10-2015

Exploring the Possibility of O And Ne Contamination in Ulysses Observations of Interstellar Helium

Brian E. Wood
Naval Research Laboratory

Hans-Reinhard Müller
Dartmouth College

Maciej Bzowski
Space Research Centre of the Polish Academy of Sciences

Justyna M. Sokół
Space Research Centre of the Polish Academy of Sciences

The Astrophysical Journal Supplement Series, 220:31 (6pp), 2015 October doi:10.1088/0067-0049/220/2/31

EXPLORING THE POSSIBILITY OF O AND Ne CONTAMINATION IN *ULYSSES* OBSERVATIONS OF INTERSTELLAR HELIUM

Brian E. Wood[1], Hans-Reinhard Müller[2], Maciej Bzowski[3], Justyna M. Sokół[3], Eberhard Möbius[4], Manfred Witte[5], and David J. McComas[6]
[1] Naval Research Laboratory, Space Science Division, Washington, DC 20375, USA; brian.wood@nrl.navy.mil
[2] Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA
[3] Space Research Centre of the Polish Academy of Sciences, Ul. Bartycka 18 A, 00-716 Warsaw, Poland
[4] Space Science Center and Department of Physics, University of New Hampshire, Durham, NH 03824, USA
[5] Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, Germany
[6] Southwest Research Institute, San Antonio, TX 78228, USA
Received 2015 March 10; accepted 2015 April 22; published 2015 October 20

ABSTRACT

We explore the possibility that interstellar O and Ne may be contributing to the particle signal from the GAS instrument on *Ulysses*, which is generally assumed to be entirely He. Motivating this study is the recognition that an interstellar temperature higher than any previously estimated from *Ulysses* data could potentially resolve a discrepancy between *Ulysses* He measurements and those from the *Interstellar Boundary Explorer* (*IBEX*). Contamination by O and Ne could lead to *Ulysses* temperature measurements that are too low. We estimate the degree of O and Ne contamination necessary to increase the inferred *Ulysses* temperature to 8500 K, which would be consistent with both the *Ulysses* and *IBEX* data given the same interstellar flow speed. We find that producing the desired effect requires a heavy element contamination level of ~9% of the total *Ulysses*/GAS signal. However, this degree of heavy element contribution is about an order of magnitude higher than expected based on our best estimates of detection efficiencies, ISM abundances, and heliospheric survival probabilities, making it unlikely that heavy element contamination is significantly affecting temperatures derived from *Ulysses* data.

Key words: ISM: atoms – Sun: heliosphere

1. INTRODUCTION

The interstellar flow vector is of fundamental importance for all studies of global heliospheric structure. Measurements of interstellar neutral helium flowing through the inner heliosphere provide our best diagnostics of the local ISM flow. Helium is much less affected by charge exchange than hydrogen, making He better for diagnosing the undisturbed ISM flow than the more abundant H. Measurements of the He flow from the GAS instrument on *Ulysses* have recently been challenged by newer measurements from the *Interstellar Boundary Explorer* (*IBEX*; Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012). From an analysis of *Ulysses* data from launch through 2002, Witte (2004) found $V_{\rm ISM} = 26.3 \pm 0.4$ km s^{-1}, $\lambda = 75.4 \pm 0.^{\circ}5$, $\beta = -5.2 \pm 0.^{\circ}2$, and $T = 6300 \pm 340$ K; where $V_{\rm ISM}$ is the flow velocity, T the temperature, and λ and β the ecliptic longitude and latitude direction in J2000 coordinates. These four parameters are highly correlated in the *IBEX* analysis, but studies of the first two years of *IBEX* data found that the central values where χ^2 is lowest disagree with the *Ulysses* vector, particularly for $V_{\rm ISM}$ and λ, where χ^2 is minimized at $V_{\rm ISM} \approx 23.2$ km s^{-1} and $\lambda \approx 79.^{\circ}0$ (Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012).

The *Ulysses*/*IBEX* discrepancy stimulated a flurry of new work on the ISM flow issue. Frisch et al. (2013) proposed that the ISM flow may have actually changed between the *Ulysses* and *IBEX* eras, particularly the flow longitude. However, observations of interstellar H from both the Solar Wind Anisotropies instrument on the *Solar and Heliospheric Observatory* and the Space Telescope Imaging Spectrograph instrument on the *Hubble Space Telescope* have been used to support the *Ulysses* vector and argue against its variability (Ben-Jaffel et al. 2013; Lallement & Bertaux 2014; Vincent et al. 2014). Efforts have been made to reanalyze the *Ulysses* data to see if a new look would lead to different conclusions. A start was made by Katushkina et al. (2014), who focused on a couple specific He beam maps from *Ulysses*, confirming that the He vector initially reported from *IBEX* data does not reproduce *Ulysses* data well. Bzowski et al. (2014) and Wood et al. (2015, hereafter WMW15) independently reanalyzed the full *Ulysses* data set. The two studies disagree on the magnitude of the uncertainties for the He flow parameters, with WMW15 reporting tight error bars ($V_{\rm ISM} = 26.08 \pm 0.21$ km s^{-1}, $\lambda = 75.54 \pm 0.^{\circ}19$, $\beta = -5.44 \pm 0.^{\circ}24$, $T = 7260 \pm 270$ K) and Bzowski et al. (2014) ultimately quoting a broad range of acceptable values ($74.^{\circ}2 < \lambda < 76.^{\circ}5$, $-7^{\circ} < \beta < -5^{\circ}$, $24.5 < V_{\rm ISM} < 27.0$ km s^{-1}, and $5500 < T < 9000$ K). Nevertheless, both analyses agree that the best fit vector is consistent with that found in the original Witte (2004) study. Both also, however, find evidence for a significantly higher temperature. Bzowski et al. (2014) finds a best estimate of $T \approx 7500$ K, while WMW15 reports $T = 7260 \pm 270$ K.

One important consequence of this higher temperature is that it helpfully weakens the *Ulysses*/*IBEX* discrepancy. Although initial work on the *IBEX* data suggested a χ^2 minimum at $T \approx 6200$ K (Bzowski et al. 2012), it is not clear that significantly higher temperatures are excluded by the data. At a temperature of $T \approx 8500$ K, the best $V_{\rm ISM}$, λ, and β values suggested by *IBEX* are in good agreement with the *Ulysses* measurements (McComas et al. 2012). For example, the most recent *IBEX* analysis associates a temperature of $T = 8650^{+440}_{-660}$ K with an ISM flow velocity of 26 km s^{-1} (Leonard et al. 2015; Möbius et al. 2015). Thus, there is a developing hypothesis that a higher ISM temperature is the key to resolving the *Ulysses*/*IBEX* discrepancy (McComas et al. 2015; WMW15).

The question is then, to what extent is a temperature of $T \approx 8500$ K truly consistent with the *IBEX* and *Ulysses* data, given that χ^2 seems to be minimized at lower temperatures? Möbius et al. (2015) and Leonard et al. (2015) both argue in favor of the *IBEX* data being consistent with the higher temperature, and therefore with the He flow vector suggested by *Ulysses*. We here focus on the *Ulysses* data. The Bzowski et al. (2014) and WMW15 reanalyses both encouragingly show higher temperatures than previous assessements, but still not quite high enough. Can a systematic error be found that, if corrected, would move these temperatures even higher? The possibility that will be explored here concerns the potential contribution of heavy neutrals, particularly O and Ne atoms, to the signal observed by *Ulysses*/GAS. The heavier weights of these atoms will yield narrower velocity distributions than that of He. Thus, the effect of O and Ne contamination on the observed particle beam is to narrow it, thereby leading to an underestimate in the temperature.

2. SIMULATING *ULYSSES* DATA

The *Ulysses* mission was launched in 1990 October to study various interplanetary constituents outside of the ecliptic plane, such as the solar wind, magnetic fields, radio waves, dust, cosmic rays, and interstellar particles (Wenzel et al. 1992; Marsden 2001). *Ulysses*'s orbit outside the ecliptic was achieved via an encounter with Jupiter in 1992 February, resulting in an orbit roughly perpendicular to the ecliptic plane, with an aphelion near Jupiter's distance of 5 AU and a perihelion at 1.3 AU. The GAS instrument on *Ulysses* was designed primarily to study interstellar neutral He atoms flowing through the inner heliosphere (Witte et al. 1992). Neutral helium provides the best diagnostic of the undisturbed ISM flow due to the high abundance of helium, and due to the fact that helium is not greatly affected by charge exchange in the outer heliosphere, in contrast to hydrogen and oxygen, for example.

However, the interstellar He could only be observed when the spacecraft was traveling fast enough for inflowing He atoms to have a high enough energy to exceed the detection threshold of the GAS instrument. With the *Ulysses* orbital plane roughly perpendicular to the ISM flow vector, the detectability of He depended mostly on the spacecraft velocity, and the threshold was only exceeded when *Ulysses* was in the near-Sun part of its orbit where the spacecraft was moving at its fastest. Thus, with the exception of some data taken during the initial cruise phase to Jupiter (Witte et al. 1993), the *Ulysses*/GAS He observations were confined to the three following periods: 1994–1996, 2000–2002, and 2006–2007.

Unlike the *IBEX*-Lo instrument, the *Ulysses*/GAS instrument has no means to discern the masses of the neutral particles that it detects. Thus, it cannot distinguish between H, He, O, or Ne atoms. Figure 1 displays the He detection efficiency as a function of particle energy (Banaszkiewicz et al. 1996). A typical velocity for an incoming ISM He atom in the spacecraft rest frame is 50 km s^{-1}, corresponding to 52 eV. As shown in Figure 1, this energy is at the knee of the efficiency curve, with the efficiency decreasing rapidly toward lower energies. Thus, ISM H atoms, with energies four times lower than He due to lower mass, are clearly undetectable despite their higher numbers.

In contrast, heavier atoms will be detectable, and O and Ne should be the dominant contributors to counts from heavy atoms. The detection efficiency curve is somewhat different for different elements. In Figure 1, we have approximated the O and Ne efficiency curve as being three times higher than the He curve (Banaszkiewicz et al. 1996; Yamamura & Tawara 1996), though uncertainties are significant. Detection efficiency is actually higher for O and Ne than for He due to both the higher efficiency curve and higher particle energies. Figure 1 illustrates the O and Ne energies corresponding to the typical 50 km s^{-1} velocity in the spacecraft rest frame. Despite this significantly higher efficiency, overall count rates will still be much lower than for He due simply to neutral O and Ne being less abundant in the ISM than neutral He: ~300 and ~2600 times less abundant, respectively (Slavin & Frisch 2008). Previous *Ulysses* analyses estimated that heavy atoms contribute no more than 5% of the counts in any direction, which was deemed insignificant (Banaszkiewicz et al. 1996; Witte 2004). However, given that the O and Ne contamination will be confined to near beam center, even a small increase in counts there could in principle yield the impression of a narrower He beam, significantly reducing the inferred temperature. It is this specific effect that we are interested in quantifying here, because of its potential for resolving the *Ulysses*/*IBEX* discrepancy (see Section 1).

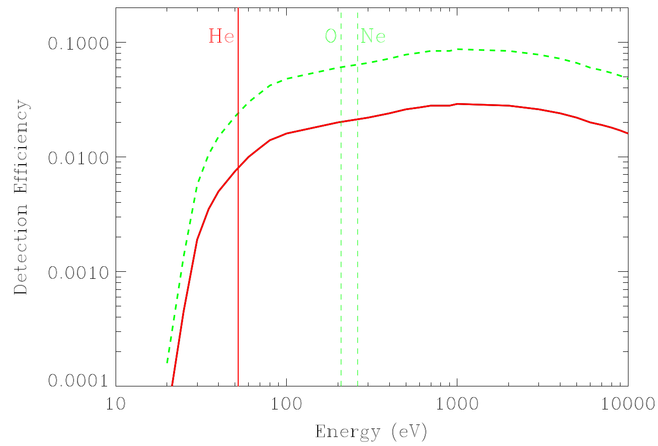

Figure 1. *Ulysses*/GAS detection efficiencies as a function of particle energy for He (solid line), and for O and Ne (dashed line), where the O and Ne efficiency curve is approximated as simply three times that of He. The vertical solid line indicates a typical He detection energy for the ISM He beam seen by *Ulysses* (52 eV), and vertical dashed lines indicate the corresponding energies of incoming O and Ne particles, which have higher energies due to higher masses.

Our approach to studying this question involves creating synthetic *Ulysses* particle beam maps assuming $T = 8500$ K, a temperature high enough to potentially resolve the *Ulysses*/*IBEX* discrepancy. We assume a variety of different contamination levels of O and Ne flux when calculating the synthesized maps. These maps are then fitted with synthetic maps computed assuming only a He contribution, as in WMW15. The parameter of interest in these fits is the temperature. The basic question is, how much O/Ne contamination does there have to be before the fits to the synthetic data decrease from $T = 8500$ K to $T = 7000$–7500 K, the temperature actually measured by Bzowski et al. (2014) and WMW15.

For simplicity, the synthetic data are computed treating O and Ne exactly like He was treated in WMW15, accounting only for the higher atomic weights of O and Ne (16 and 20, respectively). We assume the best-fit He flow vector from

WMW15 described in Section 1, with the only difference being that we assume $T = 8500$ K instead of $T = 7260 \pm 270$ K. We assume the same temperature for He, O, and Ne. Measurements of ISM absorption lines are consistent with atomic species in the ISM having consistent temperatures (Redfield & Linsky 2004), and *IBEX* measurements also imply temperature consistency for He, O, and Ne atoms (Möbius et al. 2012). The forward modeling involves the use of a particle tracking code to follow particle distributions propagating from the undisturbed ISM, where the distributions are assumed Maxwellian, into the inner heliosphere under the effects of gravity only (Müller 2012; Müller & Cohen 2012; Müller et al. 2013). We refer the reader to WMW15 for details of this procedure, and examples of how it can yield synthetic beam maps for comparison with *Ulysses* data.

Treating Ne like He in the simulations (except for the higher atomic weight) is surely fine, since Ne and He both suffer little charge exchange during their journey through the heliosphere. This approach will not be nearly as precise for O, however, which does suffer from charge exchange reactions that should significantly alter the neutral O characteristics in the inner solar system from those suggested by our basic particle tracking model. Trying to take this effect into account properly would involve extensive use of multi-component global heliosphere models (e.g., Müller & Zank 2004), where the influence of the heliosphere on the O distributions would be quite dependent on the numerous boundary conditions of the models. This kind of detailed modeling is outside the scope of our analysis here, but we will return to this issue later.

The three factors determining the degree of heavy element contamination in *Ulysses* data are ISM neutral abundances, survival probabilities of those neutrals to the spacecraft, and detection efficiencies for those neutrals. Thus, the degree of heavy element contribution can be quantified as

$$R = \frac{A_{\rm O}}{A_{\rm He}} \cdot \frac{S_{\rm O}}{S_{\rm He}} \cdot \frac{D_{\rm O}}{D_{\rm He}} + \frac{A_{\rm Ne}}{A_{\rm He}} \cdot \frac{S_{\rm Ne}}{S_{\rm He}} \cdot \frac{D_{\rm Ne}}{D_{\rm He}}, \quad (1)$$

where the neutral abundances of He, O, and Ne in the ISM are indicated by $A_{\rm He}$, $A_{\rm O}$, and $A_{\rm Ne}$, respectively. Interstellar neutrals suffer ionization as they travel through the heliosphere, particularly photoionization by solar EUV photons, and the various S parameters in the equation are the survival probabilities for He, O, and Ne. Finally, $D_{\rm He}$, $D_{\rm O}$, and $D_{\rm Ne}$ are the detection efficiencies for He, O, and Ne atoms. We assume $D_{\rm Ne} \approx D_{\rm O}$ and define $D_{\rm ONe} \equiv D_{\rm O}$, simplifying Equation (1) to

$$R = \left(\frac{A_{\rm O}}{A_{\rm He}} \cdot \frac{S_{\rm O}}{S_{\rm He}} + \frac{A_{\rm Ne}}{A_{\rm He}} \cdot \frac{S_{\rm Ne}}{S_{\rm He}}\right) \frac{D_{\rm ONe}}{D_{\rm He}}. \quad (2)$$

Note that the energy dependence of $D_{\rm He}$ is taken into account in the simulations, and this dependence is assumed to be the same for O and Ne, such that $D_{\rm ONe}(E)$ is a simple scalar multiple of $D_{\rm He}(E)$, as in Figure 1 where we assume $D_{\rm ONe}/D_{\rm He} = 3$ for all energies.

As described above, our synthetic data are computed treating O and Ne exactly like He, except for the higher atomic weights, and we do not make any correction for ionization. Essentially, we are assuming $\frac{S_{\rm O}}{S_{\rm He}} = 1$, $\frac{S_{\rm Ne}}{S_{\rm He}} = 1$, and $\frac{D_{\rm ONe}}{D_{\rm He}} = 1$; and we simply adjust the ratios $\frac{A_{\rm O}}{A_{\rm He}}$ and $\frac{A_{\rm Ne}}{A_{\rm He}}$ to experiment with different R values. The atomic weights of O and Ne are similar enough that it matters little whether O or Ne is the dominant contributor, so to first order there is a precise one-to-one connection between R and a particular calculation of synthetic data. In order to make our synthetic data correspond as closely as possible to real *Ulysses* data, we base the synthetic data on a set of 20 actual *Ulysses* maps, scattered across time from 1994 to 2007, and most importantly sampling a variety of orbital locations. As in WMW15, we define an orbital phase, ϕ, where $\phi = 0.5$ corresponds to the ecliptic plane crossing near perihelion, and $\phi = 0.25$ and $\phi = 0.75$ correspond to the south and north pole crossing, respectively. As an example, Figure 2 shows simulated data based on a *Ulysses* map from 2001 December 12, at orbital phase $\phi = 0.78$. Maps are shown for $R = 0.003$, $R = 0.03$, and $R = 0.1$. The beam becomes noticably narrower as R increases, corresponding to more O and Ne contamination.

The synthetic maps are fitted using the same methods used by WMW15 to fit real *Ulysses* data. This is done for the aforementioned 20 cases. Fits to individual beam maps are not unique without additional constraints (see WMW15), so the flow velocity in these fits is fixed to the global best-fit value of $V_{\rm ISM} = 26.08$ km s^{-1} (WMW15). Figure 3 plots the inferred temperature as a function of R for the 20 maps. As expected, for low R we recover $T = 8500$ K, as there is insufficient contamination from O and Ne to affect the synthetic data, but T starts to lower significantly for $R \geqslant 0.003$. By $R \approx 0.03$, temperatures consistent with the measurements of the real *Ulysses* data are being observed.

Thus, only a modest amount of heavy element contamination, corresponding to $R = 0.03$, would be enough to affect the *Ulysses* analysis to the required degree. This corresponds to a heavy element abundance at the spacecraft (the quantity in parentheses in Equation (2)) of ~1%, if $\frac{D_{\rm ONe}}{D_{\rm He}} \approx 3$ as in Figure 1. Connecting R to an actual percentage of particle detections that are heavy elements requires including an enhancement factor from the higher detection efficiency of heavier elements due to their higher energies. Figure 1 suggests a typical enhancement factor of 3, meaning $R = 0.03$ would correspond to a ~9% contribution of heavy element counts to the *Ulysses* data.

The measured temperatures vary from map to map, even for different maps computed assuming the same R. Some of this variation is random, but Figure 3 shows a clear dependence on orbital phase, ϕ. This phase dependency is shown explicitly in Figure 4 for $R = 0.03$ and $R = 0.04$. These results are compared with measurements from actual *Ulysses* beam maps (WMW15). As well as performing a global fit to the *Ulysses* data to find the best-fit He flow vector, WMW15 also made fits to individual maps, with the flow velocity fixed to the global best-fit value of $V_{\rm ISM} = 26.08$ km s^{-1}. The temperatures from these single-map fits are compared with the $R = 0.03$ and $R = 0.04$ synthetic map results in Figure 4. Both the real and synthetic measurements exhibit a phase dependence, with lower temperatures measured for $\phi < 0.4$ and $\phi > 0.7$.

Greater O and Ne contamination is expected for these higher and lower orbital phases. *Ulysses* moves slower away from the ecliptic plane, reducing inflowing particle energies to the point where He energies fall below the "knee" of the $D_{\rm He}(E)$ curve (see Figure 1). This does not happen for O and Ne atoms due to the higher energies of the heavier O and Ne atoms, keeping these particles above the knee. Thus, as He count rates decrease away from $\phi = 0.5$ the contribution of O and Ne increases. The similar phase dependencies of the real and synthetic data in

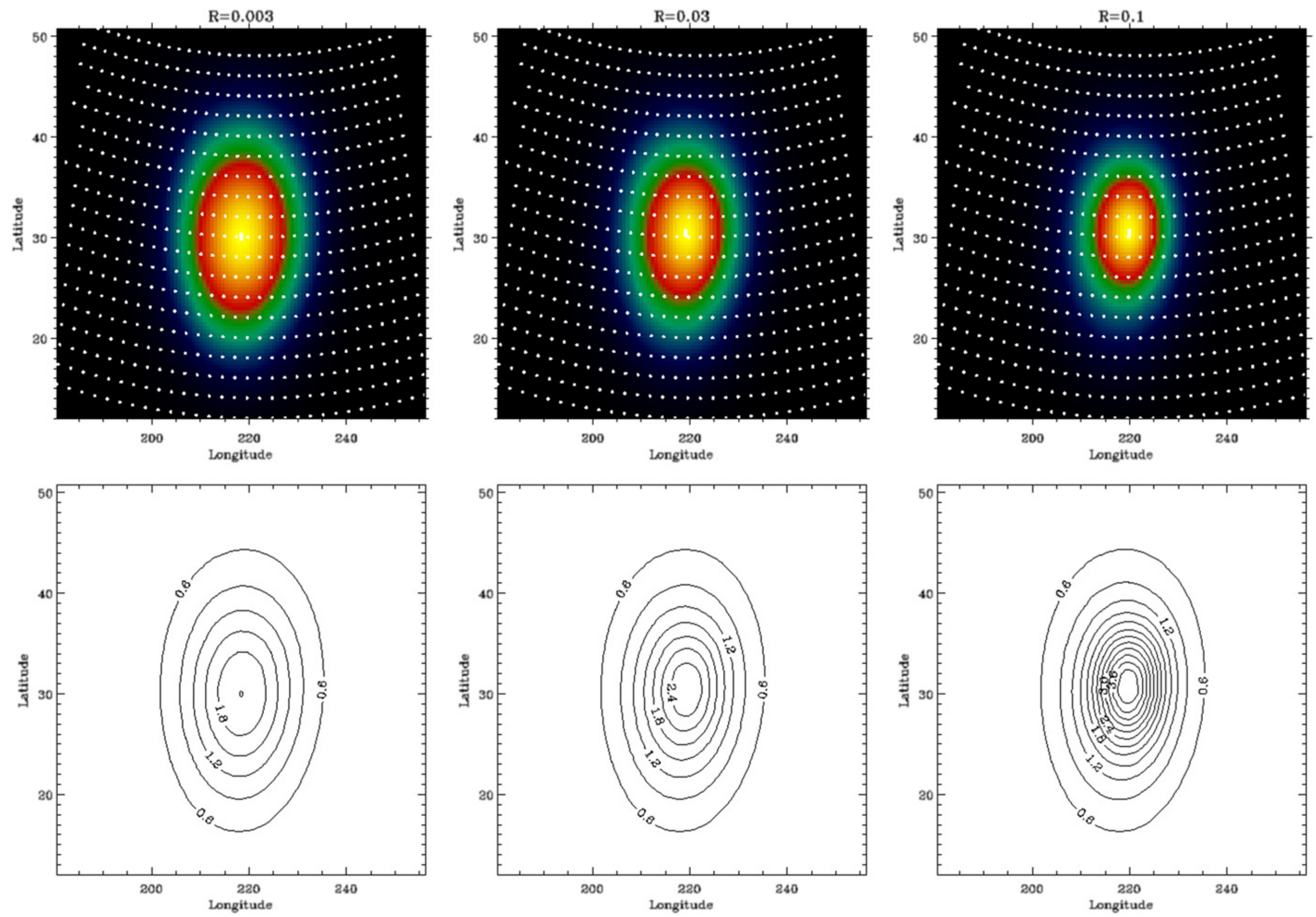

Figure 2. Simulations of an actual *Ulysses*/GAS particle beam map from 2001 December 12 (in ecliptic coordinates), shown in both image (top) and contour plot (bottom) formats. Both are smoothed for the sake of appearance. Dots in the images indicate scan positions used to build the map. The units in the contour maps are counts per second. The maps are generated assuming the best-fit He flow vector from Wood et al. (2015) and a temperature of $T = 8500$ K. The color scale in the images is rescaled in each panel so that the maximum is always bright yellow. Maps are computed assuming three different degrees of contamination from O and Ne, corresponding to $R = 0.003$ (left), $R = 0.03$ (middle), and $R = 0.1$ (right).

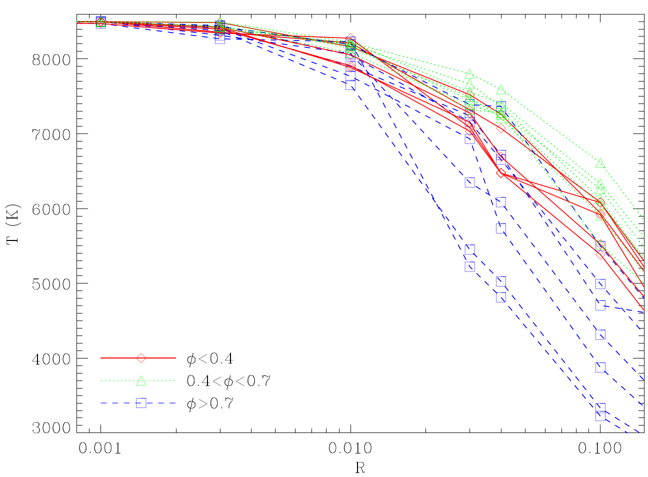

Figure 3. Single map fits have been performed on synthetic *Ulysses* particle beam maps, computed assuming various values of R (measuring contamination of O and Ne flux), with map sampling based on 20 real observations. For each of the 20 cases, the measured temperature is plotted vs. R, with different symbols and line styles indicating different ranges of orbital phase, ϕ. (The ecliptic plane crossing is at $\phi = 0.5$.)

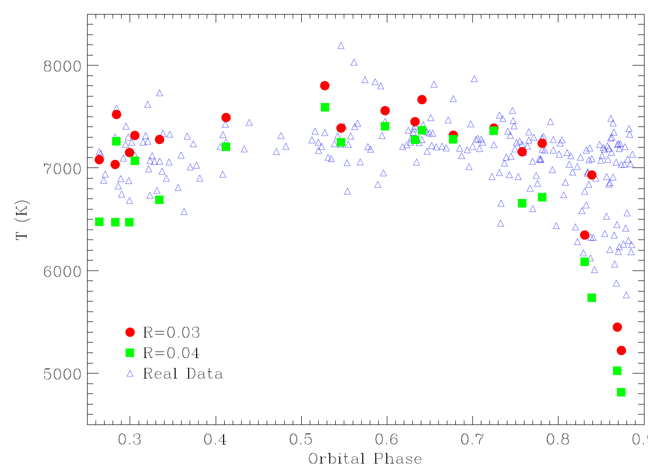

Figure 4. Temperatures measured by single map fits are plotted vs. orbital phase. Measurements are shown for the actual *Ulysses* data, as well as for the synthetic maps made assuming $R = 0.03$ and $R = 0.04$.

Figure 4 could be seen as supporting the presence of O/Ne contamination in the *Ulysses* data. However, it is possible to envision other systematic effects operating here, with average particle energy and signal-to-noise both decreasing significantly away from the ecliptic.

The case for O/Ne contamination would be strengthened further if the assumption of such contamination led to noticably improved fits to the data. Unfortunately, this is not the case. We have performed a global fit to the *Ulysses* data completely analogous to the global fit of WMW15 described in Section 1, but assuming an $R = 0.03$ level of contamination. The resulting fit parameters are similar to those found before (see Section 1), except for the temperature. The temperature is higher, as expected: $T = 8006$ K. The other flow parameters are relatively unchanged. However, the important point is that the reduced chi-squared value, χ_ν^2, of the fit is not lower than we found before. WMW15 reported $\chi_\nu^2 = 1.524$ with no assumed O/Ne contamination, while we find $\chi_\nu^2 = 1.571$ assuming an $R = 0.03$ level of contamination. Thus, assuming contamination does not improve the fit to the data, and if anything makes it slightly worse.

At this point, we return to the approximations that have been used to connect the degree of heavy element contamination with a single number, R. Probably the most questionable assumption is that O particle distributions can be treated exactly like those of He in the particle tracking code (except for the higher atomic weight). Oxygen is expected to be the most significant contaminant, being significantly more abundant than Ne. But unlike He and Ne, it will be affected significantly by charge exchange during its journey through the heliosphere, as is H. The dominant reaction is $O^0 + H^+ \rightarrow O^+ + H^0$ in between the bow shock and heliopause, which has the effect of simply ionizing O; but new neutral O can also be created via $O^+ + H^0 \rightarrow O^0 + H^+$. Accounting for this is a difficult task, which we do not attempt here, but we would expect charge exchange to effectively heat, deflect, and slow the neutral O population on average (Müller & Zank 2004), analogous to what is seen for H in the inner heliosphere (Clarke et al. 1998; Costa et al. 1999; Lallement et al. 2005). This would generally broaden the O beam, making it less likely to lower temperatures measured assuming the beam observed by *Ulysses* is entirely He, keeping in mind that it is the ability of heavy elements to narrow the beam that is of interest here. Thus, we expect that considering the effects of charge exchange could only weaken the case for O/Ne contamination lowering the *Ulysses* temperature.

Finally, we address the question of whether $R = 0.03$ is a plausible value. To answer that, we return to Equation (2). All the ratios on the right side of this equation have been empirically estimated, although all carry significant uncertainties. Given that we want to know if R can be above 0.03, it is the upper limits in these ratios that are particularly relevant.

Assessing uncertainties in the detection efficiencies is difficult. Our $\frac{D_{\rm ONe}}{D_{\rm He}} \approx 3$ assumption from Figure 1 originates primarily from past estimates by the *Ulysses* team (Banaszkiewicz et al. 1996). Yamamura & Tawara (1996) provide an extensive compilation of sputtering yields for various impactor-target combinations. However, the case of Li as a target is unfortunately not considered, which is the coating used by the *Ulysses*/GAS detector. Assuming Be can be used as a proxy (Be being adjacent to Li in the periodic table), the Yamamura & Tawara (1996) data suggest sputtering yield ratios at the relevant energy (200 eV; see Figure 1) of $\frac{D_{\rm O}}{D_{\rm He}} \approx 1$ and $\frac{D_{\rm Ne}}{D_{\rm He}} \approx 3$, suggesting the $\frac{D_{\rm ONe}}{D_{\rm He}} = 3$ assumption could be high for the case of O. Considering the level of scatter apparent in the sputtering measurements, we estimate an upper limit for the detection efficiency ratio of $\frac{D_{\rm ONe}}{D_{\rm He}} < 5$.

As for the abundance ratios, simply assuming cosmic (i.e., solar) abundances translate to neutral abundance ratios in the ISM would yield $\frac{A_{\rm O}}{A_{\rm He}} = 5.8 \times 10^{-3}$ and $\frac{A_{\rm Ne}}{A_{\rm He}} = 1.0 \times 10^{-3}$ (Asplund et al. 2009). However, for our purposes these values are probably upper limits, as correcting for ionization and (for O) dust depletion should lower these ratios. The work of Slavin & Frisch (2008) suggests instead $\frac{A_{\rm O}}{A_{\rm He}} = 3.2 \times 10^{-3}$ and $\frac{A_{\rm Ne}}{A_{\rm He}} = 3.9 \times 10^{-4}$. These values are basically consistent with measurements of the ISM Ne/O ratio made by *IBEX* (Park et al. 2014), and pickup ion measurements from the *Ulysses*/SWICS instrument (Geiss et al. 1994; Gloeckler & Fisk 2007). We note that a recent analysis of solar spectra proposes that the solar (and therefore cosmic) Ne abundance should be adjusted upwards by 40% (Landi & Testa 2015).

The survival probabilities will be variable due to the time-dependent solar wind and EUV flux, and due to the variable distance from the Sun of *Ulysses*. The assessment of ionization rates from Bzowski et al. (2013), when applied to the locations of *Ulysses* during its observations, suggests ranges of $\frac{S_{\rm O}}{S_{\rm He}} = 0.08 - 0.33$ and $\frac{S_{\rm Ne}}{S_{\rm He}} = 0.34 - 0.65$. Assuming typical values of $\frac{S_{\rm O}}{S_{\rm He}} \approx 0.20$ and $\frac{S_{\rm Ne}}{S_{\rm He}} \approx 0.45$, and plugging all our best estimates from above into Equation (2), we find $R = 0.0025$. This is an order of magnitude lower than the $R \approx 0.03$ contribution that seems to be required to affect the temperature to the required extent. We can estimate an upper limit for R by utilizing the upper limits defined above: $\frac{D_{\rm ONe}}{D_{\rm He}} < 5$, $\frac{A_{\rm O}}{A_{\rm He}} < 5.8 \times 10^{-3}$, $\frac{A_{\rm Ne}}{A_{\rm He}} < 1.0 \times 10^{-3}$, $\frac{S_{\rm O}}{S_{\rm He}} < 0.33$, and $\frac{S_{\rm Ne}}{S_{\rm He}} < 0.65$. This leads to an upper limit of $R < 0.013$, still over a factor of 2 too low, representing the strongest argument against O and Ne contamination being an important factor in the *Ulysses* analysis.

3. SUMMARY

Given that a high ISM temperature of $T \approx 8500$ K may be required to reconcile *IBEX* and *Ulysses* measurements of the ISM He flow, we have estimated the degree of heavy element contamination of *Ulysses*/GAS data required to yield this result. On the positive side, we find that a modest heavy element contribution corresponding to a contamination factor of $R = 0.03$ is enough to cause *Ulysses* to perceive an 8500 K flow as 7000–7500 K, the temperature suggested by the most recent analyses. This $R = 0.03$ factor corresponds to a heavy element abundance at the spacecraft of ∼1% relative to helium, and a heavy element contribution to *Ulysses* particle detections of ∼9%. Furthermore, we show that temperatures measured from single-map fits assuming only He contribution have an orbital phase dependence that could be indicative of heavy element contamination, although other explanations are possible.

However, assuming a heavy element contribution of $R = 0.03$ does not actually improve the quality of fits to *Ulysses*/GAS data, and in fact slightly increases χ_ν^2. More importantly, although $R = 0.03$ represents a modest degree of contamination, it is still about an order of magnitude higher than expected based on current estimates of ISM abundances and ionization loss rates, and about a factor of 2 higher than our estimated upper limit. Considering the substantial uncertainties in abundances, ionization losses, and detection efficiencies,

$R = 0.03$ may still barely be within the realm of possibility if multiple factor of 2 uncertainties all operate in the same direction, but this seems unlikely. Thus, if the interstellar temperature really is $T \approx 8500$ K, the issue of why the best fits to *Ulysses* data suggest lower temperatures remains an open one.

This work has been supported by NASA award NNH13AV19I to the Naval Research Laboratory. M.B. and J.M.S. were supported by Polish National Science Centre grant 2012-06-M-ST9-00455. Work by *IBEX* team members was supported as a part of this mission by the NASA Explorer Program.

REFERENCES

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Banaszkiewicz, M., Witte, M., & Rosenbauer, H. 1996, A&AS, 120, 587
Ben-Jaffel, L., Strumik, M., Ratkiewicz, R., & Grygorczuk, J. 2013, ApJ, 779, 130
Bzowski, M., Kubiak, M. A., Möbius, E., et al. 2012, ApJS, 198, 12
Bzowski, M., Kubiak, M. A., Hłond, M., et al. 2014, A&A, 569, A8
Bzowski, M., Sokół, J. M., Kubiak, M. A., & Kucharek, H. 2013, A&A, 557, A50
Clarke, J. T., Lallement, R., Bertaux, J.-L., et al. 1998, ApJ, 499, 482
Costa, J., Lallement, R., Quémerais, E., et al. 1999, A&A, 349, 660
Frisch, P. C., Bzowski, M., Livadiotis, G., et al. 2013, Sci, 341, 1080
Geiss, J., Gloeckler, G., Mall, U., et al. 1994, A&A, 282, 924
Gloeckler, G., & Fisk, L. A. 2007, SSRv, 130, 489
Katushkina, O. A., Izmodenov, V. V., Wood, B. E., & McMullin, D. R. 2014, ApJ, 789, 80
Lallement, R., & Bertaux, J. L. 2014, A&A, 565, A41
Lallement, R., Quémerais, E., Bertaux, J. L., et al. 2005, Sci, 307, 1447
Landi, E., & Testa, P. 2015, ApJ, 800, 110
Leonard, T. W., Möbius, E., Bzowski, M., et al. 2015, ApJ, 804, 42
Marsden, R. G. 2001, Ap&SS, 277, 337
McComas, D. J., Alexashov, D., Bzowski, M., et al. 2012, ApJS, 336, 1291
McComas, D. J., Bzowski, M., Frisch, P., et al. 2015, ApJ, 801, 28
Möbius, E., Bzowski, M., Frisch, P., et al. 2015, ApJS, 220, 24
Möbius, E., Bochsler, P., Bzowski, M., et al. 2012, ApJS, 198, 11
Müller, H.-R. 2012, in Numerical Modeling of Space Plasma Flows (Astronum 2011), Vol. 459, ed. N. V. Pogorelov et al. (San Francisco, CA: ASP), 228
Müller, H.-R., Bzowski, M., Möbius, E., & Zank, G. P. 2013, in Solar Wind 13, Vol. 1539, ed. G. P. Zank et al. (Melville, NY: AIP), 348
Müller, H.-R., & Cohen, J. H. 2012, in Physics of the Heliosphere: A 10 year Retrospective, Vol. 1436, ed. J. Heerikhuisen, & G. Li (Melville, NY: AIP), 233
Müller, H.-R., & Zank, G. P. 2004, JGRA, 109, A07104
Park, J., Kucharek, H., Möbius, E., et al. 2014, ApJ, 795, 97
Redfield, S., & Linsky, J. L. 2004, ApJ, 613, 1004
Slavin, J. D., & Frisch, P. C. 2008, A&A, 491, 53
Vincent, F. E., Katushkina, O., Ben-Jaffel, L., et al. 2014, ApJL, 788, L25
Wenzel, K. P., Marsden, R. G., Page, D. E., & Smith, E. J. 1992, A&AS, 92, 207
Witte, M. 2004, A&A, 426, 835
Witte, M., Rosenbauer, H., Banaszkiewicz, M., & Fahr, H. 1993, AdSpR, 13, 121
Witte, M., Rosenbauer, H., Keppler, E., et al. 1992, A&AS, 92, 333
Wood, B. E., Müller, H.-R., & Witte, M. 2015, ApJ, 801, 62
Yamamura, Y., & Tawara, H. 1996, ADNDT, 62, 149