Acceleration of galactic electrons at the solar wind termination shock and their journey beyond

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with

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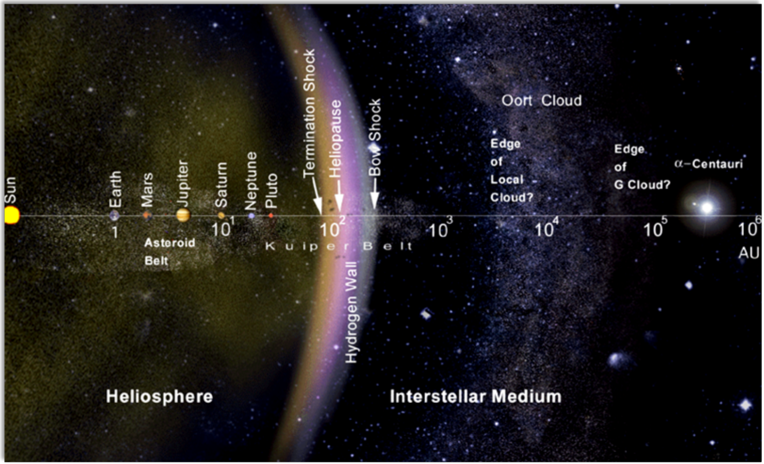
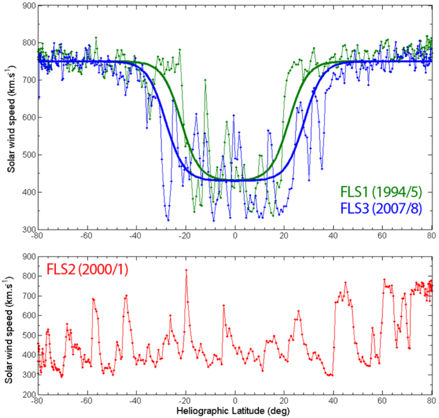
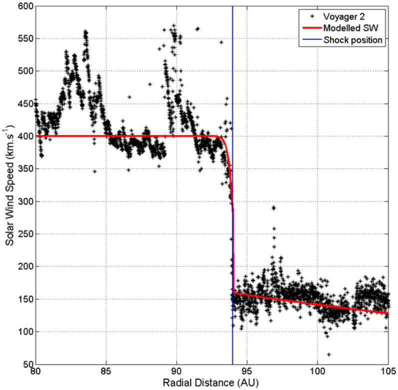
Overview

The Heliosphere



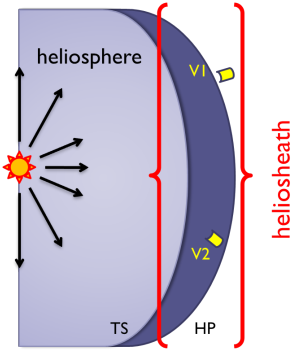
Solar wind properties



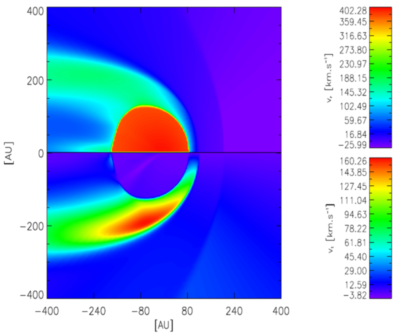


Voyager 2 SW data obtained from http://cohoweb.gsfc.nasa.gov/.

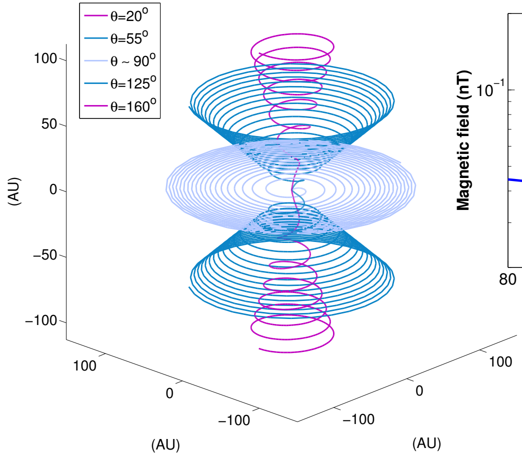
Spacecraft	Compression Ratio	Method	Reference
V1	$s = 2.6^{+0.4}_{-0.2}$	Particle data	Stone *et al.* (2005)
V1	$s = 3.05 \pm 0.05$	Magnetic field	Burlaga *et al.* (2005)
V2	$s \sim 2.5$ (max)	Magnetic field	Burlaga *et al.* (2008)
V2, TS-3	$s = 1.6 \pm 0.2$	Magnetic field, density	Burlaga *et al.* (2008)
V2, TS-3	$s = 1.6$	Solar wind	Richardson *et al.* (2008)
V2, TS-2	$s = 2.4$	Solar wind	Richardson *et al.* (2008)

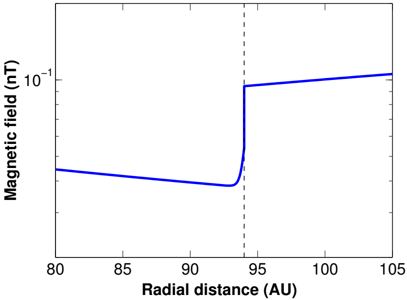


from Snyman (2007):



The Parker Spiral





$$B = B_0 \left[\frac{r_0}{r}\right] \sqrt{1 + \tan^2 \psi}$$

with $\tan \psi = \frac{\Omega\left(r - r_\odot\right) \sin\theta}{V_{sw}}$

The Parker (1965) Transport Equation

$$\overbrace{\frac{\delta f}{\delta t}}^{1} = -(\overbrace{\vec{V}_{sw}}^{2} + \overbrace{\langle\vec{v}_d\rangle}^{3}) \cdot \nabla f + \overbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}^{4} + \overbrace{\frac{1}{3}\left(\nabla \cdot \vec{V}_{sw}\right)\frac{\delta f}{\delta \ln p}}^{5} + \overbrace{Q}^{6}$$

where $f = f(\vec{r}, p, t) \implies f(r, \theta, P)$, with $P = pc/Ze$.

$1 \rightarrow \frac{\delta f}{\delta t} = 0$ for steady-state solution (changes on time scales less than one solar rotation neglected).
$2, 3 \rightarrow$ The SW velocity and the averaged pitch angle guiding centre drift velocity, respectively describing SW convection and transport via drifts.
$6 \rightarrow$ Source term to simulate the contribution of e.g. Jovian electrons.

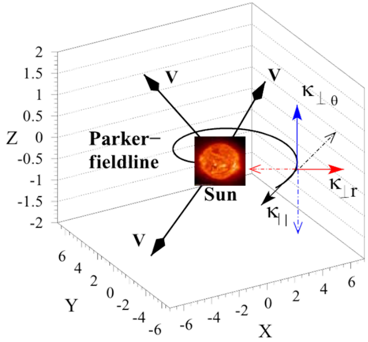
Differential intensity

Solutions are presented in units of particles / unit area/ unit time/ unit kinetic energy (per nucleus)/ unit solid angle, and is related to the distribution function through

$$j(r, \theta, P) = P^2 f(r, \theta, P).$$

Diffusion tensor

$$\overbrace{\frac{\delta f}{\delta t}}^{1} = -(\overbrace{\vec{V}_{sw}}^{2} + \overbrace{\langle \vec{v}_d \rangle}^{3}) \cdot \nabla f + \overbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}^{4} + \overbrace{\frac{1}{3}\left(\nabla \cdot \vec{V}_{sw}\right)\frac{\delta f}{\delta \ln p}}^{5} + \overbrace{Q}^{6}$$



adapted from Heber & Potigeter (2006)

$$4 : \mathbf{K}_s = \begin{pmatrix} \kappa_{||} & 0 & 0 \\ 0 & \kappa_{\perp\theta} & 0 \\ 0 & 0 & \kappa_{\perp r} \end{pmatrix},$$

with $\kappa = \frac{v}{3}\lambda$.

In 2-D spherical geometry, this translates into the elements

$$\kappa_{rr} = \kappa_{||} \cos^2 \psi + \kappa_{\perp r} \sin^2 \psi$$
$$\kappa_{\theta\theta} = \kappa_{\perp\theta}$$

with $\tan\psi = \frac{\Omega(r - r_{\odot})\sin\theta}{V_{sw}}$

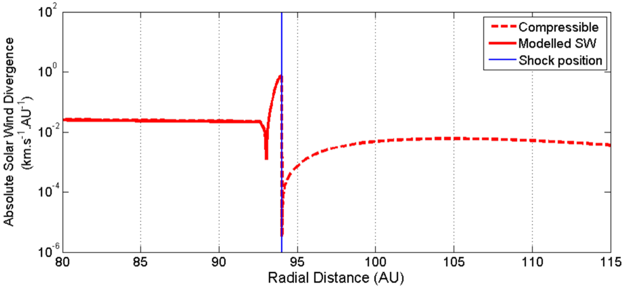
Solar wind divergence

$$\overbrace{\frac{\delta f}{\delta t}}^{1} = -(\overbrace{\vec{V}_{sw}}^{2} + \overbrace{\langle \vec{v}_d \rangle}^{3}) \cdot \nabla f + \overbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}^{4} + \overbrace{\frac{1}{3}\left(\nabla \cdot \vec{V}_{sw}\right)\frac{\delta f}{\delta \ln p}}^{5} + \overbrace{Q}^{6}$$

adiabatic cooling $\left(\nabla \cdot \vec{V}_{sw}\right) > 0$

adiabatic heating $\left(\nabla \cdot \vec{V}_{sw}\right) < 0$

incompressible flow $\left(\nabla \cdot \vec{V}_{sw}\right) = 0$



Conditions for diffusive shock acceleration (at the TS)

$$\overbrace{\frac{\delta f}{\delta t}}^{1} = -(\overbrace{\vec{V}_{sw}}^{2} + \overbrace{\langle \vec{v}_d \rangle}^{3}) \cdot \nabla f + \overbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}^{4} + \overbrace{\frac{1}{3} \left(\nabla \cdot \vec{V}_{sw} \right) \frac{\delta f}{\delta \ln p}}^{5} + \overbrace{Q}^{6}$$

Continuity of the distribution function

If $f^- = \lim_{r \to r_{TS}} f(r)$ and $f^+ = \lim_{r_{TS} \leftarrow r} f(r)$, then $f^- = f^+$.

Particle streaming condition

The particle flux that diverges from the shock must have its origin at the shock itself, that is, $\nabla \cdot \vec{S} = Q_*$, with Q_* the source of the particles and

$$\vec{S} = -4\pi p^2 \left[\frac{\vec{V}_{sw}}{3} \frac{\partial f}{\partial \ln p} + \mathbf{K}_s \cdot \nabla f \right]$$

see also e.g. Axford *et al.*, (1977), Axford (1981), Drury (1983) and Jones and Ellison (1991).

Numerical solution

The transport equation may be rewritten in spherical coordinates as

$$\frac{\partial f}{\partial t} = a\frac{\partial^2 f}{\partial r^2} + b\frac{\partial^2 f}{\partial \theta^2} + c\frac{\partial f}{\partial r} + d\frac{\partial f}{\partial \theta} + e\frac{\partial f}{\partial \ln P} + Q,$$

revealing the form of a *linear second-order partial differential equation*.
A numerical solution is required.

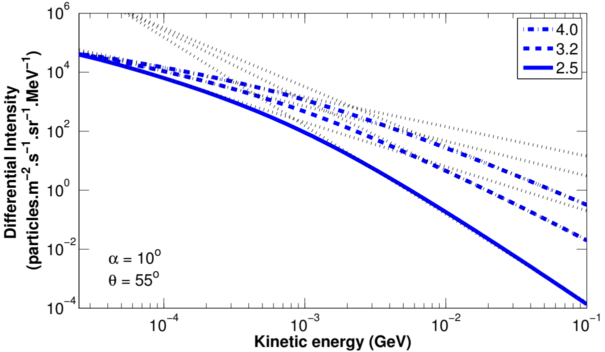
The *locally one-dimensional* (LOD) method

$$\frac{1}{3}\frac{\partial f}{\partial t} = a\frac{\partial^2 f}{\partial r^2} + c\frac{\partial f}{\partial r} \qquad \text{radial equation}$$

$$\frac{1}{3}\frac{\partial f}{\partial t} = b\frac{\partial^2 f}{\partial \theta^2} + d\frac{\partial f}{\partial \theta} \qquad \text{polar equation}$$

$$\frac{1}{3}\frac{\partial f}{\partial t} = e\frac{\partial f}{\partial \ln P} + Q \qquad \text{energy equation}$$

Compression ratio-dependent spectral index

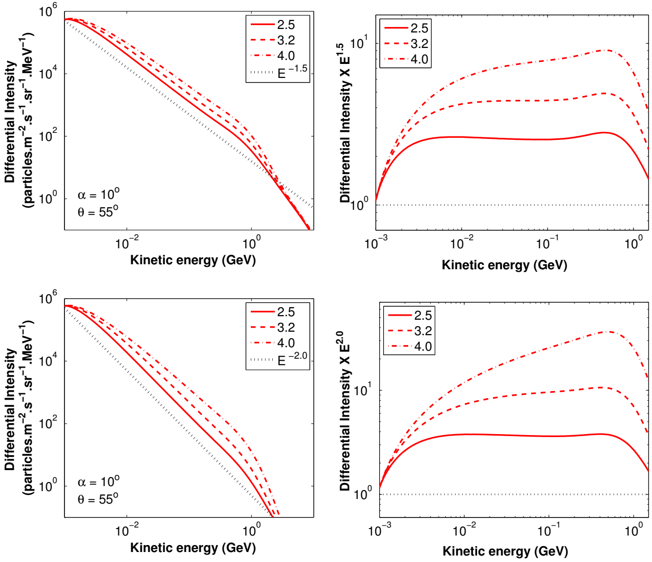


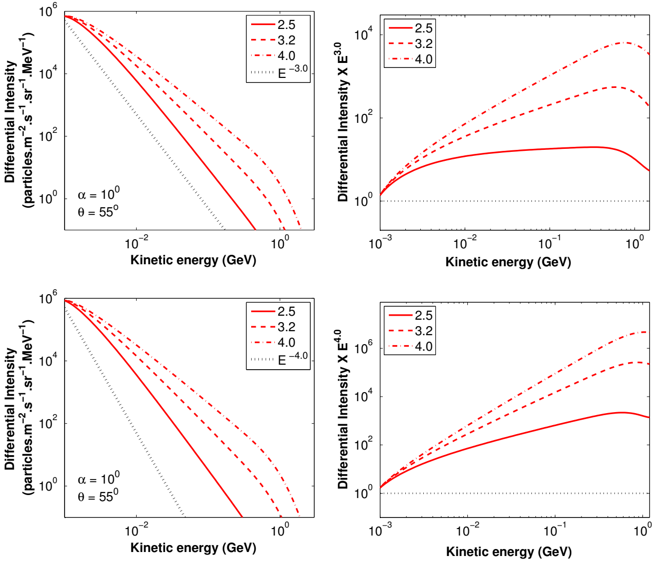
$$j \propto P^{\frac{s+2}{1-s}}$$

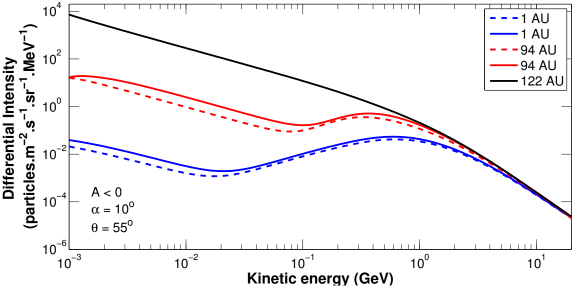
$$P = \sqrt{E\left(E + 2e_0\right)}$$

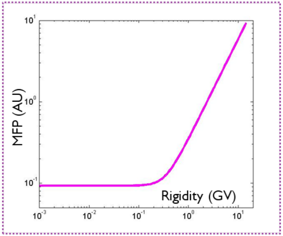
$$\text{if } E \gg e_0 : P \to E \implies j \propto E^{\frac{s+2}{1-s}}$$

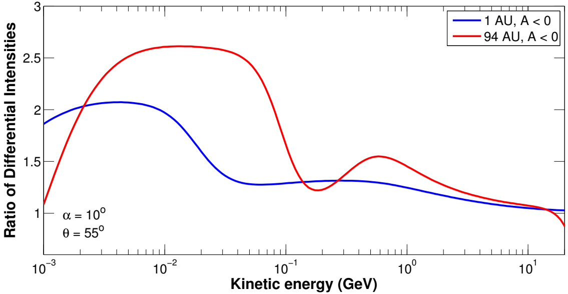
$$\text{if } E \ll e_0 : P \to \sqrt{2e_0 E} \propto E^{1/2} \implies j \propto E^{\frac{s+2}{2(1-s)}}$$

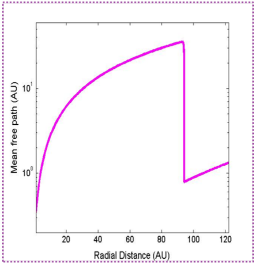

Differential Intensity (particles.m^{-2}.s^{-1}.sr^{-1}.MeV^{-1})
Kinetic energy (GeV)
2.5
3.2
4.0
E$^{-1.5}$
E$^{-2.0}$
α = 10°
θ = 55°
Differential Intensity X E$^{1.5}$
Differential Intensity X E$^{2.0}$


Differential Intensity (particles.m^{-2}.s^{-1}.sr^{-1}.MeV^{-1})
Kinetic energy (GeV)
2.5
3.2
4.0
E$^{-3.0}$
α = 10^0
θ = 55^o
Differential Intensity X E$^{3.0}$
Kinetic energy (GeV)
2.5
3.2
4.0
Differential Intensity (particles.m^{-2}.s^{-1}.sr^{-1}.MeV^{-1})
Kinetic energy (GeV)
2.5
3.2
4.0
E$^{-4.0}$
α = 10^0
θ = 55^0
Differential Intensity X E$^{4.0}$
Kinetic energy (GeV)
2.5
3.2
4.0

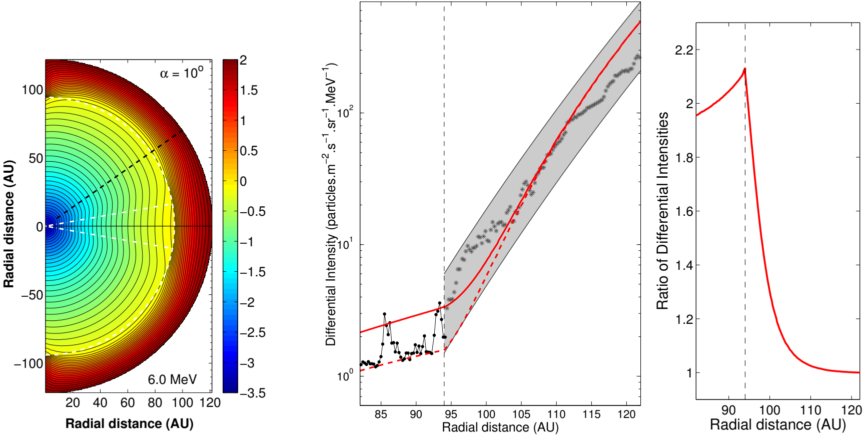

Differential Intensity (particles.m^{-2}.s^{-1}.sr^{-1}.MeV^{-1})
Kinetic energy (GeV)
1 AU
1 AU
94 AU
94 AU
122 AU
A < 0
α = 10°
θ = 55°

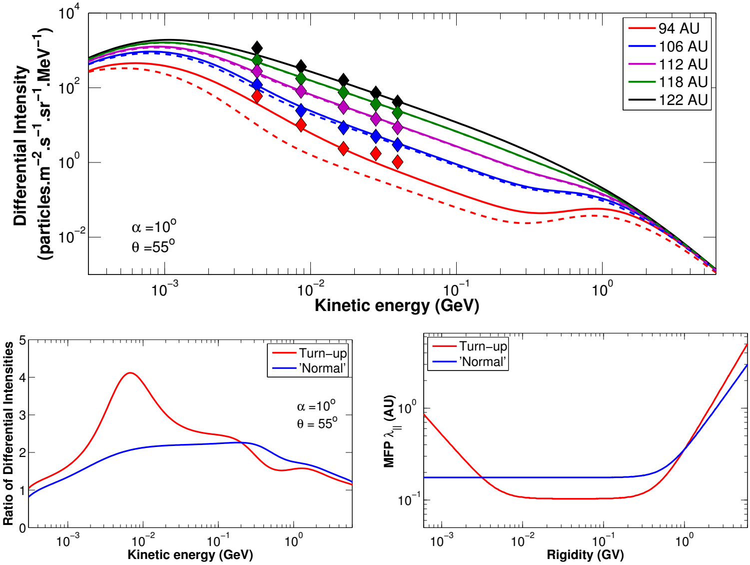

MFP (AU)
Rigidity (GV)


Ratio of Differential Intensities
Kinetic energy (GeV)
1 AU, A < 0
94 AU, A < 0
α = 10°
θ = 55°


Mean free path (AU)
Radial Distance (AU)

Radial profiles in the heliosheath (6 MeV)




Differential Intensity (particles.m^{-2}.s^{-1}.sr^{-1}.MeV^{-1})
Kinetic energy (GeV)
94 AU
106 AU
112 AU
118 AU
122 AU
α =10°
θ =55°
Ratio of Differential Intensities
Kinetic energy (GeV)
Turn−up
'Normal'
α =10°
θ = 55°
MFP $\lambda_{||}$ (AU)
Rigidity (GV)
Turn−up
'Normal'

Conclusions from presented results

- The spectral index of shock-accelerated particles is a function of the shock compression ratio.
- The shock-accelerated energy spectra ensuing from a monoenergetic source of particles injected at the shock adopts different power-law indices above and below the rest-mass energy.
- Diffusive shock acceleration cannot be detected from changes in the slope of energy distributions of particles traversing the shock if the distribution incident at the shock is already harder than what the shock is able to produce. Intensities are raised according to how similar spectral indices associated with the compression ratio and injected indices are.
- Modulation alters the form of the heliopause spectrum, yielding segments of varying hardness, which leads to different acceleration efficiencies across energy regions.
- Re-accelerated electrons raise intensities at the termination shock with at least a factor of 2.5 for energies of 3 to 50 MeV for a compression ratio of $s = 2.5$ and rigidity-independent diffusion.
- Re-accelerated electrons may double the intensity at Earth below 10 MeV under the same conditions.
- A modulation barrier is formed in the heliosheath due to impaired diffusion, causing great decreases of intensities from the heliopause to the termination shock, while also limiting the passage of re-accelerated electrons downstream of the shock.
- Diffusive shock acceleration can account for the magnitude of the spurious intensity increases, which were previously associated with this mechanism and observed for low-energy particles in the vicinity of the termination shock.
- A low-energy turn-up in the mean free paths of electrons tends to soften the modulated distribution incident at the TS at these energies, and hence facilitates acceleration. The turn-up also improves the correspondence between modelled heliosheath spectra and observations.