The solar modulation of cosmic rays: "a South African perspective"

Du Toit Strauss and many others...

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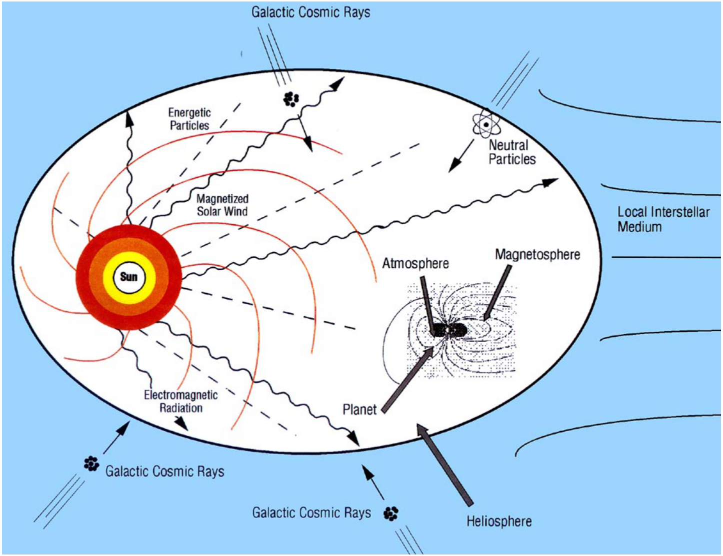
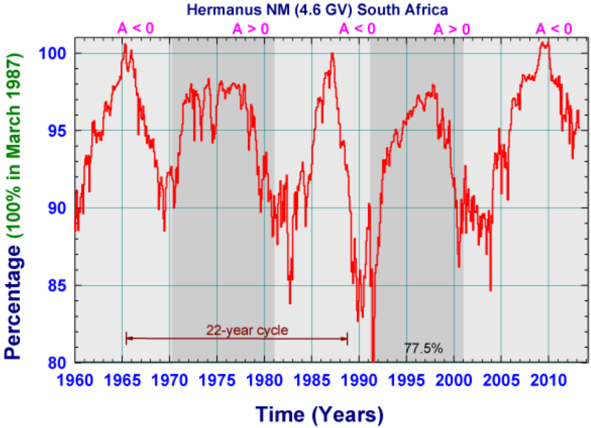
ECRS, Turino, 2016

NWU® POTCHEFSTROOM

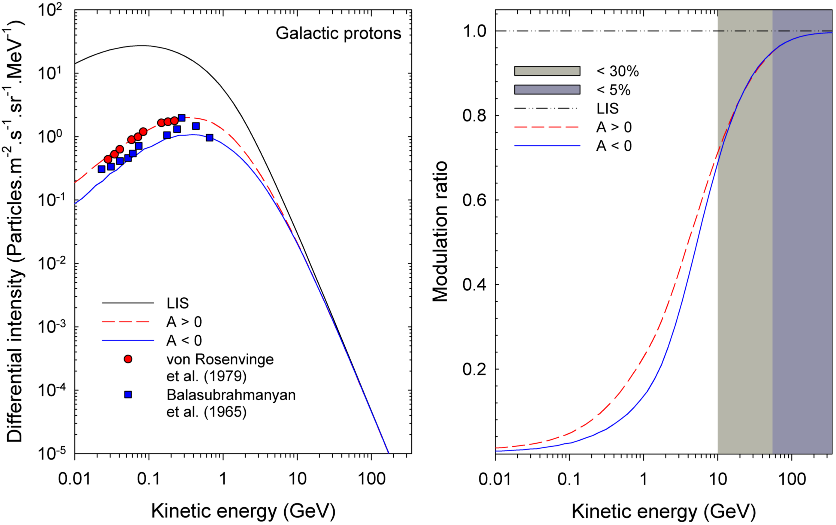
Solar modulation



Galactic Cosmic Rays
Energetic Particles
Neutral Particles
Magnetized Solar Wind
Local Interstellar Medium
Sun
Atmosphere
Magnetosphere
Electromagnetic Radiation
Planet
Galactic Cosmic Rays
Galactic Cosmic Rays
Heliosphere



- We focus only on GCRs (Jovians and Ions: Kecskemety; SEPs: Gomez-Herrero, etc.)
- also, only on long term changes (Shorter term: Lingri, Gil, Wozniak)
- lastly, more observations from Munini, PAMELA, AMS



Strauss & Potgieter (2014)

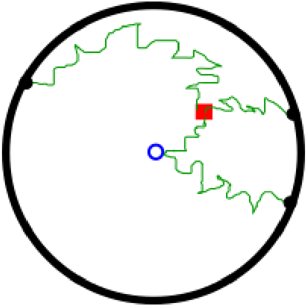
A simple description of solar modulation ...

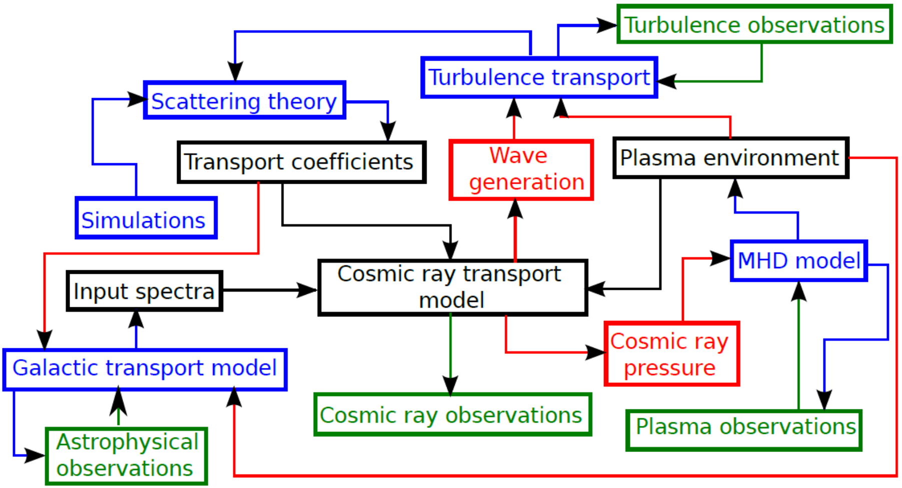
- At the boundary, $f_b(\boldsymbol{x}_b, P_b, t)$, is (assumed to be) known
- and assumed to be (spatially) isotropic and constant, $f_b(P_b)$.
- We want to determine $f_a(\boldsymbol{x}_a, P_a, t)$ at any point in the heliosphere.
- They are connected by Liouville's theorem,

$$\frac{Df}{dt} = 0 \Rightarrow f_a(\boldsymbol{x}_a, P_a, t) = f_b(P_b)$$

- So, all we need to do it calculate

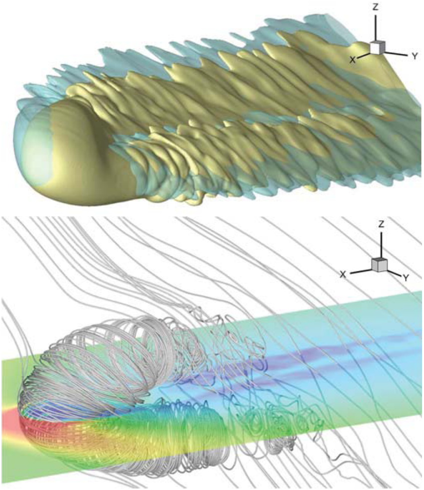
$$\Delta P(\boldsymbol{x}_a, P_a, t) = P_b - P_a$$




Turbulence observations
Turbulence transport
Scattering theory
Transport coefficients
Wave generation
Plasma environment
Simulations
MHD model
Input spectra
Cosmic ray transport model
Cosmic ray pressure
Galactic transport model
Cosmic ray observations
Plasma observations
Astrophysical observations

1. Solar modulation inputs

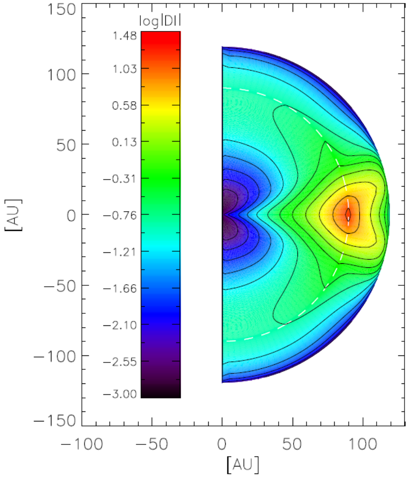
1.1. Heliospheric geometry



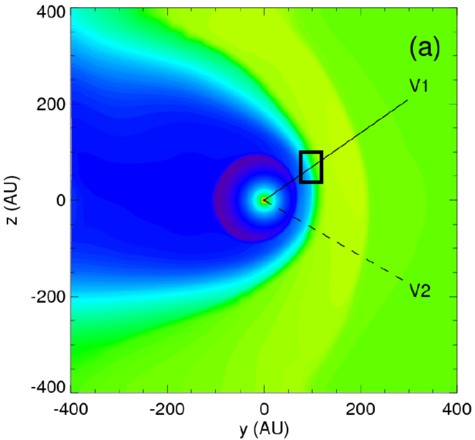
Pogorelov at al. (2015)

- IBEX, measuring neutrals at Earth, determine the plasma conditions at *infinity*...
- ... and, we measure the plasma at Earth.
- This can be included in comprehensive MHD models and compared to
- Voyager observing (disturbed) interstellar plasma *in-situ*...

We have a good idea about it, but generally neglect it...



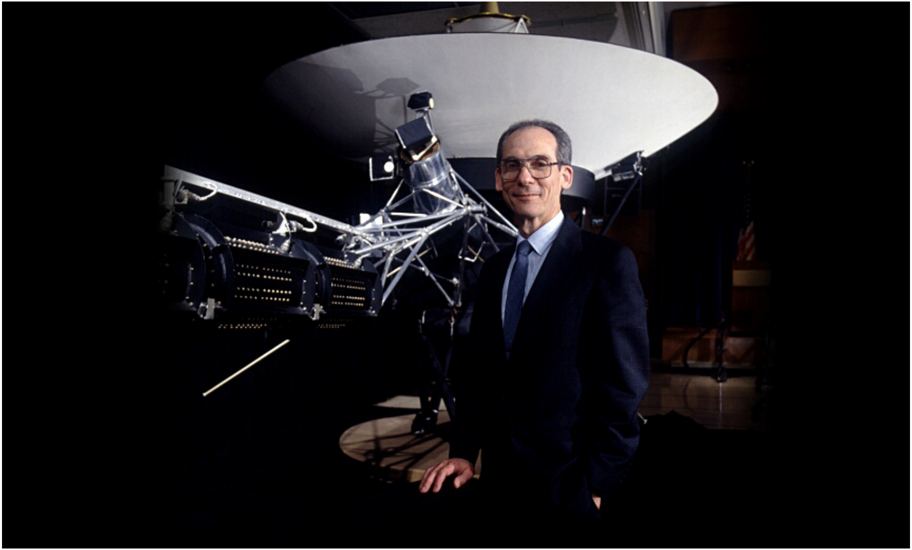
Strauss at al. (2011)



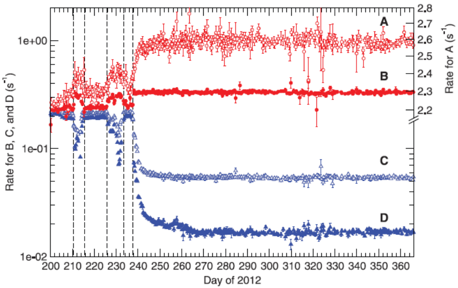
Strauss at al. (2013)

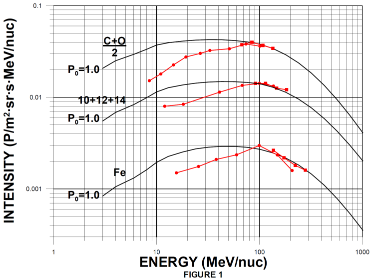
1. Solar modulation inputs

1.2. The LIS

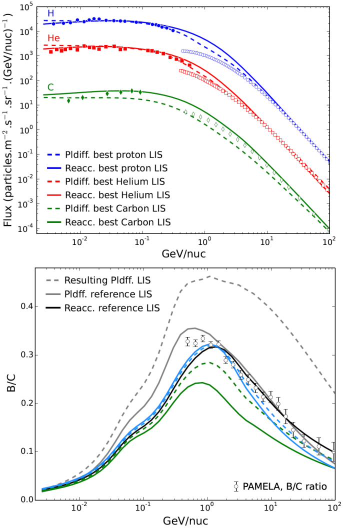


Voyager 1 in the interstellar medium...

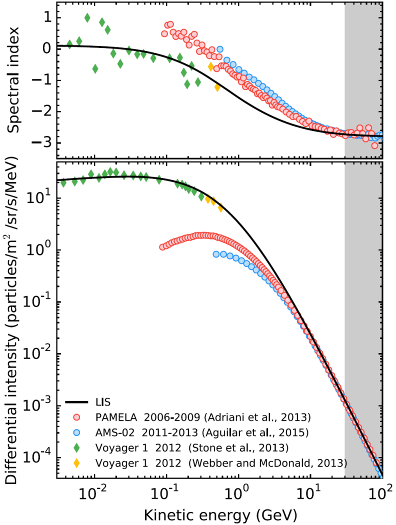




Webber (2013 - 2016)



Bisschoff & Potgieter (2016)



Vos & Potgieter (2015)

1. Solar modulation inputs

1.3. Transport coefficients

(keep this one for later...)

2. Different modelling approaches

2.1. Force-field

The Compton-Getting corrected streaming

$$\mathcal{S} = 4\pi p^2 \left(C\boldsymbol{V} f - \mathcal{K} \cdot \nabla f \right),$$

The derivation hinges on the “observational fact" that $\mathcal{S} \approx 0$, which reduces, for spherical symmetry, to

$$\frac{V}{3} \left(P \frac{\partial f}{\partial P} \right) + \kappa \frac{\partial f}{\partial r} = 0.$$

The solution is then simply

$$j(r_a, P_a) = \left(\frac{P_a}{P_b} \right)^2 j(r_b, P_b),$$

Usually, the simplified choice of $\kappa_P(P) = P/P_0$ is made, so that

$$\phi = \frac{1}{P_0} \int_{P_a}^{P_b} dP = \frac{P_b - P_a}{P_0}.$$

We can also perform an alternative derivation...

Working in the solar wind frame, and assuming a spherical symmetric system,

$$\frac{dP}{P} = \frac{2V}{3r}dt.$$

The time it takes to diffuse a distance dr,

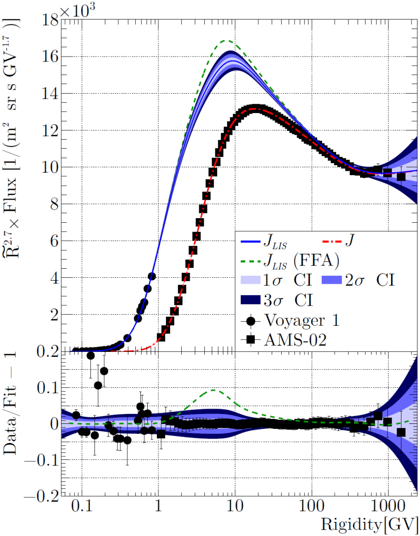
$$dt = \frac{2rdr}{6\kappa}.$$

Which, combined, yields

$$\frac{dP}{P} = \frac{2}{3} \cdot \frac{V}{3\kappa}dr,$$

and can be integrated from (r_a, P_a) to (r_b, P_b) to give an expression similar to the classical force-field solution

$$\int_{P_a}^{P_b} \kappa_P \frac{dP}{P} = \frac{2}{3} \cdot \frac{V}{3\kappa_0} \int_{r_a}^{r_b} dr = \phi.$$



Corti et al. (2016)

- Use Voyager to constrain the LIS
- Compute the spectrum at Earth using the force-field approach
- Fit this to AMS data

It doesn't work: the normal force-field is just to simple to capture the essential physics. *Corti et al. (2016)* needed to implement an energy dependent force-field parameter...

The usual assumption is that $\kappa_P(P) = P/P_0$, leading to

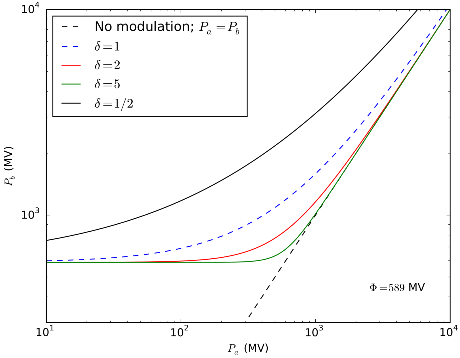
$$\Phi = P_b - P_a.$$

We would however argue that a better assumption is

$$\kappa_P(P) = \left(\frac{P}{P_0}\right)^{\delta},$$

which is still easily solvable (for $\delta \neq 0$)

$$P_b^{\delta} - P_a^{\delta} = \Phi^{\delta}.$$



But, unfortunately, for most applications, the force-field solution is an oversimplification ...

2. Different modelling approaches

2.2. Phenomenological Parker

We think most of the physics of solar modulation is captured by the Parker transport equation:

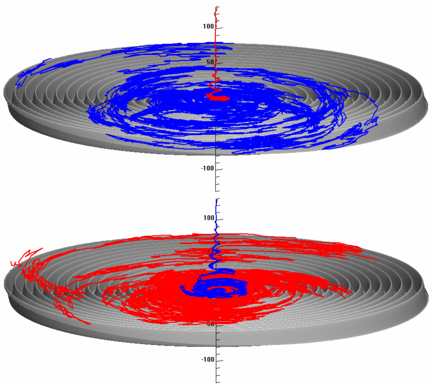
$$\frac{\partial f}{\partial t} = -(\boldsymbol{u} + \boldsymbol{v}_d) \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \boldsymbol{u}) \frac{\partial f}{\partial \ln P}$$

as long as the CR distribution, f, remains (nearly?) isotropic

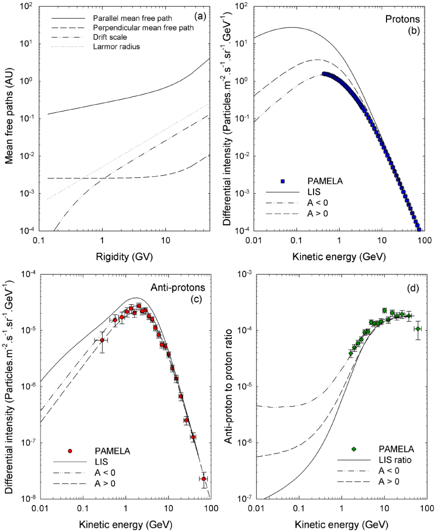
In higher dimensions only numerical solutions are possible

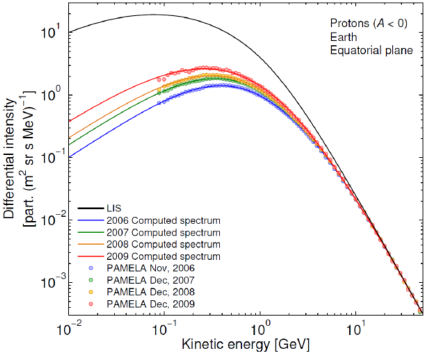
The use of stochastic differential equations (SDEs) have become increasingly popular (Grandi (Milan group), Wawrzynczak (Polish group))

Of special importance is the drift effects...

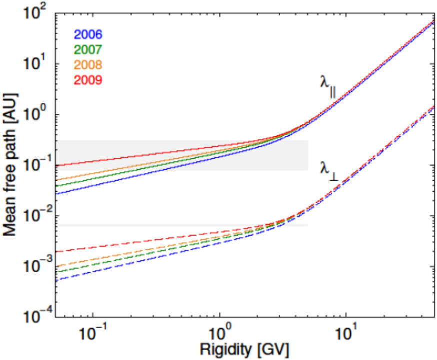


Strauss et al. (2012)



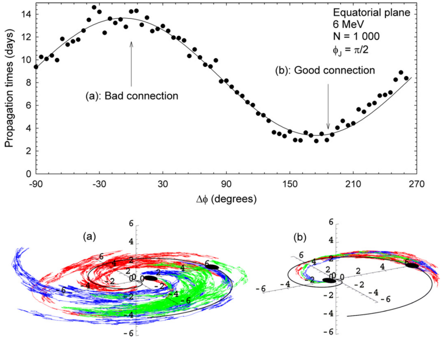


Potgieter et al. (2013)

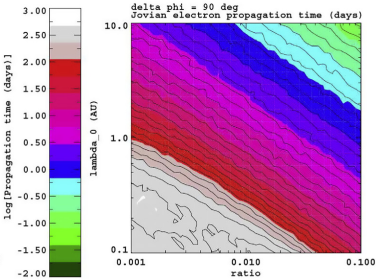


Potgieter et al. (2013)

Degenerate solutions for Jovian electron intensities and propagation times:



Strauss et al. (2013)



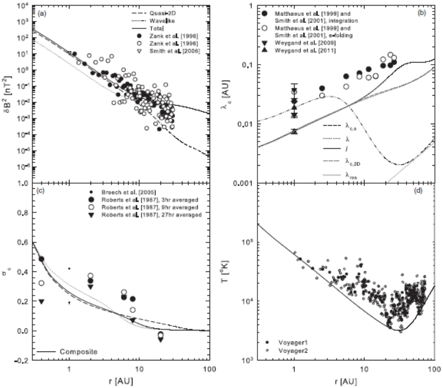
Where we assumed:

$$\lambda_{||} = \frac{\lambda_0}{2}\left(1 + \frac{r}{r_0}\right)$$

$$\lambda_{\perp} = \chi\lambda_{||}$$

2. Different modelling approaches

2.3. Theoretical Parker



Engelbrecht & Burger (2013)

We start with a set of turbulence transport equations which govern the spatial properties of the background MHD fluctuations...

This is then fed into a scattering theory to determine the diffusion coefficients...

constant along ellipses in k-space that have a k_y to k_x ratio of ξ. This would then be equivalent to the axisymmetric case, where $A(k_x, k_y)$ is constant along circles defined by $k_\perp = k_x^2 + k_y^2$ (Ruffolo et al. 2008), under the coordinate transformation $k_x' = \xi^{1/2} k_x$ and $k_y' = \xi^{-1/2} k_y$. Assuming that $\delta B_x^2 / \delta B_y^2$ is the same for slab and 2D components (see, e.g., Ruffolo et al. 2006), as might be expected for a generic suppression of turbulence in one direction, implies that $\delta B_{T,x}^2 / \delta B_{T,y}^2 = \xi^2$, which further implies that $\langle \tilde{v}_x^2 \rangle / \langle \tilde{v}_y^2 \rangle = \xi^2$. It remains now to write Equation (38) in such a way as to allow one to calculate expressions for κ_{ii} using some specified form for $S^{2D}(k_\perp') = k_\perp'^2 A(k_\perp')$. Following the approach of Ruffolo et al. (2008), one can define a geometric mean of the x and y components of the guiding center velocity such that $\langle \tilde{v}_g^2 \rangle = \sqrt{\langle \tilde{v}_x^2 \rangle \langle \tilde{v}_y^2 \rangle}$, with $\langle \tilde{v}_x^2 \rangle = \xi \langle \tilde{v}_g^2 \rangle$ and $\langle \tilde{v}_y^2 \rangle = \langle \tilde{v}_g^2 \rangle / \xi$, and the term $\sqrt{\Sigma_i k_i^2 \langle \tilde{v}_i^2 \rangle}$ becomes $k_\perp' \sqrt{\langle \tilde{v}_g^2 \rangle}$. Furthermore, taking into account that $S_{xx}^{2D} = k_y^2 A = \xi k_y'^2 A$ and $S_{yy}^{2D} = k_x^2 A = k_x'^2 A / \xi$ leads to

$$\kappa_g = \frac{a^2 v^2}{3B_0^2} \sqrt{\frac{\pi}{2}} \int \frac{k_\perp'^2 A}{2k_\perp' \sqrt{\langle \tilde{v}_g^2 \rangle}} \operatorname{erfc}\left(\frac{v^2/3\kappa_{zz}}{k_\perp' \sqrt{2 \langle \tilde{v}_g^2 \rangle}} \right) d\mathbf{k}_\perp'$$
$$= \frac{a^2 v^2}{3B_0^2} \sqrt{\frac{\pi}{2}} \int \frac{S^{2D}(k_\perp')}{2k_\perp' \sqrt{\langle \tilde{v}_g^2 \rangle}} \operatorname{erfc}\left(\frac{v^2/3\kappa_{zz}}{k_\perp' \sqrt{2 \langle \tilde{v}_g^2 \rangle}} \right) d\mathbf{k}_\perp', \quad (41)$$

where $\lambda = 3\kappa/v$, and

$$\lambda_1 = \frac{x_0}{q} \left(\sqrt{3\epsilon} B_o a \lambda_\parallel \operatorname{erfc}(x_1) - \frac{3B_o^2 \lambda_{out}}{\sqrt{2\pi}} E_{(q+1)/2}(x_1^2) \right),$$
$$\lambda_2 = x_0 \left(\frac{3B_o^2 \sqrt{2}}{\sqrt{\pi}} [\lambda_{2D} x_2 - \lambda_{out} x_3] + \sqrt{3\epsilon} B_o a \lambda_\parallel \log \frac{\lambda_{out}}{\lambda_{2D}} \right),$$
$$\lambda_3 = \frac{x_0}{\nu} \sqrt{3\epsilon} B_o a \lambda_\parallel \Big(\operatorname{erfc}(x_4) + \frac{1}{\sqrt{\pi} x_4^\nu} \left[\Gamma\left(\frac{\nu+1}{2} \right) - \Gamma\left(\frac{\nu+1}{2}, x_4^2 \right) \right] \Big), \quad (45)$$

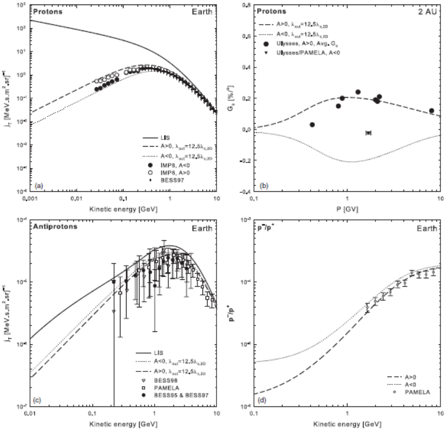
with $\epsilon = \sqrt{\delta B_{T,x}^2 \delta B_{T,y}^2}$, and, for notational convenience,

$$x_0 = \sqrt{\frac{\pi}{2}} \frac{C_0 \lambda_{2D} \delta B_{2D}^2}{2B_o^2 \epsilon \lambda_\parallel},$$
$$x_1 = \sqrt{\frac{3}{2}} \frac{B_o \lambda_{out}}{a \sqrt{\epsilon} \lambda_\parallel},$$
$$x_2 = {}_2F_2\left(\frac{1}{2}, \frac{1}{2}; \frac{3}{2}, \frac{3}{2}; -x_4^2 \right),$$
$$x_3 = {}_2F_2\left(\frac{1}{2}, \frac{1}{2}; \frac{3}{2}, \frac{3}{2}; -x_1^2 \right),$$
$$x_4 = \sqrt{\frac{3}{2}} \frac{B_o \lambda_{2D}}{a \sqrt{\epsilon} \lambda_\parallel}.$$

and the modelled intensities are compared to observations...

...with some success.

But, how do (time dependent) turbulence influence the drifts?

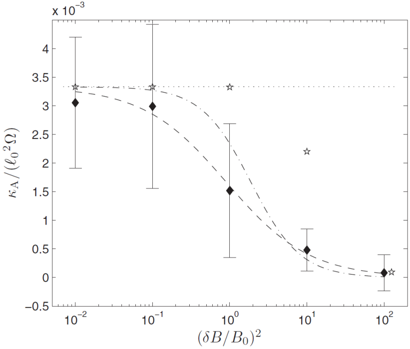


Engelbrecht & Burger (2013)

$$\boldsymbol{B} = \boldsymbol{B_0} + \boldsymbol{b}.$$

The drift velocity is then

$$\langle \boldsymbol{v} \rangle \approx \nabla \times \kappa_A f_s \mathbf{e}_{B_0}.$$



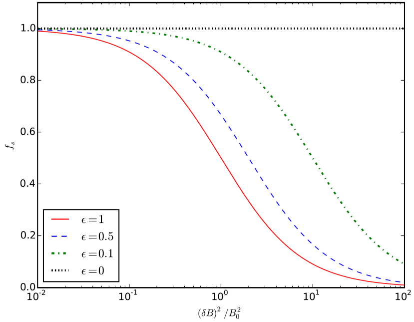
Tautz & Shalchi (2012)

The weak-scattering drift coefficient is

$$\kappa_A := \frac{pv}{3qB_0},$$

and the suppression factor

$$f_s^{-1} := 1 + \langle b^2 \rangle / B_0^2.$$



Summary and discussion

We live in interesting times...

- What will Voyager 2 encounter at the HP? *Luo et al. (2016)* suggest February 2017-ish.
- AMS and PAMELA continuing high resolution measurements over a complete solar cycle.
- We are continuously constraining the physics (and the coefficients) to include in more sophisticated models.
- We are especially interested in the charge-sign-dependent modulation over solar maximum.
- Will this coming solar minimum again be “unusual”?
- With Voyager 1 in the interstellar medium, astrophysics and heliospheric physics are moving ever closer ...