Dynamics of energetic particles scattered in the solar wind

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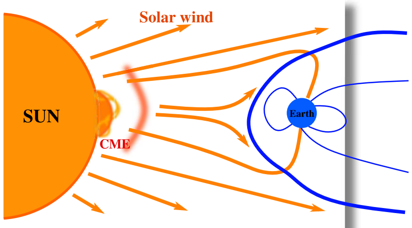
Context

Solar Energetic Particles (SEPs) are high-energy ions and electrons emanating from the Sun, accelerated impulsivly at the sites if magnetic reconnection in the solar corona or gradually, at the shock of a Coronal Mass Ejection (CME) during its propagation through the heliosphere (Reames+ 1999). Once energized, SEPs trace path along the interplanetary magnetic field lines, drifting due to gradients and curvature of the magnetic field and the presence of an electric field (Dalla+ 2015). Due to the turbulence in the solar wind, these particles experience diffusion both in velocity space (parallel diffusion) and in real space (perpendicular diffusion).



Model & numerical set-up

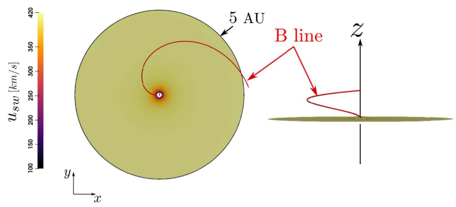
Solar wind 3D MHD simulation

Simulation domain :

- Sun centerd spherical grid
- Size: $144 \times 48 \times 128$ in $[r, \theta, \varphi]$
- Boundaries: $r \in [0\ 14\ 14]$ AU

Numerical integration of the ideal MHD equations using the MPI-AMRVAC code

(E, B, U)



Test Particles propagation

- Integrate relativistic Guiding Center equations and use (E, B,U) from MHD simulation.

$$\frac{\mathrm{d}\mathbf{R}}{\mathrm{d}t} = v_\parallel \mathbf{b} + \mathbf{v}_\mathrm{E} + \frac{\gamma m}{qB}\mathbf{b} \times \Big[\frac{\mu}{\gamma^2 m}\nabla B + \frac{v_\parallel}{\gamma}E_\parallel \mathbf{v}_\mathrm{E} + v_\parallel^2 (\mathbf{b}\cdot\nabla)\mathbf{b} + v_\parallel (\mathbf{v}_\mathrm{E}\cdot\nabla)\mathbf{b} + v_\parallel (\mathbf{b}\cdot\nabla)\mathbf{v}_\mathrm{E} + (\mathbf{v}_\mathrm{E}\cdot\nabla)\mathbf{v}_\mathrm{E}\Big]$$

E-cross-B drift ($\mathbf{v}_\mathrm{E}$); grad-B drift ($\frac{\mu}{\gamma^2 m}\nabla B$); curvature drift ($v_\parallel^2 (\mathbf{b}\cdot\nabla)\mathbf{b} + v_\parallel (\mathbf{v}_\mathrm{E}\cdot\nabla)\mathbf{b}$); polarisation drift ($v_\parallel (\mathbf{b}\cdot\nabla)\mathbf{v}_\mathrm{E} + (\mathbf{v}_\mathrm{E}\cdot\nabla)\mathbf{v}_\mathrm{E}$)

$$\frac{\mathrm{d}(\gamma v_\parallel)}{\mathrm{d}t} = \frac{q}{m}E_\parallel - \frac{\mu}{\gamma m}\mathbf{b}\cdot\nabla B + \gamma \mathbf{v}_\mathrm{E}\cdot\left[v_\parallel (\mathbf{b}\cdot\nabla)\mathbf{b} + (\mathbf{v}_\mathrm{E}\cdot\nabla)\mathbf{b}\right]$$

mirror force ($\frac{\mu}{\gamma m}\mathbf{b}\cdot\nabla B$)

where

$$\mathbf{b} = \frac{\mathbf{B}}{|\mathbf{B}|} \qquad \mathbf{v}_\mathrm{E} = \mathbf{E}\times\frac{\mathbf{b}}{|\mathbf{B}|}$$

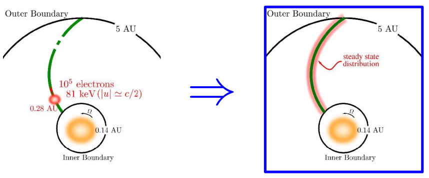
$$\mu = \frac{m\gamma^2 v_\perp^2}{2|\mathbf{B}|} \qquad (*)\ \mathbf{E} = -\mathbf{u}\times\mathbf{B} - \frac{\nabla p}{n}$$

- Parallel diffusion : probabilty of doing a collision based on a mean free path along B. If particle undergoes a collision, the pitch-angle (v,B) is randomized. When the collision is in the rest frame, the energy of the particle is conserved !

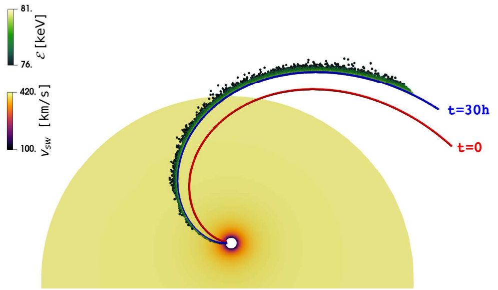
Results

Configuration

Particles crossing the inner boundary or the surface r = 5 AU are re-injected back at the same initial position with the same initial conditions.

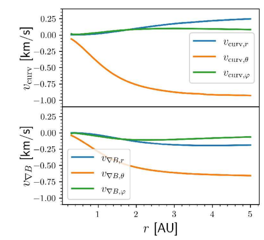


Statistically steady distribution at t = 7h



Scatter plot : particles color-coded with their enrgy

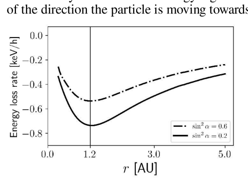
Drift velocities profiles along B-line



Dominant drifts : grad-B & cruvature drifts !

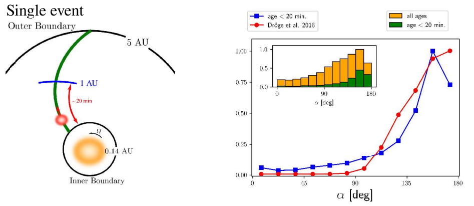
Both in -θ direction !

In the present configuration, $\mathbf{v}_\mathrm{E}$ is oriented opposite to the curvature vector $(\mathbf{b}\cdot\nabla)\mathbf{b}$ and to the magnetic field gradient $\nabla \ln B$ so that the above equations describe a systematic loss of energy regardless of the direction the particle is moving towards.

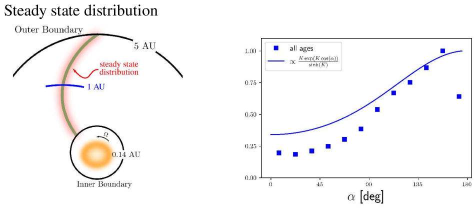


Pitch-angle distribution

Single event



Steady state distribution



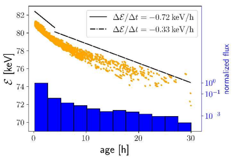
Energy evolution

Assuming time steadiness for the fields, we can then approximate (*) in terms of the time evolution a particle's kinetic energy:

$$\frac{d\mathcal{E}}{dt} \simeq m\gamma v_\parallel^2\, \mathbf{v}_\mathrm{E}\cdot(\mathbf{b}\cdot\nabla)\mathbf{b} + m\gamma\frac{v_\perp^2}{2}\, \mathbf{v}_\mathrm{E}\cdot\nabla \ln B$$

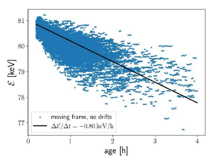
replacing $\mathbf{v}_\mathrm{E}$

$$\frac{d\mathcal{E}}{dt} \simeq q\left(\mathbf{v}_\mathrm{curv} + \mathbf{v}_{\nabla B}\right)\cdot\mathbf{E}$$



Adiabatic cooling

Energy as a function of age for electrons near r = 1 AU when scattered in the solar wind moving frame and with the absence of drifts

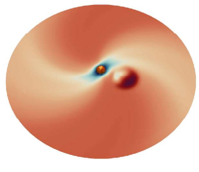


Ongoing work

The next step is to see how energetic particles are accelerated by a CME.

This PhD work is connected to current space missions as Solar Orbiter (ESA) and Parker Solar Probe (NASA).

This study has important implications for Space Weather.



References :

- Dröge, W., Kartavykh, Y. Y., Wang, L., Telloni, D., & Bruno, R. 2018,ApJ, 869, 168
- Dalla, S., Marsh, M. S., & Laitinen, T. 2015, ApJ, 808, 62
- Mignone, A., Haudemand, H., & Puzzoni, E. 2023, CPC, 285, 108625
- Parker, E. 1965, Planetary and Space Science, 13, 9
- Ripperda, B., Porth, O., Xia, C., & Keppens, R. 2017, MNRAS, 467, 3279
- Zaslavsky, A., Kasper, J. C., Kontar, E. P., et al. 2024, ApJ, 966, 60