Energetic particle diffusion in structured turbulence

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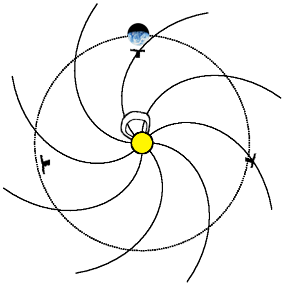
Interpreting multispacecraft observations

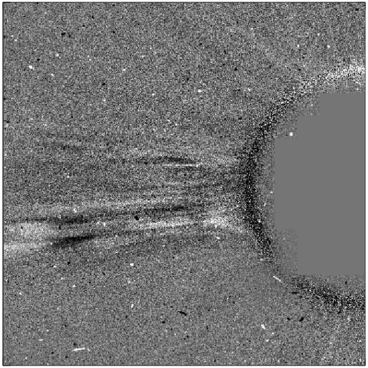
- **SEPs** observed after **propagation in turbulent medium**
  - How to interpret wide longitudinal spread?
- **To uncover the acceleration physics**, **the SEP transport must be understood**



- Recently the use of **full-orbit simulations** in modelled turbulence has **gained attention**
  - Turbulence typically modelled through **Fourier mode description** and **spatially homogeneous**

Issues in SEP transport modelling

- **Heliosphere** is a **highly varying, non-constant plasma environment**
- Transient structures, **varies spatially and temporally**
- Turbulence **evolves non-linearly**



Sheeley et al (1997)

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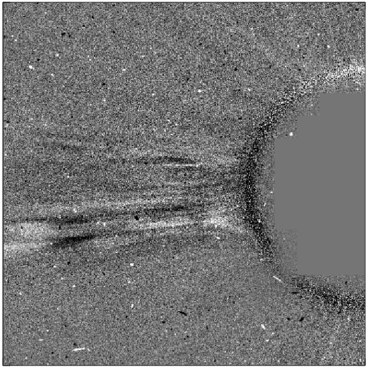

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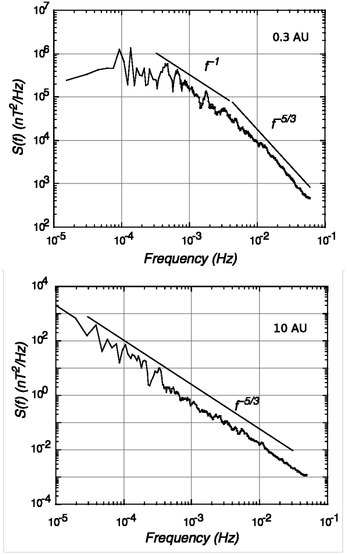
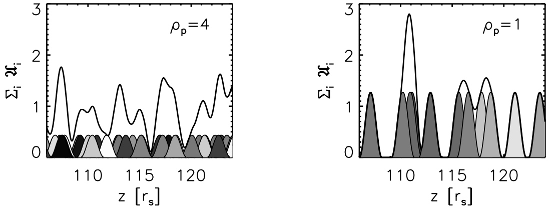


Goldstein (2001)

Enveloped turbulence



- In this work (Laitinen et al, ApJ, 2012), we **remove the assumption of homogeneity** by introducing **turbulent envelopes**

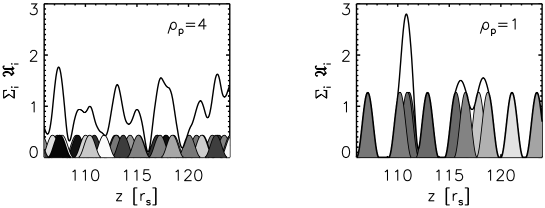
$$\mathfrak{A}_i(z) = \frac{1}{2}\left[1 - \cos\left(2\pi\frac{z - z_i}{L_p}\right)\right], \qquad z_i \leq z < z_i + L_p.$$

to form the **total magnetic field**

$$\mathbf{B}(x,y,z) = B_0\hat{\mathbf{u}}_z + \sum_{i=1}^{N_p}\mathfrak{A}_i(z)\,\delta\mathbf{B}_i(x,y,z), \text{ with}$$

$$\delta\mathbf{B}_i(x,y,z) = \sum_{n=1}^{N} A(k_n)\hat{\xi}_{n,i}\exp\{\imath(k_n z'_{n,i} + \beta_{n,i})\}$$

Enveloped turbulence



- **Two models** considered:
  - **Modulated wavefield**: Only **amplitude modulated**

$$\mathbf{B}(x,y,z) = B_0 \hat{\mathbf{u}}_z + \delta\mathbf{B}(x,y,z) \sum_{i=1}^{N_p} \mathfrak{A}_i(z)$$

  - **Random envelope**: Enveloping **breaks the coherence**

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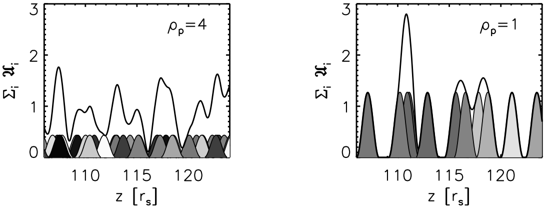
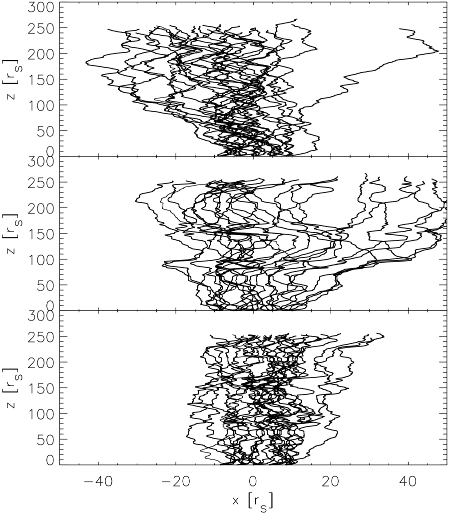
Enveloped turbulence



- $\delta\mathbf{B}_i$ defined as a **slab/2D** composite turbulence with **Kolmogorov spectrum** (Giacalone&Jokipii 1999)
- Comparison with **homogeneous turbulence** case with **same mean energy density** in the simulation volume

Field lines

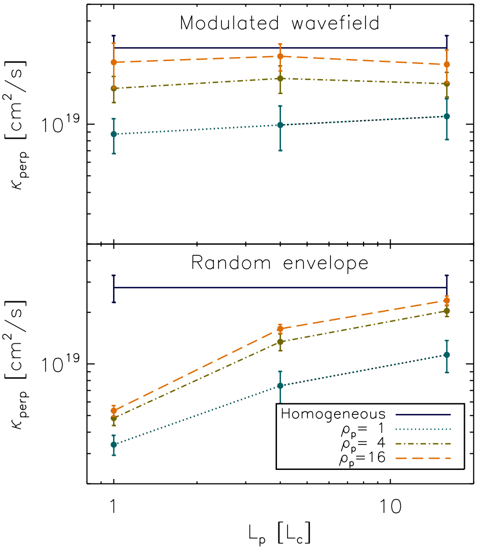
- **Homogeneous turbulence:** some field lines random-walk to large distances
- **Modulated wavefield:** qualitatively similar to the homogeneous turbulence
- **Random envelope:** random walk is more restricted



$\delta B^2/B^2 = 1, L_p = 4 \times 2.15\,r_\odot,\ \rho_p = 4$

Perpendicular diffusion coefficient

- **Modulated wavefield:** depends on **enveloping density**
- **Random enveloping:** depends on **envelope length**
- **Caused by the loss of coherence, parametrised by the envelope length**



$E = 10\,\mathrm{MeV},\ \delta B^2/B^2 = 1,\ L_c = 2.15\,\mathrm{r}_\odot$

Conclusions

- **Inhomogeneities** in turbulence **alter significantly the transport of energetic particles**
- **Parallel transport** is reduced by **up to 70%** when **structure size approaches the resonant scales**
- **Perpendicular transport reduced by up to factor 10** because of **loss of coherence** of 2D-structures along mean field direction
  - Caused by the **modified field line meandering**
- These effects **should be taken into account** when seeking understanding of the **SEP event scenarios**