Turbulent Reduction of Drifts for Solar Energetic Particles

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Motivation

- Transport perpendicular to the background magnetic field can be caused by either drifts or cross-field diffusion.
- Many studies *[Dalla et al., 2013; Marsh et al., 2013; Battarbee et al., 2017, 2018]* investigate the effect of drifts on solar energetic particles (SEPs) and advocate that drifts are important. *This might be applicable to slab turbulence.*
- However, only few studies *[Kelly et al., 2012; Wijsen et al., 2020]* include perpendicular diffusion. *Perpendicular diffusion (caused by 2D turbulence) smears out signatures of drifts.*
- **But** none of these studies consider the reduction of drifts by turbulence *[Minnie et al., 2007; Tautz & Shalchi, 2012; Engelbrecht et al., 2017]*.

See summary of this in *van den Berg et al. [2020]*

Overview

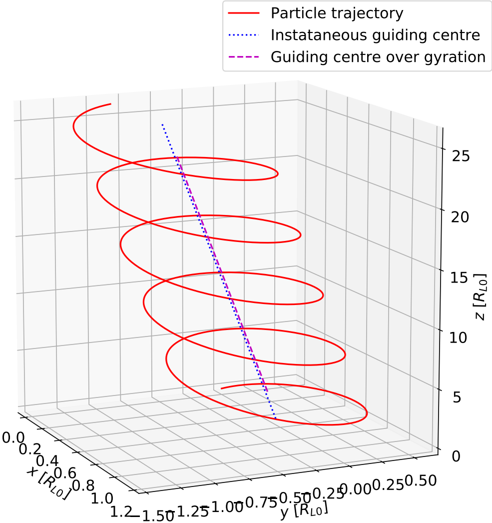
Outline

- Motivation
- Illustration
- Drift Reduction Factor
- Predictions
- Modelling Results
- Summary

Goal

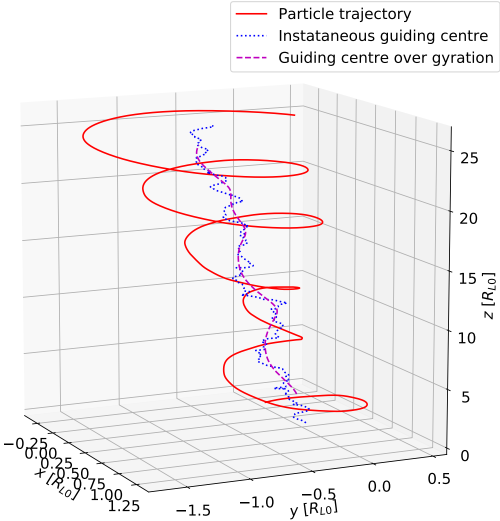
To investigate the possible pitch-angle dependence of the turbulent drift reduction factor and its implications for solar energetic particle (SEP) drifts.

Illustration



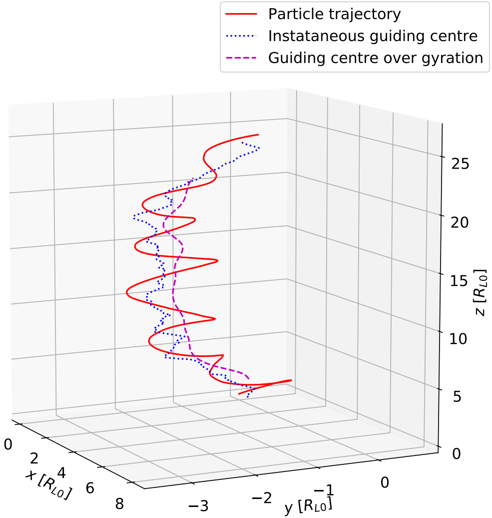
Electric field drift for proton
($\vec{B}$ along z-axis, $\vec{E}$ along x-axis, $\vec{E} \times \vec{B}/B^2$ drift along negative y-axis)

Illustration



Add slab turbulence with model presented in *van den Berg et al. [2020]*

Illustration



Now with composite 20% slab and 80% 2D turbulence

Drift Reduction Factor

Turbulent Reduced Drift Velocity

Following *Engelbrecht et al. [2017]* and based on the guiding centre drift velocity in the solar wind (SW) frame of *Wijsen [2020]* for a constant radial SW and Parker field:

$$\vec{v}_{\rm gc} = \sqrt{f_s}\,\mu v\,\hat{b}_0 + \vec{v}_{\rm sw} + f_s^{3/2}\frac{\mu p}{qB_0}\,\hat{b}_0 \times \left[(\hat{b}_0 \cdot \vec{\nabla})\vec{v}_{\rm sw} + (\vec{v}_{\rm sw} \cdot \vec{\nabla})\hat{b}_0\right] + f_s\frac{vp}{qB_0}\left\{\mu^2(\vec{\nabla} \times \hat{b}_0)_\perp + \frac{1-\mu^2}{2}\left[(\vec{\nabla} \times \hat{b}_0)_\parallel + \frac{\hat{b}_0 \times \vec{\nabla}B_0}{B_0}\right]\right\} + \frac{1+\mu^2}{4}\frac{vp}{qB_0}(\vec{\nabla}f_s \times \hat{b}_0), \quad (1)$$

f_s is the drift reduction factor

μ, v, p, and q is the particle's pitch-cosine, speed, momentum, and charge in the SW frame, respectively

$\hat{b}_0 = \vec{B}_0/B_0$ is a unit vector along the magnetic field

$\vec{v}_{\rm sw}$ is the SW velocity

Drift Reduction Factor

Isotropic Factor from *Engelbrecht et al. [2017]*

$$f_s = \frac{1}{1 + (\lambda_\perp^0 / R_L)^2 (\delta B^2 / B_0^2)} \quad (2)$$

$\lambda_\perp^0$ is the isotropic perpendicular mean free path (MFP)
$R_L = p/|q|B_0$ is the particle's maximal Larmor radius
δB^2 is the total (slab + 2D) variance of the fluctuations

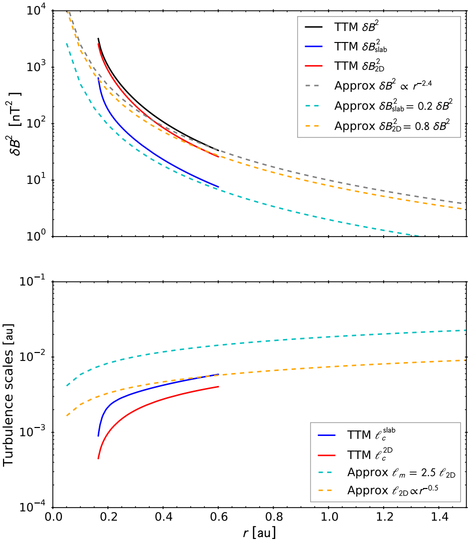
Proposed Anisotropic Factor

Following similar arguments as *Engelbrecht et al. [2017]*, but retaining pitch-angle dependencies:

$$f_s(\mu) = \frac{1}{1 + [D_\perp(\mu) / \sqrt{1-\mu^2}\kappa_A^{\mathrm{ws}}]^2 (\delta B^2 / B_0^2)} \quad (3)$$

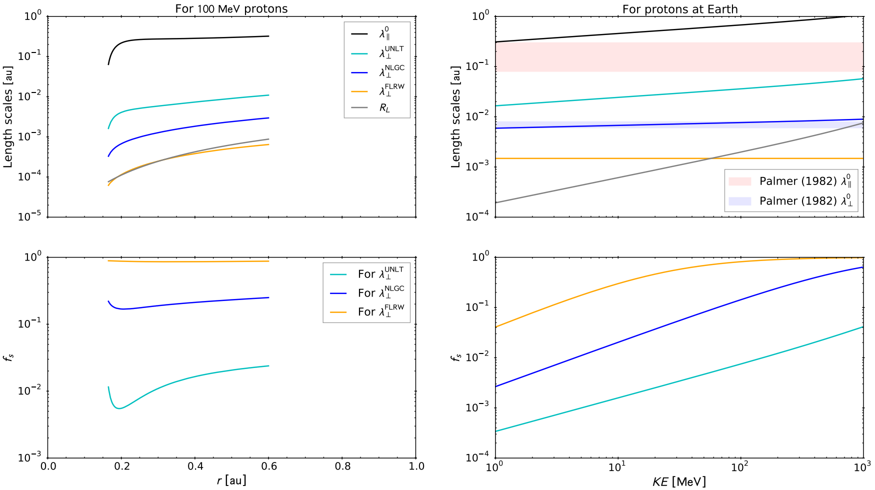
$D_\perp(\mu)$ is the pitch-angle dependent perpendicular diffusion coefficient
$\kappa_A^{\mathrm{ws}} = vp/qB_0$ is the isotropic weak-scattering drift coefficient

Predictions: Turbulence Parameters



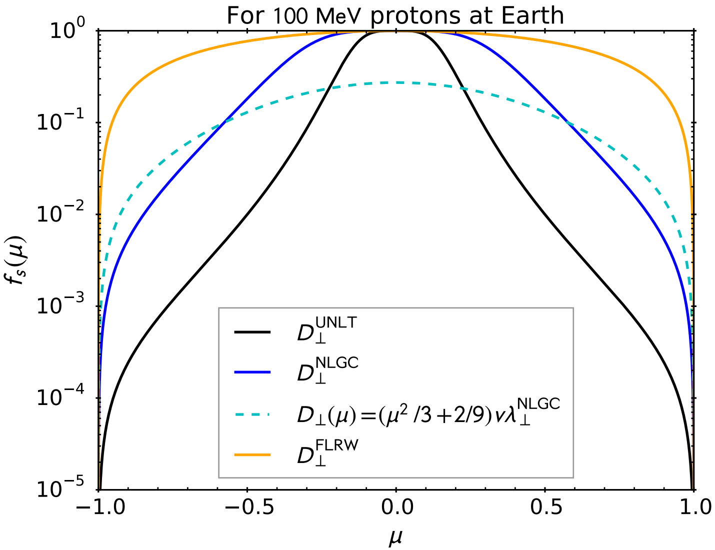
Turbulence transport model of *Adhikari et al. [2020]*

Predictions: r and KE Dependence



(see end of uploaded slides for the expressions used for the radial scalings of turbulence quantities and the mean free paths)

Predictions: Pitch-angle Dependence



Modelling with PARADISE

- Tested three perpendicular diffusion coefficients (field line random walk, FLRW, nonlinear guiding centre theory, NLGC, and unified nonlinear theory, UNLT) in the PARADISE model *[Wijsen et al., 2019, 2020; Wijsen, 2020]*.
- Mono-energetic, isotropic injection of protons

$$j \propto \frac{1}{t} \exp\left(-\frac{\tau_a}{t} - \frac{t}{\tau_e}\right) \exp\left(\frac{\phi^2 + \theta^2}{2\sigma^2}\right) \delta\left(\frac{E}{E_0} - 1\right) \delta\left(\frac{r}{r_0} - 1\right)$$

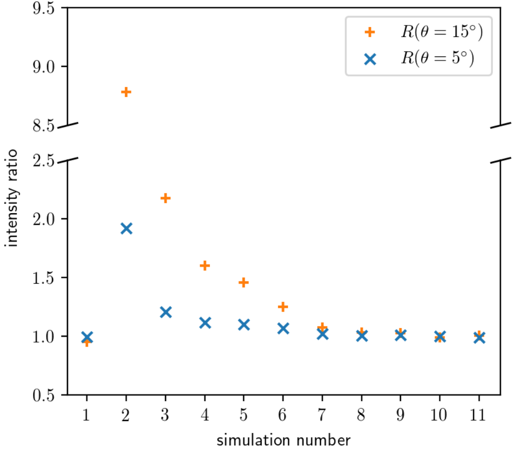
  with $r_0 = 0.05\ \mathrm{au}$, $\sigma = 5^\circ$, $\tau_a = 0.2\ \mathrm{h}$, $\tau_e = 1\ \mathrm{h}$, and $E_0 = 100\ \mathrm{MeV}$.
- Calculated the energy-integrated omni-directional intensity,

$$I(r, \theta, \phi, t) = \int_0^{E_0} \int_{-1}^{1} j(r, \theta, \phi, E, \mu, t) d\mu\, dE,$$

  and over the simulation time $T = 50\ \mathrm{h}$, the ratio

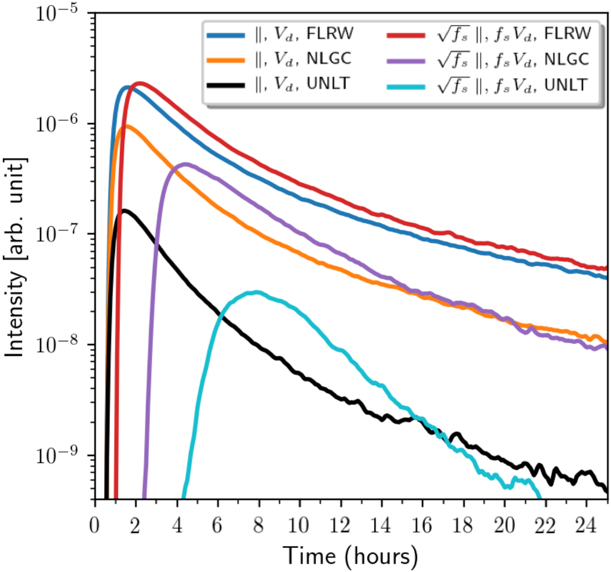
$$R(r, \theta, \phi) := \frac{\int_0^T I(r, -\theta, \phi, t) dt}{\int_0^T I(r, \theta, \phi, t) dt}. \tag{4}$$

Modelling Results: Drift Reductions



1	$\parallel$
2	$\parallel$, V_d
3	$\parallel$, V_d, FLRW
4	$\parallel$, $f_s V_d$, FLRW
5	$\sqrt{f_s}\ \parallel$, $f_s V_d$, FLRW
6	$\parallel$, V_d, NLGC
7	$\parallel$, $f_s V_d$, NLGC
8	$\sqrt{f_s}\ \parallel$, $f_s V_d$, NLGC
9	$\parallel$, V_d, UNLT
10	$\parallel$, $f_s V_d$, UNLT
11	$\sqrt{f_s}\ \parallel$, $f_s V_d$, UNLT

Modelling Results: Delayed Onsets



Summary

- We present a drift reduction factor with a pitch-angle dependence.
- For realistic turbulence conditions in the inner heliosphere, we predict that field aligned and low energy particles will experience more drift reduction and that drift reduction will have a weak radial dependence.
- We tested three different perpendicular diffusion theories (FLRW, NLGC, and UNLT) in PARADISE for solar energetic protons.
- Drifts could potentially have a large effect, but cross-field diffusion smears out these effects.
- Drift reduction further diminishes drift effects, such that drift becomes a second order process.
- We investigated the prediction that parallel streaming will also be reduced.
- Streaming reduction causes a delayed onset at an observer and further reduce drift effects.

In the absence of turbulence, particles will experience pure drifts, while this drift velocity is reduced when turbulence is present, but with the additional effect that the particle will then also experience perpendicular diffusion.

References

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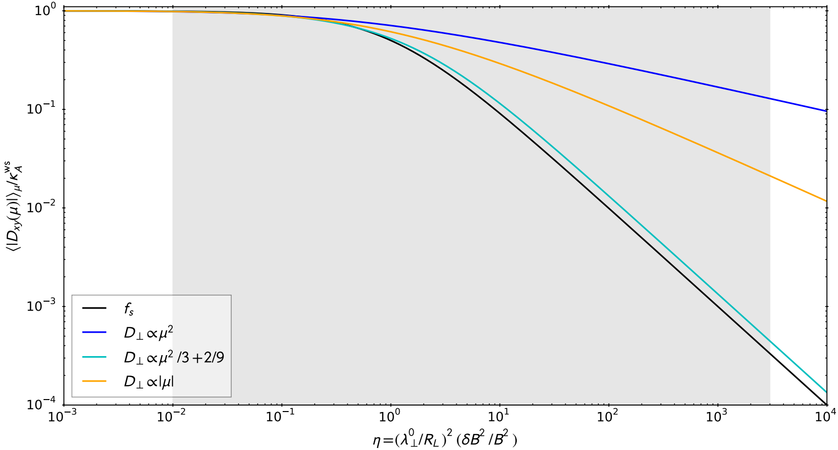
Is the proposed $f_s(\mu)$ plausible?

How does Eq. 3 compare to Eq. 2 when integrated over pitch-angle?



Transport Parameters

Perpendicular Diffusion Coefficient (FLRW)

Field line random walk (FLRW) *[e.g. Qin & Shalchi, 2014]*:

$$D_\perp(\mu) = a|\mu|v\kappa_{\mathrm{FL}} \tag{5}$$

$a = 1/\sqrt{3}$
FLRW diffusion coefficient from *Shalchi & Wienhorst [2009]*:

$$\kappa_{\mathrm{FL}} = \ell_{\mathrm{2D}}\sqrt{\frac{2\nu - 1}{2(q_{\mathrm{2D}} - 1)}\frac{\delta B_{\mathrm{2D}}^2}{B_0^2}}$$

$\delta B_{\mathrm{2D}}^2 = 8\ \mathrm{nT}^2\ (1\ \mathrm{au}/r)^{2.4}$ is the variance of the 2D component *[e.g. Smith et al., 2001; Burger et al., 2008]*
$q_{2D} > 1$ and $2\nu = 5/3$ is the 2D power spectrum's energy-containing and inertial range spectral index, respectively
$\ell_{\mathrm{2D}} = \sqrt{r/1\ \mathrm{au}}/135\ \mathrm{au}^{-1}$ is the length scale where the 2D power spectrum's inertial range starts *[e.g. Smith et al., 2001; Burger et al., 2008; Weygand et al., 2011]*

Transport Parameters

Perpendicular Diffusion Coefficient (UNLT)

Unified nonlinear theory (UNLT) in the limit of dominant pitch-angle scattering by *Qin & Shalchi [2014]*:

$$D_{\perp}(\mu) = \frac{1}{2} a^2 \mu^2 v \frac{\delta B_{\mathrm{2D}}^2}{B_0^2} \lambda_{\parallel} \quad (6)$$

Perpendicular Diffusion Coefficient (NLGC)

Nonlinear guiding centre (NLGC) theory by *Burger et al. [2008]*:

$$D_{\perp}(\mu) = \mu^2 v \lambda_{\parallel}^{1/3} \left[a^2 \sqrt{3\pi} \frac{2\nu - 1}{\nu} \frac{\Gamma(\nu)}{\Gamma(\nu - 1/2)} \frac{\delta B_{\mathrm{2D}}^2}{B_0^2} \ell_{2D} \right]^{2/3} \quad (7)$$

Transport Parameters

Parallel Mean Free Path

Quasi-linear theory with magnetostatic slab turbulence by *Teufel & Schlickeiser [2003]*:

$$\lambda_{\parallel} = \frac{3s}{\pi(s-1)} \frac{R_L^2}{\ell_m} \frac{B_0^2}{\delta B_{\mathrm{sl}}^2} \left[\frac{1}{4} + \frac{2\ell_m^s}{(2-s)(4-s)R_L^s}\right] \quad (8)$$

$\delta B_{\mathrm{sl}}^2 = 2\ \mathrm{nT}^2\ (1\ \mathrm{au}/r)^{2.4}$ is the variance of the slab component *[e.g. Smith et al., 2001; Burger et al., 2008]*
$s = 5/3$ is the slab power spectrum's inertial range spectral index
$\ell_m = 2.5\,\ell_{\mathrm{2D}}$ is the length scale where the slab power spectrum's inertial range starts *[e.g. Smith et al., 2001; Burger et al., 2008; Weygand et al., 2011]*