UNIVERSITY of NEW HAMPSHIRE

SHINE Conference 2013

Modeling The Interstellar Pickup Ion Propagation in the Corotating Solar Wind Compression Region inside 1 AU

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Abstract

We present a modeling study of interstellar pickup ion (PUI) propagation in the solar wind corotating interaction regions (CIRs). We consider gradual compressions associated with CIRs formed when fast speed streams overtake slower streams in the inner heliosphere. For the analysis, we adopt a simplified magnetohydrodynamic model of a CIR [Giacalone et al., 2002]. The Energetic Particle Radiation Environment Module (EPREM) [Schwadron et al., 2010], a parallelized particle numerical kinetic code is used to solve for the focused transport of PUIs including adiabatic change, adiabatic focusing, and parallel diffusion along magnetic field lines. The continuous injection of PUIs is handled as a source term with a ring distribution and an ionization rate of neutrals with the neutral density determined by the interstellar neutral hot gas model. EPREM computes the PUI velocity distributions in the CIR compression region at 1 AU. As an additional result, a power-law tail distribution above the PUI cut-off speed emerges, which suggests that the velocity gradient associated with the CIR formation can efficiently accelerate PUIs to very high energy before a shock forms even without stochastic acceleration. This result indicates that the local CIR compressions without shocks play a significant role in the acceleration process as suggested previously [e.g., Giacalone et al., 2002; Ebert et al., 2012].

Motivation

- Interstellar PUIs constitute a charged particle population in the heliosphere that originates from the interstellar neutrals inside the heliosphere. They have been identified as important source particles for effective further acceleration at compressions and shocks due to its very non-thermal velocity distribution.
- Recent observations of CIR associated energetic particles in the absence of shocks can not be predicted by the standard model [Fisk & Lee, 1980] , which suggest that local acceleration by CIR compression may play a role.
- Giacalone et al. [2002] suggested that low-energy particles could be accelerated in the regions of solar wind gradual compression in a process similar to diffusive shock acceleration at a quasi-parallel shock.

In this study, we want to model the PUI propagation in the solar wind gradual compression regions on the basis of EPREM numerical code.

Numerical Model

EPREM [Schwadron et al., 2010] is a highly sophisticated parallelized particle numerical kinetic code accounting for the time-dependent transport of PUIs, suprathermal and energetic particles along and across magnetic field lines for any field and flow topology in three dimensions. EPREM employs a focused transport equation to solve for particle transport:

$$\left(1-\frac{\vec{V}\cdot\vec{e_b}v\mu}{c^2}\right)\frac{df}{dt} \quad \text{(Streaming)}$$
$$+v\mu\vec{e_b}\cdot\nabla f \quad \text{(Convection)}$$
$$+\frac{(1-\mu^2)}{2}\left[v\vec{e_b}\cdot\nabla\ln B-\frac{2}{v}\vec{e_b}\cdot\frac{d\vec{V}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial\mu} \quad \text{(Adiabatic focusing)}$$
$$+\left[-\frac{\mu\vec{e_b}}{v}\cdot\frac{d\vec{V}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln(B)}{dt}\right]\frac{\partial f}{\partial\ln p} \quad \text{(Adiabatic change)}$$
$$=\frac{\partial}{\partial\mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\right) \quad \text{(Pitch-angle scattering)}$$
$$-\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2D_{pp}\frac{\partial f_0}{\partial p}\right) \quad \text{(Stochastic acceleration)}$$
$$+Q. \quad \text{(Particle source)}$$

the pitch-angle diffusion coefficient is given by:

$$D_{\mu\mu}=\frac{(1-\mu^2)v}{2\lambda_{||}}$$

where $\lambda_{||}$ is the parallel mean free path and has the form [Li et al., 2003]:

$$\lambda_{||}=\lambda_0\left(\frac{pc}{1Gev}\right)^{1/3}\left(\frac{r}{1AU}\right)^{2/3}$$

We neglect the stochastic acceleration and perpendicular diffusion in the simulation.

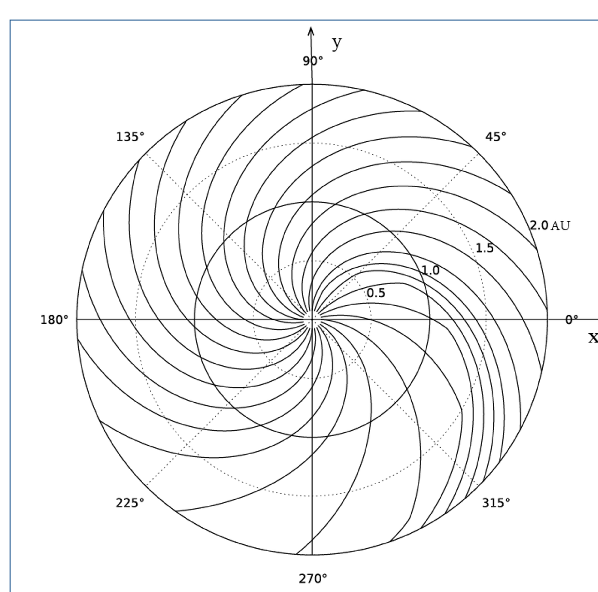

Figure 1. The magnetic filed lines configuration on the ecliptic plane for the "reverse compression" from the CIR model of Giacalone et al., [2002] inside 2 AU

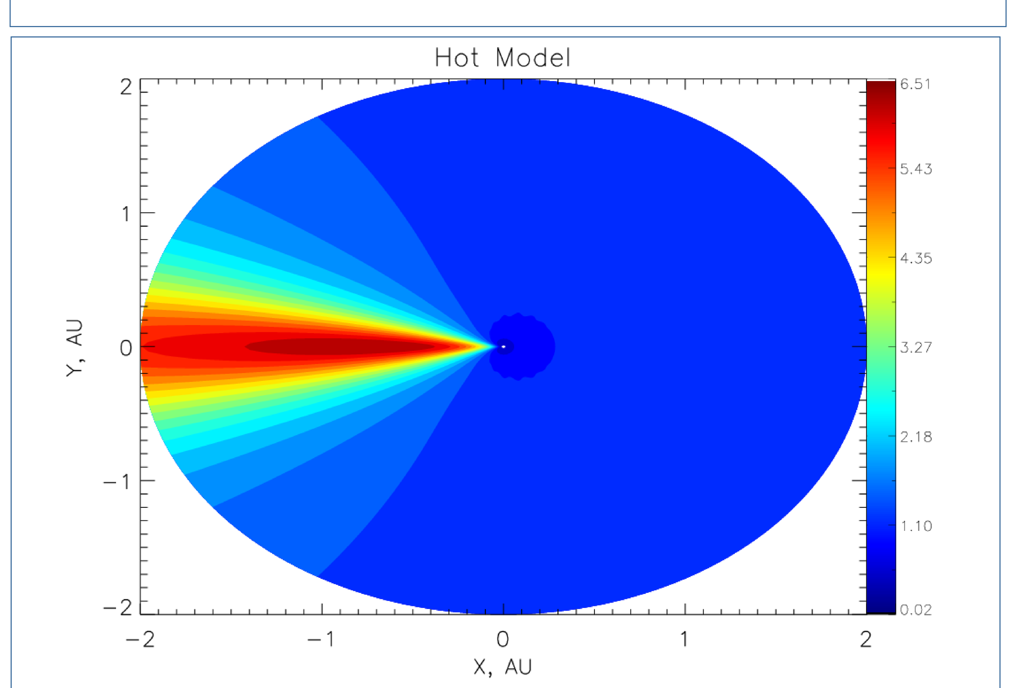

Figure 2. Interstellar helium neutral hot gas model

Results of Simulation

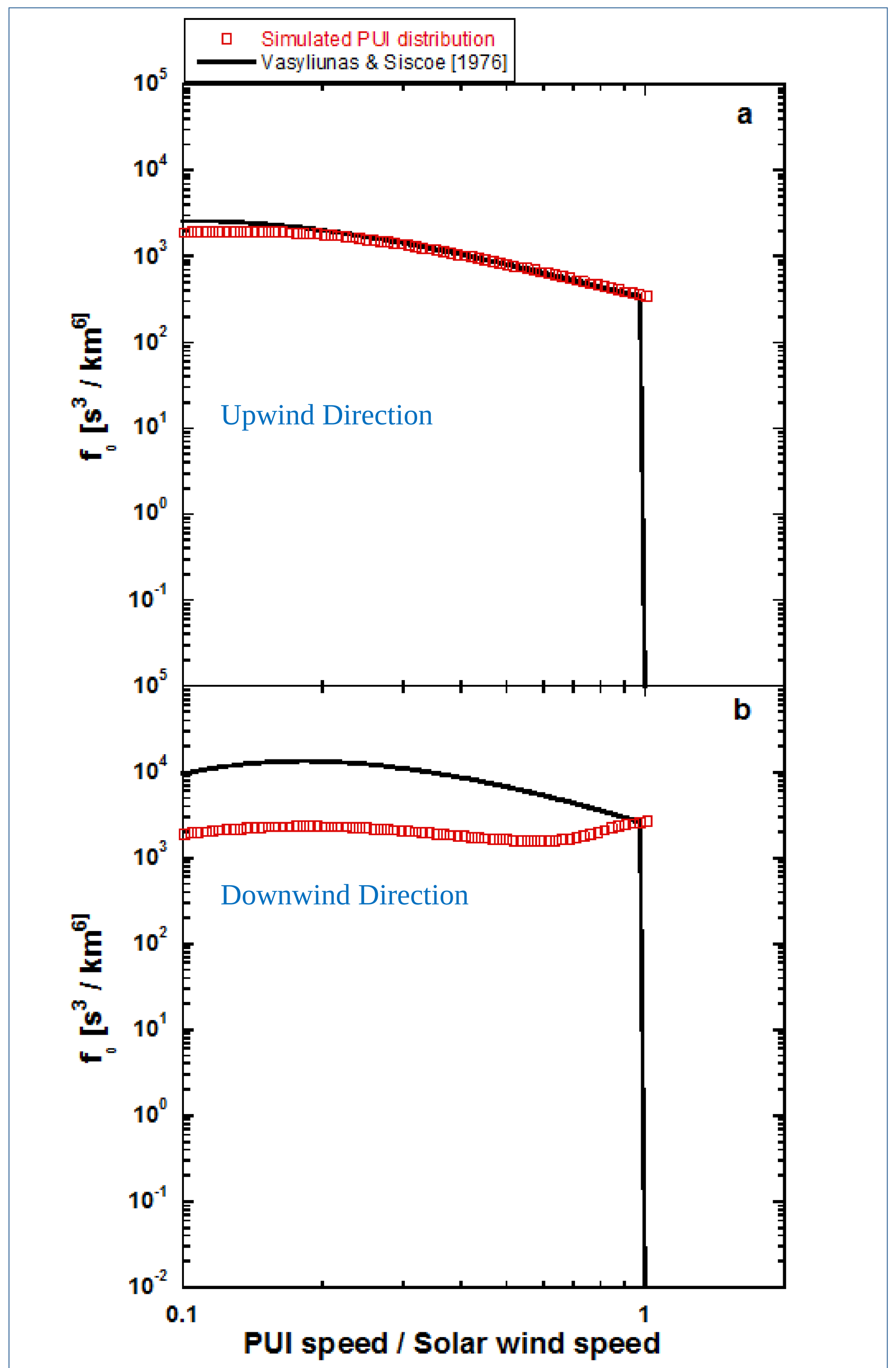

Figure 3. Comparison between simulated velocity distributions from EPREM and the analytic models of Vasyliunas & Siscoe [1976]. (a) and (b) are the distributions in the upwind and downwind direction, respectively. f_0 is the isotropic part of the distribution at 1 AU.

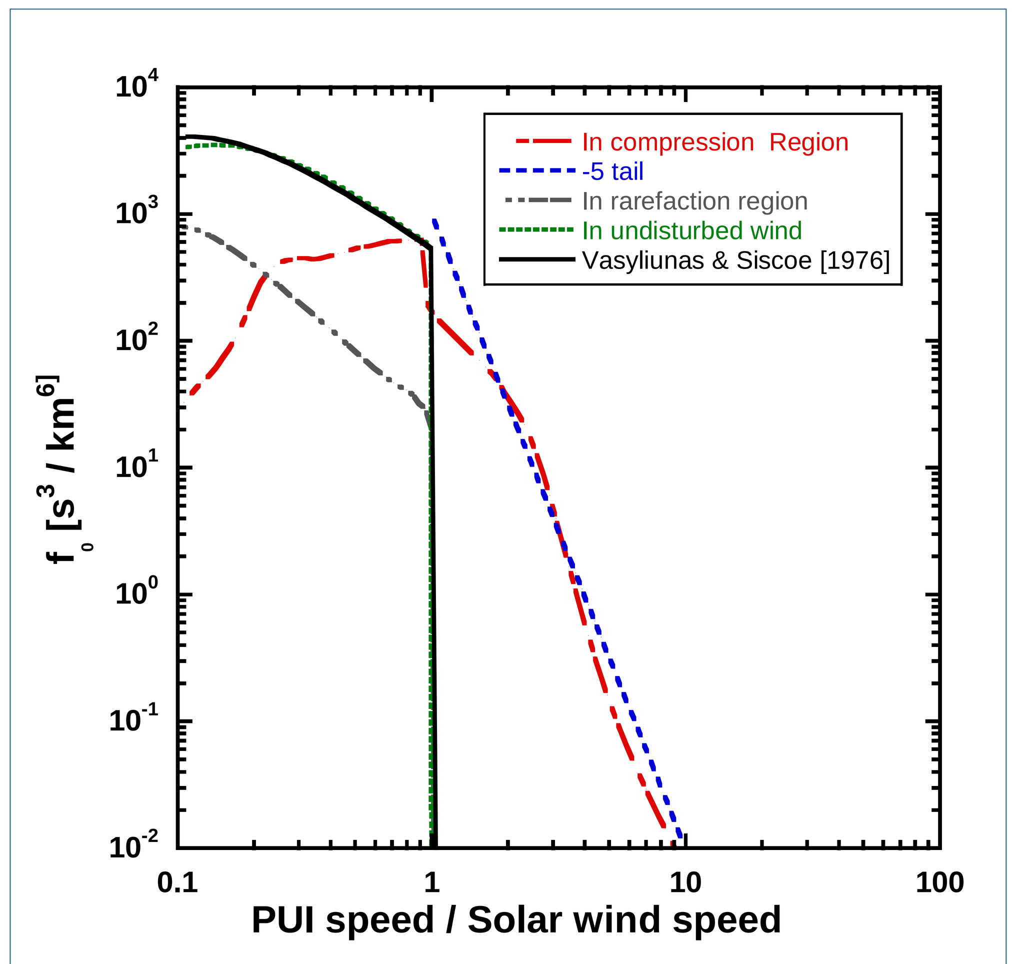

Figure 4. Simulated PUI velocity distribution at 1AU from EPREM in the undisturbed solar wind, in compression region, and in rarefaction region.

Verification of EPREM

- As shown in Figure 3a, EPREM well reproduced the analytic solution of Vasyliunas & Siscoe [1976] in the upwind direction.
- As shown in Figure 3b, due to the large gradient of helium neutral gas distribution in the downwind direction (*Shown in Figure 2*), the analytic solution of Vasyliunas & Siscoe [1976] assuming that PUIs are simply convected outwards with solar wind as an entity in radial directions cannot reflect properly the PUI transport along the Parker spiral magnetic field lines any more.

PUI Propagation in CIR

- As shown in Figure 4, in front of CIR, the analytic solution of Vasyliunas & Siscoe [1976] is again reproduced as we expected.
- In the compression region, a power law distribution above the PUI cut-off speed emerges. This significant acceleration indicates that the negative divergence of solar wind speed associated with the CIR formation can efficiently accelerate particles.
- In the rarefaction region, the shape of the spectrum is steeper. This is expected since PUIs undergo more adiabatic cooling [Chen et al., 2013].

Reference

Chen, J, H et al., *J. Geophys. Res*, 2013

Giacalone, J et al., *The Astrophysical Journal*, 2002

Li, G et al., *J. Geophys. Res.*, 2003

Schwadron, N et al., *Space Weather Journal*, 2010

Vasyliunas, V. & G. Siscoe, *J. Geophys. Res.*, 1976

Wu, F, M & Judge, D, L, *The Astrophysical Journal*, 1979