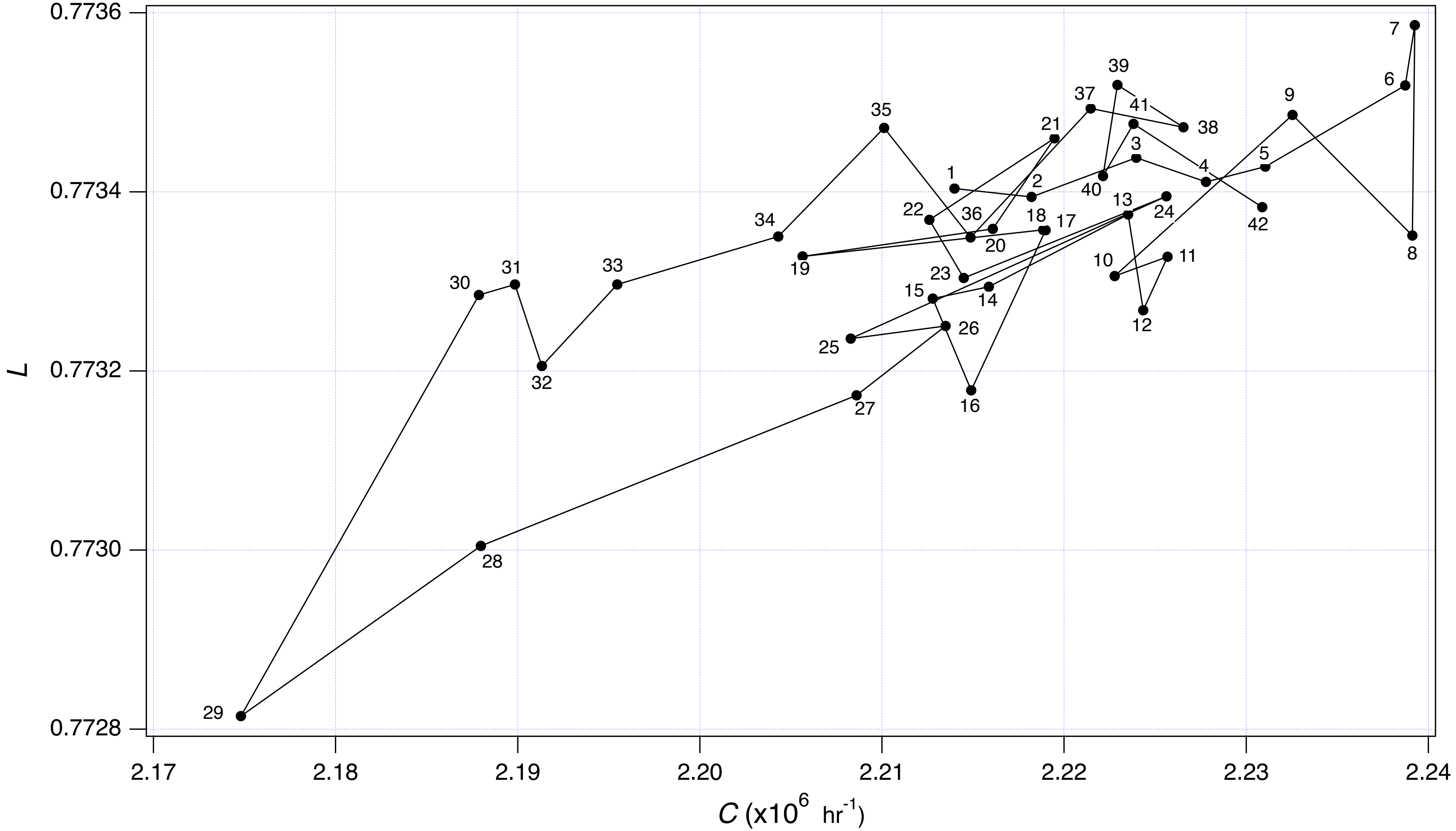


[Clem et al. 2003]

Monthly averages of *L* vs. *C*, South Pole NM



Three month averages of *L* vs. *C*, PSNM



Conclusions

- Leader fraction can be use to track spectral variations in cosmic rays by using data from a single NM station.
- We have corrected for changes in electronics and also the atmospheric effects of pressure and water vapor to develop a long-term leader fraction dataset.
- Measurements of L from the South Pole are particularly precise and will allow detailed studies of spectral variation of cosmic rays during Forbush decreases due to solar storms and over 27-day variations due to the Sun's rotation
- We find that L varied with the sunspot cycle, and the hysteresis between L and count rate implies a change in the shape of the cosmic ray spectrum due to solar modulation from before to after the solar magnetic polarity reversals of 2012-2014.
- The leader fraction at Doi Inthanon provides new information on solar modulation above ~17 GV.

Thank you

THE ASTROPHYSICAL JOURNAL, 817:38 (12pp), 2016 January 20
doi:10.3847/0004-637X/817/1/38

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MONITORING SHORT-TERM COSMIC-RAY SPECTRAL VARIATIONS USING NEUTRON MONITOR TIME-DELAY MEASUREMENTS

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Received 2015 November 3; accepted 2015 November 30; published 2016 January 20

ABSTRACT

Neutron monitors (NMs) are ground-based detectors of cosmic-ray showers that are widely used for high-precision monitoring of changes in the Galactic cosmic-ray (GCR) flux due to solar storms and solar wind variations. In the present work, we show that a single neutron monitor station can also monitor short-term changes in the GCR spectrum, avoiding the systematic uncertainties in comparing data from different stations, by means of NM time-delay histograms. Using data for 2007–2014 from the *Princess Sirindhorn Neutron Monitor*, a station at Doi Inthanon, Thailand, with the world's highest vertical geomagnetic cutoff rigidity of 16.8 GV, we have developed an analysis of time-delay histograms that removes the chance coincidences that can dominate conventional measures of multiplicity. We infer the "leader fraction" L of neutron counts that do not follow a previous neutron

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Leader fraction calculation

- For the chance coincidences only, at rate α

$$n(t) = \alpha e^{-\alpha t}$$

- Let *R(t)* be the probability that there is no repeat count in one counter tube over a time delay.
- R_n is defined as the multiplicity contribution to *R* and t_d is the electronic dead time then …

$$n(t) = \left(\alpha R_n - \frac{dR_n}{dt}\right) e^{-\alpha(t-t_d)}$$

At $t > t_n$ then $\frac{dR_n}{dt} = 0$ and $R_n(t) = L$

$$n(t) = \alpha L e^{-\alpha(t-t_d)}$$

This "no-follower" probability starts at $R_n(t_d) = 1$ and declines until $t \sim t_n$, when it reaches a value *L* that represents the "leader fraction" of counts that did not follow another neutron count in the same PC tube due to the same atmospheric secondary particle.
In the time domain, a leader count is the first neutron count measured from an interacting secondary particle.

In greater detail, the first technique for determining L from a given time-delay histogram should also take into account the overflow time $t_o = 142$ ms in the electronic recording system. Then the recorded probability density $\tilde{n}(t)$ is given by

$$\tilde{n}(t) = n(t) + n(t + t_o) + n(t + 2t_o) + ... \quad (7)$$

For $t > t_n$, we use

$$\tilde{n}(t) = \alpha L \sum_{k=0}^{\infty} e^{-\alpha(t+kt_o-t_d)} = \frac{\alpha L e^{\alpha t_d}}{1 - e^{-\alpha t_o}} e^{-\alpha t}. \quad (t > t_n) \quad (8)$$

The long-time histogram is fit to an exponential form $\tilde{n}(t) = Ae^{-\alpha t}$ using a maximum likelihood method that accounts for the Poisson distribution in the observed $\tilde{n}$ for each time bin t. We then determine L from the fit parameters using

$$\boxed{L = \frac{1 - e^{-\alpha t_o}}{\alpha e^{\alpha t_d}} A.} \quad (9)$$

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RESEARCH ARTICLE
10.1002/2016JA023515

Dependence of the neutron monitor count rate and time delay distribution on the rigidity spectrum of primary cosmic rays

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Key Points:
- For neutron monitor latitude surveys in 2000–2007 we analyzed the count rate and the leader fraction *L* from neutron time delay histograms
- We compared observations with Monte Carlo simulations of cosmic ray showers, including new yield functions for a sea-level neutron monitor
- The comparison confirms that observed changes in *L* reflect cosmic ray spectral variation with changing geomagnetic cutoff and sunspot cycle

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Abstract Neutron monitors are the premier instruments for precisely tracking time variations in the Galactic cosmic ray flux at GeV-range energies above the geomagnetic cutoff at the location of measurement. Recently, a new capability has been developed to record and analyze the neutron time delay distribution (related to neutron multiplicity) to infer variations in the cosmic ray spectrum as well. In particular, from time delay histograms we can determine the leader fraction *L*, defined as the fraction of neutrons that did not follow a previous neutron detection in the same tube from the same atmospheric secondary particle. Using data taken during 2000–2007 by a shipborne neutron monitor latitude survey,