Charge-sign dependent solar modulation for everyone

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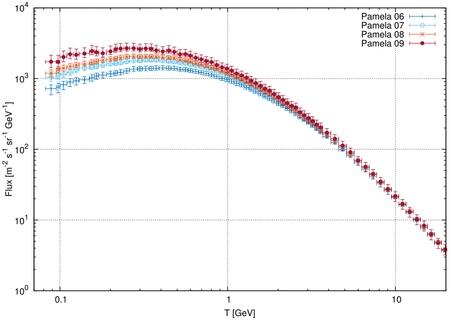
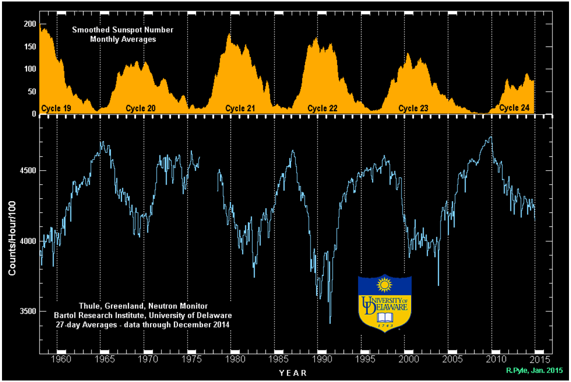
Outline

Charged Cosmic Ray Observation



- Observed charged cosmic ray fluxes at the top of the atmosphere (TOA) are time dependent
- Only low ($\mathcal{O}(1)$ GeV) energies are affected
- Origin of the modulation is the transport in the heliosphere

Time Dependent Party Activity In The Heliosphere



- Approximately 11 year solar cycle → sunspot number, solar magnetic field etc. vary with time
- Magnetic field (polarity) reversal every 11 years

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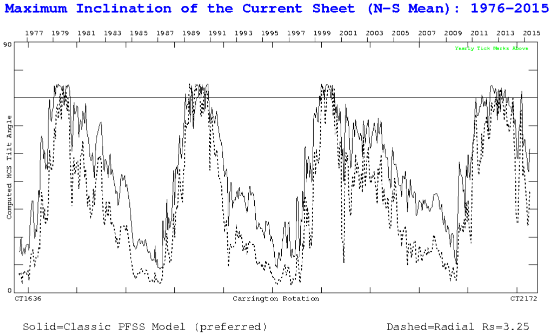

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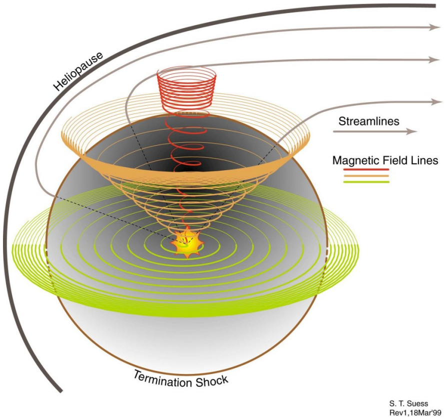
Transport Of Cosmic Rays – Fokker-Planck



- Parker transport equation (TPE) [Parker, 1965]

$$-(\mathbf{V} + \mathbf{V}_D) \cdot \nabla f + \nabla \cdot (\kappa \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \log p} = \frac{\partial f}{\partial t}$$

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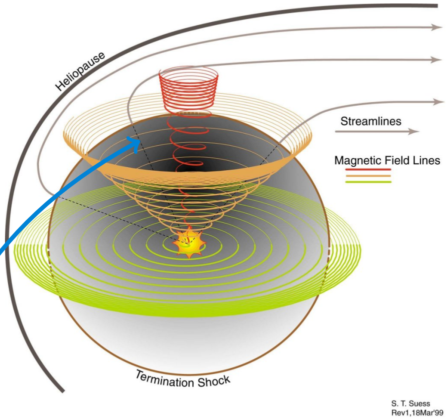

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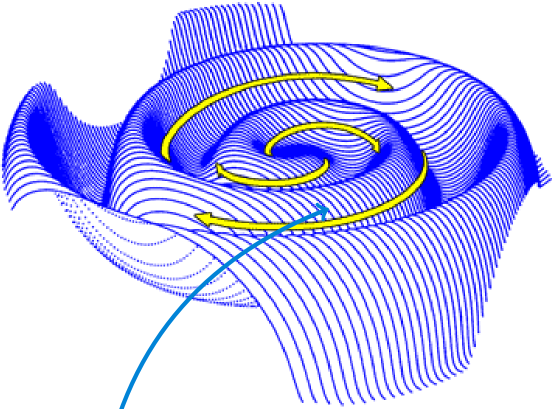

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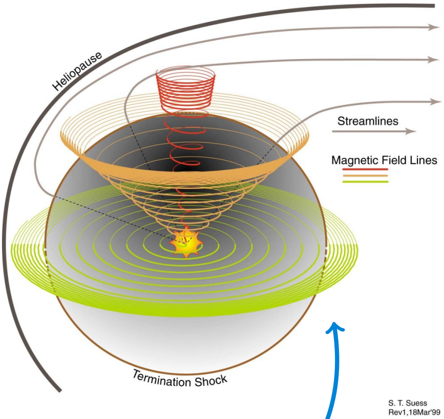

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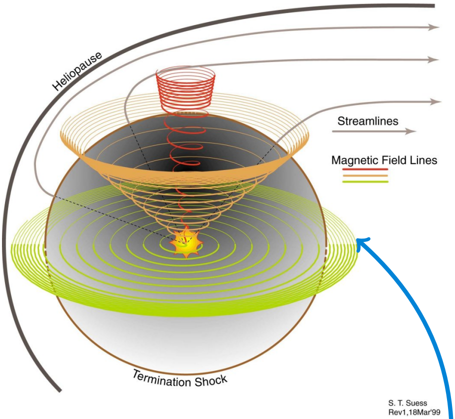

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A Simple Approach – Charge-Sign Independence

- Simplify the Parker transport equation

$$-(\mathbf{V} + \mathbf{V}_D) \cdot \nabla f + \nabla \cdot (\kappa \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \log p} = 0$$

- Cosmic ray flux is given by $\Phi = \mathcal{R}^2 f$
- Simplified equation → Analytical approximation [Gleeson & Axford, 1968]
- Force field approximation depends on one parameter

$$\Phi^{\text{TOA}}(T - |Z|\phi) = \frac{(T - |Z|\phi)^2 + 2m(T - |Z|\phi)}{T^2 + 2mT} \Phi^{\text{IS}}(T)$$

- Force field parameter ϕ takes care of the solar activity
- Easy to use, successful predictions → Great, why should we worry?

AMS-02 – A Precision Experiment For Cosmic Rays

SOLARPROP – A C++ Program For Solar Modulation

- Many sophisticated models [Strauss et al., 2011], [Bobik et al., 2012], [Potgieter et al., 2015], . . . , but no public code for solar modulation exists
- SOLARPROP simulates the particle transport in the heliosphere
- A simple and user friendly code
- Custom models can easily incorporated by the user
- Input from popular galaxy propagation tools like GALPROP and DRAGON can directly used via FITS format interface

SOLARPROP brings charge-sign dependent solar modulation for everyone!

Interlude – From TPE To SDE

- The Parker transport equation can be transformed to a set of stochastic differential equations
- General case (A_i drift term, B_{ij} diffusion term, $dW_j = \sqrt{dt}dw_j$ Wiener process)

$$dx_i = A_i(x_i)dt + \sum_j B_{ij}(x_i)dW_j$$

- Simple example (1 dimensional, no drifts)

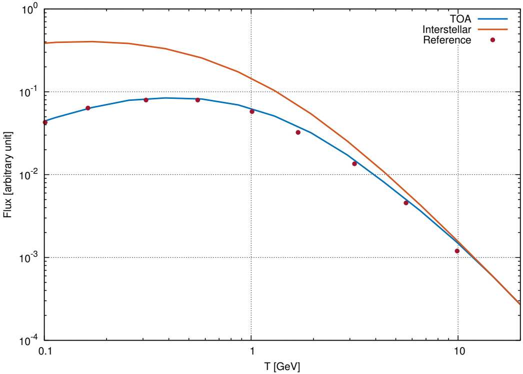
$$\Delta r = \left(-V + \frac{2\kappa_{rr}}{r}\right)\Delta t + \sqrt{2\kappa_{rr}\Delta t}dw_r$$

$$\Delta T = \frac{2V}{3r}\frac{T^2 + 2Tm}{T+m}\Delta t$$

- Simple to implement (no explicit discretization needed), easy to parallelize

Test

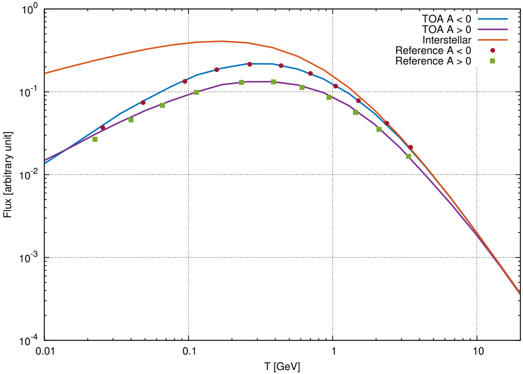
```
model ref1
outputFormat Both
charge 1
mass 0.938
totalNumber 2500
```



- SOLARPROP has been tested and incorporates four simple reference models
- Model `ref1` is a simple one dimensional diffusion model [Yamada et al., 1998]

Test, Test

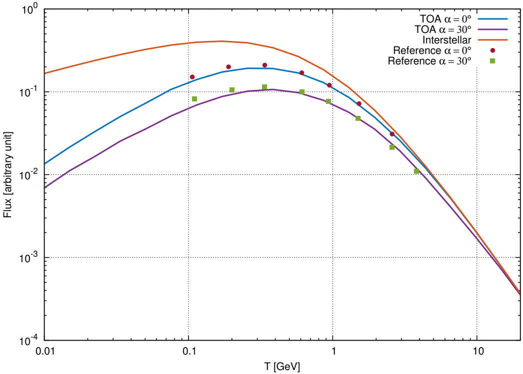
```
model ref2
outputFormat Both
charge 1
mass 0.938
totalNumber 2500
polarity 1
```



- Model `ref2` is a two dimensional model [Jokipii & Kopriva, 1979] with drifts

Test, Test, Test

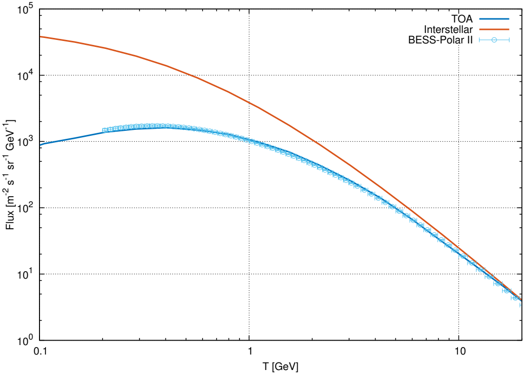
```
model ref3
outputFormat Both
charge 1
mass 0.938
totalNumber 2500
polarity -1
angle 30
```



- Model `ref3` is a two dimensional model [Burger & Potgieter, 1988] with drifts and wavy heliospheric current sheet

Some Preliminary Results – Protons

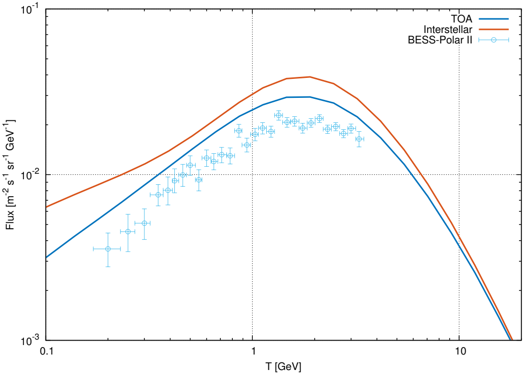
```
model standard
outputFormat Both
charge 1
mass 0.938
year 2007
month 12
tiltModel R
totalNumber 1500
```



- SOLARPROP offers also a more sophisticated model called `standard`
- Parameters are automatically calculated for a given date

More Preliminary Results – Antiprotons

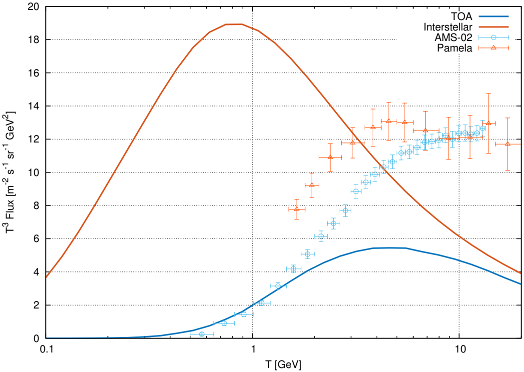
```
model standard
outputFormat Both
charge -1
mass 0.938
year 2007
month 12
tiltModel R
totalNumber 1500
```



- Result depends strongly on the interstellar input
- Difficult to find a model which works for many data sets

Positrons At Different Times

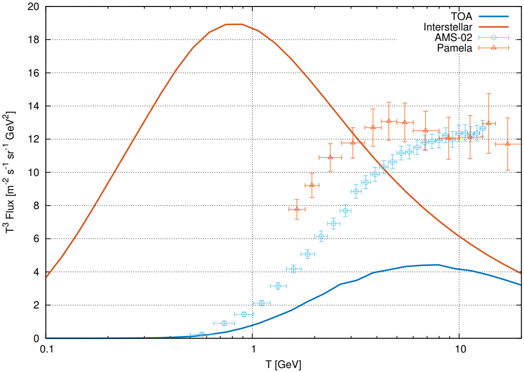
```
model standard
outputFormat Both
year 2006
month 7
yearEnd 2009
monthEnd 12
tiltModel R
modNumber 1
index 3
totalNumber 1500
```



- Interstellar flux from DRAGON (only secondaries), not representative
- Lower flux at solar maximum, higher flux for positive solar polarity

Positrons At Different Times

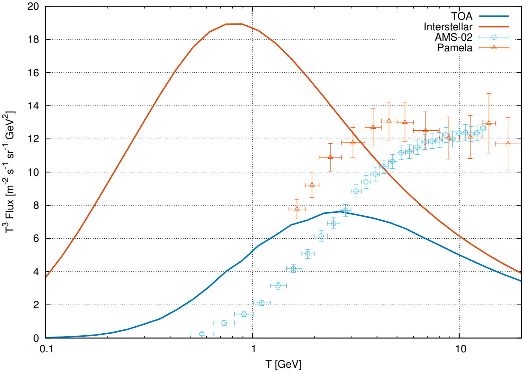
```
model standard
outputFormat Both
year 2011
month 6
yearEnd 2013
monthEnd 11
tiltModel R
modNumber 1
index 3
totalNumber 1500
```



- Interstellar flux from DRAGON (only secondaries), not representative
- Lower flux at solar maximum, higher flux for positive solar polarity

Positrons At Different Times

```
model standard
outputFormat Both
year 1994
month 8
tiltModel R
modNumber 1
index 3
totalNumber 1500
```



- Interstellar flux from DRAGON (only secondaries), not representative
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Conclusions

- SOLARPROP is a simple tool for charge-sign dependent solar modulation
- Results strongly depend on the used model and interstellar flux

Thank you for your attention!