Possible Modification of the Cooling Index of Interstellar Helium Pickup Ions by Electron Impact Ionization in the Inner Heliosphere

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J. H. CHEN, E. MöBIUS, AND P. BOCHSLER

Space Science Center and Department of Physics, University of New Hampshire, Durham, New Hampshire, USA

Motivation

- Based on the assumption of
  1. Immediate pitch-angle scattering after pickup into full sphere of velocity distribution
  2. Adiabatic cooling
  3. Solar wind expansion as *1/r²*

Vasyliunas & Siscoe (1976) (VS76 herinafter) predicted an isotropic population of interstellar PUI in solar wind frame 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 the cooling index.

- Chen et al., (2013) simulated PUI distributions based on this isotropic distribution, and compared them with ACE SWICS PUI observations in the upwind direction of interstellar neutral gas flow over the last solar cycle. They showed that the cooling index exhibits a correlation and varies with solar activity between ~1 and 2, but with large variations. These variations may, in part, be due to electron impact ionization which varies stronger with distance from the Sun than $1/r^2$.
- Here, we plan to determine the influence of electron impact ionization on the deduced cooling index using the same data sets as in Chen et al. (2013).

Modeling of Electron Impact Ionization

- The significance of the electron impact ionization for the interstellar neutral gas distribution in the inner heliosphere was pointed out by Rucinski and Fahr (1989). In their model, they treated the solar wind electron distribution as a bi-Maxwellian that consists of two separate populations : core and halo. We use the parameterization of electron impact ionization rates of Voronvo (1997):

$$\frac{\beta_{el}}{n_e} = A\frac{(1+PU^{1/2})}{X+U}U^{K}e^{-U}(cm^3/s) \qquad U = dE/T_e$$

  Here, β_{el} is the electron impact ionization rate, *ne* is the electron density, *dE* is the threshold energy, T_e is the electron temperature. For helium, dE = 24.6 eV, P = 0, A = 0.175×10⁻⁸ cm³/s, X = 0.18, and K = 0.35. In our calculation, we take this simple formula and assume a bi-Maxwellian solar wind electron distribution.

  Solar wind electrons don't cool off adiabatically. Also, they can be heated in solar wind compressions. Many authors (e.g., Marsch et al. 1989; Pilipp et al. 1990) have derived the T_e radial gradients based on spacecraft observations. Here we adopt the radial profile of the electron temperature shown in Table 1. An example of the electron impact ionization rate radial profile is shown in Figure 2.

- The electron density n_e can be adopted from the quasi-neutrality and continuity conditions in the solar wind proton and alpha particle fluxes.

Data and Model Comparison

- Bzowski et al. (2013) have shown that the variation of electron impact ionization for helium at 1AU is small. Therefore, to calculate the loss rate of the neutrals due to electron impact ionization, we assume that the electron impact ionization is 1.5×10^{-8} (1/s) at 1AU, and normalize the loss rate at 1AU to that value. As shown in Figure 1, the electron temperature does change too much, thus, we also assume constant value $T_{core} = 1.5\times10^5$ and $T_{halo} = 10^6$ K for the temperature of core and halo electrons.
- We use the daily values of photoionization rate at 1AU (Bzowski et al.,2013) to calculate the fraction of the loss rate and production rate due to photoionization.
- We restrict the ACE SWICS data sets to nearly perpendicular interplanetary magnetic field where the PUI velocity distribution function is gyrotropic within the field-of-view in the solar wind direction.
- We integrate the isotropic PUI distribution (with electron impact ionization) over the ACE SWICS field-of-view to get the predicted phase space density in the spacecraft frame. We compare the predicted phase space density with ACE SWICS observations to optimize the cooling index, which is taken as free parameter (Chen et al. 2013). An example is shown in Figure 3.

Velocity Range, km/s	α_e 0.3–1.0 AU	0.014–0.3 AU
300–400	0.527 ± 0.130	0.650
400–500	0.394 ± 0.102	0.680
500–600	0.200 ± 0.063	0.767
600–700	0.226 ± 0.079	0.805
700–800	0.296 ± 0.066	0.812
800–900	0.389 ± 0.092	0.825

Table 1. Observed gradients in the solar wind electron temperature assuming $T_e \sim r^{-\alpha_e}$ shown in Marsch et al. (1989)

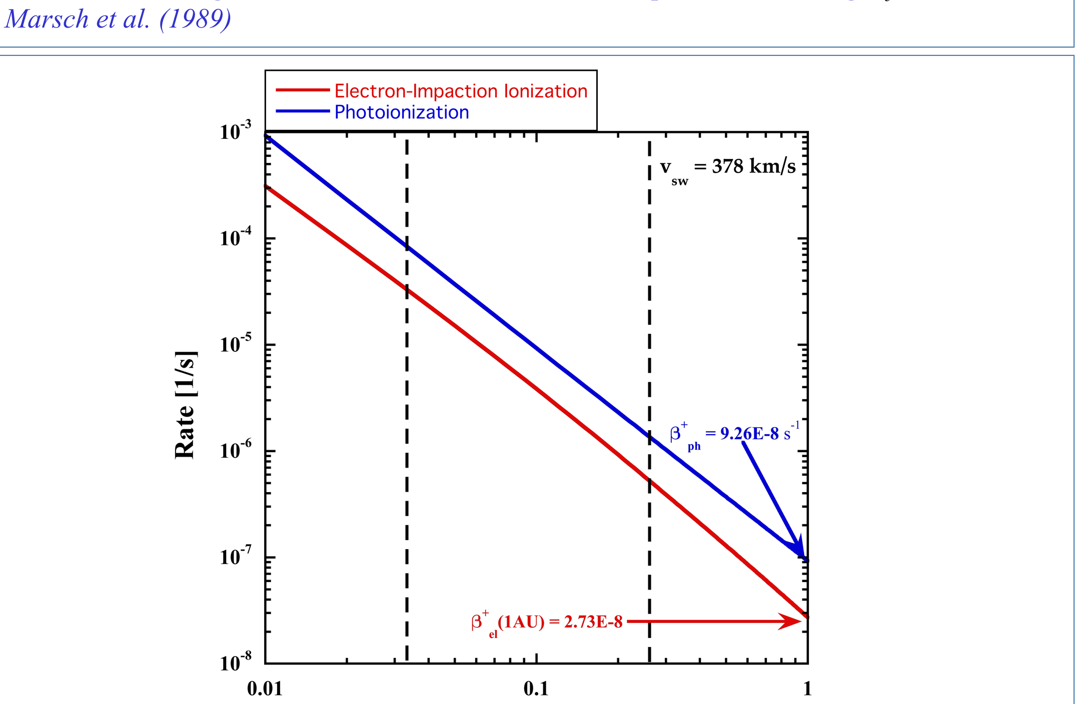

Figure 2. Radial profile of Photoionization and electron impact ionization rate in the periods of compressed solar winds as shown in Figure 2. Blue line is the average photoionization rate, and red line is the averaged electron impact ionization.

Results of Simulation

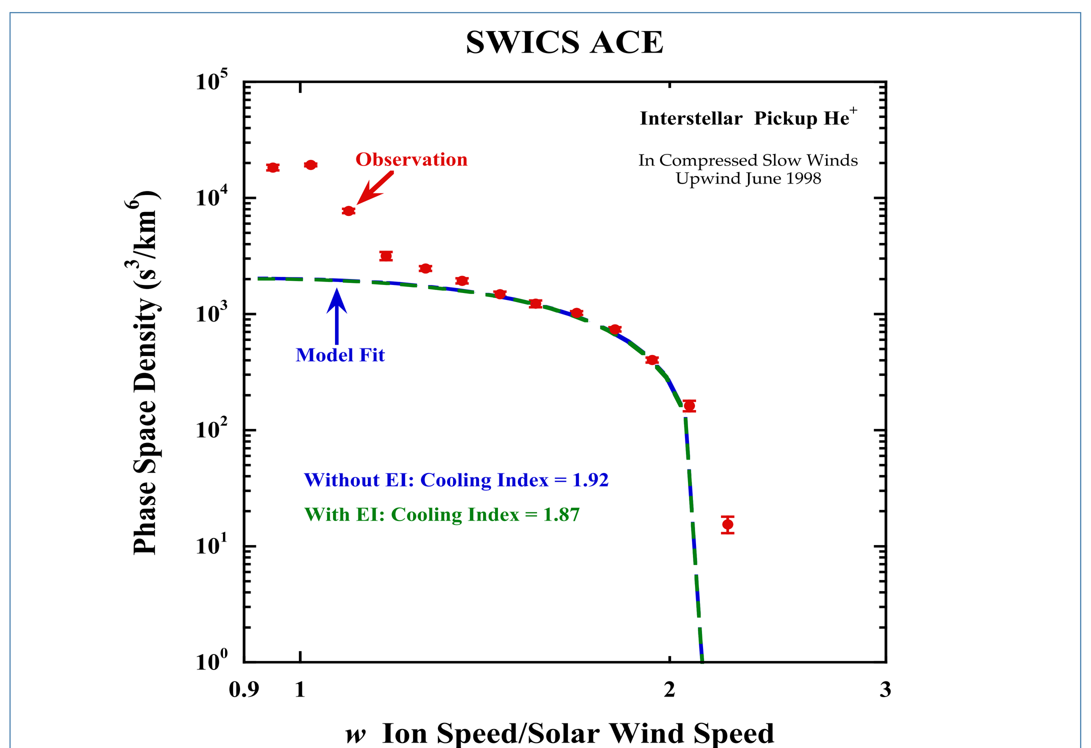

Figure 3. Phase space density of pickup He⁺ with error bars in the spacecraft frame as a function of w measured with ACE SWICS at 1AU in the upwind direction, averaged in the compressed slow winds. The model curves (dashed) represent resulting cooling indices 1.87 and 1.92 for the inclusion (green) and exclusion (blue) of the electron impact ionization, respectively.

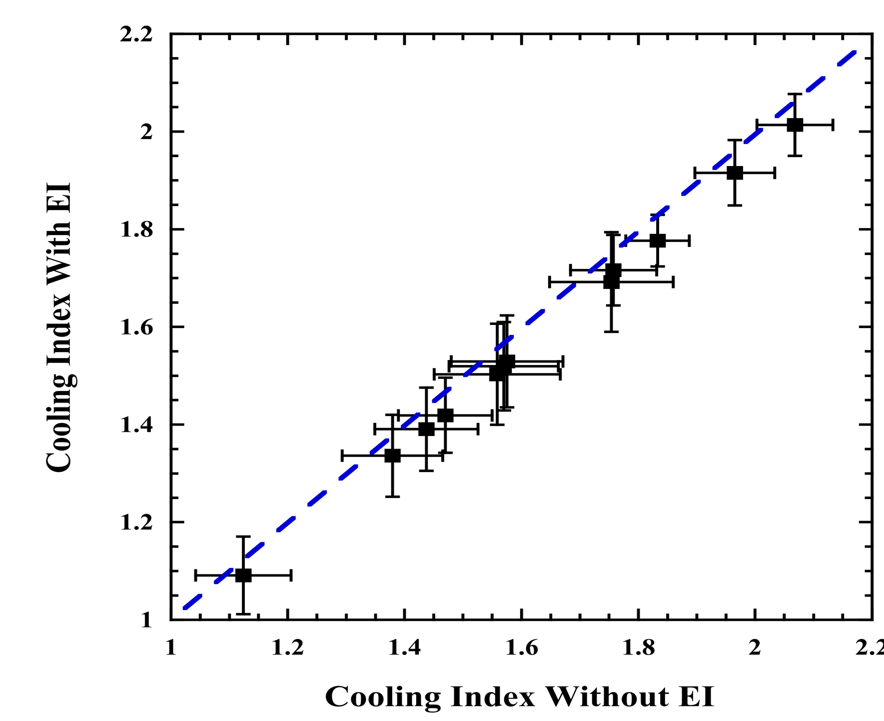

Figure 4. Cooling index with electron impact ionization as a function of cooling index without electron impact ionization for the data sets with nearly perpendicular interplanetary magnetic field. The blue line is where the cooling index with electron impact ionization is equal to that without electron impact ionization.

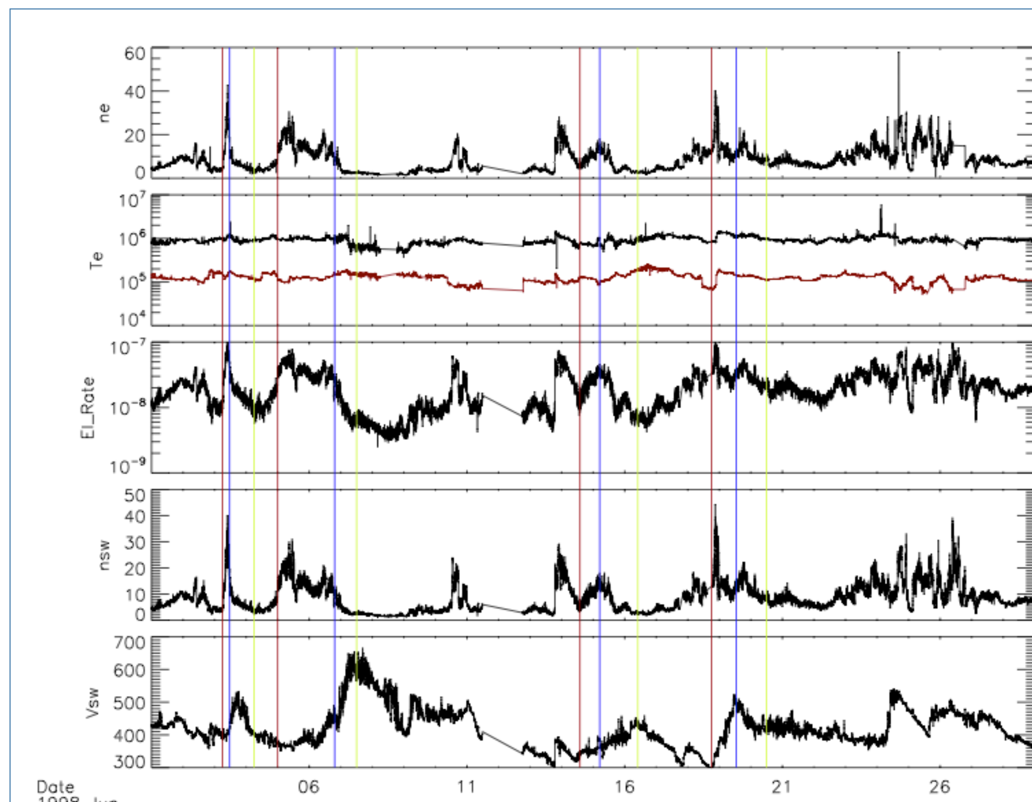

Figure 1. Solar wind plasma and electron data at 1AU as a function of time in June 1998. From top to bottom panel, they are the total solar wind electron density, solar wind electron temperature, electron impact ionization rate, solar wind speed. Vertical red lines mark the start time of CIRs, blue lines mark the stream interfaces, and yellow lines mark the end time of CIRs.

Results and Discussion

- As shown in Figure 1, the electron impact ionization is enhanced in the co-rotating interaction regions in the month of June in 1998, the average electron impact ionization rate in the compressed slow winds is nearly 30% of the photoionization rate at 1AU.
- As shown in Figure 3, the enhancement of the electron impact ionization, however, only leads to 3% difference in the cooling index. This enhancement, to some degree, compensates the PUI production which is connected to the increase in the loss rate. Therefore, the cooling index determined with electron impact ionization may exceed that with electron impact ionization for some extreme case where the electron impact ionization rate is strongly enhanced, even larger than the photoionization.
- As shown in Figure 4, the cooling indices determined with the inclusion of electron impact ionization are a little smaller than those without the inclusion of electron impact ionization. The effect is less than 5%.

Conclusion

- Overall, for a long time averages of the PUI distributions, the influence of the electron impaction on determination of the He^+ PUI cooling index is very small, and can be neglected.
- Even in the compressed slow solar wind, where electron impact ionization is enhanced, its influence is small. Therefore, the observed variations of the cooling index must be mainly due to solar wind compressions and rarefactions.

Reference

1. Chen, JH., et al. (2013), JGR, 118, 3946-3953.
2. Marsch, E., et al. (1989), JGR, 94, 6893-6898.
3. Pilipp, W.G., et al. (1990), J. Geophys., 42, 561-581.
4. Rucinski, D & Fahr, H. J (1989), A&A, 224, 290-298.
5. Vasyliunas V. M &Siscoe, G. L (1976), JGR, 81, 1247-1252.
6. Voronvo, G.S (1997), Atomic Data and Nuclear Data Tables, 65, 1-35.