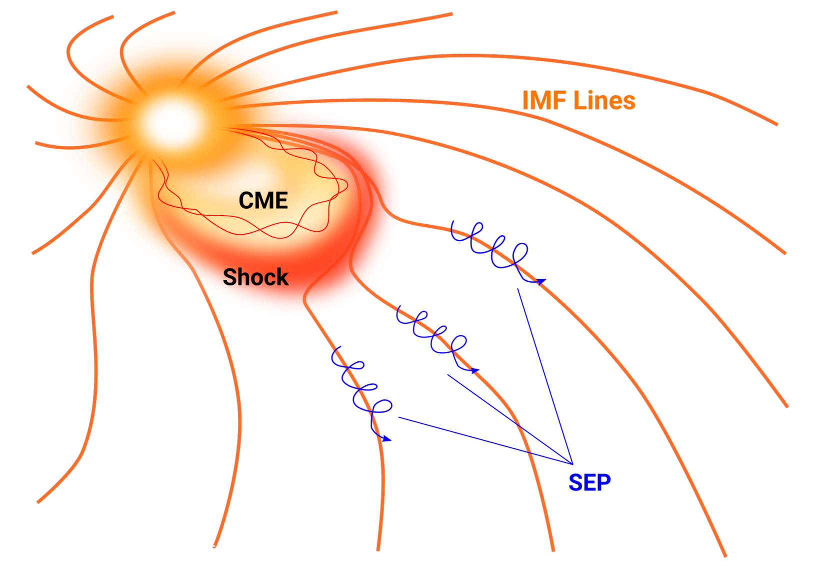
PROPAGATION OF SOLAR ENERGETIC PARTICLES IN 3D MHD SIMULATION OF THE SOLAR WIND

Ahmed Houeibib*, F. Pantellini, L. Griton
LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris Cité, 5 place Jules Janssen, Meudon, France
contact : ahmed.houeibib@obspm.fr

CONTEXT

The interplanetary medium is populated with a variety of energy-charged particles, tracing paths along the magnetic field lines.
These particles exhibit **drifts** influenced by **gradients** and **curvature** of the magnetic field and by the **presence of an electric field** (Dalla et al. 2015).
In addition, due to the presence of magnetic turbulence in the solar wind, particles experience **diffusion** both in velocity space and real space with mean free paths $\lambda_\|$ and $\lambda_\perp$, respectively, with $\lambda_\perp \ll \lambda_\|$ (see e.g. Chhiber et al. 2017).



In this study, we propagate test particles in a simulated solar wind, including the possibility of parallel diffusion.

We consider **S**olar **E**nergetic test **P**articles for which the Larmor radius is $\ll$ 1 AU and consistently integrate the equations of motion using the relativistic **G**uiding **C**enter **A**pproximation (**GCA**).

METHDOLOGY

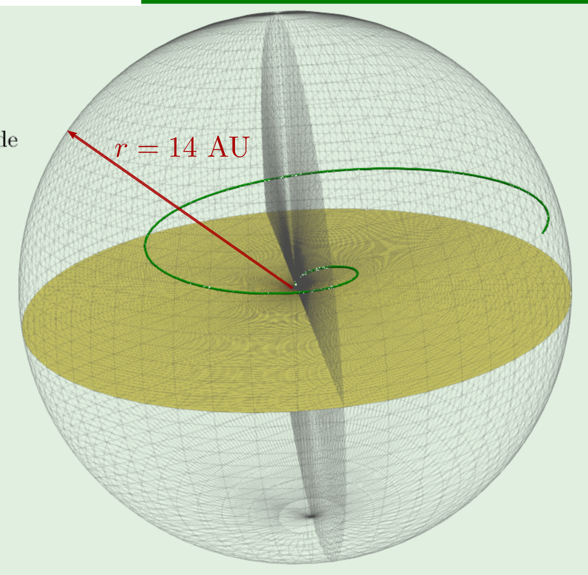
MHD Simulation

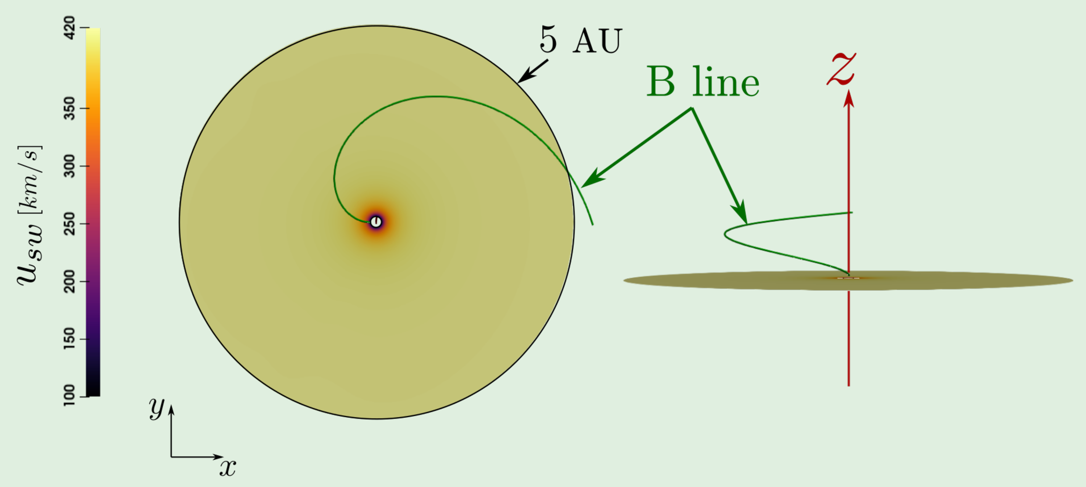
Numerical integration of the adiabatic ideal MHD equations using the MPI-AMRVAC code

Simulation domain :
- Sun centered spherical grid
- Size : $144 \times 48 \times 128$ in $[r, \theta, \varphi]$
- boundaries $r \in [0.14, 14]$ AU

Steady state simulation, dipole parallel to the rotation axis

A magnetic field line entering the domain at 24 deg. latitude is shown





Wind parameters at 1 AU along the field line

Magnetic field strength B[nT]	0.89
Wind speed u [km/s]	417.98
Speed of sound c_s [km/s]	48.24
Alfvén speed u_A [km/s]	71.94
Plasma beta β	0.54
$L_B \equiv \lvert \partial \ln B/\partial s \rvert^{-1}$ [AU]	0.93

test-Particle Propagation

- Inject particles
- Interpolate fields & integrate relativistic **GCA equations** :

$$\frac{d\mathbf{R}}{dt} = v_\| \mathbf{b} + \mathbf{v_E} + \frac{\gamma m}{qB}\mathbf{b} \times \left[\frac{\mu}{\gamma^2 m}\nabla B + \frac{v_\|}{\gamma}E_\| \mathbf{v_E} + v_\|^2 (\mathbf{b}\cdot\nabla)\mathbf{b} + v_\| (\mathbf{v_E}\cdot\nabla)\mathbf{b} + v_\| (\mathbf{b}\cdot\nabla)\mathbf{v_E} + (\mathbf{v_E}\cdot\nabla)\mathbf{v_E}\right]$$

E-cross-B drift, grad-B drift, curvature drift, polarisation drift

$$\frac{d(\gamma v_\|)}{dt} = \frac{q}{m}E_\| - \frac{\mu}{\gamma m}\mathbf{b}\cdot\nabla B + \gamma \mathbf{v_E}\cdot\left[v_\| (\mathbf{b}\cdot\nabla)\mathbf{b} + (\mathbf{v_E}\cdot\nabla)\mathbf{b}\right] \quad (*)$$

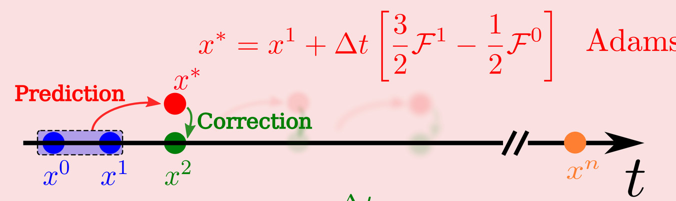
$$\frac{d\mu}{dt} = 0$$

mirror force

where $\mathbf{b} = \frac{\mathbf{B}}{|\mathbf{B}|}$, $\mathbf{v_E} = \mathbf{E} \times \frac{\mathbf{b}}{|\mathbf{B}|}$, $\mu = \frac{m\gamma^2 v_\perp^2}{2|\mathbf{B}|}$, $\mathbf{E} = -\mathbf{u}\times\mathbf{B} - \frac{\nabla p}{en}$

- Integration scheme from Mignone et al. 2023 : prediction-correction method

$$x^* = x^1 + \Delta t \left[\frac{3}{2}\mathcal{F}^1 - \frac{1}{2}\mathcal{F}^0\right] \quad \text{Adams-Bashforth 2}$$



$$x^2 = x^* + \frac{\Delta t}{12}\left[8\mathcal{F}^1 + 5\mathcal{F}^* - \mathcal{F}^0\right] \quad \text{Adams-Moulton 3}$$

- Pitch-angle scattering

We let particles undergo hard-sphere type collisions

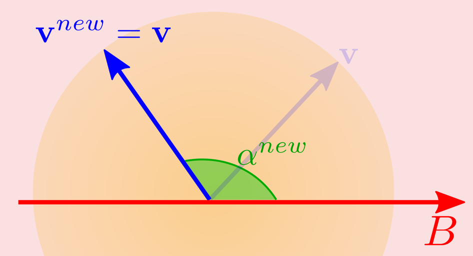
For a distance $\Delta s = \int_0^{\Delta t} v_\| dt$ during Δt, and a given a mean free path $\lambda_\|$

collision probability : $p(\Delta s) = 1 - \exp(-\Delta s/\lambda_\|)$

Each time step a random number $a \in [0, 1]$ is generated, if $a < p(\Delta s) \Rightarrow$ **elastic collision !**

In this case, the post collision pitch-angle α is :

$\alpha = \arccos(1 - 2b)$, b: random number $\in [0, 1]$.

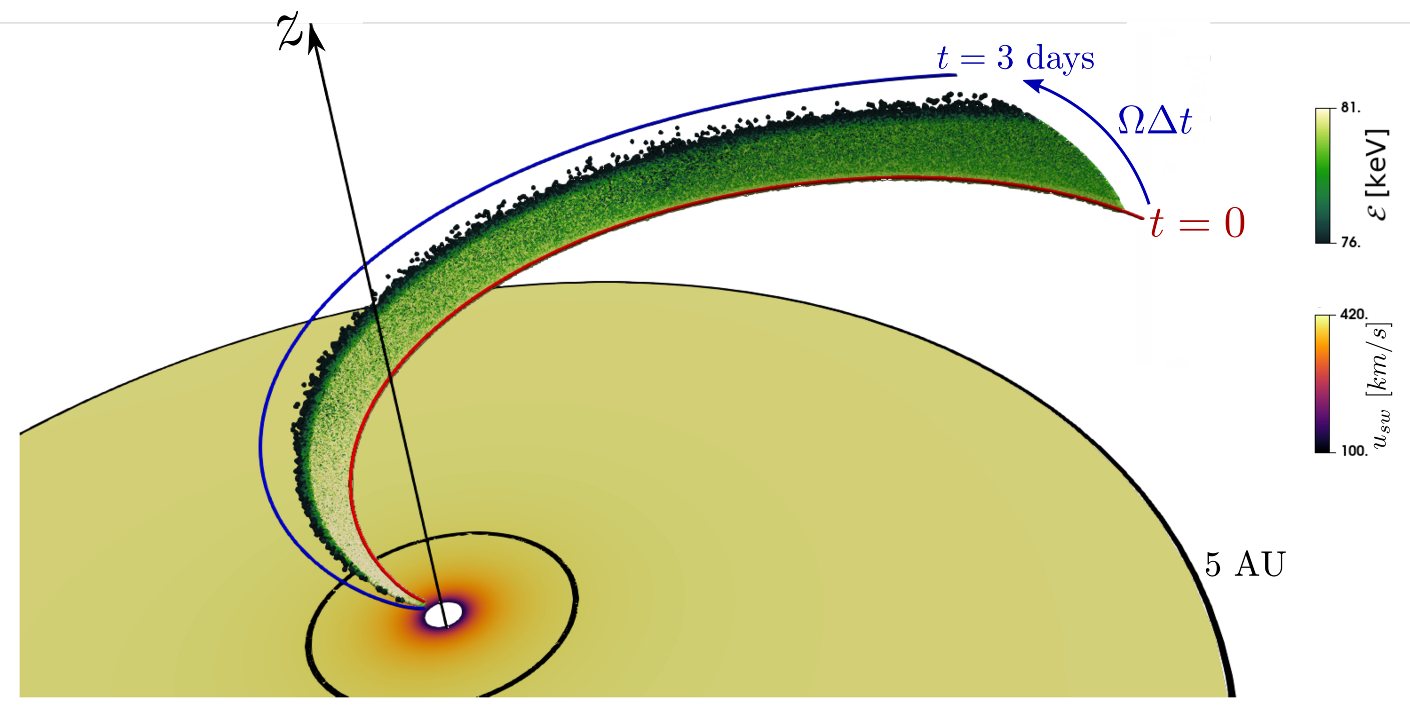


FIRST RESULTS

We inject 10^5 electrons with 81 keV energy and $\mu = 0$ at $r = 0.279$AU on the magnetic field line shown at $t = 0$.

$\lambda_\| = 0.5$ AU, $\delta t = 5.4$ s $\Rightarrow$ integrate the GCA equations with Mignone et al. (2023) over $t_{max} = 41.7$ h.

Particles crossing the inner boundary (r = 0.139 AU) or the surface r = 5 AU are re-injected at the same initial position and with the same initial conditions
⇓
At t=7h, a statistically steady distribution of particles is obtained, in the following we only consider particles aged from t=7h to 1.7 days



Magnetic field line shown at $t = 3$ days.

- Energy loss

Assuming time steadiness, we can then rewrite (*)

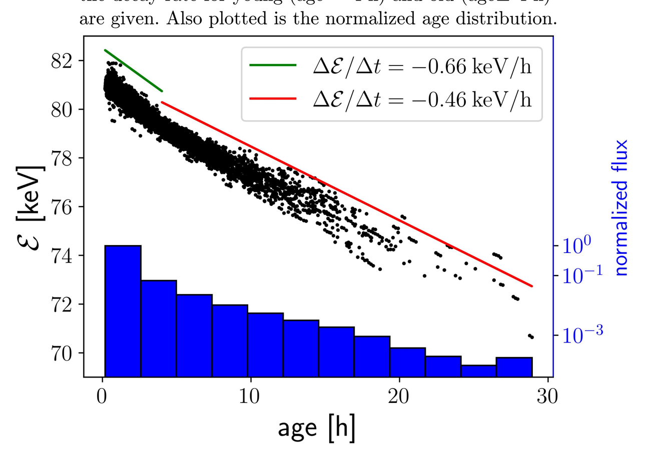
$$\frac{d\mathcal{E}}{dt} \simeq m\gamma v_\|^2 \, \mathbf{v_E}\cdot(\mathbf{b}\cdot\nabla\mathbf{b}) \quad (**)$$

where $\mathcal{E} = (\gamma - 1)mc^2$ is the particle's relativistic kinetic energy.

In the present configuration, $\mathbf{v_E}$ is oriented opposite to the curvature vector $\mathbf{b}\cdot\nabla\mathbf{b}$ so that (**) describes a systematic loss of energy regardless of the direction the particle is moving towards

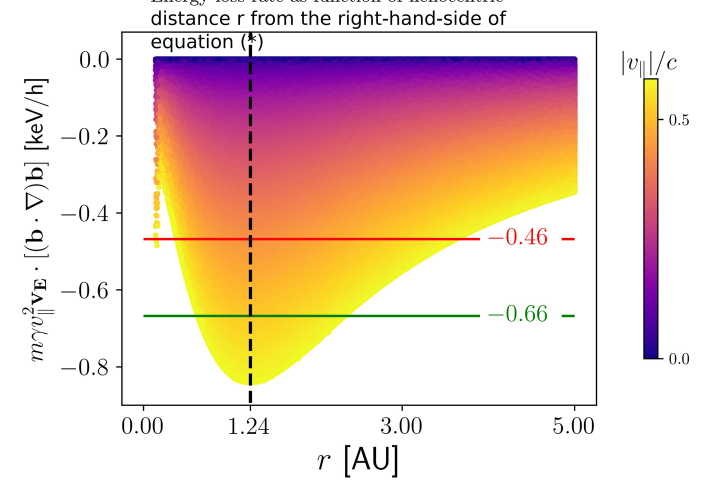
⇒

Energy vs age for electrons near r = 1 AU. Linear fits of the decay rate for young (age < 4 h) and old (age≥ 4 h) are given. Also plotted is the normalized age distribution.



The particle flux observed near $r = 1$ AU some 30 h after injection is reduced by $\sim 10^4$ with respect to the initial flux (age ≡ time since injection)

Energy loss rate as function of heliocentric distance r from the right-hand-side of equation (*)

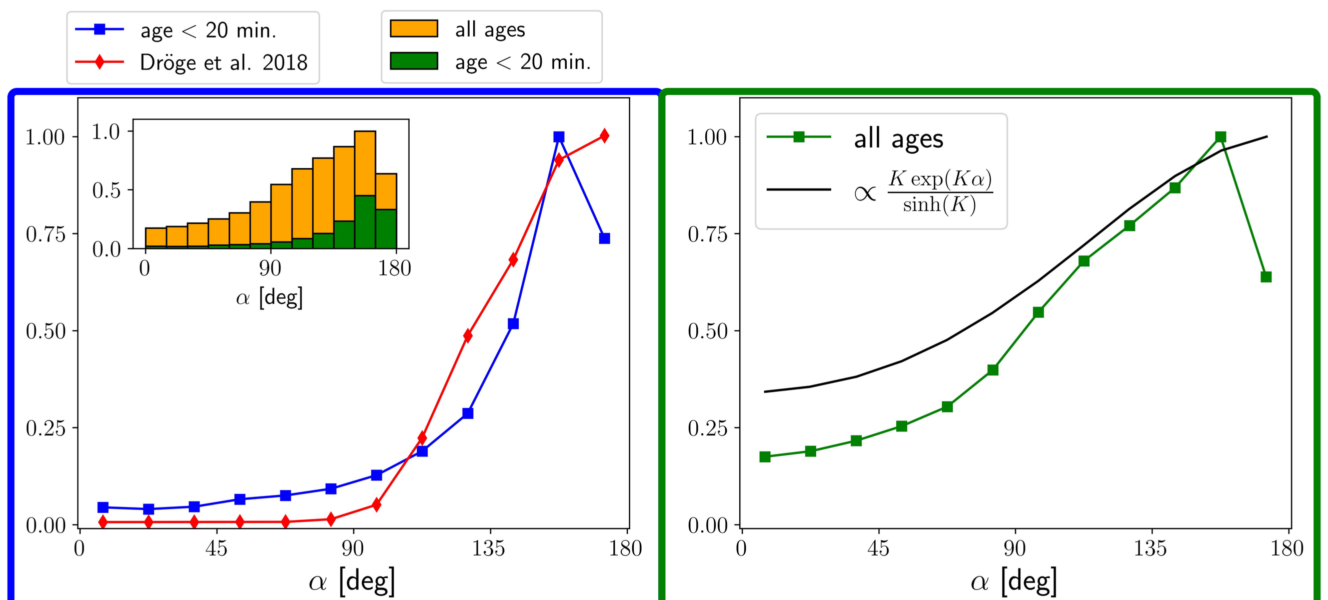


The maximum loss rate occurs at $r = 1.24$ AU :

- Loss rate ↘ when r ↗ because of the increasing radius of curvature
- Loss rate ↘ when r ↘ because $\mathbf{v_E}$ ↘ as **u** and **B** tend to align when approaching the inner boundary

- Pitch-angle distribution

The flux of 81 keV electrons at 1 AU reaches its peak after ~ 10 min from injection. As the peak intensity decreases on a timescale of the order of 10 to 20 minutes, only electrons aged less than 20 min are representative of the peak distribution.



Left : Pitch-angle distribution of young electrons compared with measurements from the Wind spacecraft during a 9 minutes interval following the peak of the 20th October 2002 solar event (adapted from Dröge et al. (2018) for particles in the range 49 to 81 keV).

Right : All ages compared to the analytic distribution obtained by Zaslavsky from a Fokker-Planck type equation in the limit of a spatially constant and small Knudsen number $K = \lambda_\|/L_B$.

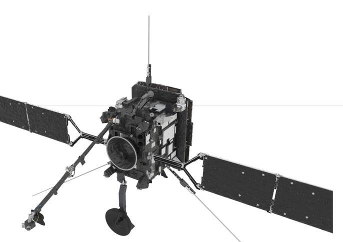
Differences compared to Dröge et al. (left) and to Zaslavsky (right) can be attributed to several factors :

- Initial condition $\mu = 0$ and the position of the injection
- Hard sphere type collisions is probably less realistic (especially when $K \gtrsim 1$) than accumulation of small angle deviations (Quenby (1983), Dröge (2018), Zaslavsky(2023))

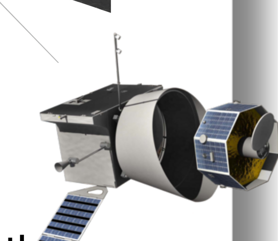
NEXT STEPS

- Inject particles in time-varying fields, essential for low energy particles and in case of transients (like CME, shocks ...)

MISSIONS



will help analyse in-situ measurements of **Solar Orbiter**



Understand the role of the electrons in the interaction of the solar wind with Mercury with the help of **BepiColombo** (Léa Griton)

Ahmed Houeibib is suppported by
the **CNES** (**C**entre **N**ational d'**É**tudes **S**patiales)
& **CNRS** (**C**entre **N**ational de la **R**echerche **S**cientifique)

[1] R. Chhiber, P. Subedi, A. V. Usmanov, W. H. Matthaeus, D. Ruffolo, M. L. Goldstein, and T. N. Parashar, Cosmic-ray diffusion coefficients throughout the inner heliosphere from a global solar wind simulation, The Astrophysical Journal Supplement Series 230, 21 (2017).
[2] L. Griton, F. Pantellini, and Z. Meliani, Three-dimensional magnetohydrodynamic simulations of the solar wind interaction with a hyperfast-rotating uranus, Journal of Geophysical Research (Space Physics) 123, 5394 (2018).
[3] B. Ripperda, O. Porth, C. Xia, and R. Keppens, Reconnection and particle acceleration in interacting flux ropes - i. magnetohydrodynamics and test particles in 2.5d, MNRAS 467, 3279 (2017), arXiv:1611.09966 [astro-ph.HE].
[4] A. Mignone, H. Haudemand, and E. Puzzoni, A guiding center implementation for relativistic particle dynamics in the pluto code, Computer Physics Communications 285, 108625 (2023), arXiv 2212.08064 [astro-ph.IM].
[5] W. Dröge, Y. Y. Kartavykh, L. Wang, D. Telloni, and R. Bruno, Transport modeling of interplanetary electrons in the 2002 october 20 solar particle event, The Astrophysical Journal 869, 168 (2018).