AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2014JA020357

Key Points:

- The influence of electron impact ionization is negligible
- Its influence is also small even in the compressions

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Citation:
Chen, J. H., P. Bochsler, E. Möbius, and G. Gloeckler (2014), Possible modification of the cooling index of interstellar helium pickup ions by electron impact ionization in the inner heliosphere, *J. Geophys. Res. Space Physics*, *119*, 7142–7150, doi:10.1002/2014JA020357.

Received 2 JUL 2014
Accepted 3 SEP 2014
Accepted article online 7 SEP 2014
Published online 30 SEP 2014

Possible modification of the cooling index of interstellar helium pickup ions by electron impact ionization in the inner heliosphere

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Abstract Interstellar neutrals penetrating into the inner heliosphere are ionized by photoionization, charge exchange with solar wind ions, and electron impact ionization. These processes comprise the first step in the evolution of interstellar pickup ion (PUI) distributions. Typically, PUI distributions have been described in terms of velocity distribution functions that cool adiabatically under solar wind expansion, with a cooling index of 3/2. Recently, the cooling index has been determined experimentally in observations of He PUI distributions with Advanced Composition Explorer (ACE)/Solar Wind Ion Composition Spectrometer and found to vary substantially over the solar cycle. The experimental determination of the cooling index depends on the knowledge of the ionization rates and their spatial variation. Usually, ionization rates increase with $1/r^2$ as neutral particles approach the Sun, which is not exactly true for electron impact ionization, because the electron temperature increases with decreasing distance from the Sun due to the complexity of its distributions and different radial gradients in temperature. This different dependence on distance may become important in the study of the evolution of PUI distributions and is suspected as one of the potential reasons for the observed variation of the cooling index. Therefore, we investigate in this paper the impact of electron ionization on the variability of the cooling index. We find that the deviation of the electron ionization rate from the canonical $1/r^2$ behavior of other ionization processes plays only a minor role.

1. Introduction

Interstellar neutral gas, which consists primarily of hydrogen and helium, enters the inner heliosphere following hyperbolic orbits and suffering ionization losses. The resulting ionized particles are picked up by the interplanetary electromagnetic field (IMF) as pickup ions (PUI) and carried by the solar wind to the heliospheric boundary. These PUIs form a distinct population that can be measured by spacecraft [e.g., *Mobius et al.,* 1985; *Gloeckler et al.,* 1993; *Geiss et al.,* 1994].

Long before PUIs could be detected in space, *Vasyliunas and Siscoe* [1976] have proposed an analytic model for the PUI distribution. This model includes three key physical processes: (1) newly created PUIs immediately gyrate about the magnetic field with an initial speed equal to the solar wind speed and form a ring velocity distribution in the solar wind frame, (2) this ring distribution is quickly pitch angle scattered into a shell distribution assuming a high pitch angle scattering rate, and (3) this shell distribution shrinks in the radially expanding solar wind due to adiabatic cooling, thus reducing their speeds in the solar wind frame. The adiabatic cooling equation can be written as $(v/v_{sw})^{\alpha} = (r/r_0)$, which connects the PUI speed v at the observer location r_0, the solar wind speed v_{sw}, the source location of PUIs r, and location of an observer. α is defined as the cooling index. In this model, the shape of the PUI velocity distribution at the observer location r_0 is determined by a combination of the distance-dependent PUI source strength and the cooling process that maps the observed position in velocity space v to the radial source location

Chen et al. [2013] have investigated He^+ PUI cooling by comparing an isotropic model of PUI distributions with ACE Solar Wind Ion Composition Spectrometer (SWICS) PUI observations in the upwind direction, neglecting electron impact ionization relative to the dominant photoionization. They have shown that the cooling index exhibits a distinct correlation with solar activity. It varies substantially between ~1 and 2, compared with a fixed value of 1.5 assumed previously [*Vasyliunas and Siscoe,* 1976]. Among other processes, *Chen et al.* [2013] argue that these variations may, in part, be due to electron impact ionization. It is the only ionization process that varies stronger with distance from the Sun than $1/r^2$, as has been assumed for ionization in the modeling, and it may become more important in the compression regions of coronal mass ejections (CMEs) and solar wind stream interaction regions (SIRs), which may arise a single occurrence or repeat as corotating interaction regions. Therefore, the present paper expands on the previous study by taking a closer look at electron impact ionization to determine how strongly it may influence the PUI cooling index as derived from observations.

2. Modeling of Electron Impact Ionization

The ionization processes, expressed in terms of the ionization rate β, play a dual role for the PUI velocity distribution: the total loss rate β^- over several months/years shapes the neutral gas distribution, and the PUI production rate β^+ changing within days/weeks determines the actual PUI production in the inner heliosphere as a function of distance from the Sun. The latter also factors into the formation of the velocity distribution. As mentioned before, ionization processes for helium include photoionization by solar EUV radiation, charge exchange with solar wind protons and alpha particles, and impact ionization by solar wind electrons. Photoionization is the dominant process that largely falls off with the square of the distance (~r^{-2}). Charge exchange ionization also varies as r^{-2} but is negligible for helium due to its small charge exchange cross section. Conversely, electron impact ionization process cannot be calculated in a straightforward way. The radial dependence of electron impact ionization differs significantly from r^{-2} due to the cooling of the electron population in the solar wind. It also exhibits a complex electron distribution function. Yet the electron conditions in the solar wind, such as temperature and density, cannot be directly observed along the entire accumulation region of PUIs. Note that electron impact ionization becomes important for helium very close to the Sun but is negligible beyond 1 AU.

Rucinski and Fahr [1989] first pointed out this potential significance of electron impact ionization for the interstellar neutral gas distribution in the inner heliosphere. They recognized through modeling that the electron impact ionization rate could be a significant fraction of photoionization inside 1 AU. In their model, they treated the solar wind electron distribution as a double-Maxwellian that consists of two separate populations: a relatively cool and dense core population and a hot and rare halo population. The density of the halo is typically at a level of ~5% of the core. To simplify the computations without loss in overall accuracy, *Voronov* [1997] presented an empirical analytic expression for the electron impact ionization rate from the ground state on the basis of a fit to the "Belfast recommended data" [*Bell et al.,* 1983; *Lennon et al.,* 1988], which consist of electron impact ionization cross sections and rates for atoms and ions from hydrogen to nickel. The best fit formula may be written as

$$<\sigma v>= A\frac{\left(1+PU^{1/2}\right)}{X+U}U^K e^{-U}\left(\mathrm{cm}^3/\mathrm{s}\right) \quad (1)$$

$$U = E/k_b T_e \quad (2)$$

Here $<\sigma v>$ is the rate coefficient and U is the dimensionless threshold energy E in relation to the electron temperature T_e. k_b is the Boltzmann constant. *A, K, and X* are adjustable parameters, which are obtained from the fit to the recommended data. The parameter P is included to better fit the particular cross-section behavior for different elements near the threshold; it only takes on the values 0 or 1. For helium, the fit parameters are $E = 24.6$ eV, $P = 0$, $A = 0.175 \times 10^{-8}$ cm^3/s, $X = 0.18$, and $K = 0.35$.

For our modeling, we use this formula and assume that the solar wind electron distribution consists of double Maxwellian, whose parameters will be specified in section 4.2. Assuming spherically symmetric, stationary solar wind flow, we use a radial profile of the electron densities proportional to r^{-2}. However, the radial dependence of the electron temperature of both populations is the key challenge in the evaluation of the electron impact ionization rate inside 1 AU. Many authors [e.g., *Montgomery et al.,* 1968; *Ogilvie and Scudder,* 1978; *Feldman et al.,* 1978, 1979; *Sittler et al.,* 1981; *Marsch et al.,* 1989; *Pilipp et al.,* 1990; *Gary et al.,* 1994; *Phillips et al.,* 1995; *Maksimovic et al.,* 1996; *Issautier et al.,* 1998] have derived radial dependencies of the electron temperature based on spacecraft observations, but with large variations in the results. Typically, the temperature gradients are evaluated in terms of power law approximations $T_e \sim r^{-k}$, where electrons are found to cool with a behavior between isothermal and adiabatic. As an illustrative example, we show a comparison between electron impact ionization rates with different values for k in Figure 1. As a consequence of this dependence, the strength of the cooling

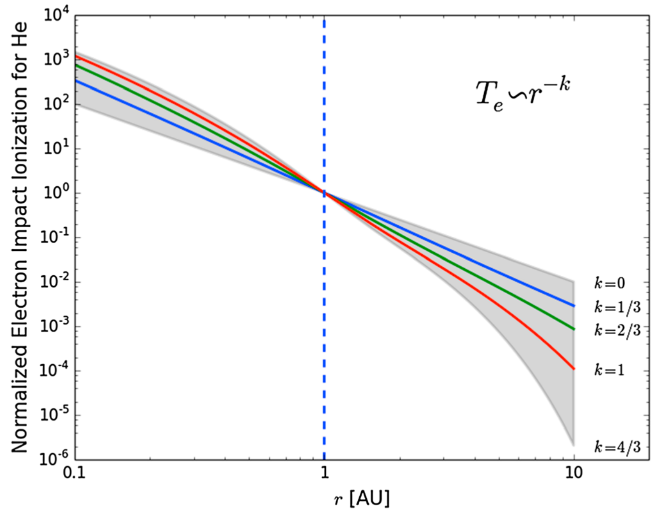

Figure 1. Electron impact ionization rate as a function of heliocentric distance according to *Voronov* [1997] for electron temperature variations with *r* using power law indices between 0 and $^4/_3$. The ionization rate is normalized to $1.0\,s^{-1}$ at 1 AU. The possible radial variation of the electron impact ionization rate falls into the gray-shaded region.

rate varies with distance from the Sun, but also with solar wind speed and heliolatitude. *Marsch et al.* [1989] have derived the radial profile of the electron temperature as a function of solar wind speed and heliocentric distance based on data obtained with the Helios plasma experiment. The correct profile is important for the radial dependence of the computed electron impact ionization rate and thus influences the determination of the PUI cooling rate from a comparison of observed and modeled PUI distributions [*Chen et al.*, 2013].

3. Modeling of PUI Distributions

As in *Chen et al.* [2013], we consider a steady state neutral helium distribution and restrict the observations around the upwind direction. This choice will simplify our analysis. Under these assumptions, the neutral helium density, as a function of heliocentric distance *r* (in AU), can be written as

$$n(r) = n_0 \exp\left(\int_{\infty}^{r} -\frac{\beta^-(r)}{\sqrt{V_0^2 + 2GM/(rr_E)}}\,\mathrm{d}r\right) \quad (3)$$

where n_0 is the neutral helium density at infinity, for which we take $n_0 = 0.015\,\mathrm{cm}^{-3}$, V_0 is the speed of the interstellar neutral helium inflow at infinity, *G* is the gravitational constant, *M* is the solar mass, and r_E is 1 AU; $\beta^-(r)$ is the total loss rate of helium as a function of heliocentric distance, which now includes both photoionization and electron impact ionization. As shown in *Bzowski et al.* [2013a, 2013b], the electron impact ionization for helium does not exhibit a clear time modulation with solar activity and is typically in the range $1\times10^{-8}{\sim}2\times10^{-8}\ \mathrm{s}^{-1}$. Therefore, an average value $\beta_{\mathrm{el}}^-(r = 1\mathrm{AU}) = \upsilon_{\mathrm{el}}^- = 1.5\times10^{-8}\ \mathrm{s}^{-1}$ for electron impact ionization of neutral helium at 1 AU is a reasonable assumption, and we adopt that value for the loss rate due to electron impact in the determination of radial neutral gas profile. Note here υ_{el}^- is ~25% of the photoionization rate at solar minimum and ~10% at solar maximum.

Then, the isotropic PUI velocity distribution can be written as

$$f(v) = \alpha\frac{1}{4\pi}\frac{r_0}{v_{\mathrm{sw}}v_{\max}^3}\,n\left[r = \left(\frac{r_0}{r_E}\right)\left(\frac{v}{v_{\max}}\right)^{\alpha}\right]\left\{\beta_{\mathrm{ph}}^+(r) + \beta_{\mathrm{el}}^+(r)\right\}r^2\left(\frac{v}{v_{\max}}\right)^{\alpha-3} \quad (4)$$

$v_{\max}$ is the injection speed of the ion into solar wind, which is equal to the sum of the solar wind speed v_{sw} and the interstellar neutral helium speed in the upwind direction [*Chen et al.*, 2013]. $\beta_{\mathrm{ph}}^+(r)r^2 = \upsilon_{\mathrm{ph}}^+$ and $\beta_{\mathrm{el}}^+(r)r^2$ are the PUI production rates at 1 AU due to photoionization and electron impact, respectively, thus, including both photoionization and electron impact ionization separately in the PUI production. To allow a quantitative comparison of the model distributions with the observations, the PUI velocity distribution function is transformed into the spacecraft frame and integrated over the sensor field-of-view and energy ranges [*Chen et al.*, 2013].

4. Determination of the Cooling Index

According to equation (4), we use a power law representation for the PUI velocity distribution in our comparison, and we optimize the cooling index α so that the model matches the observation. In combination, the total loss rate, PUI production rate, and the cooling index determine the slope of the observed PUI distribution. We will discuss each of these influences step by step below. We will briefly describe the data sets selected for this study in section 4.1, followed by a comparison between resulting cooling indices with and without the inclusion of electron ionization in section 4.2. This section is divided into two parts. The first part is devoted to the effect of electron impact ionization as part of the total loss rate on the derived PUI cooling index, followed by the impact of electron ionization as part of the PUI production rate, with emphasis on short-term variations that can boost the importance of this process.

4.1. Data Selection and Appropriate Time Resolution

As in *Chen et al.* [2013], we use ACE SWICS [*Gloeckler et al.,* 1998] data selected for the month of June each year from 1998 to 2010 when ACE is in the upwind direction of the interstellar gas inflow. We further restrict our data sets to nearly perpendicular interplanetary magnetic field (IMF), when the PUI velocity distribution is gyrotropic within the instrument field of view in the solar wind direction. To eliminate contributions from inner source PUIs [*Geiss et al.,* 1995; *Gloeckler et al.,* 2000] and from the rollover near the PUI cutoff speed, we restrict our comparison to the velocity range $1.4 \leq v/v_{max} \leq 1.8$.

As the defining process for the radial profile of the neutral gas distribution, the loss rate is effective on a time scale of months to years as the neutral gas approaches the Sun. It takes the neutral gas ~1 month to travel from 1 AU to the Sun. Therefore, the neutral gas density inside 1 AU that is relevant for the PUI distribution can be described by a combination of the absolute density at 1 AU and the average loss rate over the preceding month. The absolute density at 1 AU does not affect the shape of the neutral gas distribution nor the PUI velocity distribution inside 1 AU. Therefore, we average the daily values of the helium photoionization rate at 1 AU [*Bzowski et al.,* 2012, 2013a, 2013b] over the months of June and May to obtain the dominant contribution to the loss rate.

However, the observed PUI distributions are accumulated only over 2–4 days during their convection with the solar wind to 1 AU. Therefore, we use the daily values to calculate the appropriate He^+ PUI production rate over the relevant time period. The distinction between these two quite different ionization time scales becomes also important when trying to assess the effect of electron impact ionization, especially in solar wind structures where the electron impact ionization rate may be substantially enhanced for short time periods.

4.2. Effect of Electron Impact Ionization

In the following we will study separately the effects of electron impact ionization as a function of distance from the Sun on the total loss of He neutrals that shapes the radial gas distribution and on the PUI production that influences directly the resulting velocity distribution. It is important to note that any short-term variations of electron impact ionization, as they may occur in stream interaction regions and coronal mass ejections, will not be visible as part of the average loss rate, but they may affect PUI distributions on short (hours to days) time scales through variations of the production rate. Therefore, we separate the loss of neutrals and the production of PUIs according to their relevant time scales also in the electron impact ionization. We will start with a discussion of the effects of electron impact on PUI distributions through the loss rate, followed by a separate section on short-term variations important for the production rate.

4.2.1. Electron Impact Ionization as Part of the Loss Rate for Neutral Gas

To obtain the loss rate due to electron impact ionization, we use equation (1) from *Voronov* [1997] multiplied by the electron density. Note that the electron temperature and density are power law functions of heliocentric distance. As mentioned in section 4.1, the loss rate relevant to the neutral density is effective only on time scales of months inside 1 AU. Therefore, we use the average solar wind speed in June and May to obtain the radial profile of the electron temperature according to *Marsch et al.* [1989], who obtained the temperature gradient as a function of solar wind speed and radial distance. Following *Rucinski and Fahr* [1989] and *Bzowski et al.* [2013a, 2013b], we use constant values $T_{core} = 1.5 \times 10^5$ and $T_{halo} = 7.0 \times 10^5$ K for the temperature of core and halo electrons at 1 AU to get the constants in the power law functions. Because the radial dependence of the halo temperature is even less well known, we assume that the temperature gradient for core and halo electrons is the same. For the quiet solar wind, the electron density decreases as r^{-2}, which is tied at 1 AU to solar wind proton and alpha density observations with ACE SWEPAM, invoking quasi-neutrality. We adopt a halo-to-core density ratio 0.05. As the relevant production rate of PUIs due to

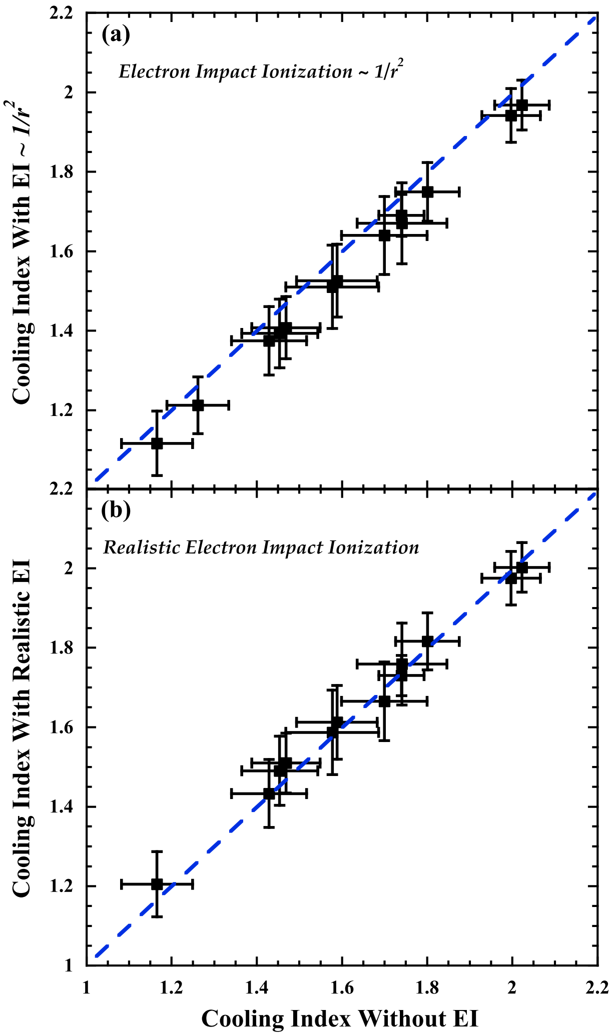

Figure 2. Comparison between cooling index with and without the inclusion of electron impact ionization for the data sets with nearly perpendicular interplanetary magnetic field in the upwind direction of the interstellar gas flow. (a) Electron impact ionization varies as $1/r^2$. (b) Realistic electron impact ionization is calculated using *Voronov* [1997] with the cooling rate of electron temperature from *Marsch et al.* [1989]. The blue line is where the cooling index is the same.

electron impact ionization for this first comparison, we also adopt monthly average for June commensurate with the data selection.

In Figure 2a, we show a comparison between the cooling index with and without inclusion of electron impact ionization in the loss rate averaged over the preceding 2 months for the PUI observations in June 1999 through 2010. In a first attempt, we include electron impact ionization varying as $1/r^2$ that corresponds to isothermal electron distribution. It is evident that the derived cooling index is smaller when we use only the photoionization rate as the total loss rate, albeit only by ≈ 2–5%. In this comparison, the addition of electron impact ionization to the He^+ production rate $\beta_{el}^{+}(r)$ has no effect on the slope of the PUI velocity distribution function, but the additional loss of neutrals due to electron impact ionization does through an increase in the neutral helium density gradient. Therefore, accounting for the combination of photoionization and electron impact ionization in the total ionization rate is important for a study of the PUI cooling behavior.

To assess how the different radial dependence of electron impact ionization may affect the PUI distribution, we computed the electron impact ionization rate based on the procedure described above for the second comparison. In Figure 2b, we compare the derived cooling indices, with a realistic radial variation of electron impact ionization included in one case, but with electron impact ionization excluded in the other case (as in Figure 2a). Interestingly, the cooling indices in this comparison are almost the same, with only small variations between the data points.

Even though the inclusion of the correct average electron impact ionization rate, apparently, leads to negligible differences in the derived cooling indices, it may still be very important to account for occasional strong short-term increases of the electron impact ionization rate with a radial dependence different from $1/r^2$ in the PUI production rate. While such a short-term increase has a negligible effect on the total average loss rate, it may potentially affect significantly the PUI production rate and thus the resulting PUI distributions for the respective time periods.

4.2.2. Short-Term Variations of Electron Impact Ionization in the PUI Production Rate

As mentioned above, electron impact ionization may vary greatly with solar wind conditions. In particular, in solar wind compression regions, electron impact ionization could become a more significant fraction of the photoionization rate or even occasionally exceed it. Such conditions can occur in stream interaction regions (SIR) when fast solar wind overtakes slow wind and in the sheath region ahead of a fast interplanetary

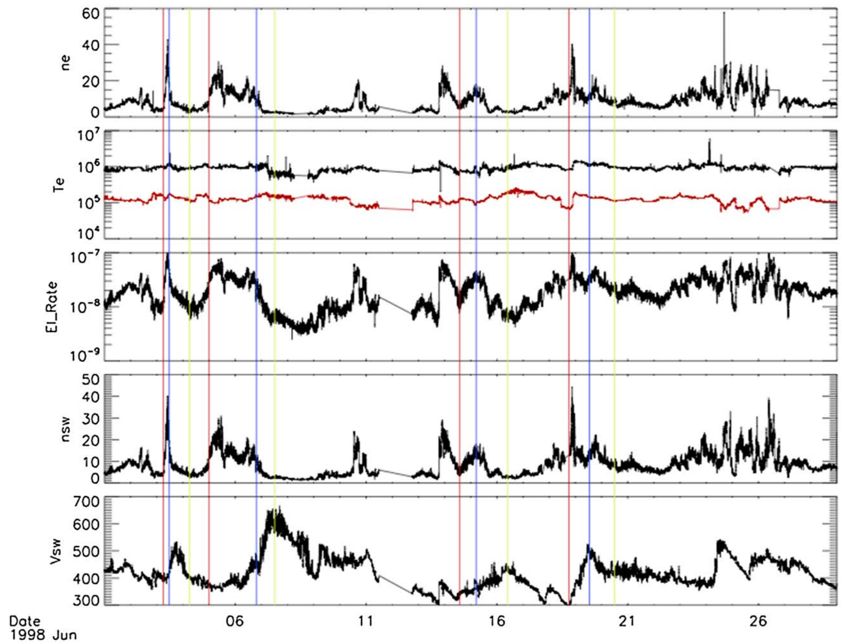

Figure 3. Hourly averaged solar wind plasma and electron data at 1 AU as a function of time in June 1998. (top to bottom) Total solar wind electron density, solar wind electron temperature, electron impact ionization rate, solar wind proton density, and solar wind speed. Vertical red lines mark the start time of SIRs, blue lines mark the stream interfaces, and yellow lines mark the end time of SIRs.

coronal mass ejection. In both cases the electron density and temperature can be substantially increased over neighboring regions. As pointed out already before, these relative short-time variations in the electron impact ionization have negligible influence on the loss of the neutrals, but they may strongly affect the production of PUIs and thus cause temporary changes of the PUI distribution, in particular, because the electron density is substantially enhanced in these regions. While the hallmark of electron impact ionization is a faster decrease with distance from the Sun than $1/r^2$, compressions partially compensate for the radial solar wind expansion so that the density of electrons decreases slower than $1/r^2$ and the electron temperature cools slower than in the quiet solar wind.

Unfortunately, the radial dependence of the electron impact ionization in these situations is poorly known thus far. Therefore, we will analyze a scenario chosen for potentially strongest influence of electron impact ionization in compression regions. For the sake of argument, we assume that the density of electrons decreases as $1/r^2$, and we adopt the radial electron temperature dependence found for the quiet solar wind [*Marsch et al.,* 1989], thus overestimating electron impact ionization inside 1 AU. In such a model situation, the faster decrease than $1/r^2$ of electron impact ionization will be maintained, but in light of the point made above, this scenario will clearly produce an overestimate of the effects of electron impact ionization on the PUI distribution.

In Figure 3, we show hourly averaged solar wind plasma data, electron density, temperature, and the derived electron impact ionization rate in three SIRs in June 1998 (http://www-ssc.igpp.ucla.edu/~jlan/ACE/Level3/SIR_List_from_Lan_Jian.pdf). In Figure 4, we show a comparison of the observed photoionization rate with the modeled electron impact ionization rate based on the actually observed electron density and temperature averaged over these three regions of compressed slow solar wind. The electron impact ionization rate at 1 AU is ~37% of the photoionization rate. In order to compare with the modeled PUI distributions, the observed PUI distributions are also averaged over these three regions of compressed slow solar wind.

In Figure 5 we show the comparison between observed and modeled PUI distributions, using the ionization rates from Figure 4 as PUI production rates. Shown is the observed He^+ phase space density as a function of *w,* averaged over the compressed slow solar wind regions in June 1998. The dashed blue and green curves represent the best model fits to the observed distribution with and without including electron impact ionization in the total PUI production rate, respectively. The resulting cooling indices are only slightly different

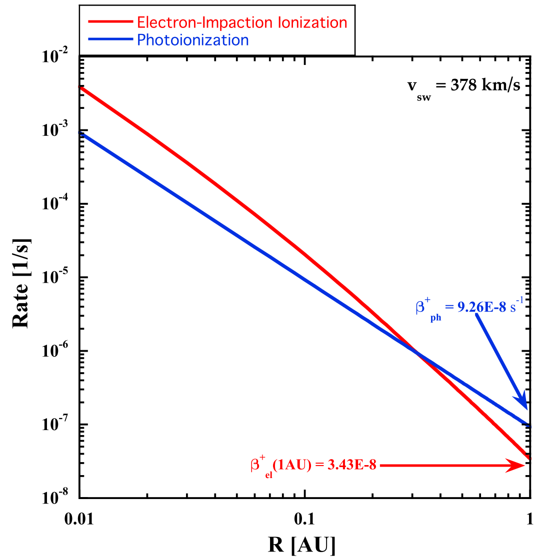

Figure 4. Radial profile of the photoionization and electron impact ionization rate averaged over the periods of compressed slow solar wind as shown in Figure 3. The blue line represents the average photoionization rate and the red line the averaged electron impact ionization. The electron impact ionization is nearly 40% of the photoionization rate at 1 AU.

even though the effect of electron impact ionization is overestimated in the model shown by the green curve. The enhanced electron impact ionization in the compression region only leads to a 7.5% increase of the cooling index ($\alpha = 1.86$ to 2.00).

5. Discussion and Conclusions

We have modeled the He^+ PUI distributions using a simple stationary model for the computation of the spatial distribution of interstellar neutral helium in the upwind direction in the inner heliosphere and an isotropic PUI velocity distribution according to equation (4) for the computation of the helium PUI spectra produced by ionization of neutral helium. The photoionization rate, which is the dominant ionization process for helium at heliocentric distances greater than about 0.5 AU, is directly taken from observations. The radial dependence of electron impact ionization, whose contributions to the ionization of helium become significant inside 1 AU, is computed based on an analytic expression by *Voronov* [1997] with the electron temperature gradients taken from observations [*Marsch et al.,* 1989]. We compare the predicted velocity distribution with He^+ PUI distributions observed by ACE SWICS for 1 month (June) over 12 years to obtain the cooling indices.

The most uncertain part in our analysis is the radial profile of the solar wind electron temperature. Although several values of the cooling rate of solar wind electron have been obtained from dozens of observations, there is no overall agreement between these results, which may be due to (1) different data selection and fitting techniques have been used and (2) different solar wind conditions and large range of heliocentric distance intervals used in these studies. For our study, we adopted the radial dependence as a function of solar wind speed and heliocentric distance derived by *Marsch et al.* [1989].

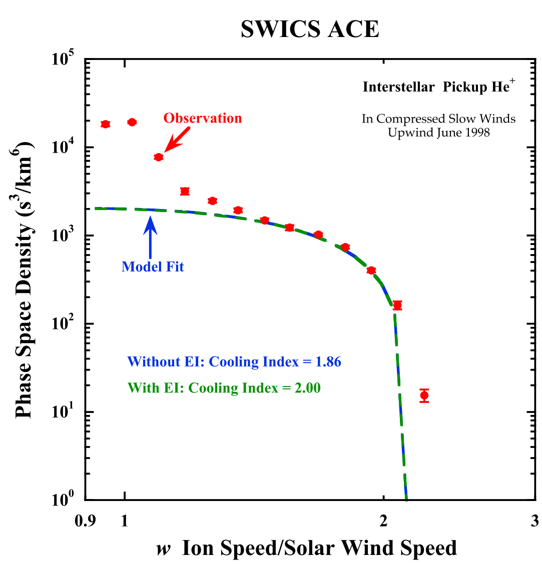

Figure 5. Phase space density $F_{He^+}(w)$ of pickup He^+ with error bars in the spacecraft frame as a function of w measured with ACE SWICS at 1 AU in the upwind direction, averaged in the compressed slow winds. The model curves (dashed) represent resulting cooling indices 1.87 and 1.92 for the inclusion (green) and exclusion (blue) of the electron impact ionization, respectively.

To assess the effect of average electron ionization rates on the derived cooling index, we started with adding electron impact ionization that varies as $1/r^2$, i.e., corresponding to an isothermal electron distribution. In this case, the electron impact ionization in the PUI production rate has no effect on the shape of the PUI velocity distributions. However, the related increase in the loss rate translates into a slightly smaller cooling index compared with our previous results [*Chen et al.,* 2013]. This finding indicates that accounting for the combination of electron impact ionization and photoionization in the total ionization rate is important for a quantitative study of PUI cooling behavior. However, this also signals how the uncertainty of the derived cooling index is coupled to the knowledge of the total ionization rate, including uncertainties in the photoionization rate. Overall, the derivation appears relatively robust, since a variation of the ionization rate by up to 25% (added electron ionization) translates into change in cooling index by only less than 4%.

Next, we computed the cooling indices with the radial electron temperature profile determined by *Marsch et al.* [1989]. Interestingly, we now find insignificant differences in the resulting cooling indices, when we compare the resulting values again with the original results obtained without any electron ionization. Apparently, the effect from the increase in the loss rate is mostly offset by the steeper radial decrease of the electron impact ionization rate, and thus, the effect of electron ionization on the resulting PUI velocity distribution is negligible on the long time scales involved in shaping the neutral gas distribution.

However, compressions induced by the interaction between fast and slow solar wind could still cause significant localized heating and density enhancements in solar wind electrons. Here electron impact ionization may be substantially increased due to the density increases and slower cooling of the electrons in the compression regions than in the ambient solar wind. Because of the inherent uncertainties in calculating the radial profile of electron impact ionization in this situation, we chose to model the potentially strongest influence of these electron enhancements by maintaining the radial temperature gradient according to *Marsch et al.* [1989] and a density profile that scales as $1/r^2$, both overestimates of the actual impact. In spite of these choices, we find that the PUI cooling index is modified only by a few percent. Therefore, we conclude that electron impact ionization only plays a minor role in shaping the PUI distribution, even in compression regions.

In summary, we have found the following:

1. For a long-term average of the PUI distributions, the influence of electron impact ionization through the loss rate on determination of the He^+ PUI cooling index is very small and can be neglected.
2. Even in the compressed slow solar wind, where electron impact ionization is enhanced occasionally to 40% of the photoionization rate at 1 AU, its influence is rather small and only leads to less than 7.5% modification of the cooling index.

Chen et al. [2013] suggested several potential contributors to the observed variations in the PUI cooling index over the course of the solar cycle, i.e., radial expansion behavior that differs from the usual $1/r^2$ scaling, incomplete pitch angle scattering, and substantial contribution of electron impact ionization that does not scale as $1/r^2$. We have now excluded the latter possibility and are left with the first two, of which likely the starkly different expansion behavior may play a leading role.

Acknowledgments
This work was carried out with support under the NASA SR&T program, grant NNX09AW32Q, and through the ACE mission, grant NNX08AI11G. The ACE SWICS PUI and solar wind plasma data are available at ACE Science Center (http://www.srl.caltech.edu/ACE/ASC/). The authors thank R.M. Skoug for providing the solar wind electron density and temperature. The electron distributions from the ACE SWEPAM instrument are also available at ACE Science Center.

Yuming Wang thanks the reviewers for their assistance in evaluating this paper.

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