Abstract
Solar wind measurements in the heliosphere predominantly comprise protons, alphas, and minor elements in a highly ionized state. The majority of low-charge states, such as He\(^{+}\), measured in situ are often attributed to pick-up ions of nonsolar origin. However, through inspection of the velocity distribution functions of near-Earth measurements, we find a small but significant population of He\(^{+}\) ions in the normal solar wind whose properties indicate that it originated from the Sun and has evolved as part of the normal solar wind. Current ionization models, largely governed by electron impact and radiative ionization and recombination processes, underestimate this population by several orders of magnitude. Therefore, to reconcile the singly ionized He observed, we investigate the recombination of solar He\(^{+}\) through charge exchange with neutrals from circumstellar dust as a possible formation mechanism of solar He\(^{+}\). We present an empirical profile of neutrals necessary for charge exchange to become an effective vehicle to recombine He\(^{2+}\) to He\(^+\) such that it meets observational He\(^+\) values. We find that the formation of He\(^+\) is not only sensitive to the density of neutrals but also to the inner boundary of the neutral distribution encountered along the solar wind path. However, further observational constraints are necessary to confirm that the interaction between solar \(\alpha\) particles and dust neutrals is the primary source of the He\(^+\) observations.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Interplanetary dust (821); Charge exchange recombination (2062)

1. Introduction
As solar material is released from the photosphere into the solar wind, it simultaneously experiences a rapid rise in temperature and decrease in density as it travels through the chromosphere and transition region layers and then enters the multimillion degree corona. As it travels through the corona, the density continues to steadily decrease as the temperature evolves more slowly. Once the density has decreased enough to effectively stop the ionization and recombination processes, the solar wind ionization status remains constant (i.e., “frozen in”) in the heliosphere. Given the high temperature of the corona, the solar wind ionization state consists of fully ionized H and He along with highly ionized minor ions. Therefore, it is predicted that the solar wind includes very few neutrals or low-ionized material as it travels through the interplanetary medium.

Consequently, low-ionized plasma detected by in situ instruments is not ordinarily attributed to the solar wind, but rather associated with pick-up ions (PUIs; Möbius et al. 1985; Gloeckler et al. 1993) of interstellar origin or inner source PUIs, which are predicted to be formed through the interaction with interplanetary dust (Geiss et al. 1994, 1995). PUIs are usually singly ionized particles that originate as neutrals of nonsolar origin such as interstellar neutrals, cometary material (Nordholt et al. 2003; Gilbert et al. 2015), interplanetary dust (Gloeckler et al. 2000; Grün & Landgraf 2001), or planetary wakes (Russell & Neugebauer 1981; Grünwaldt et al. 1997) that enter or exist in the heliosphere. Once in the heliosphere, the neutrals can be ionized through photoionization or electron impact ionization, and can also undergo charge exchange with solar wind ions. Once ionized, the charged particles are then swept up by the interplanetary electromagnetic field and travel alongside the ambient solar wind.

Additionally, low-ionized ions can be found to originate from prominence material within coronal mass ejections (CMEs; Lepri & Zurbuchen 2010; Gilbert et al. 2012). Prominences, or filaments while observed on the solar disk, are photospheric or chromospheric temperature (~10\(^4\) K) plasma that can be seen as cloud-like structures hovering over the limb of the Sun (see recent reviews by Labrosse et al. 2010 and Parenti 2014). Despite being immersed within the coronal environment, prominences can sustain a low temperature throughout their lifetime where neutral or low-ionized material is often observed. Prominences are thought to form within a twisted magnetic field that anchors them to the Sun. However, the magnetic field can become unstable, leading to a large-scale eruption that releases the prominence plasma into interplanetary space, forming a CME. Low-ionized plasma that is able to escape without being further ionized during the eruption can be observed in the extended solar corona as it travels into the heliosphere (Howard 2015; Wood et al. 2016; Ding & Habbal 2017). Therefore, prominence material can periodically contribute to the low-ionized charge states observed near Earth.

One manner in which PUIs can be differentiated from solar material such as prominence plasma is by examining their velocity distribution functions (VDFs) in phase space. PUI VDFs measured at 1 au do not exhibit a Maxwellian profile typical of the solar wind, but instead are, amid thermalization, governed by wave–particle interaction (Möbius et al. 1985; Gloeckler et al. 1993; Drews et al. 2016). The newly ionized neutrals, which now respond to electromagnetic forces, begin to gyrate around the solar wind’s magnetic field. In phase space, freshly formed PUIs form a ring distribution surrounding the solar wind ion population with a radius of the solar wind speed. Subsequently, as they evolve as part of the solar wind, the PUIs experience strong pitch-angle-scattering processes arising from plasma instabilities. This transforms their ring
distribution to a spherical shell as the particles converge toward the thermodynamic state of the solar wind. This is illustrated in measurements of H\(^+\) from the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses shown in Figure 1. The figure compares VDFs of the two main PUI populations, the interstellar and inner source PUI, to a typical solar wind distribution. The interstellar PUI VDF uniformly covers velocities below and above the proton VDF, with a sharp drop-off at twice the solar wind speed. The inner source PUI VDFs, formed closer to the Sun, are farther along the thermalization process as they have had more time to couple to solar wind properties. This distinction in the VDF profiles has become one of the main signatures used in the identification of nonsolar material in the heliosphere.

The helium focusing cone is an example of known interstellar PUIs routinely observed at the distance of Earth’s orbit (Gloeckler et al. 2004). The helium focusing cone is formed from neutral interstellar He that enters the heliosphere in the direction of the interstellar flow. The neutrals penetrate the heliosphere, are gravitationally attracted to the Sun, and subsequently photoionized along their path. This process produces a focused stream of He\(^+\) PUIs downstream of the Sun. At L1, instruments enter the interstellar He\(^+\) flow from the helium focusing cone annually during the months of November and December. These PUI measurements have been useful in the characterization of the interstellar medium, in the study of PUI processes in the heliosphere, and in the identification of nonsolar material in the solar wind (Gloeckler & Geiss 1998; Möbius et al. 2004).

The production of the inner source ions is still debated (Gloeckler & Geiss 1998; Allegreni et al. 2005); however, many studies propose a connection to the interplanetary dust and, possibly, sungrazing comets (Gloeckler et al. 2000; Wimmer-Schweingruber & Bochsler 2003; Bzowski & Królikowska 2005; Schwadron et al. 1999; Mann et al. 2010). Apart from their characteristic non-Maxwellian VDFs, the inner source ion origin is hinted at through studies of their chemical composition.

Some studies find agreement between the inner source ion and the solar wind compositional suggesting the inner source PUIs originate as part of the solar wind and subsequently formed as a result of interaction with interplanetary dust (Brownlee 1996; Gloeckler et al. 2000; Berger et al. 2015). Conversely, other studies find the elemental composition to differ from solar values (Taut et al. 2015). These discrepancies may be an indication that several processes could be taking part in forming the inner source ion population.

Earlier studies propose that neutrals (H, H\(_2\), He) outgassed from interplanetary dust grains can charge exchange with solar wind ions (Banks 1971; Fahr et al. 1981; Gruntman 1996). In this scenario, the dust neutrals encountered by the solar wind alphas and protons can charge exchange, resulting in ionized dust material along with singly ionized and neutral solar material. This is akin to charge exchange in cometary environments (Cravens 1997; Bodewits et al. 2004, 2006; Simon Wedlund et al. 2019). For the reactions \(\alpha + H_2 \rightarrow He^+ + H_2^+\) and \(\alpha + H \rightarrow He^+ + H^+\), where \(\alpha\) and He\(^+\) originate as part of the solar wind, studies find that charge exchange can produce a nonnegligible amount of solar He\(^+\) ions. This process would produce a singly ionized outgassed dust ion along with singly ionized He, from solar alphas, consistent with solar wind properties, e.g., a Maxwellian profile narrowly peaked around the proton speed that is characterized by the solar wind temperature.

Previous studies of He\(^+\) from SWICS on the Advanced Composition Explorer (ACE) investigate the interstellar component of the VDF; however, they also find a distribution that peaks at the solar wind speed often attributed to inner source ions (Chen et al. 2013). Our present work systematically analyzes He\(^+\) VDFs measured by ACE/SWICS between 1998 and 2011 to understand their source. Our analysis identifies several periods where He\(^+\) VDFs suggest a solar origin. However, we find current ionization models fail at reproducing the amount of solar wind He\(^+\) that is measured; therefore, we test the effectiveness of charge exchange with interplanetary dust neutrals as a possible mechanism in the formation of He\(^+\).

Results from this study have important implications for our current interpretation of the thermal properties of the plasma, which can be derived from ion composition measurements made in the heliosphere through nonequilibrium ionization modeling (Ko et al. 1997; Rakowski et al. 2007, 2011; Gruesbeck et al. 2011, 2012; Rivera et al. 2019). In these studies, the charge-state distributions are reconstructed from the known ionization and recombination processes that are accounted for in the ionization code, as well as the evolution of the wind plasmas’ thermodynamic properties. However, if charge exchange does play a role during the solar wind’s radial evolution, it may be an important process taking part in shaping the charge-state distributions observed in situ.

In this work, Sections 2 and 3 explore the He\(^+\) measurements from ACE/SWICS and their connection to the Sun, respectively. Section 4 describes the model for the singly ionized He\(^+\) population of solar origin formed through charge exchange of solar wind alphas with neutral H\(_2\) and H from interplanetary dust grains. Sections 5 and 6 present the simulation results and discuss neutrals in the vicinity of the Sun, respectively. Finally, Section 7 includes final remarks and further constraints to modeling results.

Figure 1. Taken from Gloeckler & Geiss (1998), this figure shows the superposition of the VDFs of interstellar pick-up ions, inner source ions, and solar wind ions in phase space. \(\xi\) is the degree of anisotropy in pitch-angle scattering from modeling results; see Vasyliunas & Siscoe (1976) and Thomas (1978) for details.

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2. Observations

2.1. Observations from ACE/SWICS

He\(^+\) measurements analyzed are taken from the time-of-flight mass spectrometer, SWICS, aboard ACE between 1998 and 2011. The identification of ions with SWICS is determined through a combination of measurements, as fully described in Gloeckler et al. (1994). The SWICS instrument is shown in Figure 2, where the track in dashed red demonstrates the particle’s trajectory.

Initially, the particle enters the instrument through the collimator and is immediately deflected by the electrostatic analyzer plates such that only ions of a specific energy per charge, \(E/Q\), reach the chamber entrance. The selected ions undergo post-acceleration prior to entering the time-of-flight (TOF) system that increases their energy to exceed the energy threshold of the solid-state detector that will measure its energy. Once in the TOF chamber, ions pass through a carbon foil that releases a secondary electron to trigger the start detector. There are a subset of particles that only log a start and stop TOF signal which are known as double coincidence counts. This occurs for many singly and low-ionized charge states such as the He\(^+\) measurements which are of interest in the present analysis. These ions are rare in triple coincidence counts except for those with high enough energy. Therefore, the double coincidence analysis enables the detailed study of He\(^+\) that would otherwise be largely unseen through the triple coincidence measurements.

In the double coincidence counts, the instrument records the TOF, \(t\), while the \(E/Q\) is known from the electrostatic analyzer. Because \(E_{\text{meas}}\) is not recorded, we cannot determine Equations (1), (2), and (4); however, we can still retrieve \(M/Q\) and \(v_{\text{ion}}\) from Equations (3) and (5). These two quantities allow us to determine the wind speed and identify the particle, although particles with the same \(M/Q\) ratio are blended together making their interpretation difficult.

Figure 3 shows a histogram of double coincidence counts collected between 2005 January 1 through October 31 plotted as a function of TOF and \(E/Q\). We include a selection of modeled tracks (including He\(^+\)) calculated using Equation (3), where individual ions are expected to be found along these tracks. Spurious background counts have been removed from the data set using a solar wind speed threshold as discussed in Gilbert et al. (2014).

A consequence of not having a direct measurement of \(E_{\text{meas}}\) is that ions with the same \(M/Q\) ratio overlap in the same track and require specific analysis (Gilbert et al. 2012). Ions from some of the most abundant elements, such as C\(^{3+}\) and O\(^{4+}\) with \(M/Q = 4\), are expected to mix with He\(^+\) counts in the double coincidence analysis. To ensure the signal extracted from the data set is dominated by He\(^+\), we determine the contribution from C\(^{3+}\) and O\(^{4+}\) during periods where He\(^+\) is observed in the triple coincidence data set. These instances occur when detector (Ipavich et al. 1978), and \(v_{\text{ion}}\) is the ion speed in km s\(^{-1}\).

The particles that produce a concurrent TOF (1) start and (2) stop signal along with the (3) particle’s energy measurement are said to produce triple coincidence measurements. However, not all ions can meet the minimum energy requirement to trigger the solid-state detector. There are a subset of particles that only log a start and stop TOF signal which are known as double coincidence counts. This occurs for many singly and low-ionized charge states such as the He\(^+\) measurements which are of interest in the present analysis. These ions are rare in triple coincidence counts except for those with high enough energy. Therefore, the double coincidence analysis enables the detailed study of He\(^+\) that would otherwise be largely unseen through the triple coincidence measurements.

From these independent measurements of the TOF, \(t\); ion energy, \(E_{\text{meas}}\); \(E/Q\) from the electric static analyzer; and the post-acceleration voltage, \(V\), ions can be unambiguously identified through the following relationships taken from Gloeckler et al. (1998):

\[
M = 2(t/d)^2(E_{\text{meas}}/\alpha), \tag{1}
\]

\[
Q = E_{\text{meas}}/\alpha + V + E/Q - E_{\text{loss}}/Q, \tag{2}
\]

\[
M/Q = 2(t/d)^2(V + E/Q - E_{\text{loss}}/Q), \tag{3}
\]

\[
E_{\text{ion}} = \frac{Q}{(Q/E)}, \tag{4}
\]

\[
v_{\text{ion}} = 438 \cdot [(E/Q)/(M/Q)]^{1/2}, \tag{5}
\]

where \(d\) is the flight path distance, \(V\) is the post-acceleration voltage, \(E_{\text{loss}}\) is the energy lost by the ion as it passes through the carbon foil, \(\alpha\) is the energy loss due to the solid-state detector (Ipavich et al. 1978), and \(v_{\text{ion}}\) is the ion speed in km s\(^{-1}\).

Figure 2. Schematic of the internal compartments of the ACE/SWICS instrument adapted from Gloeckler et al. (1998).

Figure 3. Time of flight vs. energy per charge of ion counts from ACE/SWICS for the accumulation period of 2005 January 1 to October 31.
higher-energy He\textsuperscript{+} ions manage to generate a signal in the solid-state detector, which allow for He\textsuperscript{+}, C\textsuperscript{3+}, and O\textsuperscript{4+} to be unambiguously identified. In these cases, we find $n_{\text{He}}/(n_{\text{He}} + n_{C^{3+}} + n_{O^{4+}})$ were $>80\%$ for over $95\%$ of He\textsuperscript{+} observations, suggesting that our signal is dominated by He\textsuperscript{+} counts. Additionally, in the triple coincidence counts, C\textsuperscript{3+} and O\textsuperscript{4+} are well sampled while He\textsuperscript{+} is periodically observed and less efficiently measured. Therefore, the He\textsuperscript{+} counts in the triple coincidence data are likely still underrepresented compared to C\textsuperscript{3+} and O\textsuperscript{4+}. Since the He\textsuperscript{+} counts are estimated to be a lower limit provides additional confidence that the He\textsuperscript{+} measurements likely exceed C\textsuperscript{3+} and O\textsuperscript{4+} during the periods observed together.

As Figure 3 illustrates, the He\textsuperscript{+} counts fall along the $M/Q = 4$ TOF track. The points included in this plot are those that fall within $20\%$ of the proton speed. The He\textsuperscript{+} counts cover a similar range and decrease at higher/lower $E/Q$ values along the TOF track, similar to common solar wind ions like He\textsuperscript{2+}, O\textsuperscript{6+}, O\textsuperscript{5+}.

### 2.2. Solar He\textsuperscript{+} Measurements

We can determine the origin of heliospheric ions through an inspection of the profile formed by their VDFs. Ions of solar origin resemble Maxwellian distributions while nonsolar PUIs are distinguished by their nonthermal profile. Through inspection of He\textsuperscript{+} VDFs, we identify several periods throughout 1998–2011 where the He\textsuperscript{+} VDFs peak within $20\%$ of the solar wind speed and that are well modeled by a Maxwellian profile. We search the VDFs for a fit to the distribution made up of at least five points with relative errors below $30\%$. The measurements identified through this criteria were also manually inspected to ensure the VDFs were well fitted.

As examples, we present sample VDFs in units of s\textsuperscript{3} km\textsuperscript{-6} for several 1 hr accumulation periods in 2003, shown in Figure 4. The figure includes a top plot where measurements are in black and a Maxwellian fit is in red, along with a plot of residuals between the fit and measurements plotted below. The counts in panels 2, 3, and 4 outside of the Maxwellian fits that produce large residuals, such as at $500$ km s\textsuperscript{-1} in panel 2, are counts that are not part of the solar He\textsuperscript{+} distribution and possibly associated with the PUI distribution as shown in Figure 1. Additionally, we include the solar wind properties during the four periods from Figure 4 in Figure 5. Figure 5 includes a multipanel plot between days $\sim 143–150$ in 2003 where the four colored vertical lines labeled 1 through 4 correspond to the labels in the four 1 hr VDFs. The black solid line denotes the boundary of an interplanetary CME identified in Richardson & Cane (2010).

In addition, the solar wind properties for the four periods are summarized in Table 1. We include the proton temperature, $T_p$; He\textsuperscript{+} temperature, $T_{\text{He}^+}$; mean proton speed, $V_p$; He\textsuperscript{+} speed, $V_{\text{He}^+}$. The proton speed and temperature are 1 hr averages from Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM; McComas et al. 1998) on ACE, and the He\textsuperscript{+} speed and temperature are computed from the Maxwellian fit.
Figure 6 shows a time series of all measurements that meet the VDF criteria. The top plot is the He$^+$/He$^{2+}$ density ratios between 1998.1 and 2011.63, and the bottom plot is zoomed into 2003 with the associated error bars. We note that values of He$^+$/He$^{2+}$ are used instead of an absolute abundance of He$^+$ to illustrate enhancements in He$^+$ densities compared to the alphas, as well as to easily compare with the results from the ionization code discussed in Section 4. We have removed measurements within CMEs and the helium focusing cone to capture He$^+$ in ambient solar wind. The measurements within CMEs and the focusing cone made up approximately 16% and 15% of the total points, respectively. We find that the remaining He$^+$/He$^{2+}$ measurements are observed throughout individual years and the solar cycle with values ranging an order of magnitude apart.

A summary of these values is shown in Figure 7. The figure includes the He$^+$/He$^{2+}$ annual median denoted as the red bar inside each box, annual mean as a red “+,” a blue box showing values within 25%–75%, and gray whiskers extending between the annual minimum and maximum values. We note that 1998 and 2011 were partially measured. We also include the 13 months smoothed monthly sunspot number1 in green, normalized to 0.35 for a more convenient comparison with He$^+$/He$^{2+}$ values. Generally, we find the median values of the He$^+$/He$^{2+}$ ratio range between 0.02 and 0.06, with the exception of an elevated value during 2007; however, there is no clear solar cycle dependence observed.

Figure 8 shows the distribution for all He$^+$/He$^{2+}$ values. The distribution peaks between 2.5 and 3.2 $\times$ $10^{-2}$ and range between 8.0 $\times$ $10^{-3}$ to 4.0 $\times$ $10^{-1}$. These values are larger than those previously reported from in situ measurements of

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Table 1

| VDF | $T_p$ ($10^5$ K) | $T_{he}$ ($10^5$ K) | $V_p$ (km s$^{-1}$) | $V_{he}$ (km s$^{-1}$) | He$^+$/He$^{2+}$ |
|-----|-----------------|-------------------|-------------------|-------------------|----------------|
| 1   | 1.08            | 6.77 ± 0.04       | 464               | 454               | 0.03           |
| 2   | 1.60            | 5.08 ± 0.30       | 573               | 626               | 0.01           |
| 3   | 1.85            | 5.57 ± 0.13       | 505               | 543               | 0.02           |
| 4   | 1.68            | 8.70 ± 0.02       | 718               | 720               | 0.06           |

1 http://www.sidc.be/silso/datafiles
Vela, which measured He\(^+\)/He\(^{2+}\) to be on the order of \(\sim 10^{-3}\) (Hundhausen et al. 1968).

When plotting the He\(^+\)/He\(^{2+}\) values against solar wind speed, as shown in Figure 9, the He\(^+\)/He\(^{2+}\) ratio is uncorrelated to speed; however, it appears predominantly in wind traveling faster than 400 km s\(^{-1}\). This may indicate that the process producing He\(^+\) becomes effective for plasma accelerated to a solar wind speed above this value but has no strong dependence on increasing speed. In addition, once above 400 km s\(^{-1}\), He\(^+\) appears independent of speed suggesting the production of He\(^+\) is not dependent on the mechanism accelerating the solar wind.

Furthermore, the temperature values computed for He\(^+\) coincide with previous measurements from ACE/SWICS, which find a mass proportional and super-mass proportional relationship for a large number of minor ion temperatures in the
solar wind (Tracy et al. 2015, 2016). Collectively for all ions, they find the following relationship, \( T_{\text{ion}}/T_p = S(m_{\text{ion}}/m_p) \), for \( S = 1.35 \pm 0.02 \), where \( T_{\text{ion}} \) and \( T_p \) are the ion and proton temperature, respectively, and \( m_{\text{ion}} \) and \( m_p \) are the ion and proton mass, respectively. A value of \( S = 1 \) describes a mass proportional relationship while \( S > 1 \) would suggest a supermass proportional relationship, although the relationship is sensitive to the solar wind’s collisional age, \( A_C \), as described in Tracy et al. (2016). This proportionality describes ions within low \( A_C \) and is gradually erased for ions within plasma of higher \( A_C \) as ions become increasingly coupled to the proton temperature. For the VDFs in Figure 4, we compare the \( \text{He}^+ \) temperatures within the different solar wind periods, (1) \( T_{\text{He}^+}/T_p = 1.57 \) \( m_{\text{He}^+}/m_p \), (2) \( T_{\text{He}^+}/T_p = 0.8 \) \( m_{\text{He}^+}/m_p \), (3) \( T_{\text{He}^+}/T_p = 0.75 \) \( m_{\text{He}^+}/m_p \), and (4) \( T_{\text{He}^+}/T_p = 1.30 \) \( m_{\text{He}^+}/m_p \). The normalized distribution of all values of \( S \) are presented in Figure 7. We find a relatively low \( A_C \) for the \( \text{He}^+ \) values, between \( 8.1 \times 10^{-3} \) and \( 1.7 \times 10^{-2} \). The median ± median absolute deviation value, as was computed in Tracy et al. (2016), is \( S = 1.5 \pm 0.5 \), which is consistent with \( S = 1.35 \pm 0.02 \) from Tracy et al. (2016). \( T_{\text{He}^+} \) reflects ion temperatures typical at 1 au, further suggesting the \( \text{He}^+ \) measurements undergo thermal evolution similar to the solar wind, as well as being independent of the mechanism heating the solar wind.

When examining the chemical composition of the plasma corresponding to \( \text{He}^+/\text{He}^{2+} \) measurements, we find that the solar \( \text{He}^+ \) is independent of solar wind type. The well-known first ionization potential (FIP) effect has been shown to result in...
a range of elemental compositions between different parts of the Sun, notably between the photosphere and other structures (Feldman & Widing 1993; Raymond et al. 1997; Feldman 1998; Raymond 1999; Landi & Testa 2015; Parenti et al. 2019). This makes the composition measured in the heliosphere a key indicator to the solar wind’s origin at the Sun.

Measurements of low-FIP Fe and Mg to high-FIP O compared to the ratio of its photospheric value, \( \frac{\text{Fe}}{\text{O}}/\left(\frac{\text{Fe}}{\text{O}}\right)_{\text{phot}} \) and \( \frac{\text{Mg}}{\text{O}}/\left(\frac{\text{Mg}}{\text{O}}\right)_{\text{phot}} \), are commonly used to characterize solar wind streams (von Steiger et al. 2000; Schwadron et al. 2002; Zurbuchen et al. 2012). Figure 11 shows a scatter plot of compositional values for all \( \frac{\text{He}^+}{\text{He}^{2+}} \) vs. \( \frac{X}{\text{O}}/\left(\frac{X}{\text{O}}\right)_{\text{phot}} \), where \( X = \text{Fe} \) and Mg.

3. Genesis of Solar \( \text{He}^+ \) Ions

Previously, many nonequilibrium ionization modeling studies have aimed to simulate the radial ion evolution of the solar plasma (Rakowski et al. 2007, 2011; Gruerebeck et al. 2012; Landi et al. 2012; Rivera et al. 2019). One example is a study using the Michigan ionization code (MIC), also used in the present study and further described in Section 4, to model the ionization and recombination processes governing the C, O, and Fe charge-state evolution within coronal and equatorial solar wind streams (Landi et al. 2012). We use the MIC to simulate the ion evolution of He within the same solar wind of Cranmer et al. (2007) as shown in Figure 12, and present the He evolution in Figure 13. The simulations predict a value of \( \frac{\text{He}^+}{\text{He}^{2+}} \) of \( 10^{-5} \), which are three orders of magnitude lower compared to the observations in the present study with a median value of \( \sim 10^{-2} \). This suggests that either the radial profiles of the solar wind properties do not capture these observations or some other process, unaccounted for in the MIC, is active.

In a comprehensive study comparing MIC results to measurements of C, N, O, Ne, Mg, Si, S, and Fe in the solar wind found that, generally, the three leading solar wind models consistently underestimated the ionization level of all species (Landi et al. 2014). This indicated that the thermodynamic models of the solar wind needed to be adjusted such that it increased the ionization occurring in solar wind plasma. However, increasing the ionization of the plasma is the opposite to what would produce a higher \( \frac{\text{He}^+}{\text{He}^{2+}} \) necessary to meet observations. This suggests that the ionization codes, rather than the solar wind models, may be missing the necessary process generating the \( \text{He}^+ \) that is measured.

We find the \( \text{He}^+ \) measurements in the present analysis are (1) characterized by thermodynamic properties compatible with other solar wind ions, (2) independent of wind type and source region, and (3) do not appear to show a solar cycle dependence. This aligns well with the production of \( \text{He}^+ \) from charge-exchange processes that will largely preserve the ion’s solar wind identity in phase space, assuming no significant transfer of energy, and are independent of solar wind type. Also,
zodiacal light observations measured across the solar cycle are shown to remain stable, suggesting the dust, and thus the charge-exchange processes and He$^+$ densities, is not expected to exhibit a strong solar cycle dependence (Leinert et al. 1982).

We suggest that the He$^+$ observed in the solar wind is a signature of the charge-exchange process that acts to transform a small fraction of alpha particles to He$^+$ through this interaction. As mentioned previously, charge exchange between the solar wind and dust neutrals has been investigated in the past (see Banks 1971; Fahr et al. 1981; Gruntman 1996); however, the studies did not include observations to constrain modeling results. In the present study, we test charge exchange from several reactions as a possible mechanism in the production of solar He$^+$ that is analyzed in Section 2.

4. Modeling of Solar He$^+$ Ions

To quantify the neutral population necessary to produce the He$^+$/He$^{2+}$ observed through charge-exchange processes, we simulate the radial evolution of He ions with an ionization code that includes the effects of charge exchange with outgassed dust neutrals on a parcel of plasma traveling from the Sun to 1 au. The background neutrals are test particles encountered by the solar wind and their radial distribution remains constant in time while the solar wind alpha particles recombine through charge exchange and thus decrease their abundance.

We have modified the MIC to simulate alpha particle evolution. The MIC solves a time-dependent set of equations at each step of the plasma’s radial expansion using recombination and ionization rates from the CHIANTI 9 atomic database (Dere et al. 1997, 2019). The model incorporates the following processes: excitation-autoionization, dielectric recombinations, collisional ionization, radiative recombination, and photoionization, and it has been adapted in the present work to include specific charge-exchange reactions from Table 2. Table 2 includes a collection of reactions previously investigated in the literature that are relevant to the present study (Banks 1971; Gruntman 1996). The cross-section values for each reaction are taken from Barnett et al. (1990) and plotted as a function of speed in Figure 14.

The charge-exchange reactions are included with a term denoted in the equation below as $N_{\text{CE}}$.

\[ \frac{dy_i}{dt} = n_e\{y_{i-1}I_{i-1}(T_e) + y_{i+1}R_{i+1}(T_e)\} \]
\[ + y_{i-1}P_{i-1} - y_i[n_e(I_i(T_e) + R_i(T_e)) + P_i] + N_{\text{CE}}, \]

where $y_i$ is the ion’s relative abundance of the given element in charge state $i$, $n_e$ is the electron density, $T_e$ is the electron temperature, and $R(T_e)$ and $I(T_e)$ are the total recombination and total ionization rates, respectively, that include all mentioned processes except charge exchange. In Equation (6), simulations are for $i = 0, 1, 2$ corresponding to He$^{0,1,2+}$, respectively. The $P$ is the photoionization term, described as

\[ P_i = \int_{\nu_i}^{\infty} \frac{4\pi J(\nu)\sigma_i(\nu)}{h\nu} d\nu, \]

where $J(\nu)$ is the mean spectral radiance of the Sun, $\sigma_i(\nu)$ is the photoionization cross section for ion $i$, $h$ is the Planck constant, and $\nu_i$ is the frequency for the ion’s corresponding ionization energy.
The term $N_{\text{CE}}$ is defined as follows:

$$N_{\text{CE}} = \begin{cases} \sum_j (y_j G_j^{\text{CE}} - y_j L_j^{\text{CE}}) & \text{for } \text{He}^+ \\ \sum_j (y_j L_j^{\text{CE}} - y_j G_j^{\text{CE}}) & \text{for } \text{He}^2+ \end{cases}$$

where $j$ reactions refer to reactions 1–4 that are noted in Table 2. This incorporates the effect of concurrent charge-exchange processes with neutrals below 1 au. $G_j^{\text{CE}}$ in $s^{-1}$ is the charge-exchange recombination process and $L_j^{\text{CE}}$ in $s^{-1}$ is the reverse process. For $L_j^{\text{CE}}$, we assume the principle of detail balance such that $L_j^{\text{CE}} = (y_j/n_j) T E G_j^{\text{CE}}$, where $(y_j/n_j) T E$ is the He$^2+/\text{He}^+$ charge-state ratio in thermal equilibrium. The reaction rates are computed as a function of distance as $G_j^{\text{CE}}(r) = n_{\text{H}2}(r)v(r)\sigma_j^{\text{CE}}(v)$, where $n_{\text{H}2}(r)$ is the number density of H or H$_2$ with heliocentric distance, $r$, from the Sun. The $\sigma_j^{\text{CE}}(v)$ is the cross section for each charge-exchange process, $j$, between He$^2+$ and neutrals.

The dust neutrals within the interplanetary medium are test particles in the simulation. We assume a static profile for the population of outgassed H and H$_2$ originating from the circumsolar dust grains. The dust has been observed to be distributed symmetrically across the ecliptic plane with a large concentration in the vicinity of the Sun. The outgassed neutral profile in our simulations assumes a symmetric and constant distribution surrounding the Sun that coincides with the dust population. This assumption holds given that the dust structure is not observed to undergo large changes within the timeframe of the solar wind propagation to 1 au, which is on the timescale of days.

The neutral dust profile, $n$ (cm$^{-3}$), is taken to be in the form

$$n_{\text{H}_2+\text{H}_2}(r) = \begin{cases} 0 & r < \text{Inner edge (au)} \\ \gamma \cdot r^{-\alpha} & r > \text{Inner edge (au)} \end{cases}$$

where $\alpha$ and $\gamma$ are free parameters that govern the density of neutral dust material available for charge exchange. The radial distance, $r$, is in astronomical units. The density profiles and the corresponding parameters used are shown in Figure 15 where the neutral profiles are a sum of parts H and H$_2$, where $n_{\text{H}_2} = 8 \cdot n_{\text{H}}$ as is approximated to be outgassed by the dust in Gruntman (1996). In addition, the solid black curve is the $n_{\text{H}_2+\text{H}_2}$ predicted by previous models, further discussed in Section 6.

Many different combinations of the free parameters have been used to test a range that may produce the observed He$^+/\text{He}^2+$ measured at 1 au. Parameters are motivated by observations of the distribution of dust from zodiacal light and F-corona studies previously found in the literature (Kimura & Mann 1998; Kimura et al. 1998; Mann et al. 2004). There is still a large variation between the distribution of interplanetary dust inferred through remote-sensing measurements. Observations of the F-corona continuum in the near-infrared show a sharp drop-off in brightness that scales between $r^{-1.9}$ to $r^{-2.5}$ for the equatorial and $r^{-2.3}$ to $r^{-2.8}$ for the polar solar regions below 10$R_\odot$, which correspond to freeze-in distances in our simulations (Koutchmy & Lamy 1985; MacQueen & Greeley 1995; Leinert & Jackson 1998). In Gruntman (1994, 1996), both $n_{\text{H}}$ and $n_{\text{H}_2}$ were estimated to be $\propto r^{-1.15}$ below 1 au. However, neutrals in the heliosphere are highly uncertain and remain relatively unknown in the vicinity of the Sun. For this reason, we explore a different range of values.

Furthermore, near-infrared measurements observe an intensity enhancement at an elongation angle, $\epsilon$, of 1$^\circ$. The elongation angle is defined as the angle made between the line of sight of the observer and the Sun’s center. The distance from the Sun along the plane of the sky for a corresponding $\epsilon$ is $r = \sin(\epsilon) \cdot 1(\text{au})$. For $\epsilon = 1^\circ$, this equates to approximately $r = 4R_\odot$ on the plane of the sky. An elevated intensity in remote measurements at this distance has long suggested a possible inner edge of the dust at that location (Kimura & Mann 1998; Kimura et al. 1998; Mann et al. 2004). The empirical neutral profile we test assumes a theoretical inner edge that begins at 4$R_\odot$. In addition, we investigate

![Figure 15. Empirical models of H+$\text{H}_2$ density profiles with an inner edge of 4$R_\odot$ starting at the dotted line and 8$R_\odot$ starting at the solid line. The solid line is the density of $n_{\text{H}_2+\text{H}_2}$ predicted using the dust geometric factor, $\Gamma = \Gamma_{E}(r_{E}/r)^{\gamma}$; see description in Section 6.](image-url)
Figure 16. He charge-state evolution generated using properties of slow (left column) and fast (right column) solar wind between 1 to 30\(R_\odot\). The plots show the radial evolution of He\(^+\)/He\(^{2+}\) for a neutral profile with an inner boundary of 4\(R_\odot\) (top) and 8\(R_\odot\) (bottom). The shaded purple region covers the range of He\(^+\)/He\(^{2+}\) values found in the observations.

distributions with an inner edge as far out as 8\(R_\odot\) to evaluate the sensitivity of the results to the location of the inner edge.

To simulate the solar wind ion evolution, we use models for the equatorial (slow) and coronal hole (fast) solar wind derived from Cranmer et al. (2007) shown in Figure 12.

5. Modeling Results

We simulated the charge-state distribution of He as a function of distance using the modified MIC that includes charge exchange with the surrounding outgassed dust neutrals. For each neutral distribution in Figure 15, we present the corresponding simulated He\(^+\)/He\(^{2+}\) radial evolution shown in the top plot of Figure 16, for the slow (left) and fast (right) solar wind. In addition, we include the solutions for a neutral inner edge of 8\(R_\odot\) in the bottom of Figure 16 where the simulated He charge states are presented in the same manner. Each plot includes the range of observed He\(^+\)/He\(^{2+}\) observations denoted as the shaded purple region.

We test values between a power-law exponent of \(a = 2.0\) and \(a = 2.8\) with increasing \(\gamma\) until the He\(^+\)/He\(^{2+}\) value reaches the same order of magnitude as the median He\(^+\)/He\(^{2+}\) observed with ACE/SWICS, \(\sim 10^{-5}\). The results show a sharp increase of He\(^+\)/He\(^{2+}\) as the simulated plasma parcel encounters the dust. This is due to the step function used to describe the dust in the inner corona; however, the region below the inner edge we define could be decreasing to zero in a smoother way.

In both the slow and fast cases, we can begin to see a deviation between the He values with the presence of neutrals immediately at the inner edge of the dust. The slow and the fast solar wind values respond similarly to charge-exchange processes even though their thermodynamic properties can differ significantly during radial expansion. This is consistent with the He\(^+\)/He\(^{2+}\) observations which are found to be largely independent of solar wind type, e.g., solar wind speed and composition.

6. Discussion

We find that the He\(^+\)/He\(^{2+}\) simulated values are sensitive to the density for all the neutral profiles tested. The neutral profiles that generate a value of He\(^+\)/He\(^{2+}\) within the range of the observations correspond to \(a = 2.8\) and \(\gamma > 1 \times 10^{-2}\), \(a = 2.5\) and \(\gamma > 5 \times 10^{-2}\), for an inner boundary of 4\(R_\odot\), shown at the top of Figure 16. For an inner boundary of 8\(R_\odot\), shown at the bottom of the same figure, the neutral profile within the observational range is \(a = 2.8\) and \(\gamma > 5 \times 10^{-2}\).

In addition, the He values are sensitive to the location of the inner edge along with the density of the dust profile. A distribution with an inner edge closer to the Sun produces an overall larger He\(^+\)/He\(^{2+}\) heliospheric value when maintaining the same \(a\) and \(\gamma\) values. Comparing the rows of slow and fast wind, the profile with parameters, \(a = 2.8\) and \(\gamma = 5 \times 10^{-3}\), with an inner edge of 4\(R_\odot\), produced a He\(^+\)/He\(^{2+}\) value roughly an order of magnitude higher compared to a profile with an inner edge of 8\(R_\odot\). This may be a result of charge exchange occurring earlier in the evolution, giving the alpha particles more time to recombine prior to the freeze-in height of He\(^{2+}\). Alternatively, given that the reaction rates, \(L\) and \(G\), depend on the neutral density, a higher density of neutral material can also contribute to a larger He\(^+\)/He\(^{2+}\) ratio overall.

Moreover, we expect the majority of neutral H and H\(_2\) closest to the Sun to originate from dust while the interstellar neutral values begin to dominate much farther from the Sun (Fahr et al. 1981). From Figure 16, we find that the ions are
highly sensitive to the presence of neutrals below $15R_\odot$, for the slow, and $30R_\odot$, for the fast, where the dust component dominates. Therefore, we expect that the majority of solar He$^+$ predicted to form through charge exchange from outgassed dust neutrals rather than interstellar material.

We compare our results to previous values of outgassed H$_2$ and H densities (Fahr et al. 1981). Following Fahr et al. (1981), the production rate for H and H$_2$, $D_p(r) = n_p(r)\nu_{\text{rel}}(r)\Gamma(r)$, where $n_p(r)$ is the proton density with radial distance $r$, $\nu_{\text{rel}}(r)$ is the relative velocity between solar wind and the dust grains, $\epsilon = 0.9$ and $\epsilon = 0.05$ are the desorption efficiency for H$_2$ and H, respectively, and $\Gamma(r)$ in cm$^{-1}$ is the dust cross-sectional area per unit volume of the dust,

$$\Gamma(r) = \int_{s_{\text{min}}}^{s_{\text{max}}} \pi s^2 f(s, r) ds,$$

where $s$ is the radius of the grain, and $f(s, r)$ is the distribution of grains with grain size, $s$ and distance from the Sun, $r$.

Following equilibrium conditions, $D_p(r)$, of H and H$_2$, $D_p(r) = n_{\text{H,He}}(r)(C^p(r) + C^e(r) + C^{\text{exc}}(r))$, where $C^p(r)$ is the photoionization rate, $C^e(r)$ is the electron impact ionization rate, and $C^{\text{exc}}(r)$ is the proton-charge-exchange rate of H and H$_2$ with distance from the Sun. Rearranging, density can be computed as the sum of $n_{\text{H,He}} + n_{\text{H,He}}(r)$ in cm$^{-3}$ as the following,

$$n_l(r) = \frac{\sum_{i} n_{p}(r)\nu_{\text{rel}}(r)\epsilon_i \Gamma(r)}{C^p(r) + C^e(r) + C^{\text{exc}}(r)} \tag{11}$$

for $l = \text{H}_2$ and H. Assuming $C^p(r) = C^e(r)\left(\frac{\epsilon}{\epsilon_{\text{rel}}} r^2\right)$, $C^e(r) = C^e_{\text{E}}\left(\frac{\epsilon}{\epsilon_{\text{rel}}} r\right)^2$, and $C^{\text{exc}}(r) = C^{\text{exc}}_{\text{E}}\left(\frac{\epsilon}{\epsilon_{\text{rel}}} r^2\right)$, where the subscript “E” refers to that value at 1 au, $C^e_{\text{E}} = 3.67 \times 10^{-7}$ cm$^3$s$^{-1}$, $C^{\text{exc}}_{\text{E}} = 1 \times 10^{-7}$ cm$^3$s$^{-1}$, and $C^{\text{exc}}_{\text{E}} = 1 \times 10^{-8}$, $1 \times 10^{-7}$ cm$^3$s$^{-1}$ for H$_2$ and H, respectively (Banks 1971; Gruntman 1996). There is still a large uncertainty on the value of $\Gamma$ and how it changes with radial distance from the Sun. Previous values of $\Gamma$ span five orders of magnitude, $\sim 10^{-17} \sim 10^{-21}$ (Bame et al. 1968; Banks 1971; Holzer 1977).

Fahr et al. (1981) approximated the geometric factor as $\Gamma(r) = \frac{1}{L_{\text{E}}(r)^2}$, where $L_{\text{E}} = 2 \times 10^{-19}$ cm$^{-1}$ and $\xi = 1.3$. At $4R_\odot$, this produces $n_{\text{H,He}} \sim 5 \times 10^{-2}$ cm$^{-3}$ which is four orders of magnitude lower compared to the minimum density that would generate He$^+$/$\text{He}^{2+}$ to meet observational values for the $4R_\odot$ profile case, $a = 2.8$ and $\gamma = 1 \times 10^{-2}$. For an upper limit value of $\Gamma = 9 \times 10^{-17}$, the density predicted increases to $n_{\text{H,He}} \sim 10$ cm$^{-3}$ at $4R_\odot$, which is two to three orders of magnitude lower compared to our required value, as shown with the solid black curve in Figure 15. Generally, our results suggest a much larger dust density profile or distribution of grain size, as described by $\Gamma(r) = \frac{1}{L_{\text{E}}(r)^2}$, than previously predicted in the vicinity of the Sun to generate the H and H$_2$ densities necessary to meet observational values.

Our results may also suggest that there could be an additional process contributing to the formation of solar-like He$^+$. One possibility would be the ionization of neutral He outgassed from the dust. This process would produce He$^+$ where the dust is present that could potentially have enough time to thermalize by 1 au. If so, this could generate a nonsolar He$^+$ VDF with a Maxwellian-like profile rather than a typical PUI profile. This scenario would require further testing with the MIC, along with kinetic modeling of the VDF evolution from its creation in the corona to 1 au.

Moreover, our simulations predict the presence of neutral material in the extended corona, which coincides with several decades of eclipse observations that observe He I 10830 in the vicinity of the Sun. The diffuse neutral helium found in eclipse observations was initially attributed to being geocoronal and to interstellar material (Kuhn et al. 1996, 2007); however, the most recent observations have linked the neutral He to the Sun (Moise et al. 2010; Dima et al. 2018). These studies suggest the diffuse He signal arises from the interaction between the solar wind alphas and surrounding dust, essentially acting to neutralize the alpha particles as they propagate from the Sun. In a similar manner to the present study, we can independently determine the density of neutral material in the extended corona by focusing on charge-exchange reactions between H and H$_2$ that can neutralize alpha particles. This can be another method of further constraining neutrals near the Sun.

Furthermore, if the production of solar He$^+$ is due to the presence of dust, then there will likely be a reduction in He$^+$/He$^{2+}$ at higher latitudes where dust is depleted compared to the ecliptic. This can be achieved with future off-ecliptic measurements from the Heavy Ion Sensor (HIS) on the Solar Orbiter (Müller et al. 2020). The Ulysses spacecraft has previously sampled the solar wind above and below the ecliptic outside of the orbit of Earth; however, HIS will do this around the orbit of Mercury ($\sim 60R_\odot$), where we expect the majority of newly generated He$^+$ to be primarily formed through dust interaction in the inner heliosphere.

Another important observational constraint to the charge-exchange process is the emission of X-ray and far-ultraviolet (FUV) radiation. Observations from the coma of Comet C/1996 B2 Hyakutake were discovered to emit a strong X-ray and EUV signal as a by-product of charge exchange between neutral cometary material and solar wind ions (Lisse et al. 1996; Cravens 1997). From laboratory experiments, photon emission through electron capture show that solar wind $\alpha$ particles and H and H$_2$ from interplanetary dust should produce emission in the FUV or EUV spectral range from He II 304 Å, for He$^+$ produced, and He I 584 Å, for neutralized He formed (Bodewits et al. 2006).

Lastly, in our simulations, we specified a static neutral distribution; however, the dust can vary at different spatial scales. Solar transients and periodic deposits of fragmented comet material near the Sun can disrupt the homogeneity of the dust (Jones et al. 2018). This can develop local temporal and spatial changes in the dust, allowing for periodic enhancements or depletions in neutral density that could result in sporadic fluctuations of He$^+$/He$^{2+}$ values. This could explain the relatively large fluctuations that are occasionally observed, as shown in Figure 6.

7. Summary and Conclusions

In the present work, we investigate the presence of He$^+$ observed by ACE/SWICS in the solar wind throughout the majority of cycle 23 (1998–2011) in order to understand the origin and mechanism that produce this ion. From the ACE/SWICS data set, we identified several periods where He$^+$ VDFs can be well modeled by a Maxwellian distribution traveling near the corresponding solar wind proton speed whose temperature follows a super-mass proportional relationship that coincides with previous studies of ions in the solar
wind. These properties suggest the He\(^+\) ions resemble material of solar origin.

Furthermore, He\(^+\) does not depend on the solar cycle, wind speed, composition, and source region, suggesting that the mechanism producing He\(^+\) is independent of processes that generate the distinctive properties of the solar wind but to a process common to wind traveling on the ecliptic and occurring before reaching 1 au.

Current simulations of He charge-state distributions accounting for electron impact ionization and recombination along with photoionization and radiative recombination processes are shown to underestimate He\(^+\)/He\(^{2+}\) by three to four orders of magnitude. This indicated the possibility of missing processes that may be active during the radial expansion of the solar wind. To reconcile the missing He\(^+\), we tested the effectiveness of charge exchange between the solar wind and H and H\(_2\) from dust in the production of He\(^+\) to determine if this recombination process could explain the enhancement of He\(^+\)/He\(^{2+}\) at 1 au. Our work estimates the radial distribution and density of neutrals that are required to be present during the solar wind’s radial expansion, which could make charge exchange an effective method of transforming a small fraction of solar alpha particles into singly ionized He to meet observational values. Results show that a distribution of dust neutrals (H, H\(_2\)) following a power law of the form \(\gamma r^{-a}\), with \(\gamma > 0.05\) for \(a = 2.8\), with an inner edge between 4\(R_\odot\) and 8\(R_\odot\) can produce the He\(^+\)/He\(^{2+}\) values. Our results predict a density of H and H\(_2\) that is several orders of magnitude larger than previous models, suggesting (1) that dust density and distribution of grain size in the vicinity of the Sun are larger than previously described, and/or (2) there may be additional processes contributing to the solar He\(^+\) population below 1 au.

Further observations are needed to better constrain the density of H and H\(_2\) near the Sun. However, our modeling results may be an indication of the importance in accounting for processes between the dust and solar wind. One of the key implications from our results is the importance of charge-exchange processes during the radial propagation of the solar wind. This may be a significant process shaping the ion composition measured in the heliosphere.

Further constraints to the presence of neutrals are necessary to continue testing our hypothesis more rigorously. Remote observations remain limited to the progress of dust studies due to the loss of spatial information from intensities integrated along the line of sight. A more effective manner of probing the dust environment near the Sun is through a combination of remote and in situ observations.

The authors thank the anonymous referee for insightful comments that greatly improved the final manuscript. J.Y.R. was supported by a Rackham Graduate School Fellowship from the University of Michigan and the Newkirk Fellowship from the High Altitude Observatory. J.Y.R. thanks Jim Raines, Sarah Spitzer, and Ryan Dewey for valuable discussion in preparing this manuscript. E.L. acknowledges support from NASA grants 80NSSC18K0647, 80NSSC18K1553, 80NSSC20K0185 and NSF grants AGS-1408789 and AGS-1621686. S.T.L. was supported by NSF grant award AGS-1460170, AGS-1358268 NASA grants 80NSSC18K0645, 80NSSC20K0185, 80NSSC19K0853, 80NSSC20K0192, and 80NSSC18K0101. J.Y.R. and S.T.L. acknowledge the International Space Science Institute in Bern, Switzerland, for helpful discussion related to this work. CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA), and the University of Cambridge (UK).

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