Observational study of the cooling behavior of interstellar helium pickup ions in the inner heliosphere

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Received 22 February 2013; revised 14 May 2013; accepted 9 June 2013; published 11 July 2013.

[1] The velocity distribution of interstellar pickup ions (PUIs) has typically been described as evolving through fast pitch angle scattering followed by adiabatic cooling while being transported radially outward with the solar wind. In combination, the ionization rate, which controls the radial profile of the interstellar neutrals, and the cooling process determine the slope of the observed PUI distributions. Thus far, a cooling index of 3/2 for the PUI velocity distributions has been used in almost all studies. This value is based on the implicit assumptions of immediate PUI isotropization due to pitch angle scattering and solar wind expansion with the square of the distance from the Sun. Here we determine the observed cooling index in a comparison of He^+ PUI distributions taken for 1 month in the upwind direction with ACE SWICS from 1999 through 2010 over the past solar cycle with such an isotropic PUI model, treating the cooling index as a free parameter. The ionization rate is obtained simultaneously from independent observations. To separate effects of slow pitch angle scattering of PUIs, the comparison is repeated for times restricted to perpendicular interplanetary magnetic field (IMF). When averaged over the entire data set, the cooling index is very close to 3/2. However, it varies substantially from 1.1 to 1.9 between samples, shows a distinct variation with solar activity, and has a significant correlation with sunspot number when data are restricted to nearly perpendicular IMF ($\theta_{Bv_{\rm sw}} > 60°$) excluding the slow pitch angle scattering in the radial IMF direction. The potential influence of slow pitch angle scattering, solar wind structures, and electron ionization on the cooling index and its variations is discussed.

Citation: Chen, J. H., E. Möbius, G. Gloeckler, P. Bochsler, M. Bzowski, P. A. Isenberg, and J. M. Sokół (2013), Observational study of the cooling behavior of interstellar helium pickup ions in the inner heliosphere, *J. Geophys. Res. Space Physics*, *118*, 3946–3953, doi:10.1002/jgra.50391.

1. Introduction

[2] Interstellar pickup ions (PUIs) constitute a charged-particle population in the heliosphere that originates from interstellar neutrals inside the heliosphere. They are produced by photoionization, charge exchange with the solar wind, and electron impact ionization. Once ionized, they are picked up by the interplanetary magnetic field (IMF) and rapidly swept outward with the solar wind. In the absence of observation, the basic characteristics of interstellar PUIs created from these interstellar neutrals were predicted [*Vasyliunas and Siscoe*, 1976] by considering two extreme cases, either involving no scattering of the PUIs or assuming rapid scattering to isotropy by waves in the solar wind frame. Assuming that ions attain instantaneous isotropy in the solar wind frame, the latter case is equivalent to treating PUIs as an ideal gas with adiabatic expansion. Under these constraints, the adiabatic cooling process provides a simple mapping between the speed v of a portion of the pickup ion distribution, observed at position r_0, and the radial position r, where these ions were picked up. The relation can be written as a power law:

$$r = r_0 \left(\frac{v}{v_{\rm sw}} \right)^{\alpha} \tag{1}$$

where $v_{\rm sw}$ is the solar wind speed and α represents the cooling index, where a higher cooling index corresponds to slower cooling. This mapping of the radial interstellar neutral gas distribution onto a PUI velocity distribution is schematically depicted in Figure 1. Assuming that on average, the solar wind density is inversely proportional to the square of the distance from the Sun and the PUI velocity distribution has 3 degrees of freedom, we arrive at a cooling index $\alpha = 3/2$ for adiabatic cooling [*Vasyliunas and Siscoe*, 1976; *Möbius et al.*, 1988].

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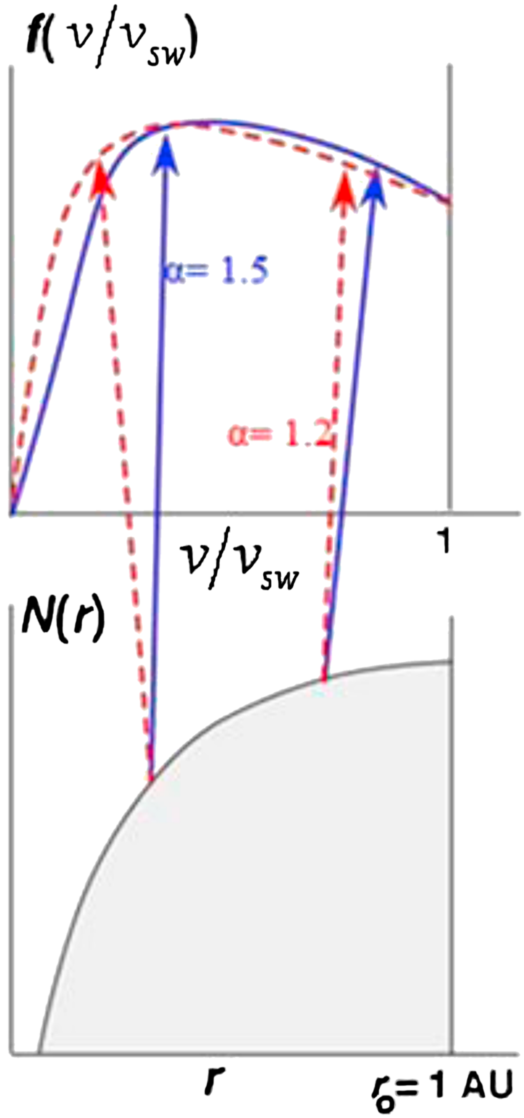

Figure 1. Schematic representation of the mapping of the neutral gas density along the Sun-spacecraft line into the observed velocity distribution in the solar wind direction assuming perfect isotropization. (bottom) The radial variation of the neutral gas density (dark shading). The arrows indicate how the radial variation of the neutral gas density translates into (top) the velocity distribution function $f(v)$ for different cooling indices α.

[3] Interstellar PUIs were first discovered through the identification of interstellar He^+ PUIs at 1 AU with the AMPTE SULEICA instrument by *Möbius et al*. [1985]. They interpreted the observations in terms of an isotropic velocity distribution in the solar wind according to the model by *Vasyliunas and Siscoe* [1976]. The observational base was broadened by the discovery of additional species, such as H, O, and Ne [*Gloeckler et al*., 1993; *Geiss et al*., 1994]. However, PUI observations also showed signs that appeared to deviate from the simple model. *Gloeckler et al*. [1995] reported a substantial anisotropy consistent with a mean free path of ~ 1 AU in the pickup proton velocity distributions for observations with Ulysses SWICS at high ecliptic latitudes, where the interplanetary magnetic field (IMF) is oriented largely along the solar wind direction. Strongly anisotropic PUI distributions also became apparent when *Möbius et al*. [1998] found that pickup helium fluxes, measured with 20 min integration time with AMPTE SULEICA, were substantially reduced and showed a strong decrease as a function of energy just below the PUI cutoff energy for time periods when the IMF was near radial. In the solar wind frame, ions that are injected under quasi-radial field conditions initially stream toward the Sun. They need to be scattered effectively in pitch angle to be detected in the antisunward hemisphere of the PUI distribution. However, pitch angle scattering of these PUIs appears to be substantially inhibited in contrast to their expected behavior in the simple model. Consequently, the observed anisotropies may be related to inefficient or incomplete pitch angle scattering.

[4] To account for the observed anisotropies in the pickup ion distributions, *Fisk et al*. [1997] suggested that the long mean free path was caused by a low scattering rate through 90° pitch angle, leading to the application of the hemispherical approximation [e.g., *Isenberg*, 1997; *Schwadron*, 1998]. *Isenberg* [1997] divided the PUI distribution into two separate antisunward and sunward streams, where the rapid scattering assumption is retained within each hemisphere in velocity space. *Lu and Zank* [2001] extended this hemispherical model. They used a higher-order truncation of the underlying Boltzmann equation, thus allowing a more detailed analysis of the evolving PUI distribution, and included a finite scattering rate within each velocity space hemisphere. In an alternate approach, *Chalov and Fahr* [1998] studied the evolution of hydrogen PUIs from 1 to 6 AU by solving the transport equation numerically, including drifts and energy diffusion. They found that substantial PUI anisotropies persist for relatively low magnetic turbulence levels. In a statistical study of helium PUI with Geotail, *Oka et al*. [2002] found anisotropic (toroidal) velocity distributions during low magnetic turbulence levels ($\Delta B/B < \sim 0.1$) and evolution toward isotropic distributions for higher magnetic turbulence levels ($\Delta B/B > \sim 0.2$). *Saul et al*. [2007] applied the hemispherical model to deduce a cross-hemispherical scattering rate from observations. With these assumptions, they found that the resulting mean free path varies with the observed wave power from 0.1 to 1.2 AU and the cross-hemispherical scattering rate is exponentially dependent on wave power.

[5] However, for the case of rapid pitch angle scattering, i.e., when the scattering mean free path is short, the PUI velocity distribution function can be treated as isotropic. For almost perpendicular IMF, the gyrotropic pickup ion distribution exhibits no anisotropy within the field of view (FOV) in the solar wind direction. For collisionless solar wind plasma confined by magnetic field, *Fahr* [2007] pointed out that the conservation of the first magnetic adiabatic moment leads to a cooling index $\alpha = 1$ if PUIs are freely convected with the solar wind and the magnitude of the magnetic field magnitude varies inversely with the square of the distance from the Sun. Magnetic confinement only cools the two velocity components perpendicular to the magnetic field.

[6] Any modification of the cooling law may result in a somewhat different mapping of a given neutral gas distribution into the PUI velocity distribution. For these reasons, we suggest that the original assumption of

Vasyliunas and Siscoe [1976] with regard to the cooling rate deserves some additional scrutiny. Recently, *Saul et al.* [2009] have studied the cooling index with a data set from CTOF/CELIAS during a solar minimum. They found a cooling index $\alpha = 1.35 \pm 0.2$. However, the available data set did not allow separating in a straightforward manner the solar cycle effect on the neutral gas distribution which is determined by the average ionization rate. In this paper, we will test the previous implicit assumptions of a constant cooling index that is equal to 3/2 over a wide range of independently measured ionization rates, which determine the radial gradient of the neutral gas distribution. We will treat the cooling index α as an independent free parameter in the isotropic PUI model according to *Vasyliunas and Siscoe* [1976] that is compared with observations. We will briefly introduce the instrument in section 2 and then describe the simulation of the PUI velocity distribution as seen by the instrument in section 3. The observed distributions are compared with the simulated PUI velocity distributions in section 4. The results from the data and model comparison and some implications are discussed in section 5.

2. Instrumentation and Spacecraft

[7] The observations presented in this paper were obtained with the SWICS (Solar Wind Composition Spectrometer) instrument [*Gloeckler et al.*, 1998] onboard the Advanced Composition Explorer (ACE). ACE is a spin-stabilized spacecraft which orbits the Lagrangian L1 point about 200 Earth radii upstream from the Earth and is always in interplanetary space, thus providing nearly continuous coverage of interstellar He^+. The particle identification technique of the SWICS sensor is based on a combination of an electrostatic deflection analyzer covering a solid angle of 10° in azimuth and 69° in polar angle, postacceleration, a time-of-flight spectrometer, and energy measurement. Combining these techniques, we can determine mass per charge, mass, speed, and arrival direction of incoming ions. The energy range from ~0.6 to ~100 keV/charge is covered by stepping the deflection analyzer voltage through up to 60 logarithmically spaced voltage steps. SWICS readily identifies He^+ ions and determines their velocity distribution for normalized ion speeds $w = v/v_{sw}$ (v is the ion speed and v_{sw} the solar wind speed) between ~0.9 and ~5. A more detailed description of the instrument may be found elsewhere [*Gloeckler et al.*, 1998]. The interplanetary magnetic field was measured by the fluxgate magnetometer MAG onboard ACE [*Smith et al.*, 1998].

[8] The photoionization rates were derived from Solar EUV Experiment (SEE) data [*Woods et al.*, 2005] onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft, Solar EUV Monitor (SEM) data [*Hovestadt et al.*, 1995] onboard the Solar and Heliospherical Observatory (SOHO), and a system of EUV radiation proxies (for details, see *Bzowski et al.* [2012, 2013]).

3. Isotropic PUI Transport Model

3.1. Interstellar Neutral Density

[9] The starting point for a model of PUIs is the spatial distribution of the interstellar neutral gas in the heliosphere. To calculate the neutral gas distribution neutrals on the upwind side of the heliosphere, we consider a cold model of interstellar gas. As *Fahr* [1971] and *Blum et al.* [1975] have shown, a finite temperature has a minor influence on the density distribution in the upwind direction, and the cold gas model is accurate enough for most purposes. For this study, we have restricted the ACE SWICS observations to 1 month each year around the upwind direction, which justifies the use of the cold gas approximation. In this case, the steady state density of neutral helium as a function of heliocentric distance r can be written in a simplified form as

$$n(r) = n_0 \exp\left[-\lambda C\left(\sqrt{1+2/Cr}-1\right)\right] \quad (2)$$

where n_0 is the neutral helium density at infinity for which we take $n_0 = 0.015\ \mathrm{cm}^{-3}$; λ is the penetration depth, or the distance from the Sun where the neutral density falls to $1/e$ of the value at infinity,

$$\lambda = \frac{r_E^2}{V_0}\beta_0^- \quad (3)$$

V_0 is the speed of the initial interstellar neutral helium inflow, and β_0^- is the loss rate of helium at r_E = 1 AU.

[10] The constant C is described as

$$C = \frac{V_0^2}{GM} \quad (4)$$

where G is the gravitational constant and M is the solar mass.

[11] Furthermore, we approximate the loss rate by the integration of the helium photoionization rate [*McMullin et al.*, 2004; *Woods et al.*, 2005] over the year preceding the observation. We take the initial speed of a neutral atom as $23.2\ \mathrm{km\,s}^{-1}$ [*Möbius et al.*, 2012]. We neglect charge exchange (less than 1%) and electron impact ionization (about 10% of the total ionization rate in the ecliptic at 1 AU) for now. It should be noted that electron impact ionization could become important closer to the Sun because it varies stronger than $1/r^2$ with distance from the Sun [e.g., *Ruciński et al.*, 1996; *McMullin et al.*, 2004; *Bzowski et al.*, 2012, 2013]. The evaluation of the potential influence of electron ionization close to the Sun is left to future investigations.

3.2. Formation of an Isotropic PUI Distribution

[12] Interstellar He^+ pickup ions originate from ionization of interstellar neutral helium atoms which penetrate into the inner heliosphere as a neutral interstellar wind. Hence, the radial source function $S(r)$ for pickup ions is the product of the density of neutral helium $n(r)$ and the PUI production rate $\beta^+(r)$, for which we concentrate again on photoionization:

$$S(r) = n(r)\beta^+(r) \quad (5)$$

[13] After being ionized, the newly born ions are picked up by the IMF into the solar wind. As a consequence, they perform a gyromotion with pitch angle Θ, i.e., the angle between the IMF direction and the PUI velocity in the solar wind frame, forming a ring distribution in velocity space around the IMF.

[14] Because of the IMF fluctuations embedded in the solar wind, the ions are scattered in pitch angle. Typically, a mean free scattering length of He^+ pickup ions during convection

with the solar wind of the order of 0.1 AU [*Möbius et al.*, 1988] has been used, which is small compared with the distance of the observer from the Sun or with the total integration length. In this case, the ions are effectively pitch angle scattered, thus quickly transforming the initial velocity ring distribution into a spherical shell in velocity space. During its outward convection with the expanding solar wind, the PUI distribution is adiabatically cooled [*Vasyliunas and Siscoe*, 1976]. The spherical shell shrinks in velocity space, and newly born He^+ pickup ions are added to the outermost shell. The relationship for adiabatic cooling from the point of ionization to the observer location provides a direct mapping of the local neutral helium density distribution $n(r)$ as a function of distance from the Sun into the resulting PUI velocity distribution function according to equation (1). The mapping is shown in Figure 1 for two different values of α. Since the ions are quickly distributed over the surface of a sphere in velocity space, with the number of ions conserved, the source function can be written as

$$n(r)\beta^{+}(r)\mathrm{d}t = S(r)\frac{\mathrm{d}r}{v_{\mathrm{sw}}} = 4\pi f(v)v^2\mathrm{d}v \tag{6}$$

or

$$f(v) = \frac{S(r)}{v_{\mathrm{sw}}4\pi v^2(\mathrm{d}v/\mathrm{d}r)}$$

[15] The source function $S(r)$ has its maximum close to the Sun due to the $1/r^2$ dependence of the photoionization rate. However, the density of newly generated PUIs also varies as $1/r^2$ with distance from the Sun, so that the $1/r^2$ dependence cancels in the velocity distribution function when observed at a specific distance r from the Sun [*Möbius et al.*, 1988]. Therefore, the distribution function can be described with a fixed photoionization rate β_0^+ at the observer location. As the appropriate production rate, we use the average value over the month of June of each year which is justified by the fact that the accumulation of the local PUI distribution occurs only over 3–4 days that it takes the solar wind to travel from the Sun to 1 AU. Combined with the cooling law from equation (1) and including the interstellar gas inflow speed, the PUI velocity distribution reads

$$f(v) = \alpha\frac{1}{4\pi}\frac{\beta_0^+ r_0}{v_{\mathrm{sw}}v_{\mathrm{max}}^3}n\left[r = r_0\left(\frac{v}{v_{\mathrm{max}}}\right)^{\alpha}\right]\left(\frac{v}{v_{\mathrm{max}}}\right)^{\alpha-3} \tag{7}$$

v_{max} is the injection speed of the ion into the solar wind, which is equal to the sum of the solar wind speed and the interstellar neutral helium inflow speed in the upwind direction, and v_{sw} is the measured solar wind speed. v_{max} varies with distance from the Sun as

$$v_{\mathrm{max}}(r) = v_{\mathrm{sw}} + v_{\mathrm{ISM}}(r) \tag{8}$$

where $v_{\mathrm{ISM}}(r)$ is determined by

$$v_{\mathrm{ISM}}(r) = \sqrt{V_0^2 + \frac{2GM}{r}} \tag{9}$$

[16] Combining equations (7), (8), and (9), we find an isotropic PUI velocity distribution function with a modified PUI injection speed in the solar wind frame as follows:

$$f(v) = \alpha\frac{1}{4\pi}\frac{\beta_0^+ r_0}{v_{\mathrm{sw}}\left(v_{\mathrm{sw}} + v_{\mathrm{ISM}}\left[r = r_0\left(\frac{v}{v_{\mathrm{max}}}\right)^{\alpha}\right]\right)^3}n\left[r = r_0\left(\frac{v}{v_{\mathrm{max}}}\right)^{\alpha}\right]\left(\frac{v}{v_{\mathrm{max}}}\right)^{\alpha-3} \tag{10}$$

3.3. Modeling of PUI Observations

[17] In order to allow a quantitative comparison of the model distributions with the observations, the velocity distribution function is transformed into the spacecraft frame. The differential flux is calculated from the distribution function and integrated over the instrument field of view (FOV) $\Delta\Omega$ and energy range ΔE to obtain the predicted counting rate C_{He^+} of He^+

$$C_{\mathrm{He}^+} = \Delta E \times G_F \times \frac{v_{\mathrm{sw}}^4}{\Delta\Omega\Delta E}\iint_{\Delta\Omega\Delta E} f'(w')w'^3\mathrm{d}w'\mathrm{d}\phi\sin\theta\mathrm{d}\theta \tag{11}$$

where G_F is the geometrical factor of the instrument and $f'(w')$ is the distribution function in the spacecraft frame, with $w' = v'/v_{\mathrm{sw}}$, where v' is the ion speed in the spacecraft frame, which can be directly related to the measured ion energy E.

[18] Here we use the fact that the velocity distribution function is Lorentz invariant [*Forman*, 1970]:

$$f(v) = f'(v') \tag{12}$$

[19] The ion velocities in the two frames of reference are related by the following transformation:

$$\vec{v'} = \vec{v} + \vec{v}_{\mathrm{sw}} \tag{13}$$

[20] Finally, the phase space density $F_{\mathrm{He}^+}(w')$ [*Gloeckler et al.*, 2004] in unit of $\mathrm{s}^3\ \mathrm{km}^{-6}$ is computed from the predicted counting rate using the following:

$$F_{\mathrm{He}^+}(w') = 378.4 \times (m/q)^2 \times \left(C_{\mathrm{He}^+}/\varepsilon^2\right) \tag{14}$$

where ε is the mean energy per charge for each voltage step, $m/q = 4$ is the mass per charge of He^+, and the constant 378.4 includes the nominal geometric factor and efficiency of the SWICS instrument as well as all unit conversions. The predicted phase space density can now be compared with the observed distribution or the phase space density, which is averaged over spin and instrument field of view and already corrected for the instrument efficiency.

4. Data and Model Comparison

4.1. Data Selection

[21] In order to allow a comprehensive comparison of the observed and predicted phase space densities based on the simplified neutral helium profile in the upwind direction, the ACE SWICS data have been selected for the month of June each year from 1999 to 2010 when Earth is on the upwind side. To eliminate contributions from inner source PUIs [*Geiss et al.*, 1995; *Gloeckler et al.*, 2000] and from the rollover near the PUI cutoff, we restrict our analysis to the velocity range $1.4 \le v/v_{\mathrm{sw}} \le 1.8$.

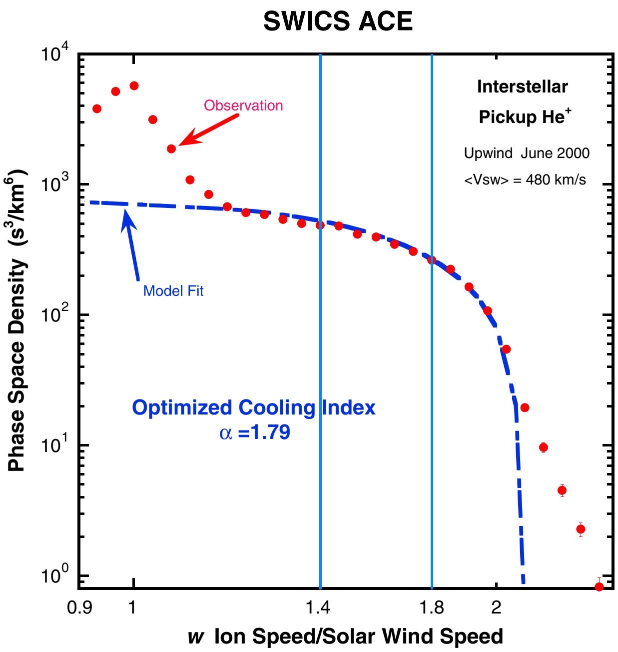

Figure 2. Phase space density $F_{He^+}(w)$ of pickup He^+ in the spacecraft frame as a function of w measured with ACE SWICS at 1 AU in the upwind direction, averaged over a 30 day time period in 2000. The model curve (dashed) represents a resulting cooling index $\alpha = 1.79$. It is normalized to match the observed phase space density.

[22] We average the daily values of helium photoionization rate (at 1 AU) [*Bzowski et al.*, 2012, 2013] over the preceding year to obtain the loss rate β_0^- of neutral helium atoms and over the month of June to obtain the He^+ PUI production rate β_0^+. It should be noted that electron impact ionization has a stronger dependence than $1/r^2$ [*McMullin et al.*, 2004]. Its contribution at 1 AU is about 10%, but it could be a significant fraction of the photoionization rate or for short times may even exceed it, very close to the Sun. We ignore such occasional increases in the current study but plan to address these in the future work.

4.2. Cooling Index Optimization

[23] To directly compare the predicted and observed phase space densities, we use a power law representation according to $F_{He^+}(w') = Aw'^{\gamma}$. We fit the power law index $\gamma = \alpha - 3$ and the constant A that is associated with the absolute value of the observed distribution. The cooling index α is optimized in the fit so that the predicted phase space density has the observed power law index γ. In combination, the total loss rate and the adiabatic cooling index determine the slope of the observed PUI distribution, but we already include the observed ionization rate as a known quantity in the model.

[24] In Figure 2, we show a comparison between the model and the observation. Plotted is the observed He^+ phase space density averaged over June 2000 as a function of w. The dashed curve is a model fit to the observed distribution with a resulting cooling index $\alpha = 1.79$. It can be seen that the model curve reproduces well the observed distribution in the phase space density region $1.4 \leq v/v_{sw} \leq 1.8$. Also, the cutoff appears to be reflected correctly when including nonzero interstellar medium (ISM) inflow speed in the model [*Möbius et al.*, 1999]. An extension of the He^+ pickup distribution beyond the cutoff speed $v = 2v_{sw}$, or a suprathermal tail, as seen here, has been reported as a ubiquitous feature in the solar wind [e.g., *Gloeckler*, 2003], which may be explained by acceleration mechanisms [e.g., *Fisk and Gloeckler*, 2006] that are active even in the quiet solar wind. The increase in the observed phase space density at lower energies may be attributed to a contribution of inner source PUIs at $0.9 < w \leq 1.17$, which completely dominate the pickup He^+ spectrum. However, the resulting cooling index for the selected range of w is larger than the previously assumed value of $\alpha = 1.5$.

[25] In order to see whether the cooling index is consistently different from the assumed value, we use the 12 min averaged ACE SWICS data sets in June from 1999 to 2010 along with hourly averaged solar wind velocity and IMF data sets and apply the same analysis method. Figure 3 shows the resulting cooling indices as a function of the sunspot number (averaged over the month of June each year, ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/monthly/MONTHLY). It is evident that the resulting cooling indices can be substantially larger or smaller than the ideal value of $\alpha = 1.5$. Furthermore, there appears to exist a trend with solar activity, but with large scatter. Because it is known that during radial IMF condition, PUI distributions show a strong and varying anisotropy [*Gloeckler et al.*, 1995; *Möbius et al.*, 1998], we restricted the data sets in a second step to nearly perpendicular IMF ($\theta_{Bv_{SW}} > 60^0$). Figure 4 shows the resulting cooling indices for this data selection in the same representation as in Figure 3. Here the correlation with solar activity appears significant, but still with noticeable scatter. We also calculated the correlation with the monthly averaged 10.7 cm solar radio flux; the correlation coefficient is similar ($r_{Corr} = 0.77, p_{Value} = 0.003$) for nearly perpendicular IMF and smaller ($r_{Corr} = 0.65, p_{Value} = 0.02$) for all IMF directions.

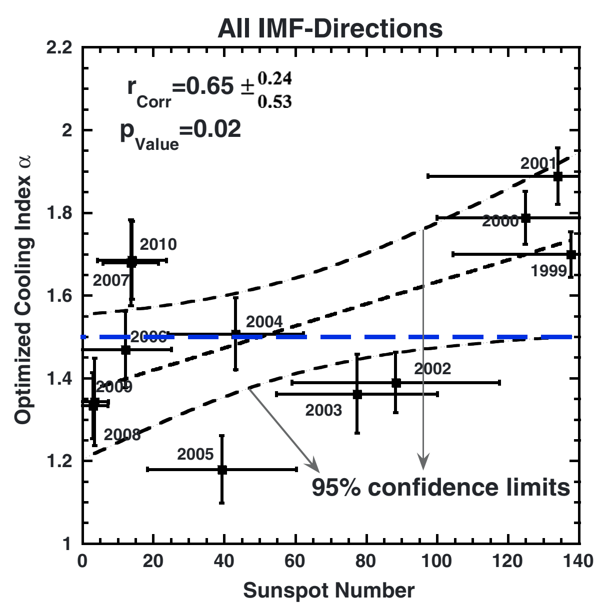

Figure 3. Resulting cooling indices (with uncertainties from the fit) as a function of 1 month averaged sunspot number in all IMF directions. r_{Corr} is the correlation coefficient and p_{Value} is the probability from the Student's t test for the fit relation to arise by chance. The blue dashed line is $\alpha = 1.5$.

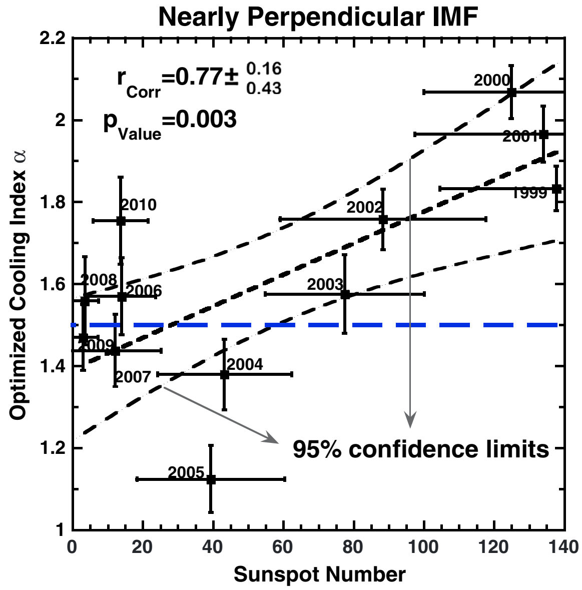

Figure 4. Same representation as in Figure 3, but the observed He^+ phase space density is constrained to nearly perpendicular IMF (> 60°).

5. Discussion and Conclusions

[26] We have presented observations of interstellar pickup He^+ distributions taken with ACE SWICS over 1 month (June) each year in the upwind direction over the previous solar cycle from 1999 to 2010. We compared these distributions with predicted velocity distributions, which are based on a stationary interstellar neutral gas distribution and ionization rates from direct observations of the solar EUV flux. Assuming rapid pitch angle scattering, an isotropic PUI velocity distribution was used according to equation (7) (based on *Vasyliunas and Siscoe* [1976]). It is characterized by a cooling index α, taken as a free parameter. In the comparison with the observations, we find that the cooling index averaged over the entire data set is $\alpha = 1.53 \pm 0.02$, i.e., rather close to the value of 1.5 attained by *Vasyliunas and Siscoe* [1976]. However, the individual monthly averages show a substantial variation from ≈ 1.1 to ≈ 1.9.

[27] As pointed out in the introduction, a value of 1.5 for the cooling index would only be justified if the PUI distribution cools adiabatically like an ideal gas with 3 degrees of freedom in a solar wind that expands exactly as $1/r^2$. Ideal gas-like adiabatic cooling can only be achieved if the PUIs are pitch angle scattered to isotropy on a shorter time scale compared with that for the expansion. In addition, the ionization of interstellar gas must scale strictly as $1/r^2$. Based on these conditions, the cooling index α may vary due to the following effects.

[28] 1. Slow and thus incomplete pitch angle scattering can substantially reduce the observed PUI fluxes in the antisunward hemisphere for IMF directions that are not perpendicular to the solar wind and lead to a steeper slope of the PUI distribution. Therefore, the slope of the distribution also depends on the IMF orientation and wave power.

[29] 2. For slow pitch angle scattering, the ideal gas approximation with 3 degrees of freedom as assumed in the numerator of $\alpha = 3/2$ is not valid. Then the conservation of the magnetic moment can only cool the velocity components perpendicular to the IMF and thus would lead to a cooling index $\alpha < 3/2$ for solar wind expansion as $1/r^2$.

[30] 3. Solar wind expansion as $1/r^2$ is only valid for an idealized radial and isotropic expansion at constant solar wind speed. However, there are many reasons for deviations, such as solar wind overexpansion at high latitudes, compressive stream interaction regions (SIRs), the compressed turbulent sheath ahead of fast coronal mass ejections (CMEs), and rarefaction or expansion in trailing edges of SIRs and CMEs.

[31] 4. Electron ionization typically decreases steeper with distance from the Sun than $1/r^2$. At times, electron ionization may become substantial inside 1 AU and then lead to a steeper neutral gas source function for PUIs with distance from the Sun than assumed.

[32] To eliminate as much as possible effects due to anisotropic distributions caused by incomplete pitch angle scattering noted in Point 1 which may show steeper and varying slopes, we repeated our analysis for a subset of our data restricted to pitch angles within 60°–120° when the PUI distributions show no anisotropy in the solar wind direction, which eliminates the direct steepening effects of incomplete pitch angle scattering. However, the distributions are not necessarily isotropic and, thus, may still not reflect an ideal gas behavior. In this sample, we find generally larger values for α, on average and for individual monthly averages. As shown in equation (7), the slope of the PUI distribution function is expressed as $\alpha - 3$; thus, a larger value of α is equivalent to a PUI distribution with a shallower slope as one would expect after eliminating cases with substantial steepening due to incomplete pitch angle scattering. A more detailed analysis of individual potential causes for the variation of the cooling index goes beyond the scope of this paper and will be the topic of future studies.

[33] As can be seen in Figures 3 and 4, the cooling indices appear to increase with the sunspot number. At least for the subset of the data taken for nearly perpendicular IMF, the correlation with the sunspot number appears to be significant, as the probability for the slope to occur by chance is only 0.3%. This result implies that the cooling index correlates with some conditions in interplanetary space that are related to solar activity. However, there are still large variations in the cooling index beyond the correlation with sunspot number. Let us explore a few potential sources for the observed correlation with solar activity and for the remaining variations.

[34] In our analysis, the resulting cooling index represents an average cooling over the entire PUI accumulation and transport to the observer and does not yet provide detailed insight into PUI transport processes. Although there is no anisotropy for pickup ion distribution which is a gyrotropic distribution within the field of view in the solar wind direction when the IMF is perpendicular, this gyrotropic distribution still does not represent an isotropic distribution if the pitch angle scattering is not as rapid as what is implicitly assumed equation (7) to apply. The related effects may result in a smaller cooling index as pointed out in Point 2. Therefore, wave power also plays a significant role in forming an isotropic distribution.

[35] Another possible source of the variations may be the presence of large-scale structures in the solar wind, such as solar wind compression and rarefaction regions. When the

fast solar wind overtakes the slow wind, a compression region is formed on both sides of the interface and a rarefaction region at the trailing edge of the fast wind. If the flow pattern persists over consecutive solar rotations, such a compression region is called a corotating interaction region (CIR); otherwise, it is a transient interaction region. Additionally, the shock and sheath ahead of a fast interplanetary coronal mass ejection (ICME) and the ICME itself contain compression and rarefaction regions, respectively. Compressions partially compensate the solar wind expansion if the expansion is described as r^{-k}, where k is the expansion factor resulting in $k<2$ for compression regions and $k>2$ for rarefaction regions. This behavior leads to an increase in α under the ideal gas assumption for compression regions. Also, PUI fluxes are higher in the compression regions, so their influence on the averaged PUI distribution is more pronounced. More ICMEs occur during high solar activity, which should lead to a higher value of α during this time. On the other hand, the occurrence rate and the compression strength of these events are varying stochastically. Thus, they can contribute to the remaining observed variations.

[36] As mentioned in Point 4 above, another cause for the variability of α may be enhanced electron impact ionization under certain solar wind conditions and at small heliocentric distance. It should be pointed out that the ionization processes play a dual role for the PUI velocity distribution function as given by equation (7): (1) The loss rate β_0^- for several months/years shapes a specific pattern of neutral density distribution and (2) the production rate β_0^+ which changes within days/weeks determines the actual production and the resulting phase space density of pickup He^+ observed by spacecraft. Because electron impact ionization becomes important only for short time periods, it has only a small effect on the overall loss rate β_0^-, and thus, the neutral gas distribution is still largely shaped by the $1/r^2$ dependence of the dominant ionization processes. However, electron impact ionization does affect the production rate β_0^+ for times when it becomes important and cannot be neglected. The electron impact ionization rate depends strongly on the actual distribution function of the electrons in interplanetary space, which varies greatly with solar wind conditions and the distance from the Sun. In particular, downstream of strong CME-driven shocks, where the solar wind density and temperature are very high, electron impact ionization could become a significant fraction of the photoionization rate [*Isenberg and Feldman*, 1995; *Feldman et al*., 1996] and, at times, may even exceed it. Contrary to photoionization and charge exchange, electron impact ionization is steeper than the distance dependence of $1/r^2$, which is relatively strong when it is very close to the Sun. This behavior will result in a steeper slope of the PUI distribution, which corresponds to a smaller cooling index α. Therefore, the distance dependence of electron impact ionization counteracts the effect of a compression and, thus, may lead to partial compensation. Therefore, both effects need to be studied separately in the future. As a corollary to this discussion, it should be noted that observational uncertainties in the total ionization rates used here have only minimal influence on our result. A relative 10% uncertainty (over the solar cycle) in the total rate results in a cooling index uncertainty of less than 5%, and such a variation does not change the correlation with sunspot number.

[37] In a comparison of PUI observations over one solar cycle with ACE SWICS, we found that, while the evolution of the PUI distributions in the inner heliosphere may be described, on average, over a long time period sample with adiabatic cooling and a cooling index $\alpha \approx 1.5$, as proposed by *Vasyliunas and Siscoe* [1976], the index varies substantially under a variety of interplanetary and solar activity conditions. In particular, it shows an increase with sunspot number as an indicator of varying solar activity. The resulting cooling index is generally larger and still shows some variations around the trend with solar activity when the observations are restricted to near-perpendicular IMF conditions and thus almost gyrotropic PUI distributions. Several potential causes related to varying conditions in interplanetary space have been identified that may contribute to the observed trend with solar activity and to the remaining variations in the cooling index. Among them, the expected effects of compressions and expansions in the solar wind, through CIRs and CMEs, on PUI cooling hold the promise of further insight. Therefore, a study comparing PUI distributions in individual compression and expansion regions with the same modeling technique presented here making use of the improved counting statistics with plastic stereo is underway. Furthermore, the potential effects of electron impact ionization in strong solar wind compressions and of varying degrees of pitch angle scattering need to be investigated in detail in the future by comparing the observations with a more sophisticated model of the PUI distributions. However, this work is beyond the scope of this introductory study.

[38] **Acknowledgments.** This work was carried out with support under the NASA SR&T program, grant NNX09AW32Q, and through the ACE mission, grant NNX08AI11G. E. Möbius also gratefully acknowledges support of the U.S. Department of Energy through LANL's Laboratory Directed Research and Development (LDRD) Program and Institute of Geophysics and Planetary Physics. M.B. and J.S. were supported by Polish Ministry for Science and Higher Education grant N-N203-513-038, managed by the Polish National Science Center

[39] Philippa Browning thanks the reviewers for their assistance in evaluating this paper.

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