Variations of the Pickup Ion Cooling Behavior in Solar Wind Compressions and Rarefactions

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OVERVIEW

The velocity distribution of interstellar pickup ions(PUI) has typically been described as evolving through fast pitch angle scattering followed by adiabatic cooling while being transported radially outward with the expanding solar wind.

Based on the assumptions of

- Immediate pitch-angle scattering after pickup
- Adiabatic cooling
- Stationary spherical-symmetric solar wind.

Vasyliunas & Siscoe (1976) [VS76 hereinafter] predicted an isotropic population of interstellar PUI in the solar wind with a cooling law described as

$$\left(\frac{v}{v_{sw}}\right)^{\alpha} = \left(\frac{r_{Ion}}{r_{Obs}}\right) \quad \alpha = 3/2$$

α is defined as cooling index.

Chen et al. (2013) have shown that the cooling index exhibits a distinct correlation with solar activity, but with large variations. One potential cause that may contribute to the variation is identified as the effects of solar wind compressions and rarefactions.

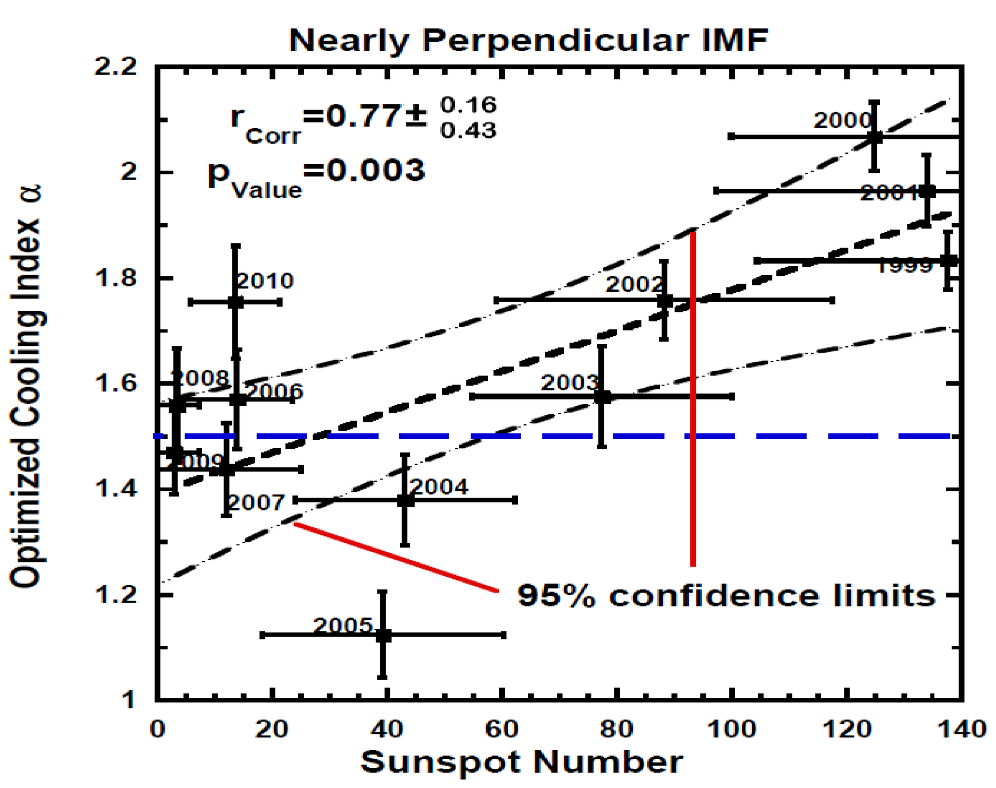

Fig 1. Optimized cooling indices as a function of Sunspot Number for nearly IMF direction. There appears to be a trend with solar activity, but with large scatter (Figure 4 in Chen et al. 2013).

Here, we plan to

- Compare the PUI distributions in individual compression and rarefaction regions in 2007-2010 with model distributions based on the technique in Chen et al. (2013) making use of the improved counting statistics with PLASTIC STEREO-A.
- Use the Energetic Particle Radiation Environment Module (EPREM) (Schwadron et al. 2010) kinetic code to simulate the PUI distributions in a simplified model of Co-rotating Interaction Regions (Giacalone et al. 2002).

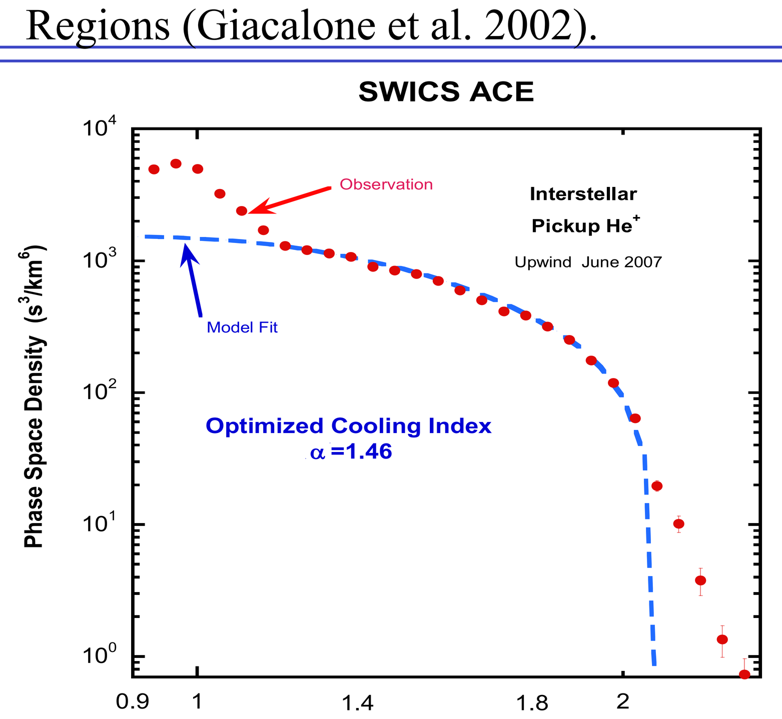

Fig. 2. Spacecraft-frame phase space density, of the pickup He^{+} as a function of W(ratio of ion speed and solar wind speed) measured with SWICS on ACE at 1AU in the upwind direction, averaged over 30-day time period indicted in the figure.

NUMERICAL MODEL

EPREM

EPREM is a highly sophisticated and flexible parallelized numerical kinetic particle code that accounts for the time-dependent transport of PUIs, superathermal, and energetic particles along and across magnetic field lines for any field and flow topology in three dimensions. The parallel transport in EPREM is modeled with focused transport of particles along each field line:

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

the pitch-angle diffusion coefficient is given by:

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

where $\lambda_{\parallel}$ is the parallel mean free path and has the form (Li et al. 2003:)

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

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

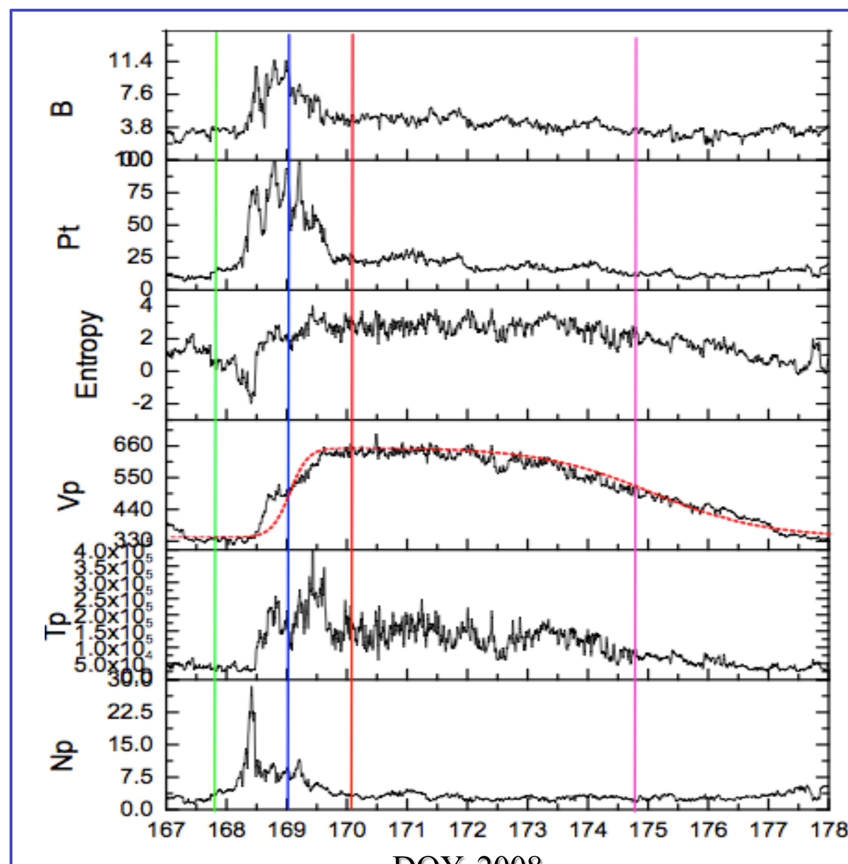

Fig 5. Solar wind plasma data for one CIR in 2008. The red dashed line is the solar wind speed from the model.

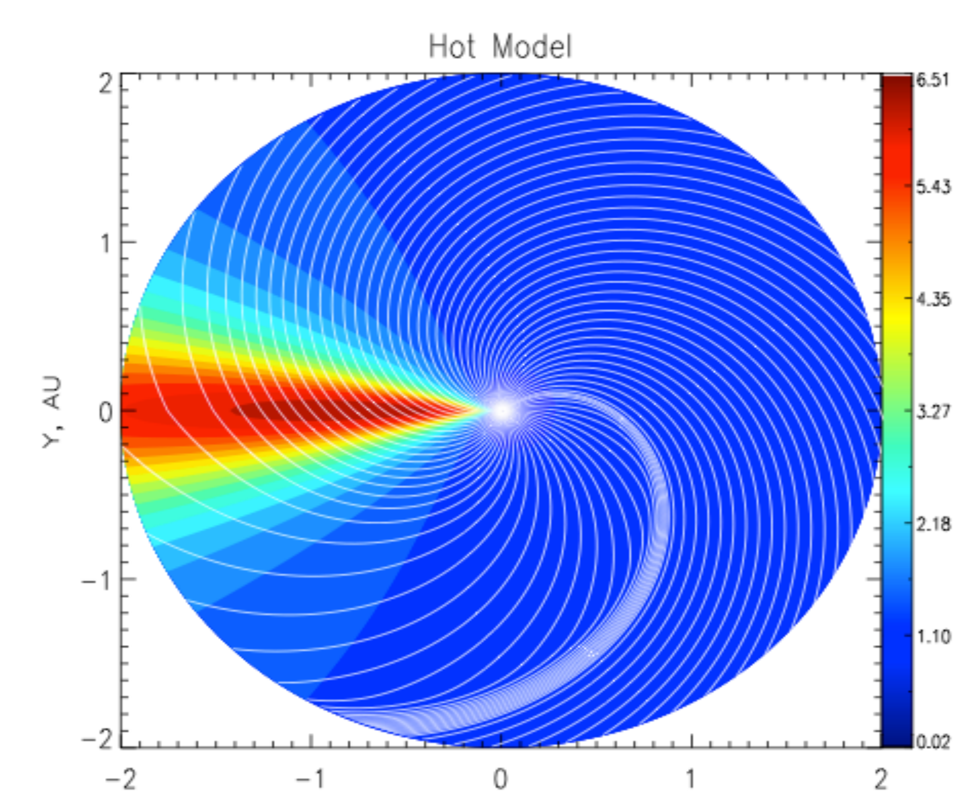

Fig 6. Interstellar neutral helium distribution in ecliptic plane based in hot gas model. White lines are the model magnetic field lines of CIR in Fig 5 (Giacalone et al., 2002)

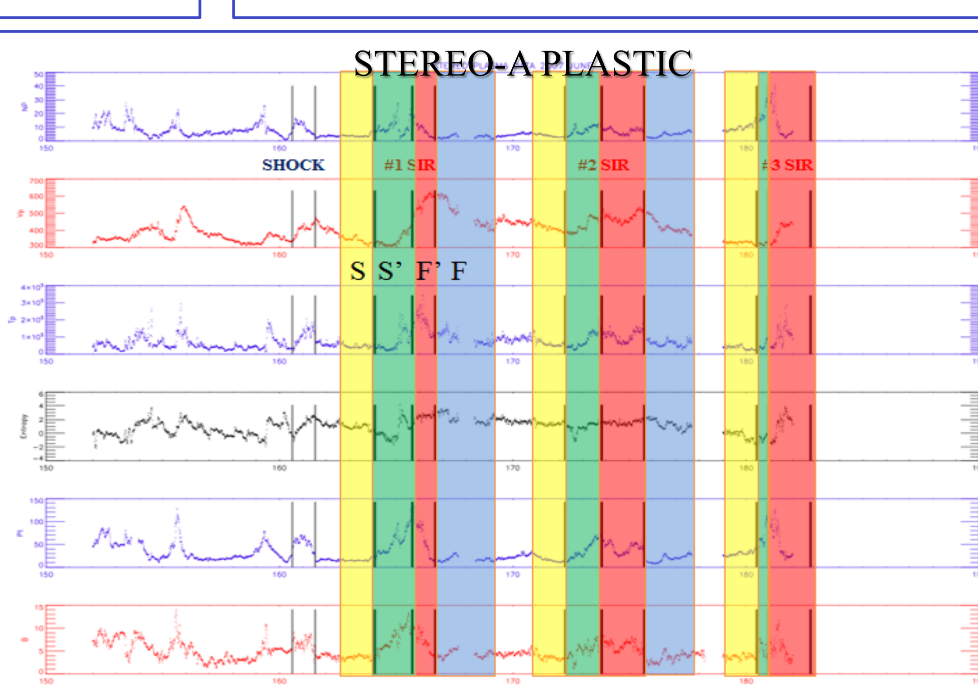

Fig 3. Solar wind plasma data in June 2007 from STEREO PLASTIC. S is slow wind before Stream Interaction Region (SIR), S' is the slow in SIR, F' is the fast wind in SIR, F is the fast wind behind SIR

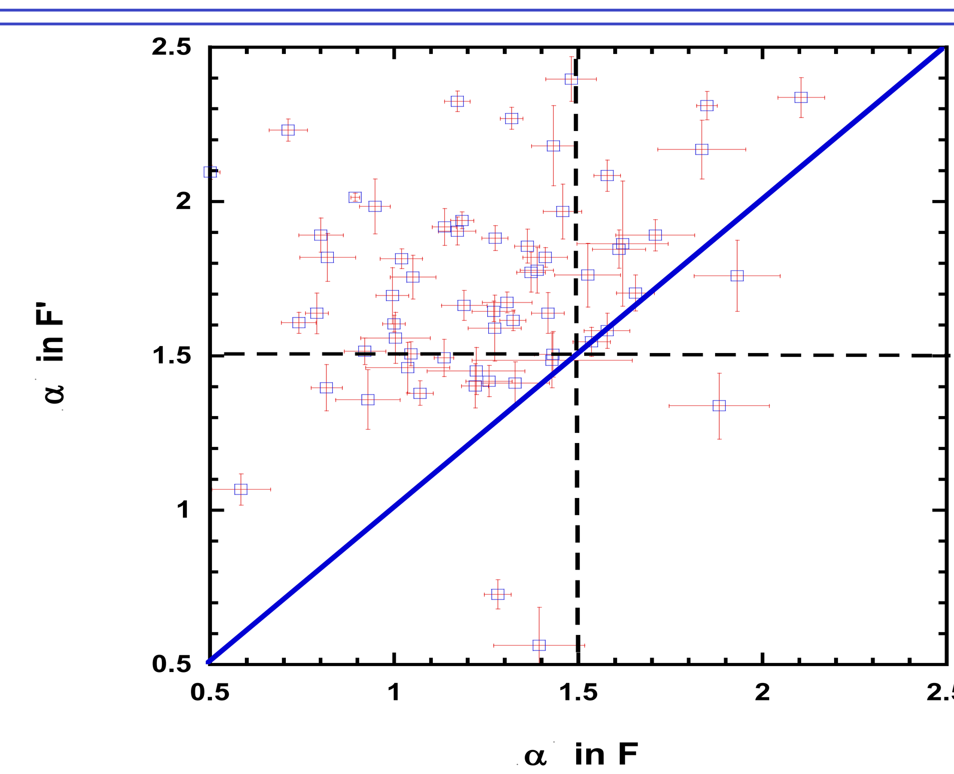

Fig 4. Cooling indices in the fast compressed wind in comparison with the cooling indices in the adjacent rarefaction region.

LARGE SCALE SOLAR WIND STRUCTURE

- We compare the predicted PUI distribution in the fast wind in each individual compression and rarefaction region with observations from STEREO PLASTIC between 2007 and 2010.
- We model the He^{+} PUI propagation in the solar wind of a CIR in 2008 with a structured as shown in Fig. 6 in the co-rotating frame. The observations are shown in Fig. 5.
- We neglect the perpendicular diffusion and stochastic acceleration in the simulation.
- The PUI distributions are the averaged over the time period when the spacecraft passes through the structures.
- We compare the simulated distributions with the observations from STEREO-A PLASTIC in solar wind CIR structures.

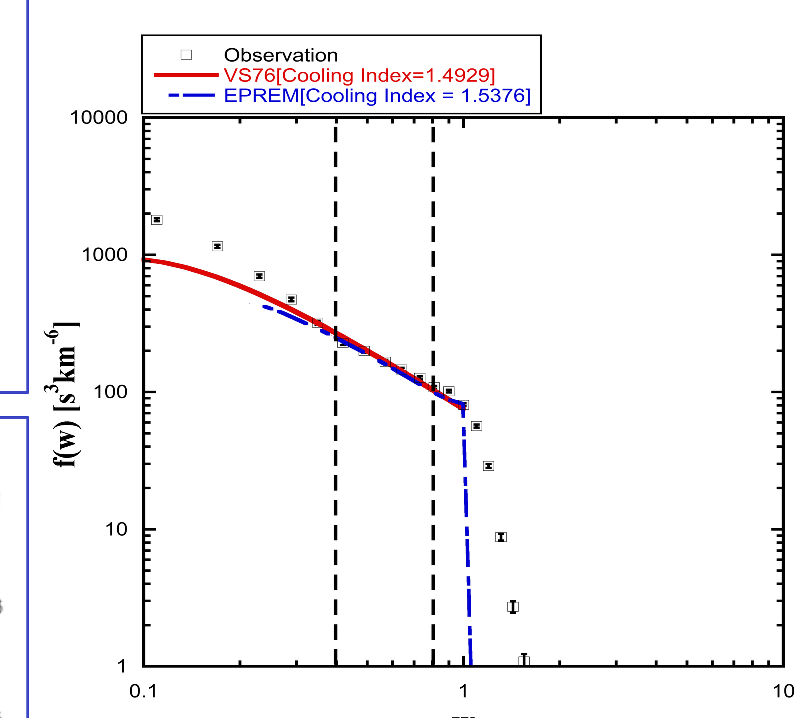

Fig 7. Comparison of model and simulated distributions with observations in the F' region of CIR in Fig. 5 in the solar wind frame.

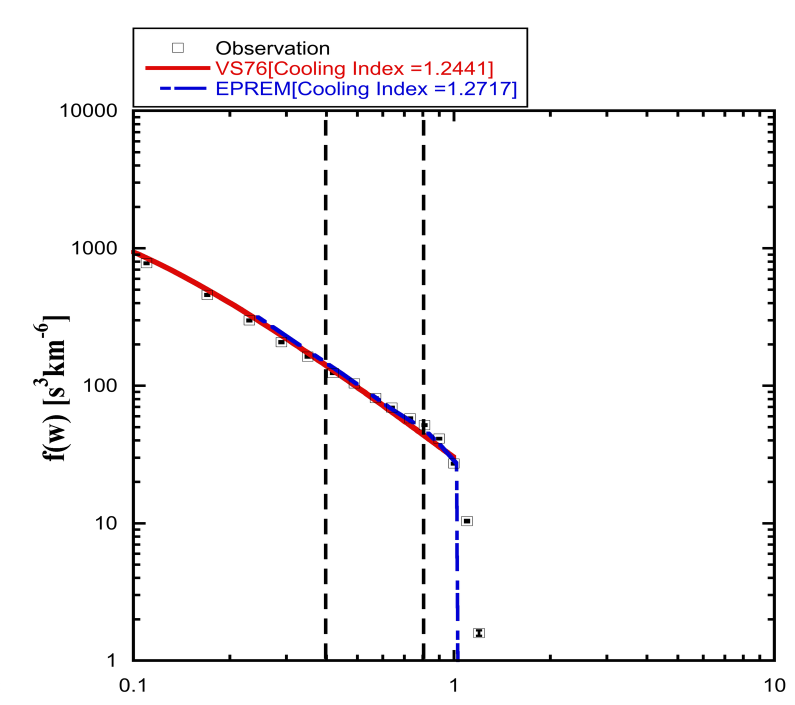

Fig 8. Comparison of model and simulated distributions with observations in the F region of CIR in Fig. 5 in the solar wind frame.

CONCLUSIONS

- The cooling index is substantially increased in the compressed (F') in comparison with uncompressed fast wind. The variation in the cooling index is due to the different solar wind expansion behaviors in these regions.
- For the CIR case study in 2008, the simulated PUI velocity distribution based on a simple CIR model matches the VS76 model and observations well. The result indicates that the solar wind expansion pattern mainly affect the cooling behavior of PUIs in the structured solar winds.

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