Cosmic Ray Transport in the Heliosphere and its Connection to the Local Interstellar Spectra

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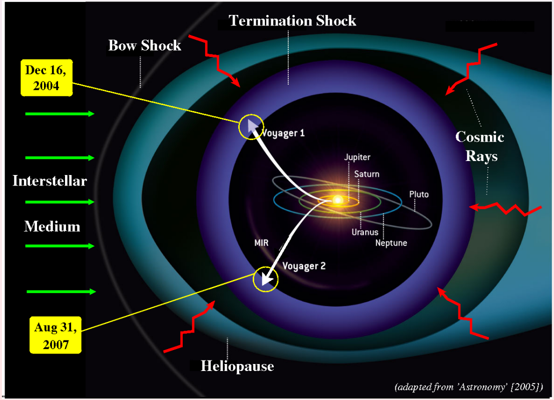

Outline of the Talk

- The 'State-of-the-Art'

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- A Reformulation of the Diffusion Tensor?

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- A Contribution from Astrospheric Cosmic Rays?
- A New Constraint on (Local) Interstellar Spectra?
- Résumé

The ‘State-of-the Art’ of Heliospheric Cosmic Ray Transport

The Theoretical Framework

Kinetic transport equation:

$$\frac{\partial f}{\partial t} = \nabla \cdot \left[\overleftrightarrow{\boldsymbol{\kappa}} \nabla f \right] + \frac{1}{p^2} \frac{\partial}{\partial p} \left[p^2 D \frac{\partial f}{\partial p} \right] - \mathbf{u} \cdot \nabla f + \frac{p}{3} (\nabla \cdot \mathbf{u}) \frac{\partial f}{\partial p} + S(\mathbf{r}, p, t)$$

- anisotropic spatial diffusion: tensor $\overleftrightarrow{\boldsymbol{\kappa}} (\mathbf{r}, p, \mathbf{B}(t))$
- scalar momentum diffusion: coefficient $D(\mathbf{r}, p, \mathbf{B}(t))$
- convection and drift: velocity $\mathbf{u}(t)$
- adiabatic energy changes: $\nabla \cdot \mathbf{u}(t) \neq 0$
- sources/sinks: $S(\mathbf{r}, p, t)$

Solution in ≤ 4-D phase space with
– finite difference/volume solver or
– stochastic differential equations

The Theoretical Framework

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Key transport quantities = **diffusion tensor** and **momentum diffusion**:

$$\overleftrightarrow{\kappa} (\mathbf{r}, p, t) = \begin{pmatrix} \kappa_{\perp 1} & \kappa_{xy} & 0 \\ \kappa_{yx} & \kappa_{\perp 2} & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix} \quad ; \quad \kappa_{||} = \frac{v^2}{8} \int_{-1}^{1} \frac{(1-\mu)^2}{D_{\mu\mu}(\mu)} \, d\mu \quad \ldots$$

$$D = \int_{-1}^{1} D_{pp}(\mu) - \frac{D_{\mu p}^2(\mu)}{D_{\mu\mu}(\mu)} \, d\mu \quad ; \quad D_{\mu\mu} = D_{\mu\mu}(\mathbf{r}, p, \mu, \mathbf{B}(t)) \quad \ldots$$

The Theoretical Framework

Transport processes can be studied separately: for energetic particles

- in the MeV-GeV range spatial diffusion is dominant
- in the keV-MeV range momentum diffusion is dominant

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  allowing study of **the structure of the diffusion tensor**

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($\kappa_{xy} = \kappa_{yx} = 0$ for axisymmetric turbulence and vanishing magnetic helicity assumed in the following)

The Theoretical Framework

Parallel diffusion from quasilinear theory (QLT):

$$\kappa_{||} = \frac{v l_{slab}}{16\pi C(s)} \left(\frac{B_0}{\delta B_{slab}}\right)^2 R^{2-s} \left[\frac{8}{(2-s)(4-s)} + R^s\right]$$

Isotropic perp. diffusion from nonlinear (guiding center, NLGC) theory:

$$\kappa_{\perp 1} = \kappa_{\perp 2} = \frac{\pi a^2 v^2}{3 B_0^2} \int_0^\infty \frac{g^{2D}(k_\perp)}{4/3\, \kappa_\perp k_\perp^2 + v/\lambda_{||}}\, dk_\perp$$

Anisotropic perp. diff. from non-axisym. turbulence/magnetic field:

$$\frac{\kappa_{\perp 2}}{\kappa_{\perp 1}} = \frac{\tan^2\Phi + \xi^2}{1 + \xi^2, \tan^2\Phi} \;\; ; \;\; \xi = \frac{\alpha}{\beta}$$

(see, e.g., review by *Shalchi [2009]*)

Summary I: The Theoretical Framework

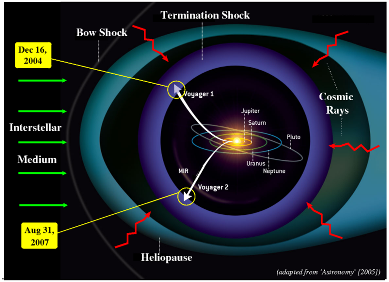
- The **transport equation is well-established**.
- The **major processes are identified**.
- The **diffusion tensor** can be **derived from basic theory**:
  - parallel diffusion from quasilinear theory (QLT)
  - perpendicular diffusion from nonlinear theory (NLGC)
  - anisotropic diffusion from non-axisymmetric plasma turbulence or magnetic field

Jovian Electrons and the Diffusion Tensor

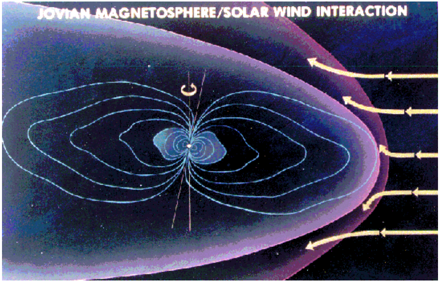
Jovian Electrons & the Diffusion Tensor

In order to explore fully anisotropic diffusion ($\kappa_{||} \neq \kappa_{\perp 1} \neq \kappa_{\perp 2}$) **3-D study** of 'point source' Jupiter's magnetosphere: **Jovian electrons** ($\sim 7\ MeV$)

Heliospheric Source:



Jovian Magnetosphere



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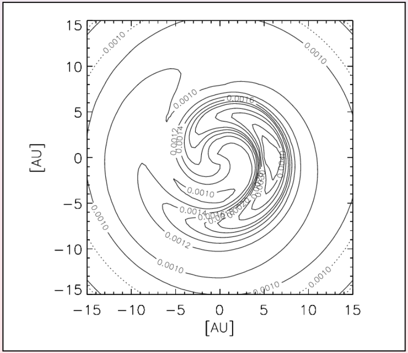
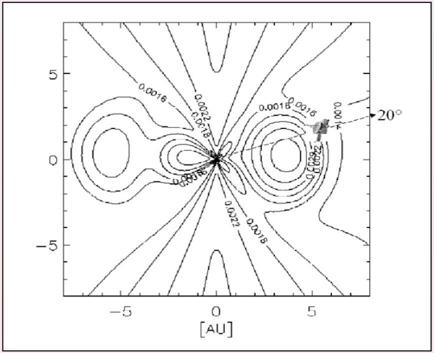
spatial distribution: x-y-plane



x-z-plane



HF et al. [2000], Ferreira et al. [2001], Lange & HF [2006]

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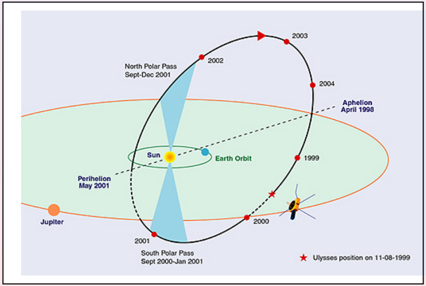
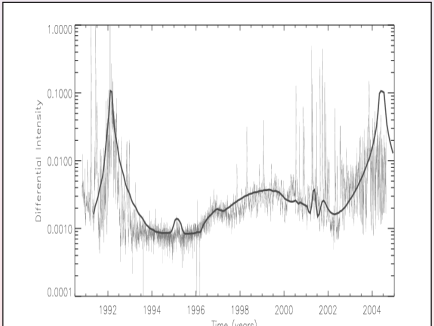
spacecraft trajectory



flux variation at spacecraft



Balogh et al. [2008]

HF et al. [2000], Ferreira et al. [2001], Lange & HF [2006]: measurements ✓

$$\Longrightarrow \kappa_{\perp 1} = 0.02\,(p/p_0)^2 \kappa_{||} \quad ; \quad \kappa_{\perp 2} = 0.015\, f(\vartheta)\, \kappa_{||}$$

The Diffusion Tensor & An Overlooked Rotation?

Study of large-scale transport requires transformation of the diffusion tensor from a (field-aligned) local to a global system:

- Which local system is the most 'natural' one?

The Diffusion Tensor & An Overlooked Rotation?

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- One principal direction aligned with magnetic field.

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- One principal direction aligned with magnetic field.
- The correct choice of the 'perpendicular' directions is important for the case of anisotropic perpendicular diffusion (e.g. for Jovian electrons).

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Study of large-scale transport requires transformation of the diffusion tensor from a (field-aligned) local to a global system:

- Which local system is the most 'natural' one?
- One principal direction aligned with magnetic field.
- The correct choice of the 'perpendicular' directions is important for the case of anisotropic perpendicular diffusion (e.g. for Jovian electrons).
- The most natural directions are defined with the Frenet-Serret trihedron, i.e. by the curvature and torsion of a magnetic field:

$$\mathbf{t} = \mathbf{B}/B \quad ; \quad \mathbf{n} = (\mathbf{t} \cdot \nabla)\,\mathbf{t}/k \quad ; \quad \mathbf{b} = \mathbf{t} \times \mathbf{n}$$

This has not been considered for (heliospheric) CR transport, so far...

The Diffusion Tensor & An Overlooked Rotation?

The **general transformation** reads:

$$\overset{\leftrightarrow}{\kappa}_{global} = A^T \, \overset{\leftrightarrow}{\kappa}_{local} \, A$$

with $A = \begin{pmatrix} n_1 & b_1 & t_1 \\ n_2 & b_2 & t_2 \\ n_3 & b_3 & t_3 \end{pmatrix}$ and $\overset{\leftrightarrow}{\kappa}_{local} = \begin{pmatrix} \kappa_{\perp 1} & 0 & 0 \\ 0 & \kappa_{\perp 2} & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$

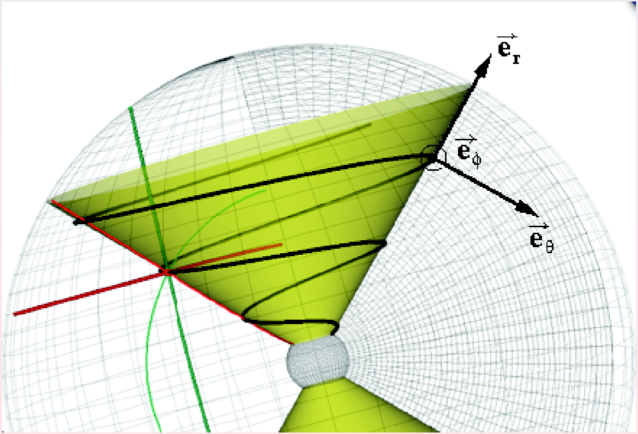
resulting in

$$\begin{aligned}
\kappa_{11} &= \kappa_{\perp 1}\, n_1^2 + \kappa_{\perp 2}\, b_1^2 + \kappa_{||}\, t_1^2 \\
\kappa_{12} &= \kappa_{\perp 1}\, n_1\, n_2 + \kappa_{\perp 2}\, b_1\, b_2 + \kappa_{||}\, t_1\, t_2 \\
\kappa_{13} &= \kappa_{\perp 1}\, n_1\, n_3 + \kappa_{\perp 2}\, b_1\, b_3 + \kappa_{||}\, t_1\, t_3 \\
\kappa_{22} &= \kappa_{\perp 1}\, n_2^2 + \kappa_{\perp 2}\, b_2^2 + \kappa_{||}\, t_2^2 \\
\kappa_{23} &= \kappa_{\perp 1}\, n_2\, n_3 + \kappa_{\perp 2}\, b_2\, b_3 + \kappa_{||}\, t_2\, t_3 \\
\kappa_{33} &= \kappa_{\perp 1}\, n_3^2 + \kappa_{\perp 2}\, b_3^2 + \kappa_{||}\, t_3^2
\end{aligned}$$

The Diffusion Tensor & An Overlooked Rotation?

Example: **Parker Field**

'Classical' Choice: $\kappa_{\perp 2}$ always along $\mathbf{e}_\theta$



$$\begin{pmatrix} \kappa_{\perp r} & 0 & 0 \\ 0 & \kappa_{\perp\theta} & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$$\downarrow$$

transformation

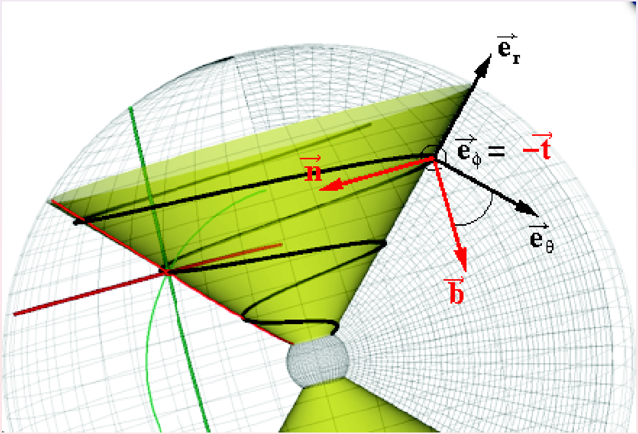
$$\downarrow$$

$$\begin{pmatrix} \kappa_{\perp r} & 0 & \kappa_{r\phi} \\ 0 & \kappa_{\perp\theta} & 0 \\ \kappa_{r\phi} & 0 & \kappa_{||} \end{pmatrix}$$

The Diffusion Tensor & An Overlooked Rotation?

Example: **Parker Field**

'Natural' Choice: $\kappa_{\perp 2}$ along $\mathbf{b} = \mathbf{t} \times \mathbf{n}$



$$\begin{pmatrix} \kappa_{\perp 1} & 0 & 0 \\ 0 & \kappa_{\perp 2} & 0 \\ 0 & 0 & \kappa_{\|} \end{pmatrix}$$

$\downarrow$

transformation

$\downarrow$

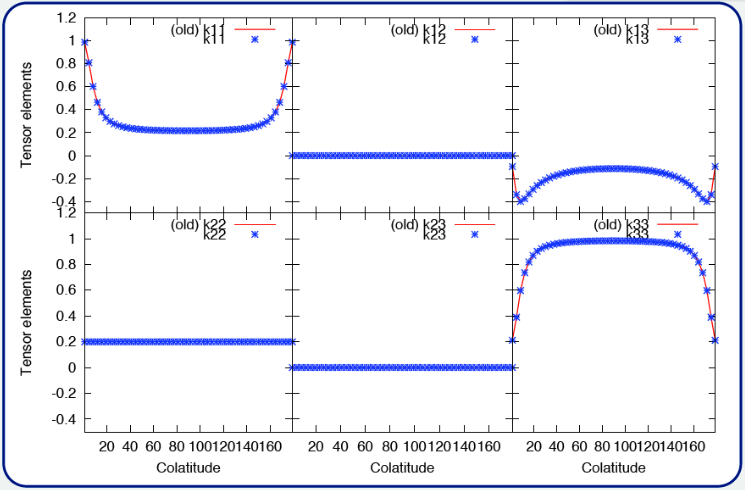
$$\begin{pmatrix} \kappa_{\perp 1} & \kappa_{r\theta} & \kappa_{r\phi} \\ \kappa_{r\theta} & \kappa_{\perp 2} & \kappa_{\theta\phi} \\ \kappa_{r\phi} & \kappa_{\theta\phi} & \kappa_{\|} \end{pmatrix}$$

The Diffusion Tensor & An Overlooked Rotation?

First Example: The Parker-Field

(Effenberger et al. 2011)

$\kappa_{\|} = 1,\ \kappa_{\perp 1} = 0.2,\ \kappa_{\perp 2} = 0.2$
$r = 10\mathrm{AU},\ \varphi = \pi$

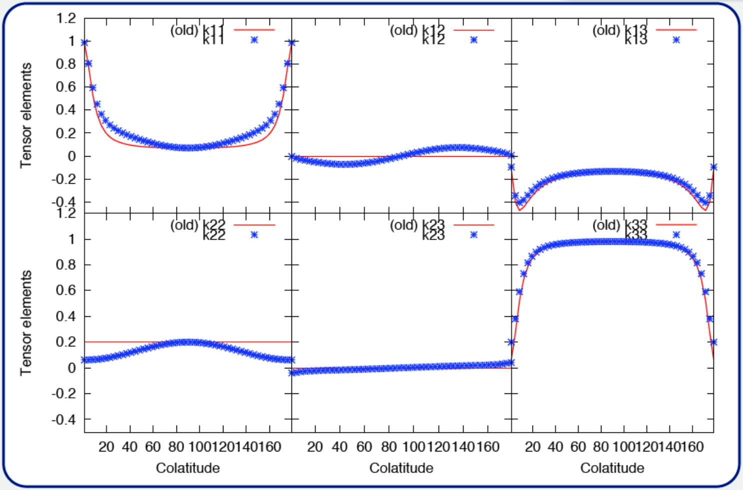


The Diffusion Tensor & An Overlooked Rotation?

First Example: The Parker-Field

(Effenberger et al. 2011)

$\kappa_{||} = 1, \kappa_{\perp 1} = 0.05, \kappa_{\perp 2} = 0.2$
$r = 10\text{AU}, \varphi = \pi$

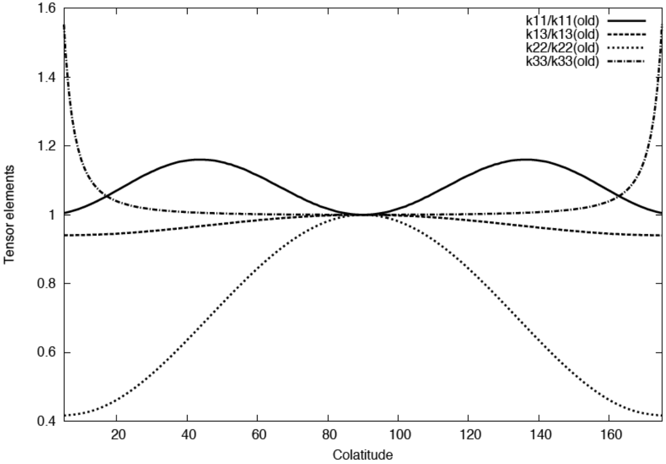


The Diffusion Tensor & An Overlooked Rotation?

First Example: The Parker-Field

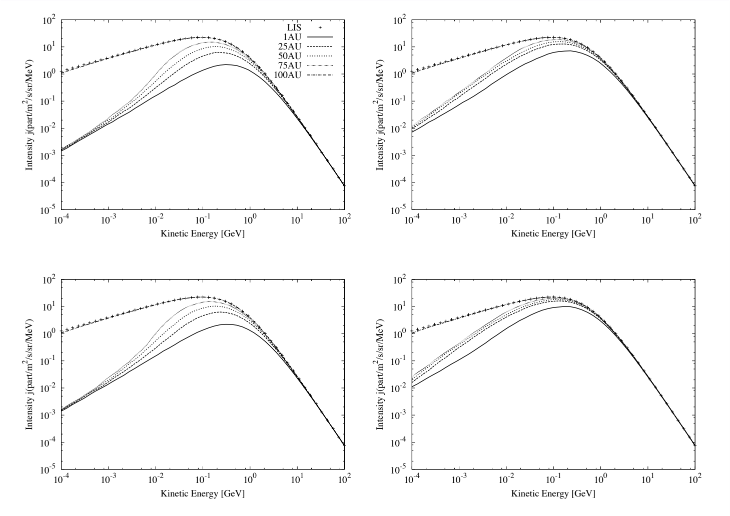
(Effenberger et al. 2011)

$\kappa_{\|} = 1,\ \kappa_{\perp 1} = 0.1,\ \kappa_{\perp 2} = 0.02$
$r = 10\mathrm{AU},\ \varphi = \pi$



(Preliminary) Application to Modulated Spectra

Burger & Hitge [2008] new tensor



$\kappa_{\perp 2} = 5\kappa_{\perp 1}$

$\kappa_{\perp 2} = 10\kappa_{\perp 1}$

Summary II: The Diffusion Tensor

- In case of **anisotropic perpendicular diffusion** a re-derivation of the tensor in the global frame results in **modified tensor elements** that should be considered for the simulation of spacecraft data.

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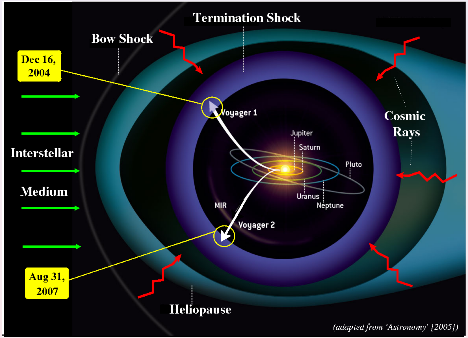
- In case of **anisotropic perpendicular diffusion** a re-derivation of the tensor in the global frame results in **modified tensor elements** that should be considered for the simulation of spacecraft data.

- While this might not play a role on large galactic scales, it may well be of **significance for the determination of local interstellar spectra**.

$\longrightarrow$ | For a talk on anisotropic diffusion and galactic propagation, see Frederic Effenberger @11:20

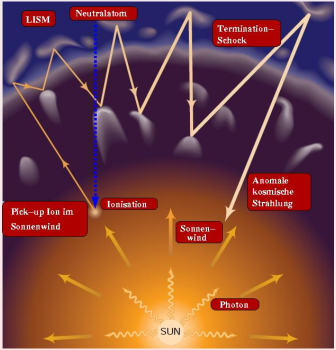
Astrospheric Contributions to the Interstellar Spectrum of Cosmic Rays

Anomalous Cosmic Rays - Still a Riddle



(adapted from 'Astronomy' [2005])

Before the V1/V2 shock crossings ACRs were thought to be diffusively accelerated at the solar wind termination shock...

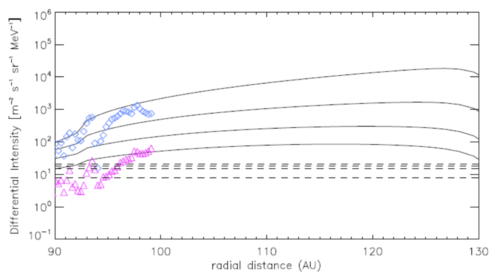


Fermi-II Acceleration in the Helio/-Astrosheaths

Voyagers see an increase of the ACR intensity on their way deeper into the heliosheath:

Idea: effective momentum diffusion

Ferreira et al. [2007]

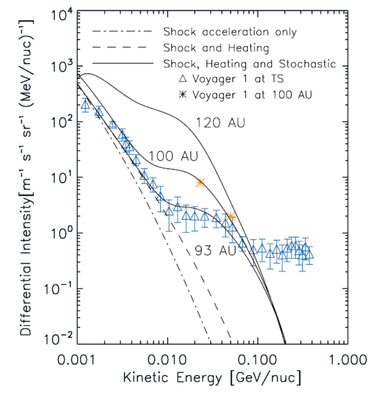


$$\frac{\partial f}{\partial t} = \nabla\cdot\left[\overset{\leftrightarrow}{\boldsymbol{\kappa}}\nabla f\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D\frac{\partial f}{\partial p}\right] - \mathbf{u}\cdot\nabla f + \frac{p}{3}\left(\nabla\cdot\mathbf{u}\right)\frac{\partial f}{\partial p} + S(\mathbf{r}, p, t)$$

- scalar momentum diffusion coefficient $D = D_0 \dfrac{p^2 v_A^2}{9\kappa_{||}}$

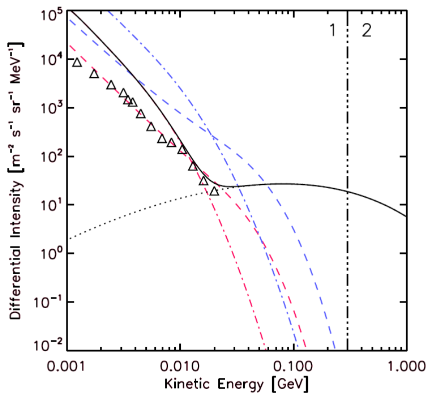
Fermi-II Acceleration in the Helio/-Astrosheaths

data fit



Ferreira et al. [2007]

extrapolated heliopause spectrum



Scherer et al. [2008]

Fermi-II Acceleration in the Helio/-Astrosheaths

The Astrophysical Journal, 680: L105–L108, 2008 June 20

ARE ANOMALOUS COSMIC RAYS THE MAIN CONTRIBUTION TO THE LOW-ENERGY GALACTIC COSMIC RAY SPECTRUM?

K. Scherer,[1] H. Fichtner,[1] S. E. S. Ferreira,[2] I. Büsching,[2] and M. S. Potgieter[2]
Received 2007 October 31; accepted 2008 May 9; published 2008 June 2

ABSTRACT

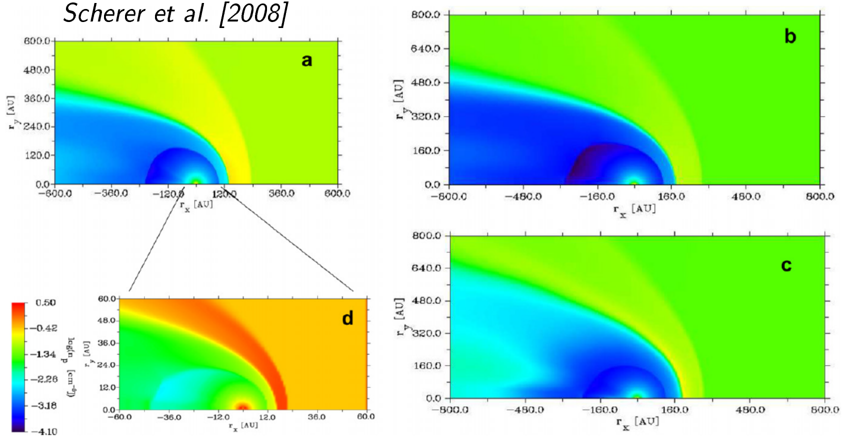
While the high-energy part of the Galactic cosmic ray spectrum is well observed, its nature at energies below about 1 GeV nucleon^{-1} is still not known well. Recent in situ measurements made with the *Voyager 1* spacecraft in the heliosheath between the solar wind termination shock and the heliopause have added further constraints on the local interstellar spectrum of Galactic cosmic rays at low energies. We show here that they also suggest how the low-energy proton part is formed locally in the heliosphere and globally in the Galaxy. The measured flux of anomalous cosmic rays in the heliosheath is unexpectedly high compared to expectations before *Voyager 1* reached the shock, which might be a temporal effect or due to an additional acceleration beyond the termination shock. Combining this finding with recent model results for astrospheres immersed in different interstellar environments shows that the astrospheric anomalous cosmic ray fluxes of solar-type stars can be a hundred times higher than thought earlier and, consequently, their total contribution to the lower end of the interstellar spectrum can be significant.

Cosmic Rays from Astrospheres of Solar-like Stars

The interstellar proton (n_p) and hydrogen (n_H) number density, the relative inflow speed (v_{LISM}), and temperature (T_{LISM}) of the local interstellar medium

Model	n_p (cm^{-3})	n_H (cm^{-3})	v_{LISM} (km/s)	T_{LISM} (K)	TS (AU)	HP (AU)	BS (AU)
a	0.1	0.1	25	8000	80	120	221
b	0.04	0.04	26	7000	126	180	290
c	0.04	0.24	15	3000	120	200	285
d	0.4	0.4	100	8000	11	16	22

Scherer et al. [2008]



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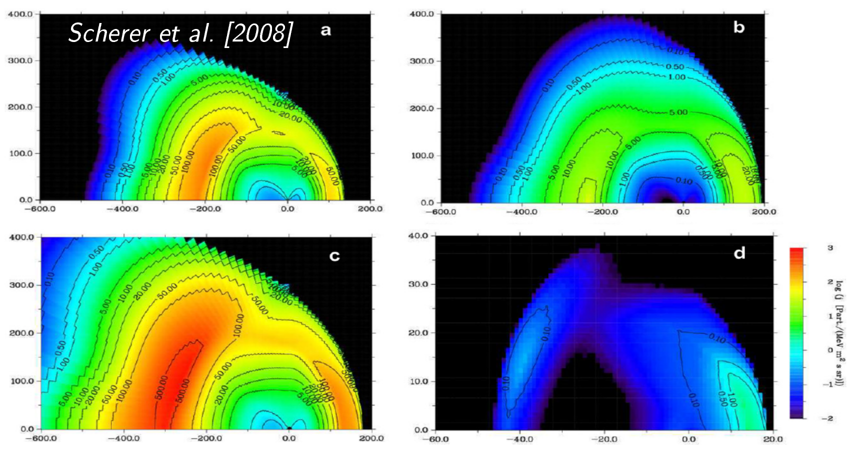
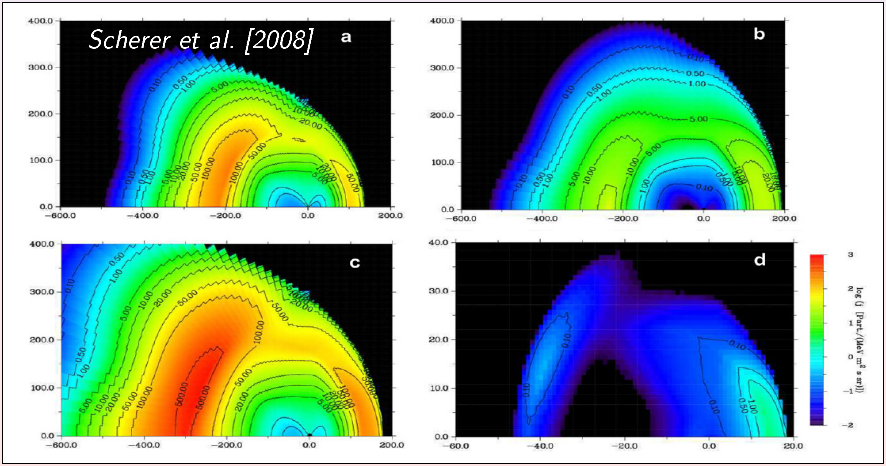


Cosmic Rays from Astrospheres of Solar-like Stars

- acceleration of 'Anomalous' Cosmic Rays can be significant and depends on the interstellar environment of the Sun/a star



Cosmic Rays from Astrospheres of Solar-like Stars

Given that...

- ...there are about 10^{11} F, G, and K stars, representing about 1/4 of all stars in the Galaxy...
- ...the energization of ACRs can easily be more than twenty times as efficient as in the present day heliosphere...
- ...the resulting total energy density below 300 MeV is at least in the range $0.3 - 7.6 \cdot 10^{-2}$eV/cm^2...

...up to 50% of the energy density of the interstellar cosmic ray spectrum below 300 MeV could be provided by ('solar-type') low-mass stars.

Summary III: Astrospheric Cosmic Rays

- An **ACR source region deeper in the helio-/astrosheath** results in a **contribution to the interstellar CR spectrum**.

⇒ *Adding up the contributions of all solar-like stars results in a contribution to the interstellar spectrum below 300 MeV (with re-acceleration also at higher energies?).*

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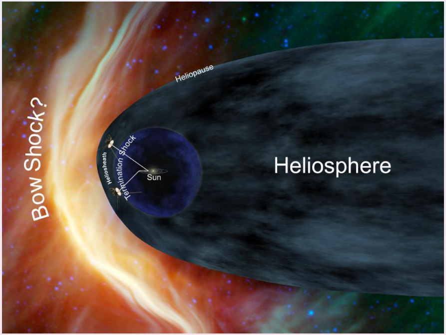
⇒ *Adding up the contributions of all solar-like stars results in a contribution to the interstellar spectrum below 300 MeV (with re-acceleration also at higher energies?).*

- **ACRs appear not to be shock-accelerated** (at least in the regions probed by the Voyager spacecraft, *e.g. Stone et al. [2008]*).

⇒ *Does this signify difficulties for the standard diffusive shock acceleration?*

Cosmic Ray Modulation beyond the Heliopause

A Moving Horizon

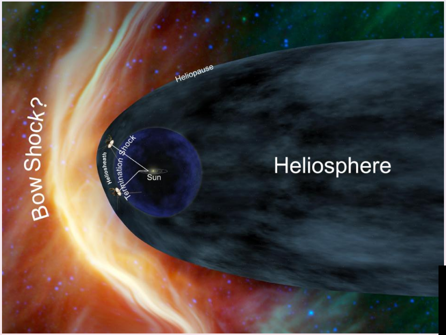


Stone et al. [2008], McComas et al. [2009]

- Voyager 1 & 2 in the heliosheath, approaching the heliopause:

$\Rightarrow$ *better constraints on (local) interstellar spectra of cosmic rays*

A Moving Horizon



Stone et al. [2008], McComas et al. [2009]

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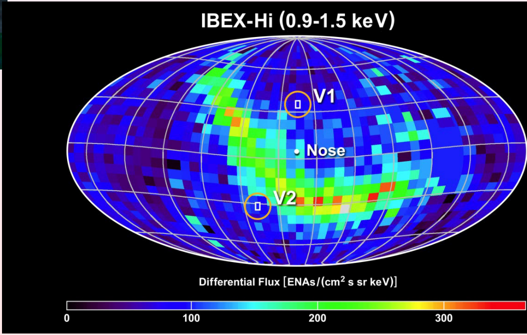
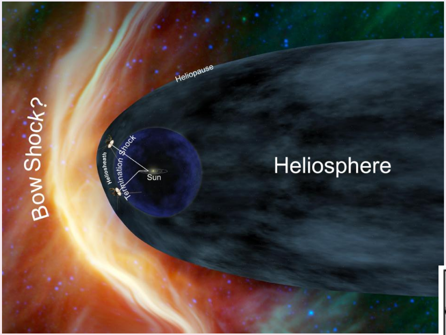


- Interstellar Boundary Explorer (IBEX): all-sky energetic neutral atom (ENA) fluxes

⇒ *knowledge about the interstellar magnetic field out to* $\sim$ *400AU?*

A Moving Horizon



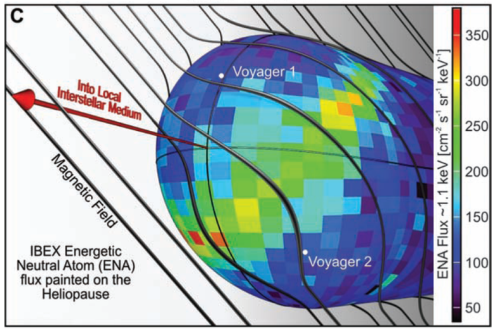
Stone et al. [2008], McComas et al. [2009]

- Voyager 1 & 2 in the heliosheath, approaching the heliopause:

⇒ *better constraints on (local) interstellar spectra of cosmic rays*

- Interstellar Boundary Explorer (IBEX): all-sky energetic neutral atom (ENA) fluxes

⇒ *knowledge about the interstellar magnetic field out to* $\sim$ *400AU?*



Modulation beyond the Heliopause?

THE ASTROPHYSICAL JOURNAL, 734:1 (5pp), 2011 ??? doi:10.1088/0004-637X/734/1/1

ON COSMIC RAY MODULATION BEYOND THE HELIOPAUSE: WHERE IS THE MODULATION BOUNDARY?

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Received 2011 April 8; accepted 2011 April 27; published 2011 ???

ABSTRACT

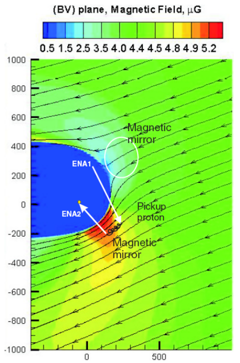
Two of the paradigms in modeling the transport of galactic cosmic rays are that the modulation boundary is the heliopause and that the local interstellar spectra are identical to the galactic cosmic ray spectra. Here we demonstrate that the proton spectrum is already modulated due to an altered interstellar diffusion in the outer heliosheath as a consequence of the heliospheric "obstacle" in the interstellar flow. The main modulation effect however is adiabatic energy losses during a "confinement time" of cosmic rays inside the heliosphere.

(just appeared in the July 10 issue of ApJ)

Re-visiting considerations by *Jokipii [2001]*...

Modulation beyond the Heliopause?

- On the scale of the heliosphere (i.e., several hundred AU) **the cosmic ray diffusion cannot be expected to be isotropic** because of the ordered local interstellar magnetic field.



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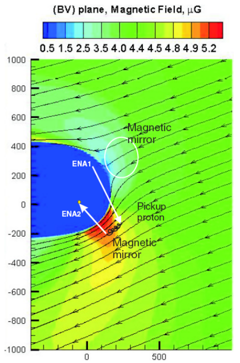
- On the scale of the heliosphere (i.e., several hundred AU) **the cosmic ray diffusion cannot be expected to be isotropic** because of the ordered local interstellar magnetic field.
- This magnetic field is not homogeneous but wrapped around and piling up in front of the 'obstacle' heliosphere resulting in an **effective increase in the local field strength & turbulence** (*Chalov et al. [2010]*).



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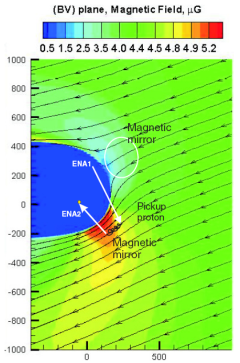
- If a **bow shock** exists, it should **further enhance the turbulence** in the outer heliosheath (OHS).



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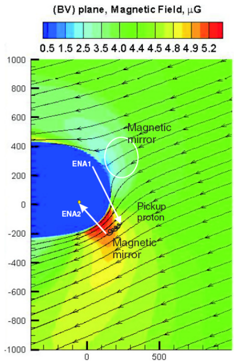
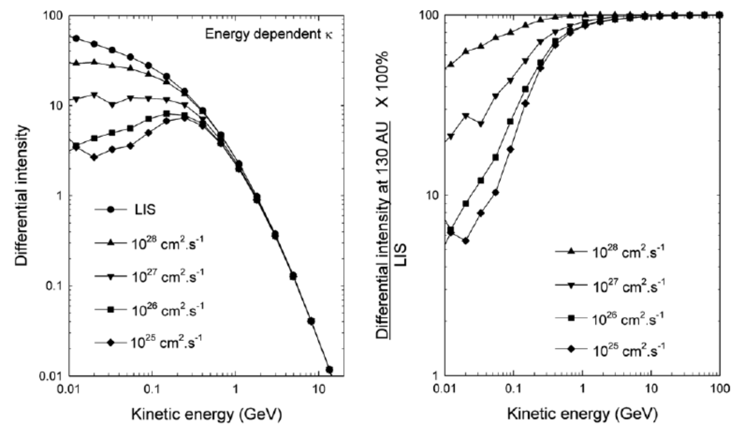


- If a **bow shock** exists, it should **further enhance the turbulence** in the outer heliosheath (OHS).
- The lower diffusion coefficients in the heliosphere imply **an increased confinement time in the heliosphere**, during which the cosmic ray particles are efficiently cooled.

Modulation beyond the Heliopause?

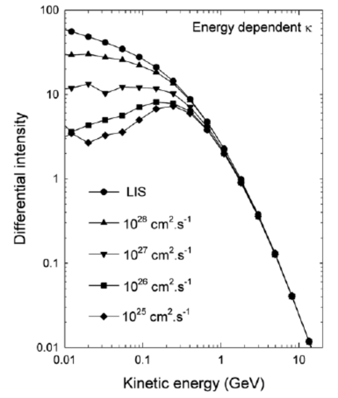
Solving the cosmic ray transport equation results in:



A Hierarchy of Spectra

So, one should **distinguish** between...

- a **'true' local interstellar spectrum** ⟶
- a **'heliopause' spectrum** ⟶



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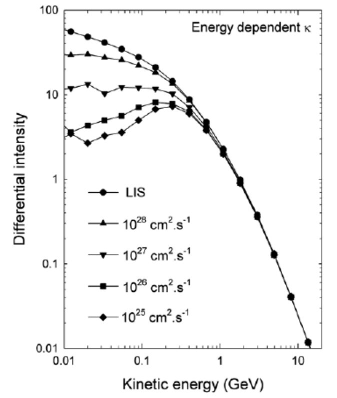

⇒ *V1 & V2 will probably not be able to observe the LIS below 1 GeV*

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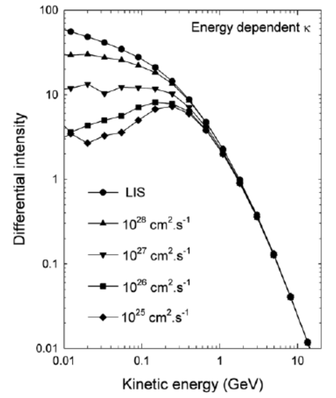


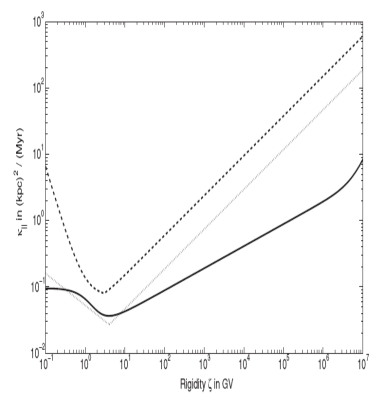
⇒ *V1 & V2 will probably not be able to observe the LIS below 1 GeV*

⇒ *flattening of spectrum not necessarily a consequence of break in the diffusion coefficient*

Contraints on Interstellar Diffusion & Turbulence

Flattening of cosmic ray spectra

- originally explained phenomenologically with break in the diffusion coefficient $\kappa_{||}$ around 3-4 GV *(Moskalenko et al. [2002], Ptuskin et al. [2006])*
- recently derived from a model of interstellar turbulence (solid line) *(Shalchi & Büsching [2010])*



If modulation beyond the heliopause is confirmed, it will provide **additional contraints on interstellar turbulence**.

Summary IV: Modulation of Interstellar CR Spectra

- Given the physical nature of the interstellar medium surrounding the heliosphere, **one must expect the interstellar spectra to be modulated beyond the heliopause** (downstream of the bow shock if it exists).

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Summary IV: Modulation of Interstellar CR Spectra

- Given the physical nature of the interstellar medium surrounding the heliosphere, **one must expect the interstellar spectra to be modulated beyond the heliopause** (downstream of the bow shock if it exists).
- One must distinguish between a **heliopause spectrum** and the **'true' interstellar spectrum**.
- It is unlikely that the Voyager spacecraft will observe the 'true' interstellar spectrum.
- A quantitative understanding of this additional modulation provides **constraints on the interstellar spectra and the interstellar turbulence**.

Résumé

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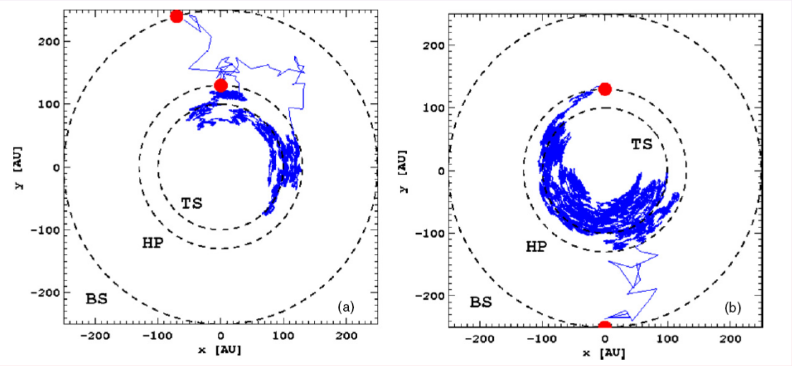
- Diffusion tensor for anisotropic perpendicular diffusion needs to be tested.
- Solar-type stars might feed the galactic cosmic ray population below 300 MeV.
- Confirmation of modulation of interstellar spectra beyond the heliopause will provide new contraints on both interstellar spectra and interstellar turbulence.

The always existing conceptual link between heliospheric and interstellar transport of cosmic rays is significantly growing because first measurements (Voyagers, IBEX) of the region close to the heliopause and beyond are providing constraints on the physical link of the two media.

An Adiabatic Cooling Effect

Sample particle 'trajectories' (from SDEs):



Particles spend long time in the region enclosed by the termination shock and experience adiabatic cooling.