LHAASO合作组会议（威海）

宇宙线传播的关键物理机制：以太阳高能粒子为例

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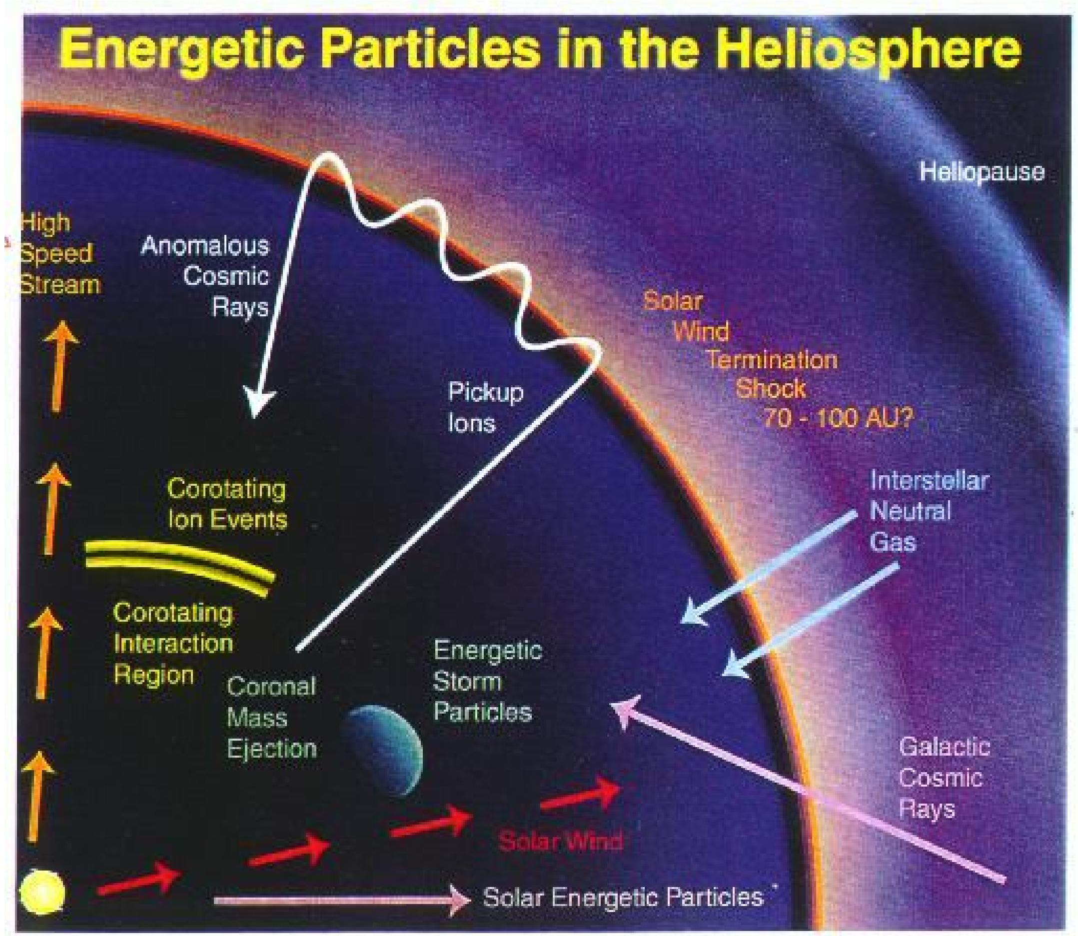
2017年9月23日

- 研究背景
- 观测现象与数值模拟
  - 反向流动粒子束
  - 东-西经度非对称分布
  - **SEP**强度的径向依赖性
  - **SEP**水库(**Reservoir**)现象
- 总结

研究背景

空间高能粒子家族



太阳高能粒子(SEP)

银河宇宙线(GCR)

异常宇宙线(ACR)

CIR相关粒子

木星电子

起源不同
传播机制类似

宇宙线起源——世纪之谜

Vol 460|6 August 2009|doi:10.1038/nature08127 nature

PROGRESS

Beyond the myth of the supernova-remnant origin of cosmic rays

Yousaf Butt[1]

The origin of Galactic cosmic-ray ions has remained an enigma for almost a century. Although it has generally been thought that they are accelerated in the shock waves associated with powerful supernova explosions—for which there have been recent claims of evidence—the mystery is far from resolved. In fact, we may be on the wrong track altogether in looking for isolated regions of cosmic-ray acceleration.

Victor Hess

1912.8.7 6:00 am

↓

2017

Butt 2009, Nature

Nature of cosmic ray sources: One of the eleven fundamental physics questions for the 21st century

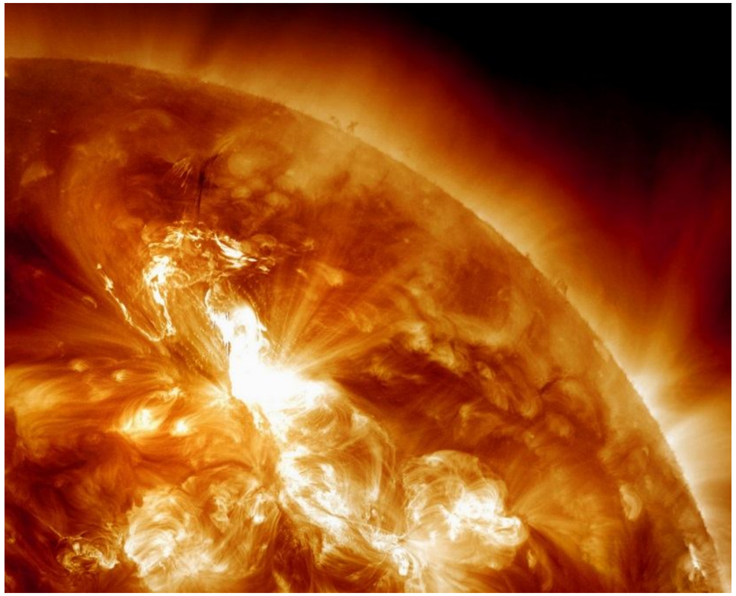
宇宙线起源是21世纪11个基本物理问题之一

Turner et al. 2002, report to the National Academy of Sciences

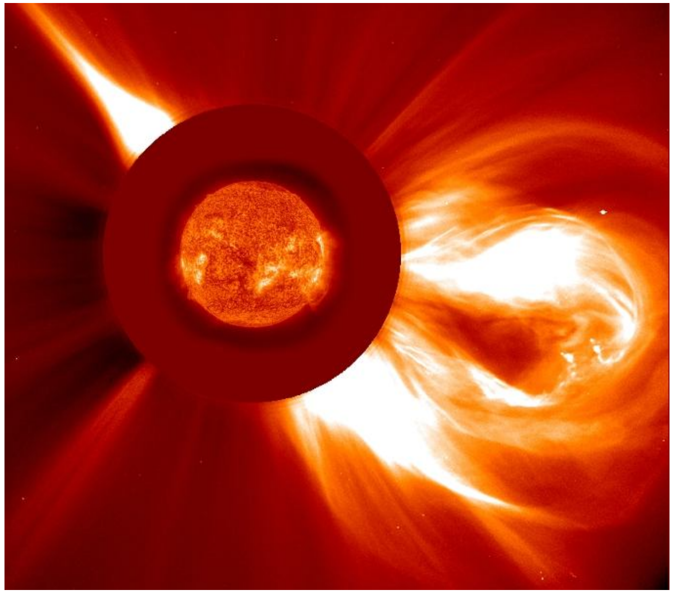
太阳高能粒子(SEP): 研究宇宙线传播机制的样本

Solar Energetic Particles (SEP)

Charged energetic particles of up to GeV energies emitted by the Sun

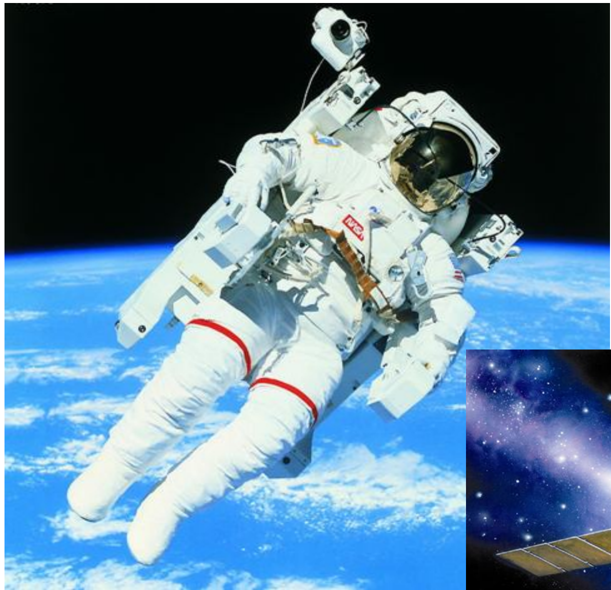


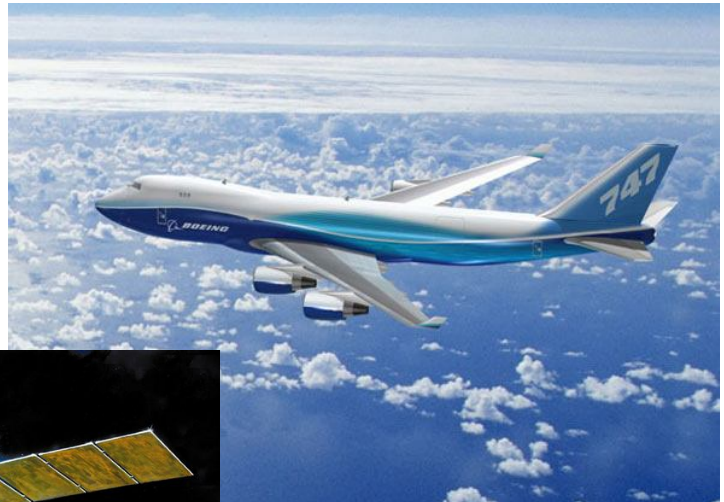
耀斑(solar flare)

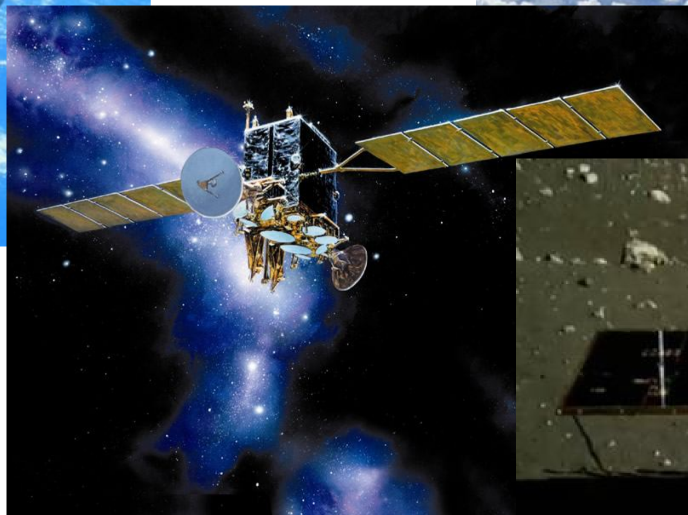


日冕物质抛射(coronal mass ejection)

太阳高能粒子（SEP）：最高可达10GeV量级，对宇航员、卫星（通信、测控、导航等）、极区航班均构成严重危害，成为影响日地空间环境和空间天气的重要因素。定量理解和描述太阳高能粒子在日地空间的传播过程十分重要。







宇宙线传播的物理机制

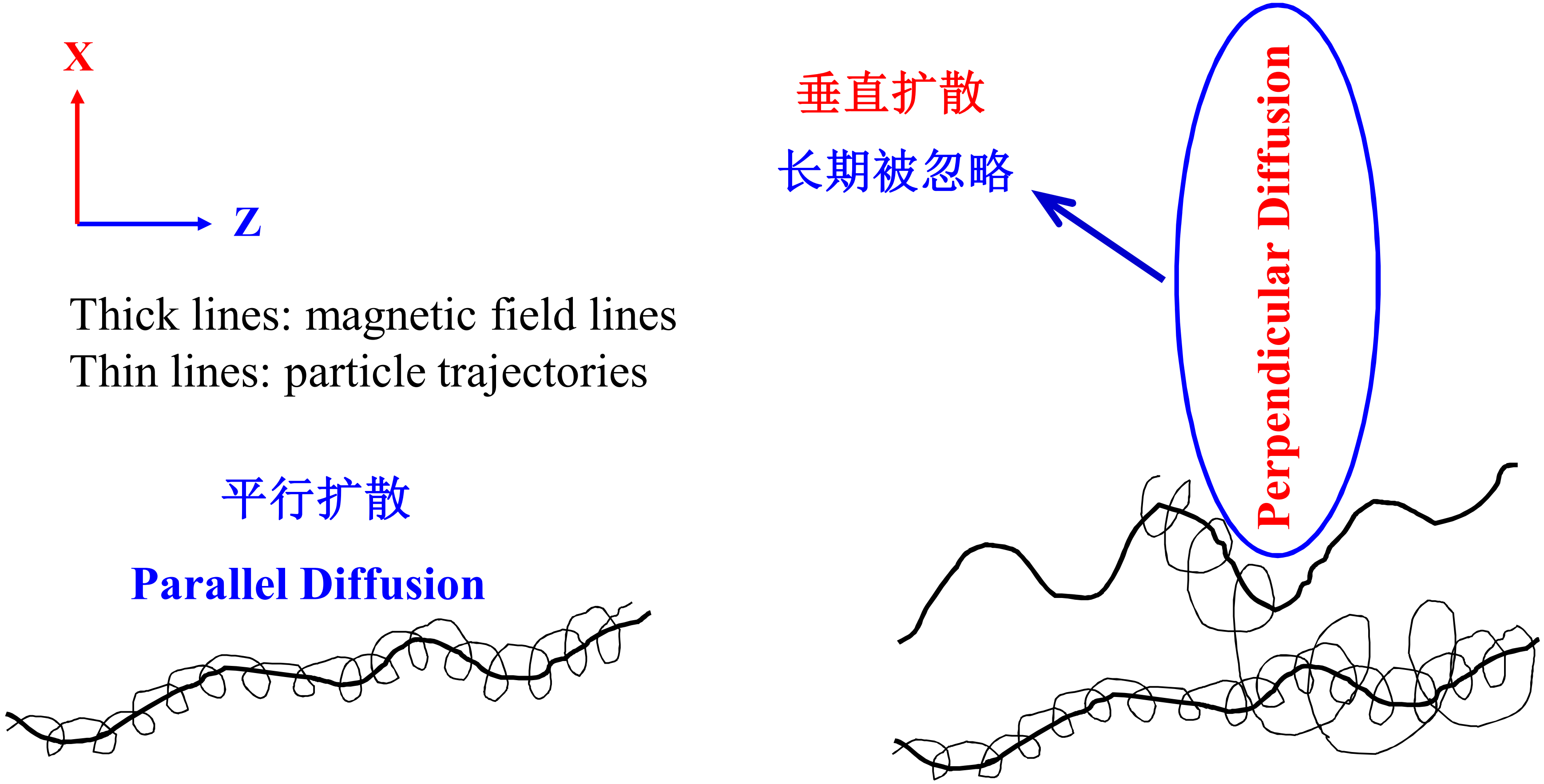
Transport Equation (Parker 1965)

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x_i}(U v_i) + \frac{\partial}{\partial T}\left(U \frac{dT}{dt}\right) - \frac{\partial}{\partial x_i}\left(\kappa_{ij} \frac{\partial U}{\partial x_j}\right) = 0$$

Fokker-Planck Transport Equation

$$\overbrace{\frac{\partial f}{\partial t}}^{\text{Distribution}} + \overbrace{\mu v \frac{\partial f}{\partial z}}^{\text{Streaming}} + \overbrace{V^{sw} \cdot \nabla f}^{\text{Convection}} + \overbrace{\frac{dp}{dt}\frac{\partial f}{\partial p}}^{\text{Adiabatic Cooling}} + \overbrace{\frac{d\mu}{dt}\frac{\partial f}{\partial \mu}}^{\text{Magnetic Focusing, Flow Divergence}}$$

$$\underbrace{-\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)}_{\text{Pitch-angle Diffusion}} \underbrace{-\frac{\partial}{\partial x}\left(\kappa_{xx}\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial y}\left(\kappa_{yy}\frac{\partial f}{\partial y}\right)}_{\text{Perpendicular Diffusion}} = \underbrace{Q(\vec{x}, \vec{p}, t)}_{\text{Source}}$$

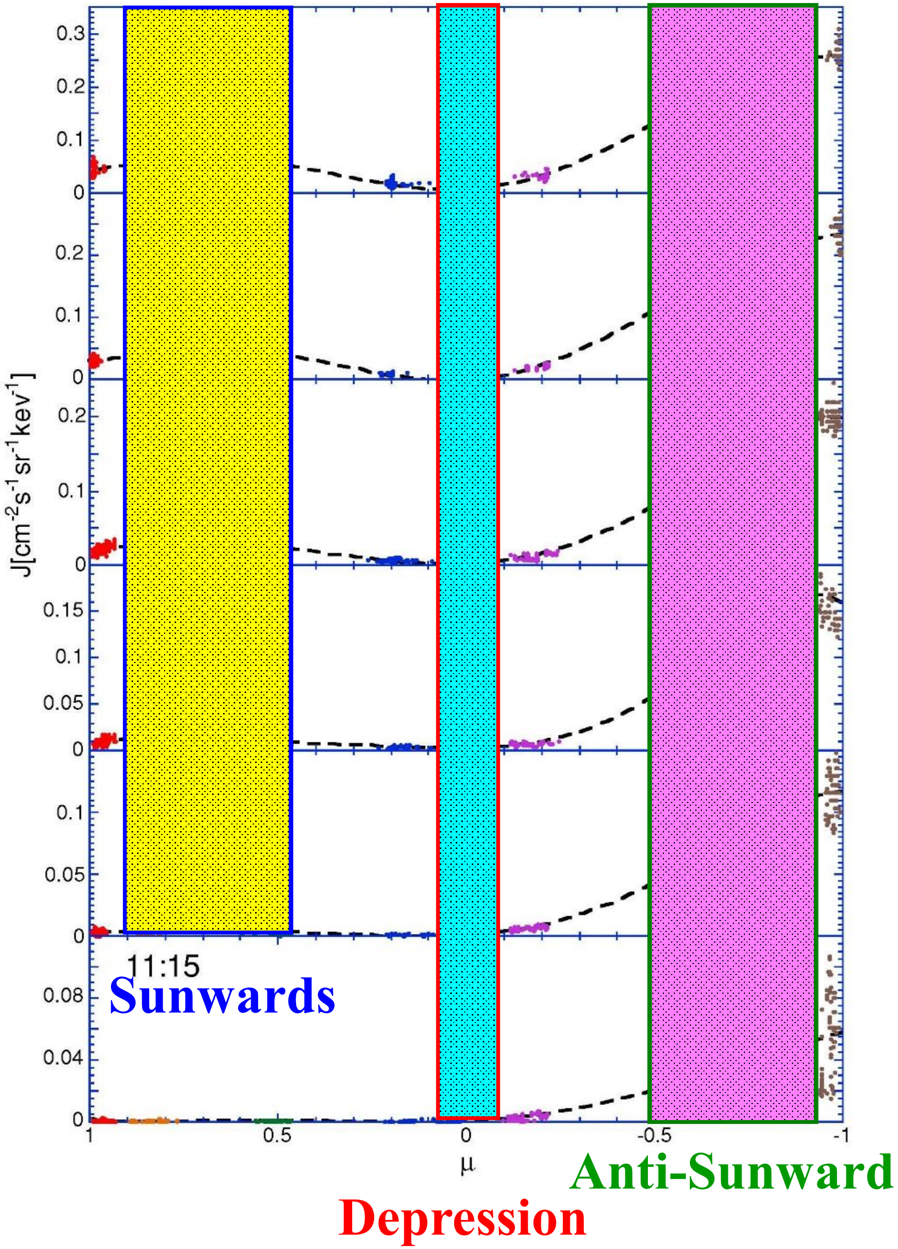


According to the quasi-linear theory for cosmic ray diffusion (Jokipii 1966), the perpendicular diffusion coefficient is usually much smaller than the parallel diffusion coefficient. Therefore, the effect of perpendicular diffusion was ignored in previous studies of SEP propagation.

The SEP observations detected by *Helios* mission proposed non-linear effects near 90° pitch angle of particles (e.g. Hasselmann & Wibberenz 1968, 1970; Beeck & Wibberenz 1986; Beeck et al. 1987).

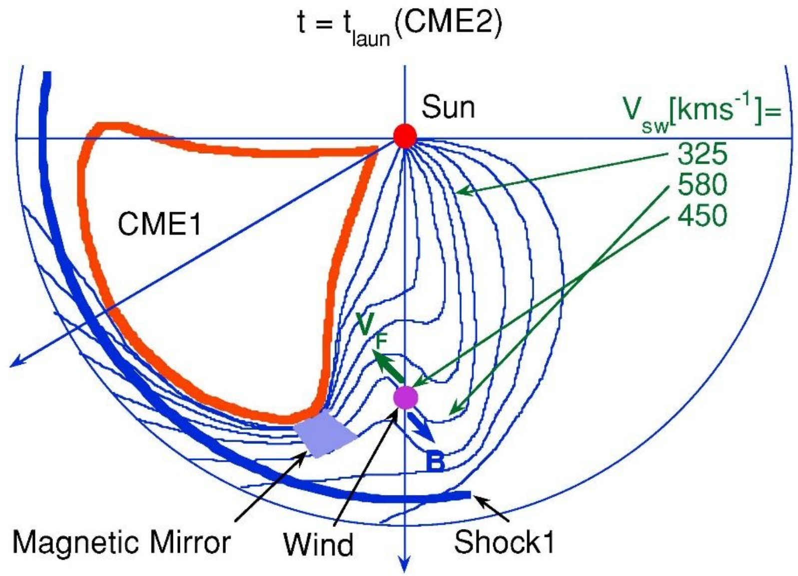
2001 September 24 SEP event

Wind 3DP 40 keV Electrons



反向流动粒子束现象

Counter-streaming particle beam with a deep depression at 90° pitch angle during onset phase.



Tan et al. 2009

数值模拟

Fokker-Planck SEP Transport Equation

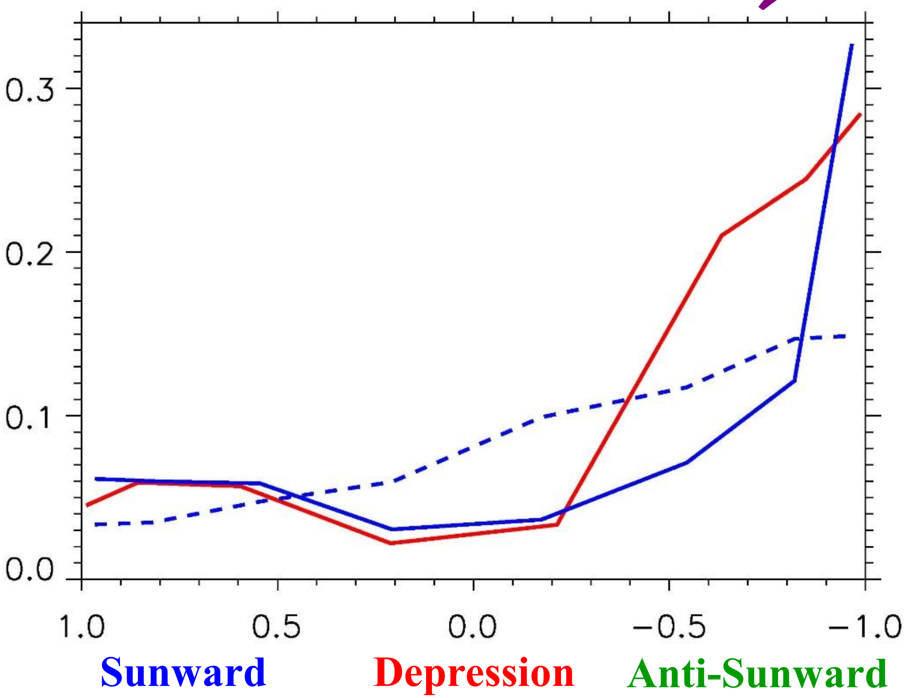
$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + V^{sw} \cdot \nabla f + \frac{dp}{dt}\frac{\partial f}{\partial p} + \frac{d\mu}{dt}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) - \frac{\partial}{\partial x}\left(\kappa_{xx}\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial y}\left(\kappa_{yy}\frac{\partial f}{\partial y}\right) = Q(\vec{x}, \vec{p}, t)$$

Markov Stochastic Process Method

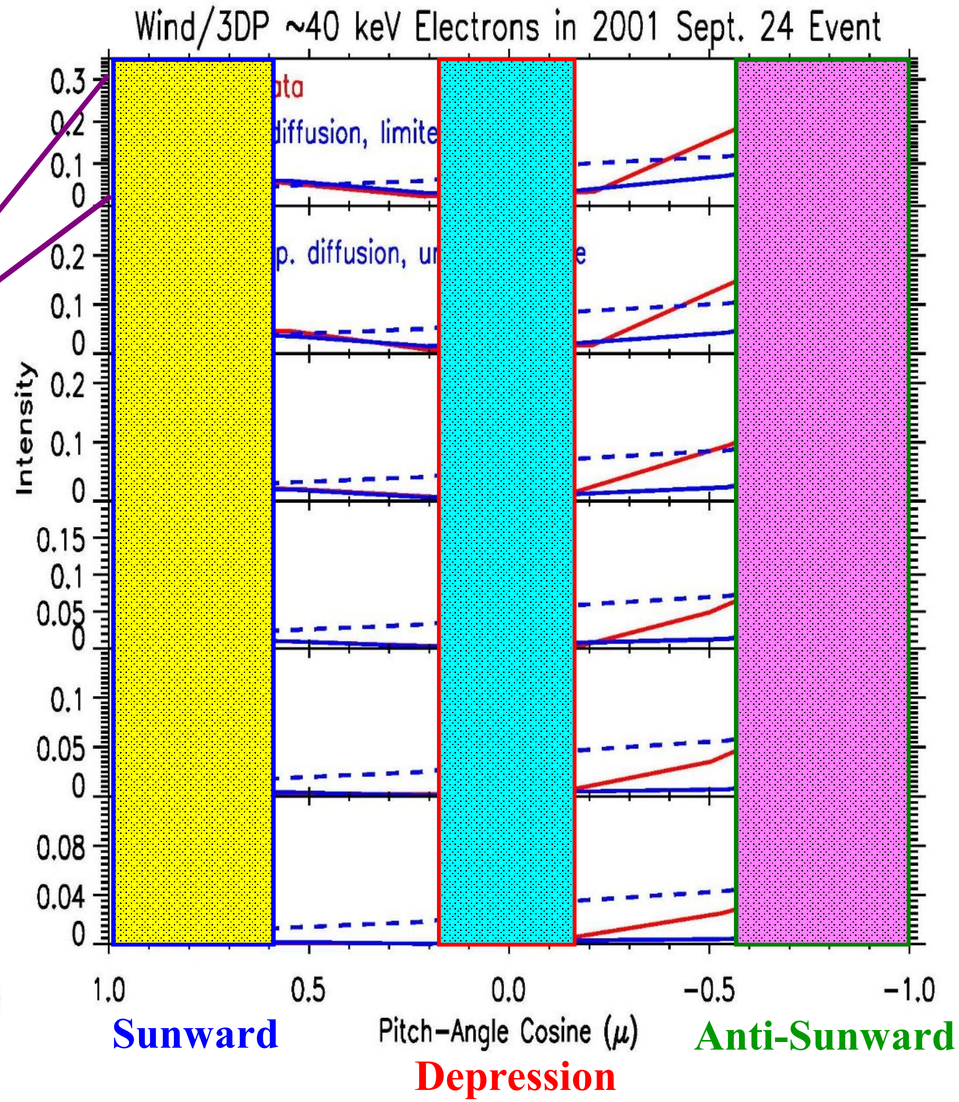
$$\begin{aligned}
dX &= \sqrt{2\kappa_{xx}}dW_x(s) - V_x^{sw}ds \\
dY &= \sqrt{2\kappa_{yy}}dW_y(s) - V_y^{sw}ds \\
dZ &= -(\mu V + V_z^{sw})ds \\
d\mu &= \sqrt{2D_{\mu\mu}}dW_\mu(s) \\
&\quad -\frac{1-\mu^2}{2}\left[\frac{V}{L} + \mu\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z}\right)\right]ds \\
&\quad + \left(\frac{\partial D_{\mu\mu}}{\partial \mu} + \frac{2D_{\mu\mu}}{M+\mu}\right)ds \\
dP &= P\left[\frac{1-\mu^2}{2}\left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y}\right) + \mu^2\frac{\partial V_z^{sw}}{\partial z}\right]ds
\end{aligned}$$

Stochastic Differential Equations (SDEs)

Counter-streaming particle beams with a deep depression at 90° pitch angle during onset phase.

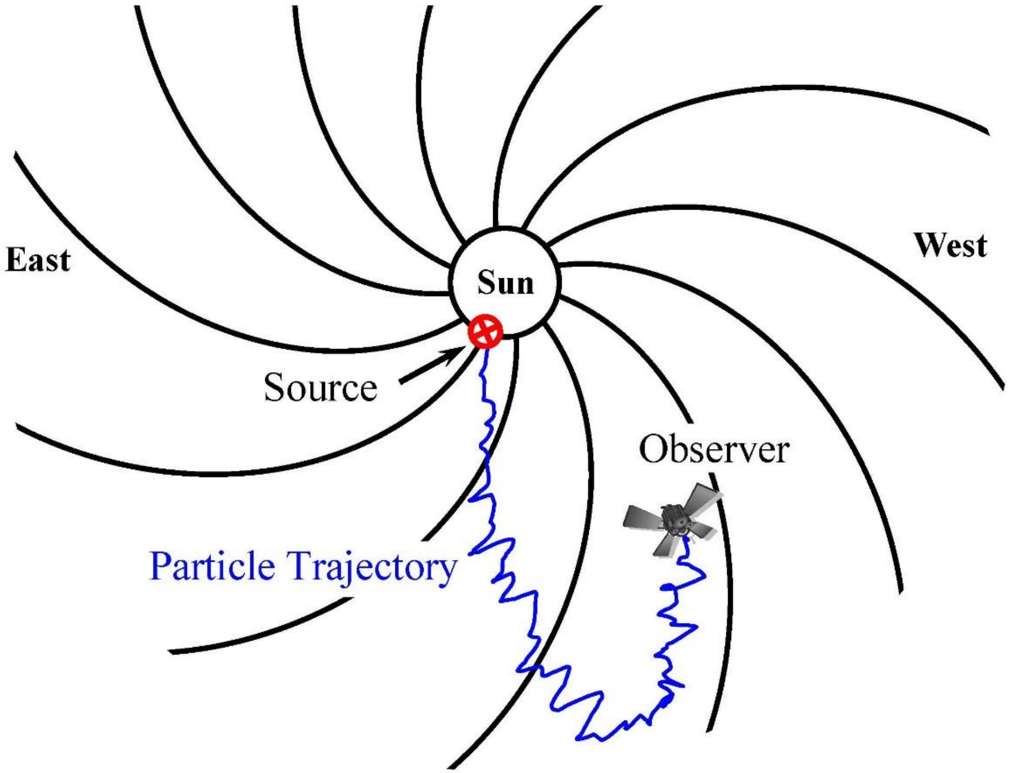


He 2015 ApJ



***Wind* Observation & SEP Simulation**

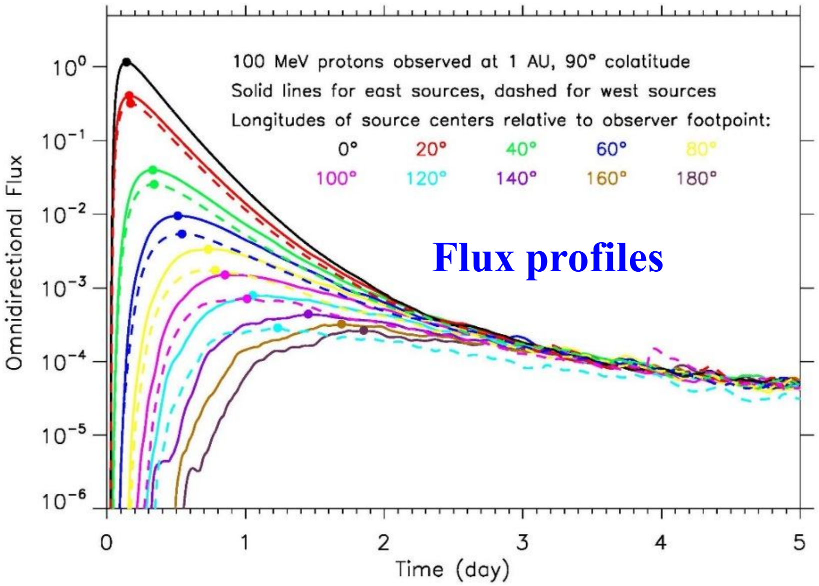
Perpendicular diffusion to form counter-streaming particle beams
(without invoking a reflecting boundary / magnetic mirror)

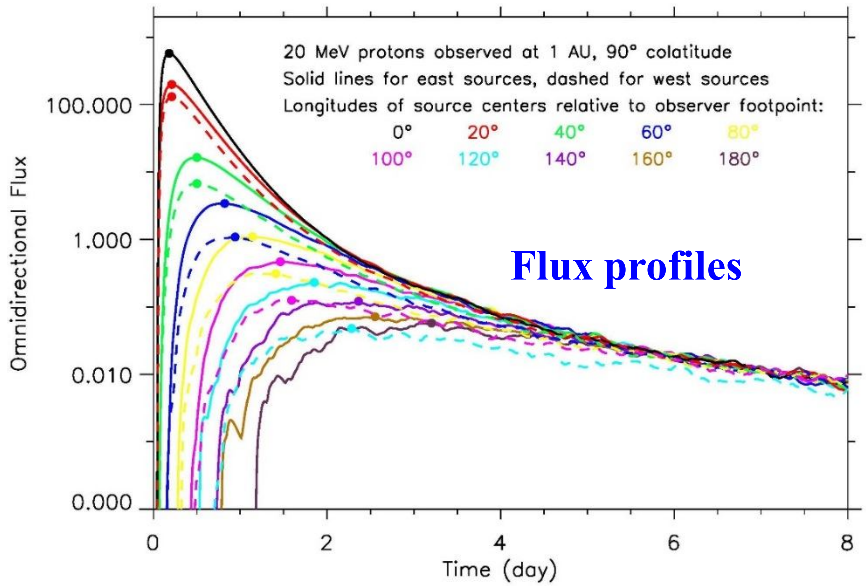


We do not need a "magnetic mirror"!

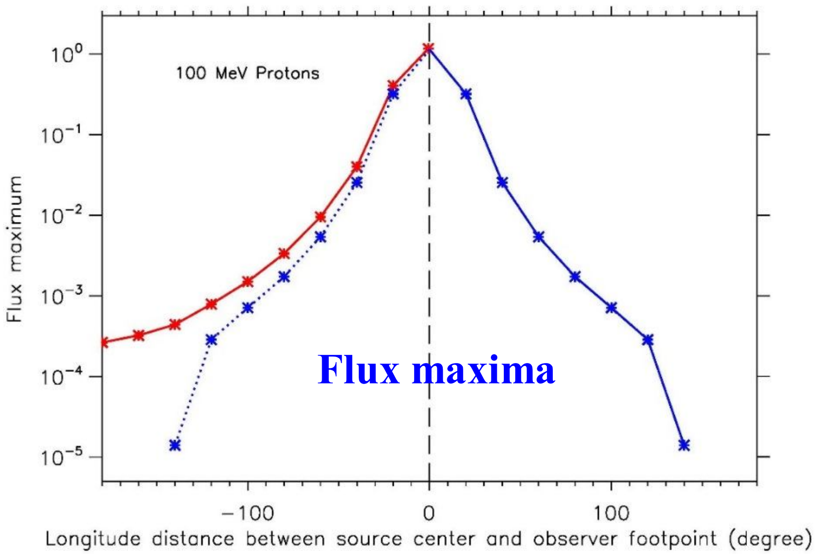
To observe a counter-streaming particle beam requires specific conditions: a limited source, observers disconnected from source, SEP diffusion processes (both parallel and perpendicular), and appropriate locations of observers.

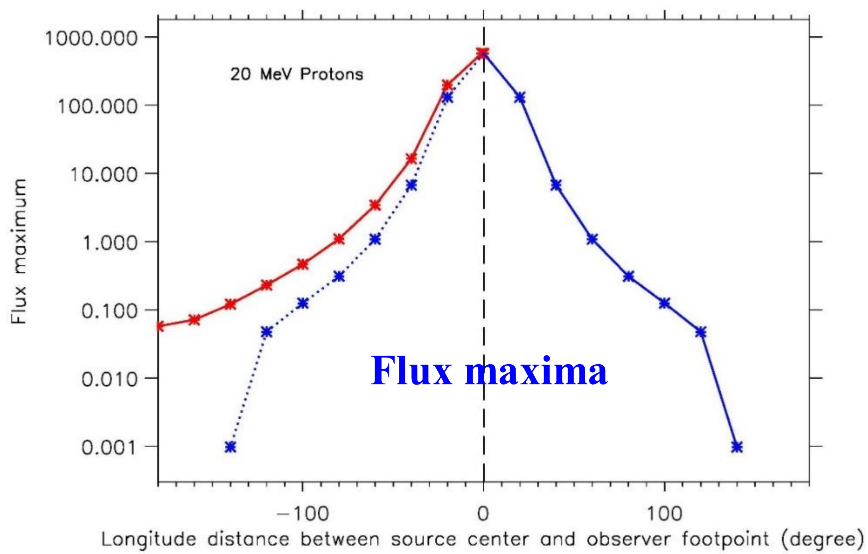
东-西经度非对称分布





100 MeV protons **20 MeV protons**

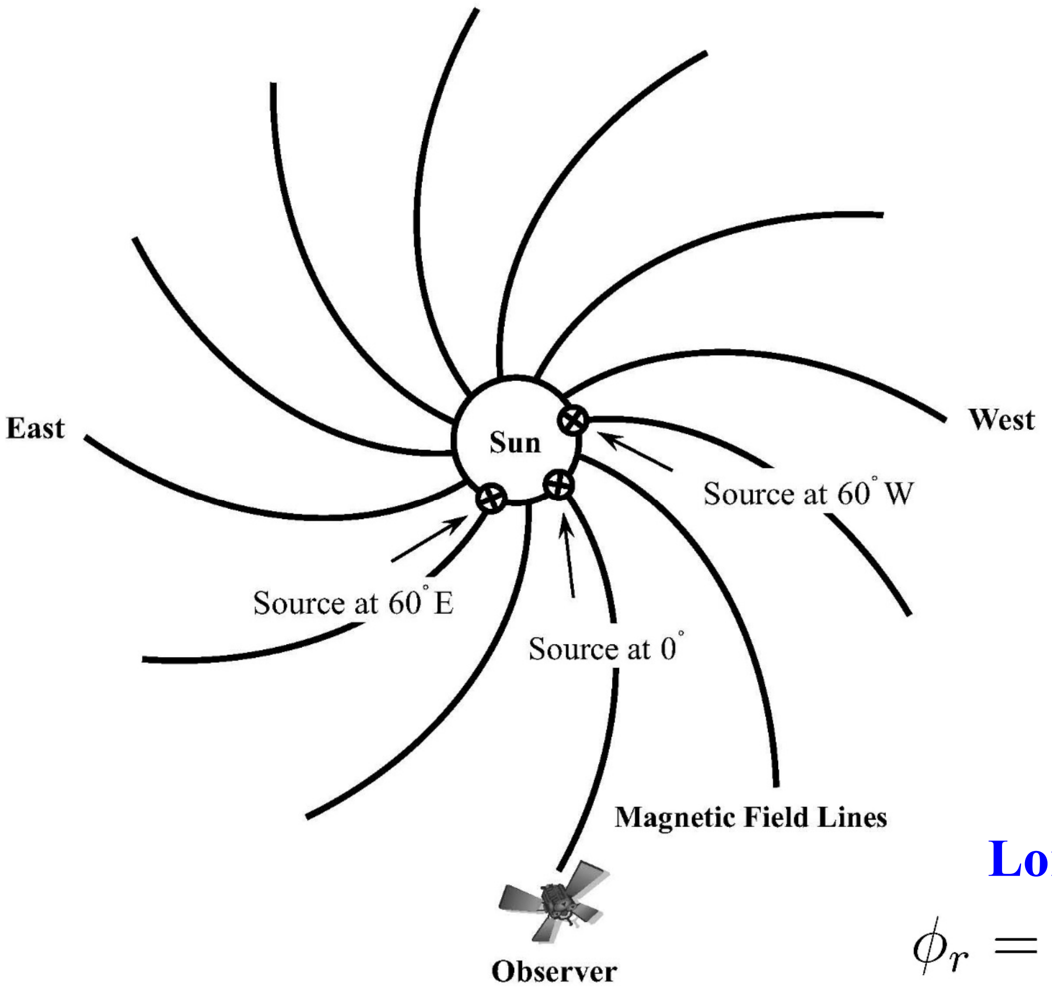




He & Wan 2015 ApJS

SEP事件统计分析

Data Set: Collect 78 solar proton events in the time period 1996-2011



SOHO ACE

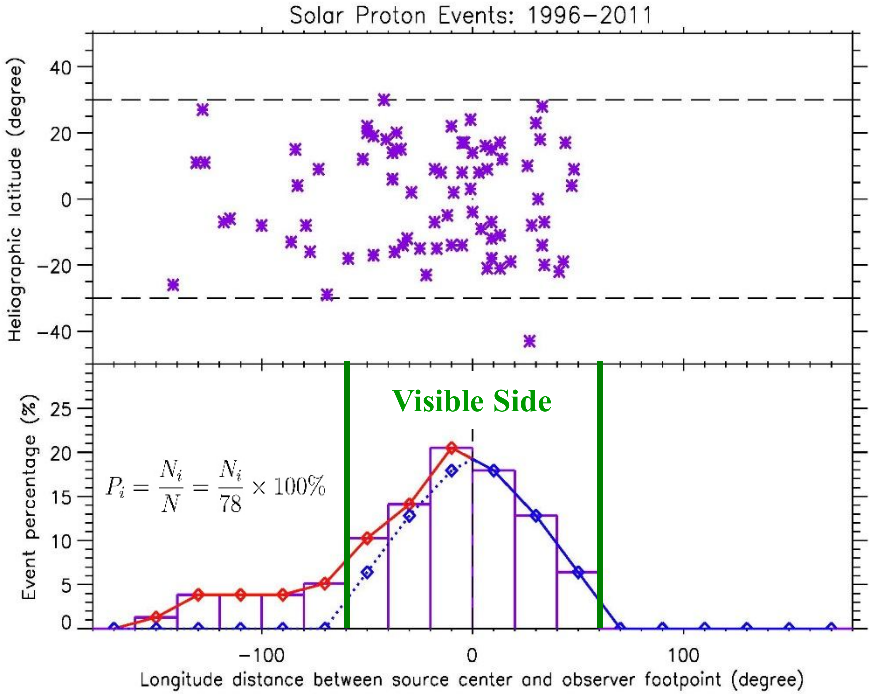
Solar Wind Speed

Longitudinal separations

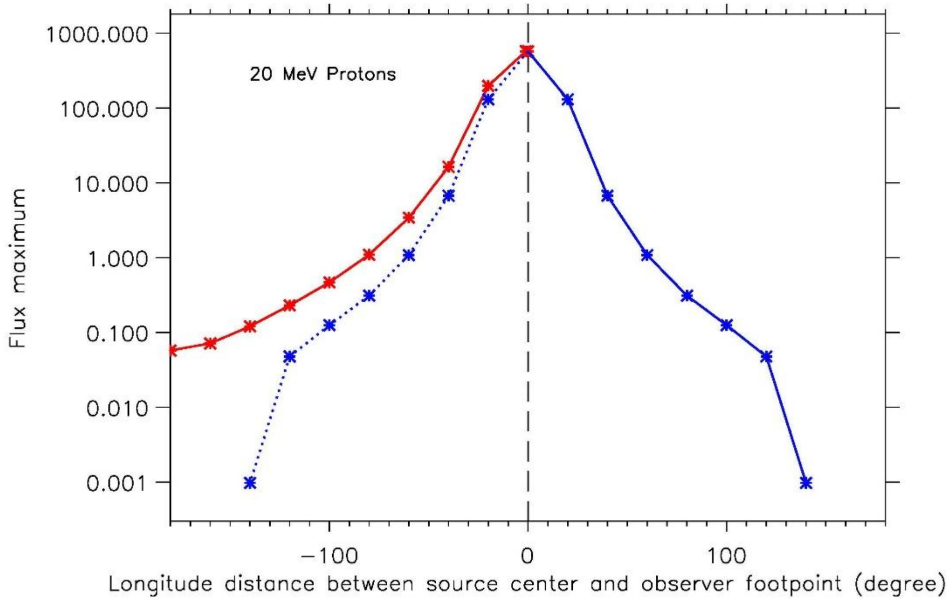
$$\phi_r = \phi - \phi_s = \phi - \Omega r / V^{sw}$$

SEP events with higher fluxes will be more easily observed

SEP通量越强，越易于被观测到



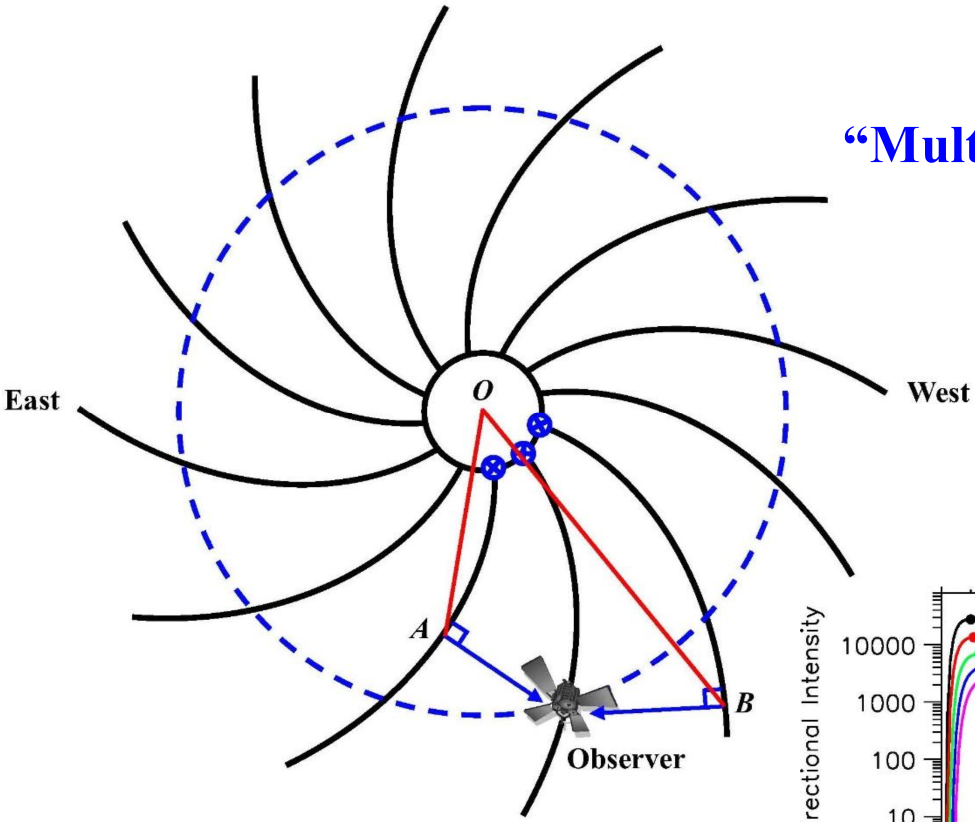
SEP事件源区经度分布



SEP通量经度分布

He & Wan 2017 MNRAS

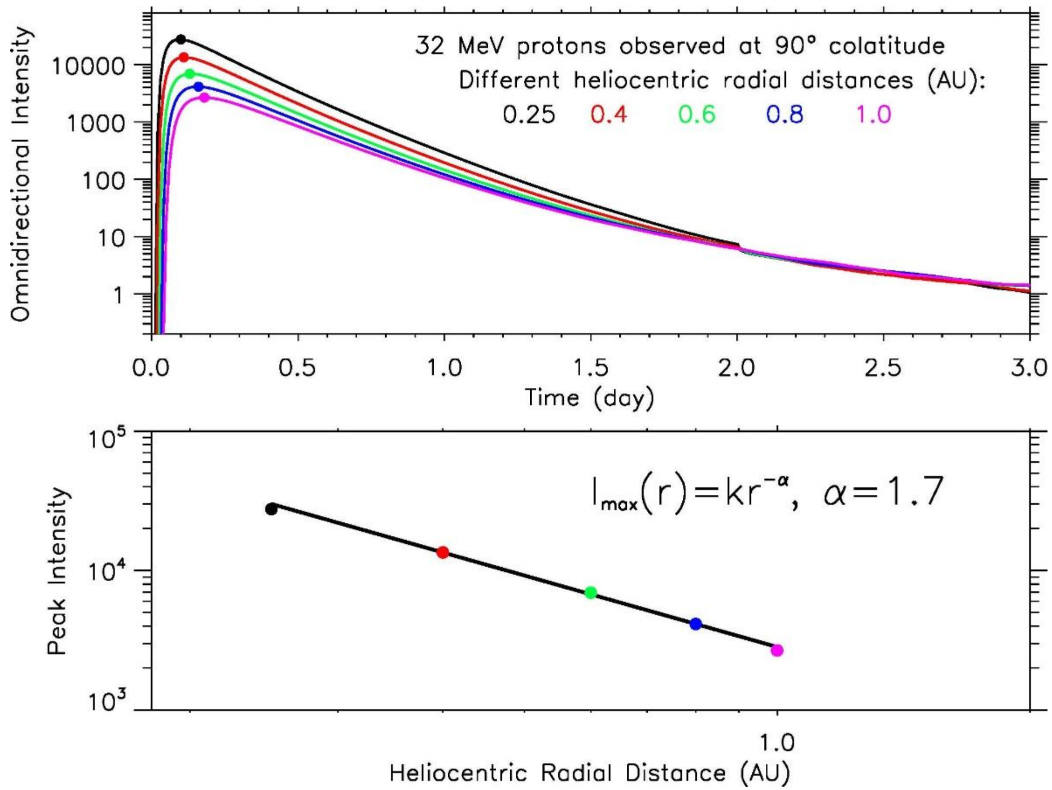
“Multiple SEP events with one spacecraft”



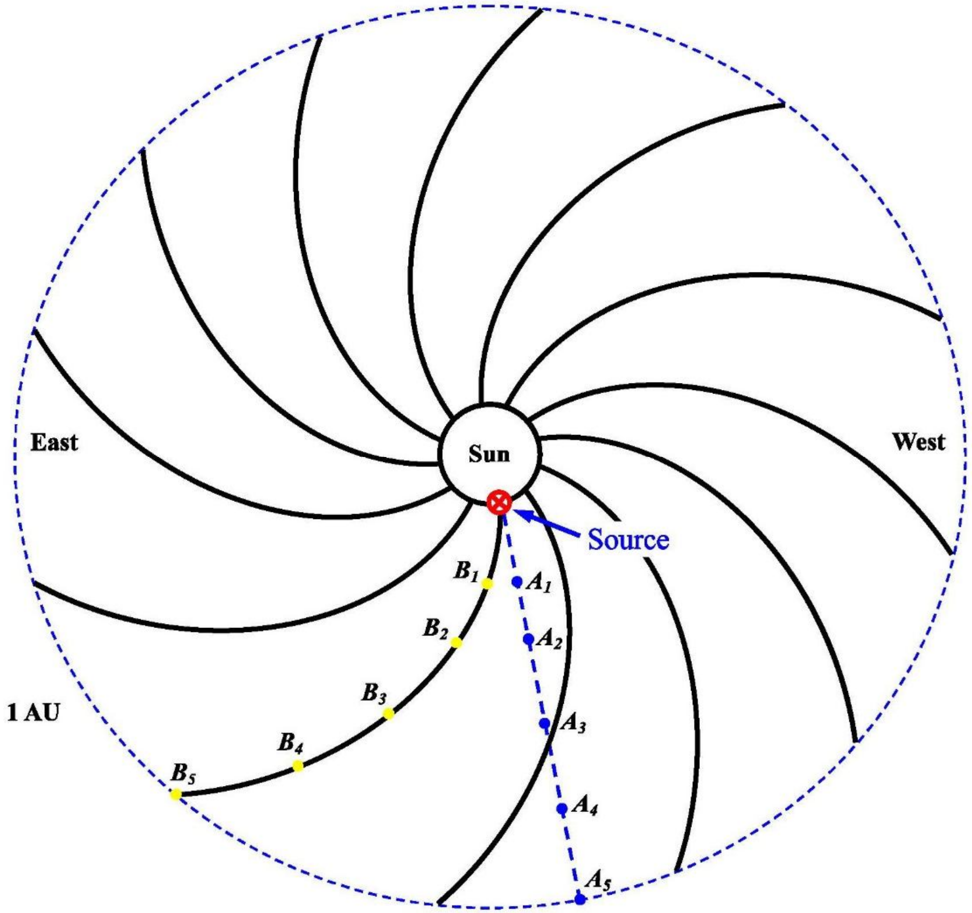
$$\overline{OA} < \overline{OB}$$

Intensity$_{east}$ > Intensity$_{west}$

物理机制



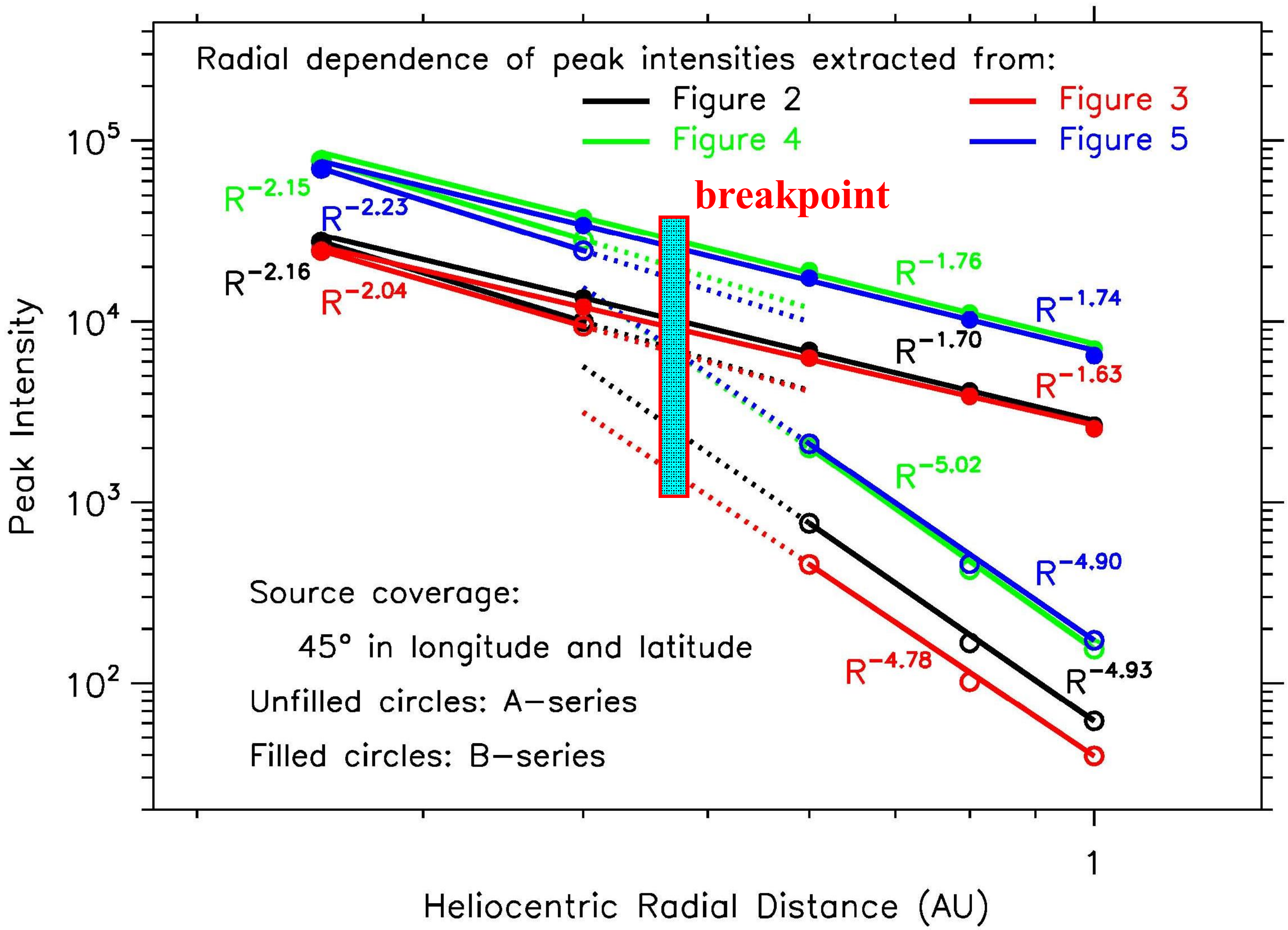
SEP强度的径向依赖性



Spacecraft fleet:

A-series: along the radial direction line

B-series: along the Parker field line



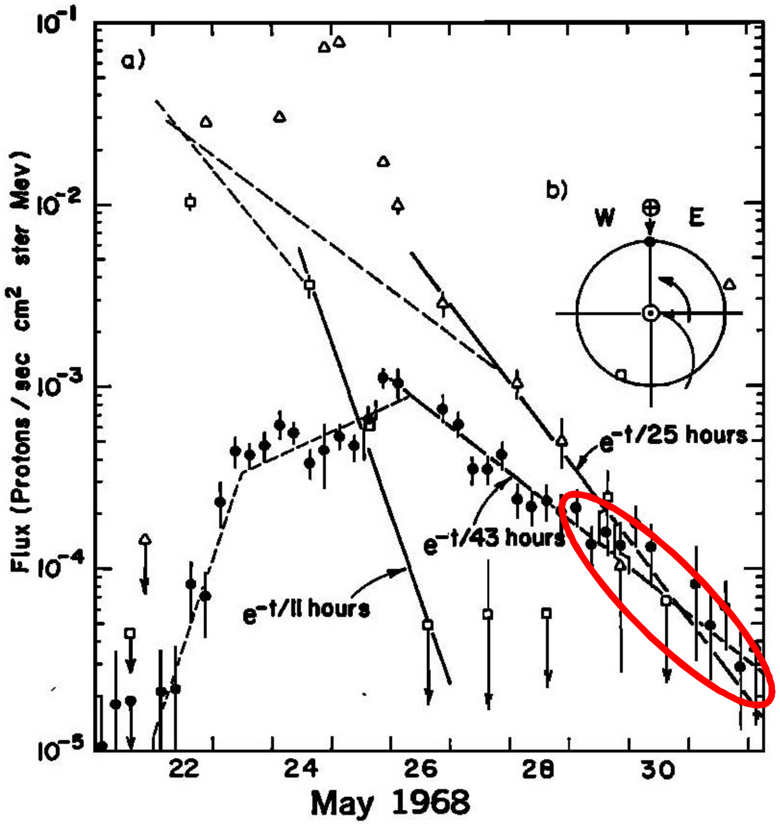
He et al. 2017 ApJ

VOLUME 77 AUGUST 1, 1972 NUMBER 22

Azimuthal Propagation of Low-Energy Solar-Flare Protons as Observed from Spacecraft Very Widely Separated in Solar Azimuth

R. BRUCE MCKIBBEN

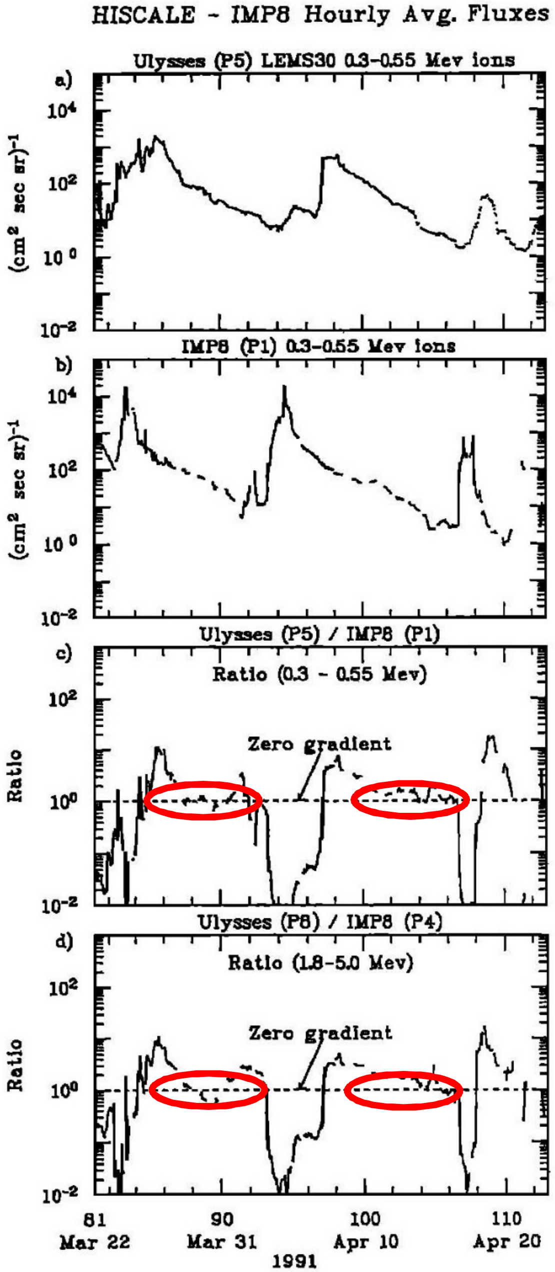
Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, Illinois 60637



SEP水库(Reservoir)现象

first noted by McKibben (1972)

GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 12, PAGES 1243-1246, JUNE 19, 1992



LOW-ENERGY SOLAR ELECTRONS AND IONS OBSERVED AT ULYSSES FEBRUARY-APRIL, 1991: THE INNER HELIOSPHERE AS A PARTICLE RESERVOIR

E. C. Roelof[1], R. E. Gold[1], G. M. Simnett[2], S. J. Tappin[2], T. P. Armstrong[3], and L. J. Lanzerotti[4]

SEP水库(Reservoir)现象

named “reservoirs” by Roelof et al. (1992)

Possible Mechanisms

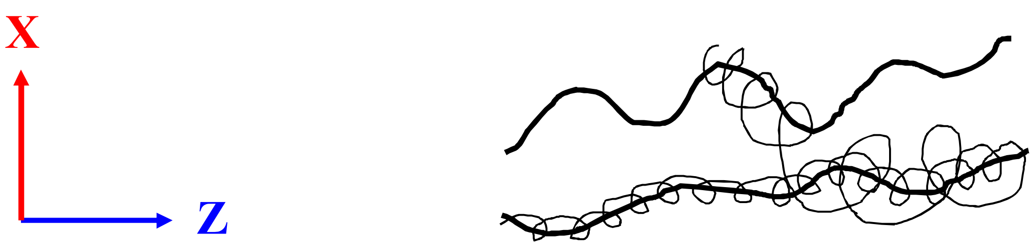
1. Reflecting boundary (magnetic mirror) / diffusion barrier

To contain the SEPs long enough for them to be distributed uniformly

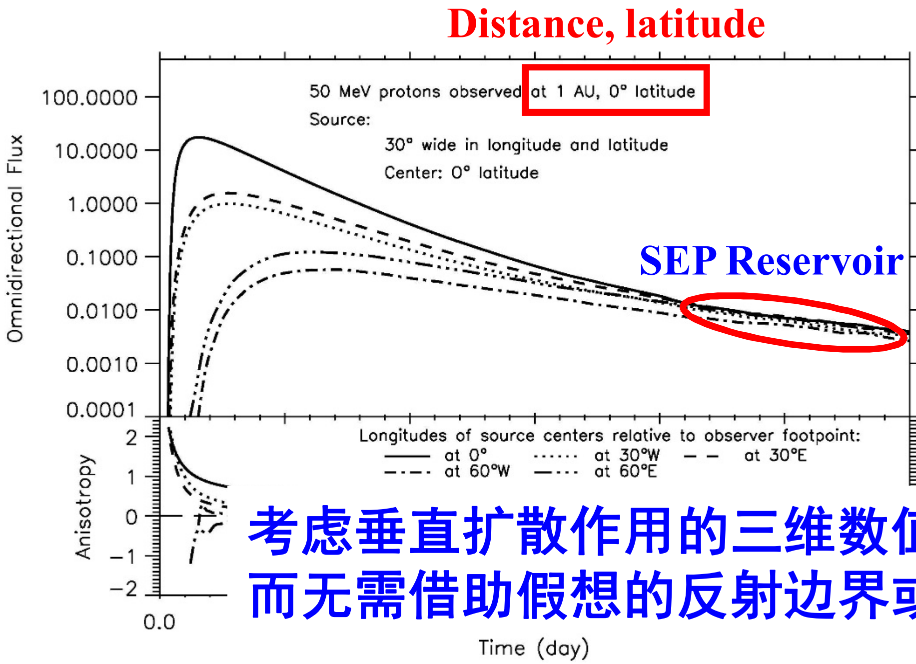
Is there a magnetic mirror?

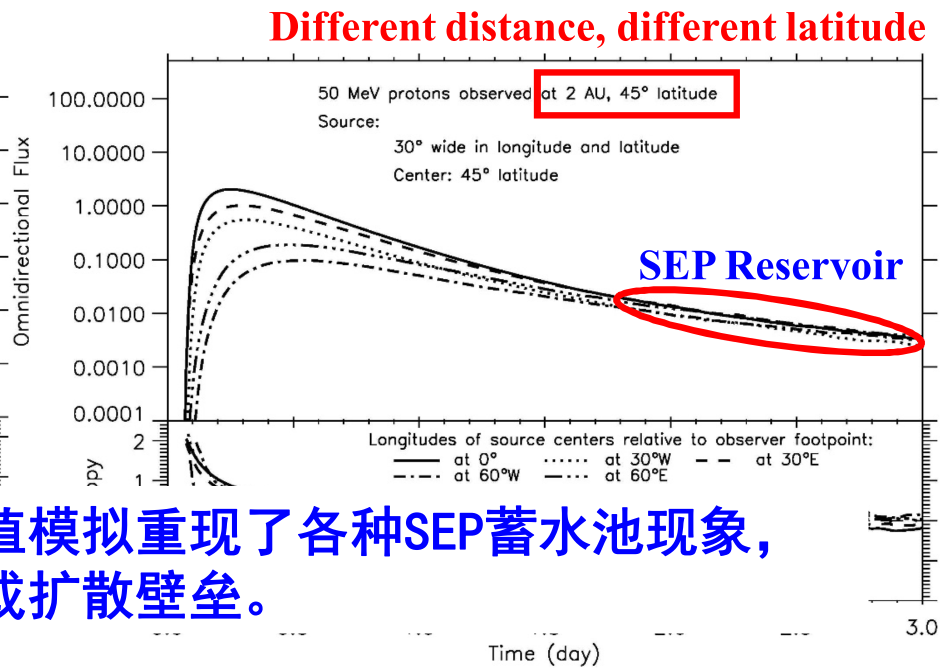
2. Effective cross-field diffusion (perpendicular diffusion)

To distribute the SEPs uniformly through perpendicular diffusion

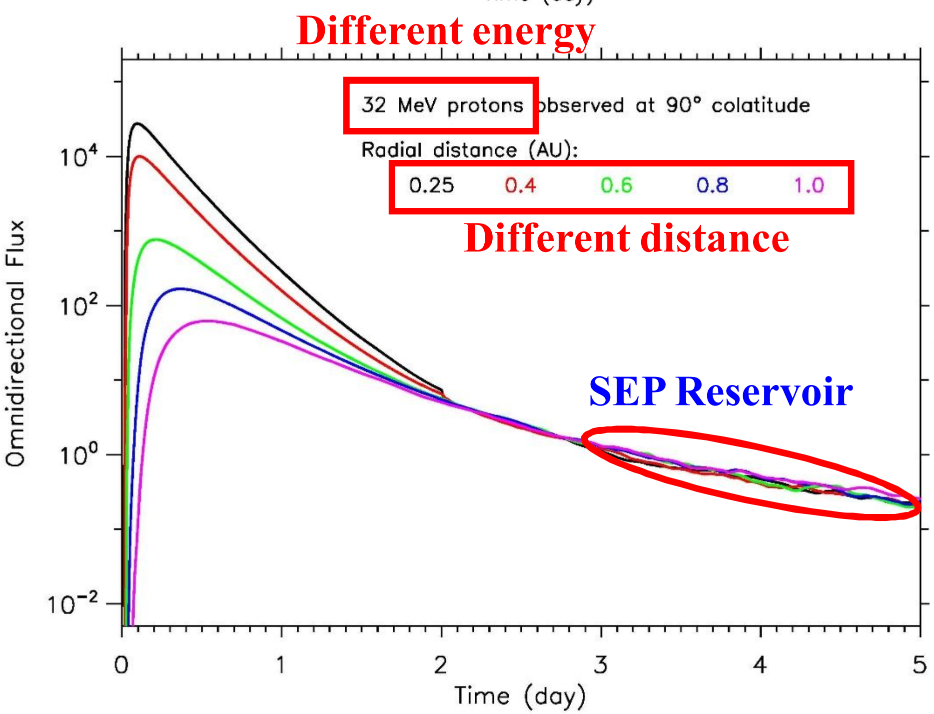


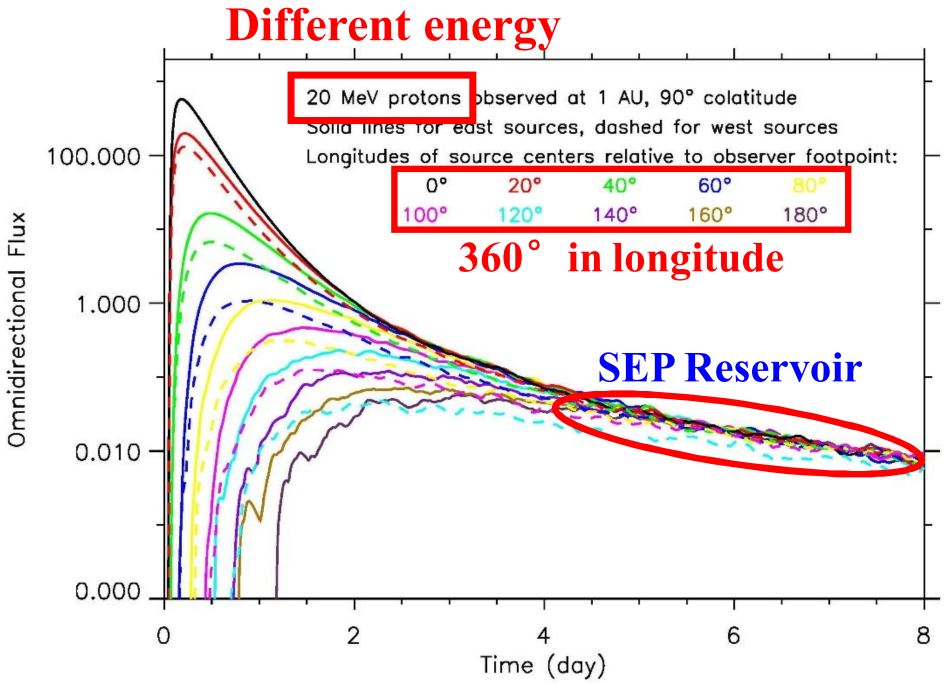
(3. Combination of 1 and 2 ?)





考虑垂直扩散作用的三维数值模拟重现了各种SEP蓄水池现象，而无需借助假想的反射边界或扩散壁垒。





VS

很难想象如此“势不可挡”的反射边界或扩散壁垒——覆盖所有的经度、所有的纬度、甚至所有的日心距离（实心球？）

In the sense of perpendicular diffusion, the so-called SEP “reservoir” should be renamed SEP “flood” (He & Wan 2017)

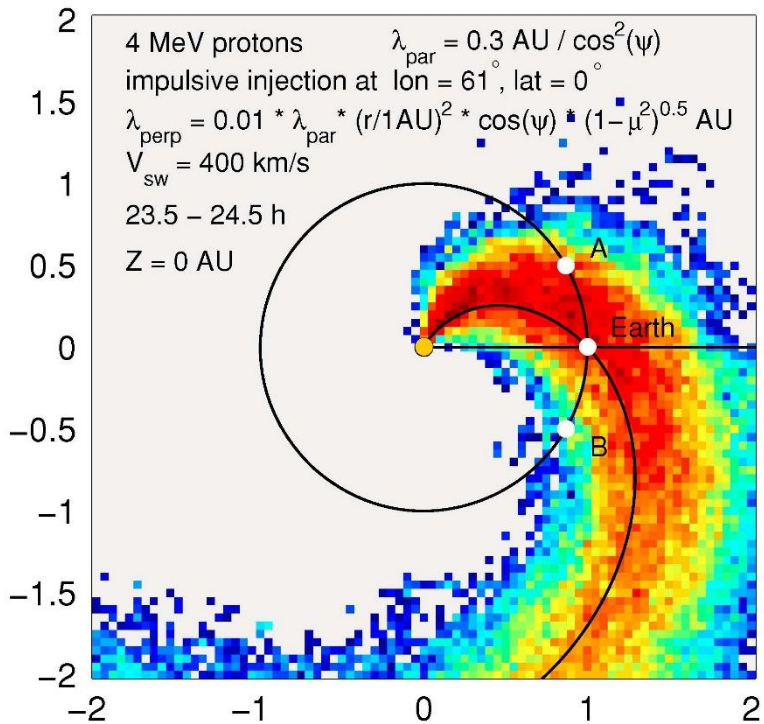
McKibben (1972) — **note**

↓ **20 yr**

Roelof et al. (1992) — **name**

↓ **25 yr**

He & Wan (2017) — **rename**



Dröge et al. 2010

总 结

1. 五维 Fokker-Planck 传播方程

$$\overbrace{\frac{\partial f}{\partial t}}^{\text{Distribution}} + \overbrace{\mu v \frac{\partial f}{\partial z}}^{\text{Streaming}} + \overbrace{V^{sw} \cdot \nabla f}^{\text{Convection}} + \overbrace{\frac{dp}{dt}\frac{\partial f}{\partial p}}^{\text{Adiabatic Cooling}} + \overbrace{\frac{d\mu}{dt}\frac{\partial f}{\partial \mu}}^{\text{Magnetic Focusing, Flow Divergence}}$$

$$\underbrace{-\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)}_{\text{Pitch-angle Diffusion}} \underbrace{-\frac{\partial}{\partial x}\left(\kappa_{xx}\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial y}\left(\kappa_{yy}\frac{\partial f}{\partial y}\right)}_{\text{Perpendicular Diffusion}} = \underbrace{Q(\vec{x}, \vec{p}, t)}_{\text{Source}}$$

2. 发现太阳质子事件经度非对称分布现象，为垂直扩散机制的重要作用提供了一个独特的观测证据，其独特性表现在该现象很难用其他任何传统物理机制体面地解释。

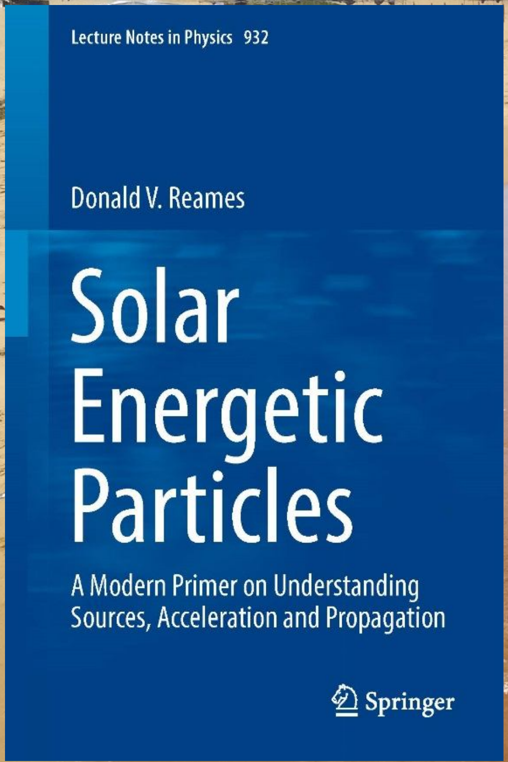
3. 基于垂直扩散机制和**Fokker-Planck**传播方程，许多太阳高能粒子现象（水库效应，反向流动粒子束，经度非对称分布，空间依赖性）得以定量解释或重现。

For details see papers:

He & Wan 2017 MNRAS
He et al. 2017 ApJ
He 2015 ApJ
He & Wan 2015 ApJS

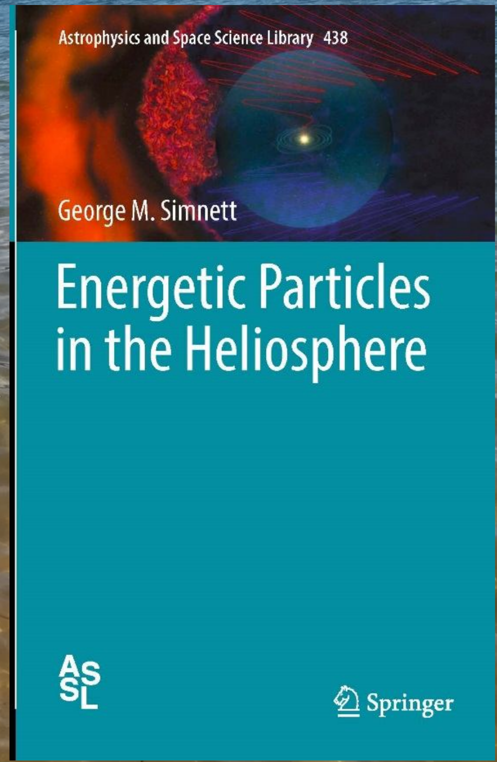
“我们终将改变潮水的方向”——与LHAASO共勉

Is it the time to revise textbooks?
修改教材的时候到了？



出现26次reservoir

McKibben (1972) note
↓ 20 yr
Roelof et al. (1992) name (“reservoir”)
↓ 25 yr
He & Wan (2017) rename (“flood”)



出现15次reservoir