Evidence for Asymmetry in the Velocity Distribution of the Interstellar Neutral Helium Flow Observed by IBEX and Ulysses

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Abstract

We use observations from the Interstellar Boundary Explorer (IBEX) and Ulysses to explore the possibility that the interstellar neutral helium flowing through the inner solar system possesses an intrinsic non-Maxwellian velocity distribution. In fitting the IBEX and Ulysses data, we experiment with both a kappa distribution and a bi-Maxwellian, instead of the usual Maxwellian assumption. The kappa distribution does not improve the quality of fit to either the IBEX or Ulysses data, and we find lower limits to the kappa parameter of $\kappa > 12.1$ and $\kappa > 6.0$ from the IBEX and Ulysses analyses, respectively. In contrast, we do find evidence that a bi-Maxwellian improves fit quality. For IBEX, there is a clear preferred bi-Maxwellian solution with $T_{\parallel}/T_{\perp} = 0.62 \pm 0.11$ oriented about an axis direction with ecliptic coordinates ($\lambda_{\text{axis}}, b_{\text{axis}}$) = (57°2 ± 8°9, −126 ± 5°9). The Ulysses data provide support for this result, albeit with lower statistical significance. The axis direction is close to the interstellar medium (ISM) flow direction, in a heliocentric rest frame, and is therefore unlikely to be indicative of velocity distribution asymmetries intrinsic to the ISM. It is far more likely that these results indicate the presence of asymmetries induced by interactions in the outer heliosphere.

Key words: ISM: atoms – Sun: heliosphere

Supporting material: animation

1. Introduction

The global characteristics of the heliosphere surrounding the Sun are defined in large part by the characteristics of the surrounding very local interstellar medium (VLISM). The plasma component of the VLISM is deflected around the heliosphere at the heliopause and has therefore been unavailable for direct observation, at least until recently with the Voyager 1 and 2 spacecraft crossing the heliopause in 2012 and 2018, respectively (Gurnett et al. 2013; Stone et al. 2013; Stone 2018). Much of what we know about the VLISM comes instead from interstellar neutrals (ISNs), which can penetrate the heliopause and therefore be observed more locally in the inner solar system at or near 1 au.

The first studies of the local ISN flow involved the analysis of solar Ly$\alpha$ backscatter from neutral H (Bertaux & Blamont 1971; Quémerais et al. 1999). However, better measurements of VLISM properties come not from neutral H but from neutral He. This is because charge exchange processes significantly alter the characteristics of neutral H as it travels through the heliosphere. In contrast, He has much lower charge exchange rates and therefore reaches the inner solar system in a more pristine state.

Somewhat analogous to H, the first detections of ISN He in the inner solar system were radiative in nature, specifically scattered solar He I $\lambda584$ emission from the He focusing cone downwind from the Sun (Meier & Weller 1972). However, the most precise measurements of the neutral He properties have come from particle detectors that can study the He flow directly. The GAS instrument on the Ulysses spacecraft was the first instrument capable of these measurements (Witte 2004; Wood et al. 2015). The ongoing Interstellar Boundary Explorer (IBEX) mission continues this legacy, specifically with the IBEX-Lo instrument (Möbius et al. 2012; Bzowski et al. 2015).

Analysis of these He measurements requires a forward modeling exercise, where ISNs, with a velocity distribution function (VDF) defined by some set of parameters, are propagated into the inner solar system under the influence of the Sun’s gravity and various loss processes, particularly photoionization close to the Sun. The parameters of the assumed VDF are varied to maximize agreement with the data. The usual assumption in such studies is to assume that the VDF is a Maxwellian far from the Sun.

One indication that the Maxwellian assumption may be overly simplistic is the discovery of a secondary neutral He component (Kubiak et al. 2014, 2016). This component is very clear in IBEX data, but hints of it have also been found in the noisier Ulysses data (Wood et al. 2017). The secondary component is likely created by charge exchange processes in the outer heliosheath beyond the heliopause. Its existence therefore demonstrates that despite low charge exchange rates, even He undergoes some level of interaction in the outer heliosphere, which might affect the primary He flow properties as well.

Even in the absence of heliospheric interaction, it is far from certain that the pristine ISN He VDF is a pure Maxwellian. Measurements of interstellar absorption lines toward nearby stars indicate the presence of substantial nonthermal velocities in the nearby interstellar medium (ISM), generally interpreted as turbulence of some sort (Redfield & Linsky 2008), but which could also be indicative of velocity gradients in the ISM (Gry & Jenkins 2014). In the presence of turbulence, it is possible that a kappa distribution may more accurately describe the ISN VDF than a Maxwellian (Fisk & Gloeckler 2006; Livadiotis 2018). Furthermore, there is a significant magnetic
field in the VLISM, and magnetohydrodynamic (MHD) wave/particle interactions could lead to the plasma component being bi-Maxwellian in nature, with different effective temperatures parallel and perpendicular to the magnetic field. Charge exchange processes could imprint such plasma properties onto the neutrals. Spangler et al. (2011) collectively used measurements of nearby interstellar temperatures and nonthermal velocities to search for evidence of anisotropies indicative of such MHD processes. They found none, but the quoted limit of $T_{\perp}/T_\parallel < 1.67$ still allows for the possibility of significant undetected anisotropy.

We here present a reanalysis of IBEX and Ulysses data, experimenting with both kappa and bi-Maxwellian distributions. The goal is to assess whether such assumptions are better than the usual Maxwellian assumption. We will also assess whether assuming a non-Maxwellian VDF far from the Sun in any way affects the flow velocity and direction inferred from the data.

2. Assuming a Bi-Maxwellian Distribution

The usual assumption for the VLISM He VDF far from the Sun is a simple Maxwellian,

$$F(v) = n \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left( -\frac{m(v - U)^2}{2kT} \right),$$

where $m$ is the mass of the He atom, and $k$ the Boltzmann constant. The flow parameters of interest are the temperature, $T$, the He density $n$, and the flow vector $U = (V_{flow}, \lambda_{flow}, \beta_{flow})$; where $V_{flow}$ is the flow magnitude, and $\lambda_{flow}$ and $\beta_{flow}$ are the flow longitude and latitude, respectively, in ecliptic coordinates.

However, here we replace the Maxwellian with a bi-Maxwellian VDF,

$$F(v) = \frac{n}{T_{\parallel} T_{\perp}^{1/2}} \left( \frac{m}{2\pi k} \right)^{3/2} \times \exp \left[ -\frac{m}{2k} \left( \frac{(v - U)^2}{T_{\parallel}} + \frac{(v - U)^2}{T_{\perp}} \right) \right],$$

where the velocities $v$ and $U$ have been decomposed into components perpendicular $(v_{\perp}, U_{\perp})$ and parallel $(v_{\parallel}, U_{\parallel})$ to some axis direction, the axis being defined by a direction in ecliptic coordinates, $(\lambda_{axis}, \beta_{axis})$. Different temperatures are assumed perpendicular $(T_{\perp})$ and parallel $(T_{\parallel})$ to the axis. The five parameters of the Maxwellian increase to eight parameters for the bi-Maxwellian $(n, V_{flow}, \lambda_{flow}, \beta_{flow}, T_{\parallel}, T_{\perp}, \lambda_{axis}, \beta_{axis})$.

A bi-Maxwellian assumption makes the most physical sense if the axis direction is defined by the magnetic field, since MHD processes might be expected to produce a bi-Maxwellian VDF ordered about the field direction. However, a bi-Maxwellian can also be considered to be a generic parametrized approximation of any asymmetric VDF. In that spirit, we will not be forcing the axis to be in the VLISM field direction.

2.1. IBEX Data Analysis

We first describe our bi-Maxwellian analysis of IBEX data. The IBEX spacecraft was launched into a highly elliptical orbit around Earth on 2008 October 19, and has been accumulating data since that time. The goal of the mission is to generate maps of various populations of neutrals coming from the outer heliosphere and the VLISM (McComas et al. 2009). The spacecraft operates in a continuous spin, with the spin axis pointed very near the Sun, and with IBEX’s two instruments, IBEX-Lo and IBEX-Hi, observing radially away from the spin axis. Observations are therefore made along a $7^\circ$ wide latitudinal strip that is roughly normal to the Sun-spacecraft line. The spin axis is maintained in a steady orientation in an inertial rest frame for a time period of many days, during which the spin axis drifts westward of the Sun due to the Earth’s orbital motion. The spin axis is periodically adjusted to reorient it toward the Sun. In this way, IBEX gradually scans across the entire sky once every 6 months.

The low energy ISNs are studied using the IBEX-Lo instrument (Fuselier et al. 2009). Although its spin-oriented design allows the sky to be mapped every 6 months, in practice the ISNs can only be observed when the orbital motion around the Sun is moving the spacecraft toward the upwind direction of the flow, which only happens once per year. The IBEX-Lo instrument is capable of detecting a number of different ISN species, but we will be focusing only on He here. The ISN He observing season is in the months of January and February each year, during which IBEX gradually scans across the He beam (Möbius et al. 2009).

The IBEX observations are typically organized by sequential Earth orbit number. The IBEX spacecraft initially orbited Earth once every 7.6 days, but in mid-2011 IBEX was shifted to a more stable orbit with an orbital period closer to 9 days. The data are carefully screened to consider only data free from various sources of contamination (Möbius et al. 2012, 2015). Figure 1 in Bzowski et al. (2015) provides a useful illustration of the good time intervals available in each orbit. Figure 1 (in this paper) shows a sequence of He count rates as a function of latitude observed during the orbits of the 2012 ISN He observing season. (See Bzowski et al. 2015 for depictions of count rates from other years.) Originally, the IBEX spin axis was adjusted only once per orbit, but since the 2011 orbit adjustment the spin axis has been reoriented toward the Sun twice per orbit; hence the “a” and “b” appendages to the orbit numbers in Figure 1. The count rates actually vary significantly within each orbit, due to the ever-changing pointing direction relative to the He beam, induced by the Earth’s orbital motion and also due to IBEX’s own orbital motion around the Earth. The count rates displayed are averages over the full orbital time periods.

Figure 1 illustrates how the He count rates increase with orbit as the IBEX scan direction moves closer to the center of the He beam, and then decrease thereafter. The pattern is not as smooth as might be expected, due in part to irregularities in the periodic spin axis adjustments, and also due to the data screening described above, which leads to the actual observing times varying significantly from orbit to orbit. A substantial fraction of the total observing time is excluded by the screening. Orbit 155 is missing entirely from Figure 1, with there being no acceptable observing periods during that orbit.

Our data selection philosophy mirrors that of Bzowski et al. (2015), with the general idea being to focus only on the orbits with the highest fluxes from the primary He beam, where the effects of minor contaminating sources, such as the secondary neutral population mentioned in Section 1, should be minor. Figure 1 shows the only orbits considered from 2012.
Compared to Bzowski et al. (2015), we consider a slightly broader latitudinal range of ±25° from the ecliptic.

Fitting the data requires a forward modeling exercise of propagating particles with an assumed initial VDF toward the Sun under the influence of the Sun’s gravity. Our particle tracking code, which has been used in past analyses of Ulysses data (Wood et al. 2015, 2017), and which is described in detail elsewhere (Müller 2012; Müller & Cohen 2012; Müller et al. 2013), takes advantage of certain conservation properties for particles moving in Keplerian orbits to map a VDF at infinity to one close to the Sun. This approach is significantly different from that of Bzowski et al. (2015), which is described in detail by Soköl et al. (2015).

For IBEX, it is important to consider the effects of loss processes, particularly photoionization. The Earth’s orbital position changes significantly during the 2 months it takes to scan across the He beam, which means exposure to photoionization changes significantly. In particular, earlier orbits (e.g., orbit 153b in Figure 1) suffer larger losses than later orbits (e.g., orbit 158a). Thus, the loss processes will affect how the overall flux level changes with orbit, which must be corrected for in the analysis. In principle, the loss rates will be both time and latitude dependent, in a way that is difficult to precisely model. We do not attempt to account for this dependence in any great detail. Instead, we use the loss rates estimated by Soköl et al. (2015) to compute the average rate during the observing season in question, and that single value is assumed in the particle tracking for that entire season, and for particles coming from all directions. For 2009–2014, the assumed loss rates at 1 au in units of 10⁻⁸ s⁻¹ are 0.73, 0.84, 0.95, 1.18, 1.22, and 1.44, respectively. The actual time variability of the loss rate within an observing season is estimated to be no more than ~10%.

The particle tracking code provides a model VDF at IBEX’s location at any time and location, which when put into the spacecraft rest frame can then be used to infer model count rates. Figure 2 shows examples of VDFs at IBEX’s location in the spacecraft frame, or at least slices through the threedimensional VDFs for the Vₗ = 0 km s⁻¹ plane appropriate for viewing directions near the ecliptic. The coordinate system used is a heliocentric Aries ecliptic coordinate system, with the z-axis toward ecliptic north, and the x-axis toward the vernal equinox (i.e., the first point of Aries). Dashed lines show IBEX’s viewing angle through the VDF in the ecliptic, illustrating how IBEX gradually scans across the VDF over the course of many orbits.

In order to compare with the data as displayed in Figure 1, it is necessary to integrate over the full orbital period to model the displayed average count rates over this period. The particle tracking computations are numerically intensive, which places practical limits on the time resolution for which VDFs can be computed. We ultimately determine that a time resolution of 1 day is sufficient for our purposes. Using a set of VDFs with this time resolution, we can compute the observed count rate as a function of time with this temporal resolution, and then compute the average rate within the orbit for comparison with the data as displayed in Figure 1, naturally taking into account the exact time intervals utilized within the orbit.

The calculation considers the collimator transmission function of IBEX-Lo (Fuselier et al. 2009; Bzowski et al. 2012; Sokól et al. 2015), which describes how the instrument response varies as a function of angular location relative to the central pointing direction. The exact response curve is not purely a function of angular distance from the centerpoint, but has an azimuthal component with a hexagonal character. For simplicity, we average over this azimuthal dependence in order to reduce the collimator response to a simple dependence on angle from the centerpoint.

Finally, the calculation also includes a correction for latitudinal scan smoothing. In Figure 1, the counts collected by IBEX are placed into 6° latitude bins, but due to IBEX’s spinning nature the exposure time is distributed uniformly throughout the ±3° range of each bin, which will smooth the curves in Figure 1 somewhat. We account for this in our model by computing count rates for 10 sub-bins within each 6°
latitude bin, and then use the average of the sub-bin rates as the model rate for that bin.

Initially, we consider the first 6 years of IBEX data in our analysis, from 2009–2014, limiting ourselves to the orbits where He count rates are high, as in Bzowski et al. (2015). Although the secondary He component is comparatively weak for these orbits, we correct for it assuming the secondary He flow parameters of Kubiak et al. (2016). From those parameters, the model secondary He count rates are derived using our particle tracking code, and then subtracted from the data before doing a data/model comparison for the primary He component. In addition to the flow parameters of interest, there is a normalization factor and a flat background count rate that are additional free parameters of the fit. These are allowed to be different for each year’s data, so this adds up to an additional 12 free parameters if 6 years of data are considered.

The normalization factors are redundant with the density parameter, \( n \), with \( n \) also acting as a simple multiplicative factor (see Equations (1) and (2)). If the He detection efficiency was known well, the normalization factors would provide an \( n \) measurement for each year. However, the detection efficiencies are not well quantified, due to uncertainties in the absolute calibration of the instrument with respect to He detection. Interstellar densities are very unlikely to change from year to year, but we allow the normalization factors to vary each year to account for possible changes in detector sensitivity with time. For noble gases like He, the IBEX-Lo detector detects He via sputtering, where the ISN neutrals produce various ionized sputtering products within the IBEX-Lo detector, and it is these ions that are actually being observed.

We use the \( \chi^2 \) parameter as our quality-of-fit indicator (Bevington & Robinson 1992), so the fitting process involves finding the set of parameters that minimizes \( \chi^2 \). If \( \nu \) is the number of degrees of freedom of the fit (the number of data points minus the number of free parameters), then the reduced chi-squared is defined as \( \chi^2 = \chi^2/\nu \), which should be \( \sim 1 \) for a good fit. The \( \chi^2 \) minimization is performed using the Marquardt method (Press et al. 1989). This involves an initial guess for the fit parameters, a determination of the \( \chi^2 \) value associated with that guess, and then an iterative process of changing the parameters to follow the \( \chi^2 \) gradient down to its minimum value in parameter space.

Our first fits to the IBEX data simply assume a Maxwellian VDF. Considering all 2009–2014 data, we initially find best-fit flow parameters that are not in very good agreement with canonical Ulysses measurements, with a low velocity of \( V_{\text{flow}} = 24.2 \text{ km s}^{-1} \) and a high flow longitude of \( \lambda_{\text{flow}} = 77^\circ \). However, these discrepancies disappear when the 2009–2010 data are ignored, consistent with the results of Bzowski et al. (2015), who also find lower \( V_{\text{flow}} \) and higher \( \lambda_{\text{flow}} \) for 2009–2010. Furthermore, ignoring the 2009–2010 data also improves our quality of fit overall.

Thus, we ultimately decide to exclude the 2009–2010 data from our analysis, considering only the 4 years of 2011–2014. Based on the 2011–2014 data, our best Maxwellian fit parameters become \( V_{\text{flow}} = 25.4 \text{ km s}^{-1} \), \( \lambda_{\text{flow}} = 75^\circ \), \( b_{\text{flow}} = 8.9 \), and \( T = 7700 \text{ K} \). Table 1 shows that these results are in reasonable agreement with our past Ulysses measurements (Wood et al. 2015), and the IBEX measurements of

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**Figure 2.** An illustration of how IBEX scans across the ISN He beam each year. Contours of the ISN He VDF in the \( V_z = 0 \text{ km s}^{-1} \) plane are shown, at the location of Earth/IBEX and in the spacecraft rest frame, for three different Earth longitudinal locations (a heliocentric Aries ecliptic coordinate system). The dashed lines are the scan directions of IBEX through the VDF in the ecliptic plane, using the spin axis directions of the 2012 observing season, defined by the orbit numbers provided in the figure. An animation of this figure is available. In the movie version the effects of the spacecraft orbital motion around Earth are easily distinguishable from the effects of Earth’s motion around the Sun. The movie runs from orbit number 150a–158b with a duration of 20 s.

(An animation of this figure is available.)

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**Table 1**

| Recent Interstellar He Flow Measurements |
|----------------------------------------|
| Data source   | Ulysses (2015) | IBEX (2015) | IBEX |
|--------------|----------------|-------------|------|
| Assumed VDF  | Maxwellian     | Maxwellian  | bi-Maxwellian |
| \( V_{\text{flow}} \) (km s\(^{-1}\)) | 26.08 ± 0.21 | 25.8 ± 0.4 | 25.6 ± 1.2 |
| \( \lambda_{\text{flow}} \) (deg)     | 75.54 ± 0.19 | 75.8 ± 0.5 | 75.6 ± 1.5 |
| \( b_{\text{flow}} \) (deg)           | −5.44 ± 0.24 | −5.16 ± 0.10 | −5.09 ± 0.14 |
| \( T \) (K)                              | 7260 ± 270 | 7440 ± 260 | ... |
| \( T_s / T \)                            | ...         | ...       | 7580 ± 960 |
| \( \lambda_{\text{flow}} \) (deg)     | ...         | ...       | 12700 ± 2960 |
| \( b_{\text{flow}} \) (deg)           | ...         | ...       | 0.62 ± 0.11 |
| \( \lambda_{\text{flow}} \) (deg)     | ...         | ...       | 57.2 ± 8.9  |
| \( b_{\text{flow}} \) (deg)           | ...         | ...       | −1.6 ± 5.9  |
Bzowski et al. (2015). With regards to the quoted uncertainties, it is worth noting that in this paper and in Wood et al. (2015) we use $3\sigma$ uncertainties, while Bzowski et al. (2015) quote $1\sigma$ errors. It is not entirely clear why the 2009–2010 data seem problematic, but one possibility is contamination from interstellar H and secondary He. The IBEX-Lo detector is capable of observing ISN H, which could in principle be a contaminant in the He count rates (Möbius et al. 2009; Swaczyna et al. 2018). Furthermore, the H contamination would have been stronger in the solar minimum period of 2009–2010 than in subsequent more active years, with photoionization losses greatly reducing H fluxes (Saul et al. 2013; Galli et al. 2019).

The fit is explicitly shown in Figure 1, at least for the 2012 data. There are significant discrepancies with the data, discrepancies that are essentially identical to those seen in the Bzowski et al. (2015) fits. For example, the underprediction of counts for orbits 156a and 157a is also apparent in Figure 6 of Bzowski et al. (2015). This consistency implies that the models are not an issue here, but unknown systematic uncertainties in the data are instead the cause. As a consequence of these uncertainties, the best-fit $\chi^2$ value of the fit is higher than it should be, specifically $\chi^2 = 2.28$, with the number of degrees of freedom for the fit being 291. Swaczyna et al. (2015) provide an extensive discussion of many possible sources of systematic error in IBEX data.

One of the fundamental issues that plagues analysis of IBEX data is parameter degeneracy, which means that the fit parameters are highly dependent on each other. Among the strongest dependencies is the one between $V_{\text{flow}}$ and $\lambda_{\text{flow}}$. This can be understood by considering the following question: If you see the He beam coming from a given direction, does that imply a fast He flow coming from that direction, or is it a slower He flow being deflected into that direction by the Sun’s gravity? Since the VLISM flow is roughly in the ecliptic plane where IBEX is operating, the issue mostly expresses itself as a correlation between velocity and longitude rather than latitude. Using a sequence of single-Maxwellian fits, we determine the best-fit velocity as a function of assumed flow longitude, to which we fit a second-order polynomial, yielding:

$$V_{\text{flow}} = 163.4 - 2.854\lambda_{\text{flow}} + 0.01364\lambda_{\text{flow}}^2,$$

which applies for a longitude range of $\lambda_{\text{flow}} = [72^\circ, 82^\circ]$. Within this range the relation agrees very well with a similar relation quoted by McComas et al. (2012). The best-fit $\chi^2$ value shows relatively little variation along this relation, making it difficult to determine where along the relation is the true best fit.

As we turn our attention from Maxwellian VDFs to bi-Maxwellians, we actually use Equation (3) to remove $V_{\text{flow}}$ as a free parameter of our bi-Maxwellian fits. Decreasing the number of free parameters in this fashion is desirable given that a bi-Maxwellian VDF adds three new fit parameters, which in turn makes the fits less robust. The term “robust” in this context relates to the ability of our fitting routine to find its way to the same best fit regardless of our initial guess for the best-fit parameters. We conducted a number of tests to confirm that the change from a Maxwellian to a bi-Maxwellian does not affect the best-fit flow direction or magnitude, validating our use of Equation (3) in reducing the number of free parameters by one.

A bi-Maxwellian analysis is still impractical without first doing a full grid search of the $(\lambda_{\text{axis}}, b_{\text{axis}})$ parameter space to search for local minima in $\chi^2$. With $(\lambda_{\text{axis}}, b_{\text{axis}})$ fixed, and with $V_{\text{flow}}$ set by Equation (3), the remaining bi-Maxwellian fit parameters of interest are the flow direction $(\lambda_{\text{flow}}, b_{\text{flow}})$, $T_\perp$, and $T_\parallel$. The fits are now sufficiently robust for us to begin the process of zeroing in on the best bi-Maxwellian fit to the IBEX data. By systematically varying the $(\lambda_{\text{axis}}, b_{\text{axis}})$ orientation of the bi-Maxwellian, we produce a map of $\chi^2$ with $(\lambda_{\text{axis}}, b_{\text{axis}})$. The result is shown in Figure 3(a), which shows a very clear $\chi^2$ minimum at $(\lambda_{\text{axis}}, b_{\text{axis}}) = (57^\circ, -2^\circ)$. A bi-Maxwellian has $180^\circ$ symmetry, so the two minima in Figure 3(a) are really the same minimum. In this paper, we will use the convention of quoting only the direction with the longitude closest to $0^\circ$. This map is actually a product of two $(\lambda_{\text{axis}}, b_{\text{axis}})$ grids, one with an angular resolution of $30^\circ$ covering the full map, and one with a higher angular resolution of $10^\circ$ surrounding the $\chi^2$ minimum region.

Further support for the bi-Maxwellian solution at $(\lambda_{\text{axis}}, b_{\text{axis}}) = (57^\circ, -2^\circ)$ is provided by the map of best-fit $T_\perp/T_\parallel$ ratio shown in Figure 3(b). This map shows a clear minimum at exactly the same location as the $\chi^2$ minimum. This supports the validity of the bi-Maxwellian solution, because if the He VDF
is truly bi-Maxwellian with $T_{\perp}/T_{\parallel} < 1$, then in a map like Figure 3(b) there should be a minimum in best-fit $T_{\perp}/T_{\parallel}$ only where the correct ($\lambda_{\text{axis}}, b_{\text{axis}}$) is assumed. If an incorrect bi-Maxwellian axis direction is assumed, the best-fit $T_{\perp}/T_{\parallel}$ value will be closer to one. It is only when the correct axis orientation is assumed that the true low temperature ratio is recovered. Figure 3(b) is by itself suggestive of a preferred fit with $T_{\perp}/T_{\parallel} < 1$, at $(\lambda_{\text{axis}}, b_{\text{axis}}) = (57^\circ, -2^\circ)$, regardless of whether there is a $\chi^2$ minimum at that location. It is worth noting that Figure 3(b) shows no evidence for a preferred fit anywhere with $T_{\perp}/T_{\parallel} > 1$.

With Figure 3 clearly identifying the location of the best-fit bi-Maxwellian axis, we now conduct an error analysis for the various bi-Maxwellian parameters of interest, which is shown in Figure 4. The temperature ratio, $T_{\perp}/T_{\parallel}$, is not an independent parameter from the $T_{\perp}$ and $T_{\parallel}$ temperatures, but as a quantity of interest it is included in Figure 4 as well. For each parameter, the analysis involves a sequence of fits with that parameter held constant but the others allowed to vary, with the assumed value of the parameter then stepped across the $\chi^2$ minimum value to see at what point the increase in $\chi^2$, $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$, becomes too large to be considered acceptable. The acceptable $\Delta \chi^2$ value depends on the number of free parameters of the fit, which include the 7 bi-Maxwellian parameters of interest, plus 4 background and 4 normalization factors for the 4 years of data considered (see above). Based on these 15 free parameters, we assume a $3\sigma$ confidence contour corresponding to $\Delta \chi^2 = 34.7$, based on relation 26.4.14 of Abramowitz & Stegun (1965). The error bars displayed in Figure 4 are based on this threshold.

The final bi-Maxwellian parameters and uncertainties are listed in Table 1, where they are compared with recent Maxwellian measurements from both Ulysses (Wood et al. 2015) and IBEX (Bzowski et al. 2015). The flow vector $(V_{\text{flow}}, \lambda_{\text{flow}}, b_{\text{flow}})$ is in very good agreement across all these analyses. Changing from a Maxwellian VDF to a bi-Maxwellian clearly has no effect on the flow vector. It is instructive to compare our IBEX He flow parameter uncertainties with those that we previously measured for Ulysses (Wood et al. 2015), because the uncertainties have been computed in a consistent fashion, with consistent $3\sigma$ $\Delta \chi^2$ thresholds. The $V_{\text{flow}}$ and $\lambda_{\text{flow}}$ uncertainties are significantly lower for Ulysses than for IBEX, despite the significantly higher signal-to-noise ratio $(S/N)$ of the IBEX data. The causes of the large IBEX uncertainties are the parameter degeneracies alluded to above, and explicitly provided in Equation (3). Unlike IBEX, which essentially makes a single He beam map each year from the same location, the Ulysses mission observed the He beam at many different

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**Figure 4.** An assessment of best-fit values and uncertainties for the bi-Maxwellian He flow parameters inferred from IBEX data. In each panel, $\Delta \chi^2$ is plotted as a function of one of the parameters of interest. Each point corresponds to a fit where that parameter is held constant, but the other parameters are allowed to vary. Solid lines are high order polynomial fits to the $\Delta \chi^2$ values. The horizontal dotted–dashed line indicates our assumed $\Delta \chi^2$ threshold, which is used to define the region of acceptable fit, shown explicitly as vertical dashed lines.
locations in the inner heliosphere. As long as these data are considered collectively, the Ulysses measurements are free from the parameter degeneracy problem (Wood et al. 2015), leading to smaller parameter uncertainties despite the lower S/N.

In the bi-Maxwell fit, the $T_\perp = 7580 \pm 960$ K value is very similar to the temperature inferred in the Maxwellian analyses. It is $T_\parallel$ that changes greatly, increasing to $T_\parallel = 12,700 \pm 2960$ K. Perhaps this might provide an explanation for why certain analyses of IBEX data have ended up preferring higher temperatures, such as that of Möbius et al. (2015), who quote $T_\parallel = 8710^{+440}_{-680}$ K. If there is indeed $T$ anisotropy in the He VDF, then different types of analyses that assume a simple Maxwellian VDF could be sensitive to $T_\perp$ and $T_\parallel$ to different degrees.

Although of less interest than the He flow parameters, for completeness we now list the best-fit backgrounds and normalization factors for the four considered years of IBEX data. For the former, our best-fit background count rates are $0.0145$, $0.0235$, $0.0208$, and $0.0077$ s$^{-1}$ for 2011–2014, respectively. The cause of the factor of 2 drop after 2012 is a reduction in the post-acceleration voltage at that time, which changed the instrument sensitivity (e.g., Bzowski et al. 2015).

The best bi-Maxwell fit to the IBEX data has $\chi^2 = 1.83$, a significant improvement over the best Maxwellian fit with $\chi^2 = 2.28$. In order to try to identify where the bi-Maxwellian model is fitting the data better than the Maxwellian one, Figure 5 compares residuals of the fits for all 33 orbits considered in 2011–2014. It is difficult to distinguish between the fits in a figure like Figure 1, which is why here we show only the residuals.

Unfortunately, Figure 5 fails to provide a clear indication as to what aspects of the IBEX measurements are being reproduced better by the bi-Maxwellian model than by the Maxwellian one. The most fundamental problem is that the residual pattern is not precisely repeated from one year to the next. For example, the overestimate of flux apparent in the 2011 orbits 156a and 156b is not necessarily seen in analogous orbits in other years that correspond to the same position in Earth’s orbit around the Sun (e.g., orbits 196b and 197b in 2012). Some of this irreproducibility is due to the good time intervals in one orbit being significantly different from the good

![Figure 5. The residuals of three fits to IBEX data, with the black points the best fit assuming a Maxwellian VDF, the red points the best bi-Maxwellian fit, and the green points the best kappa distribution fit with $\kappa = 3$ (see Section 3).](image-url)
time intervals in the corresponding orbit in other years, meaning that the observations may be from different characteristic locations in IBEX’s orbit around the Earth, leading to different systematic effects on the data. Nevertheless, there are some orbits like 196a and 196b where the bi-Maxwellian fit is clearly doing significantly better than the Maxwellian fit.

Figure 6 provides a clearer illustration of how the best-fit bi-Maxwellian count rates compared to the best-fit single-Maxwellian count rates, using year 2012 as an example, as in Figure 1. The bi-Maxwellian has lower rates at early orbits in the observing season, followed by higher rates in the middle orbits. There is little difference in the fits for the last orbits. This basic pattern is reproduced each year.

In order to further explore how and why the analysis is ending up at the bi-Maxwellian solution indicated in Figure 3, we conduct the analysis for the 4 years (2011–2014) separately, to see if all 4 years independently suggest the same best fit. The results are shown in Figure 7. As in Figure 3, we use a 30° resolution grid for the full map, but a higher 10° resolution grid around the $T_\perp/T_\parallel$ minimum region of interest, with the merging and interpolation process involved in combining the two grids introducing some artifacts. The $T_\perp/T_\parallel$ maps are shown on the same color scale for ease of comparison. This is not possible for the $\chi^2_s$ maps, since $\chi^2_s$ is quite different for the different years.

All four maps in Figure 7 show a $T_\perp/T_\parallel$ minimum region near $(\lambda_{axis}, b_{axis}) = (57^\circ, -2^\circ)$, similar to that in Figure 3. Thus, we conclude that all 4 years are independently supporting the bi-Maxwellian fit suggested by the collective analysis in Figure 3. By far the biggest discrepancies with the Figure 3 maps are seen in 2011, where the $T_\perp/T_\parallel$ minimum is much less pronounced, and there is no longer any $\chi^2_s$ minimum at all at that location.

It is necessary to discuss the possibility that the apparent success of the bi-Maxwellian fit might be due to systematic errors in the data or artifacts of an imprecise analysis, rather than being an indication of asymmetries in the actual He VDF. The signature of the preferred bi-Maxwellian fit in Figure 3 seems very strong, but the difficulty in clearly identifying in the data why this particular fit works significantly better than the Maxwellian model is worrisome. There is also some reason for concern that the bi-Maxwellian fit results could be indicative of inconsistencies in two distinct temperature constraints provided by the IBEX data. Using Figure 1 as an example, the first constraint is the width of the latitudinal scans seen in the individual panels of the figure, while the second constraint is the width of the peak-flux-versus-orbit behavior seen when considering all panels together. Increasing a Maxwellian temperature should broaden the distribution in both senses, but in a bi-Maxwellian paradigm the two distinct constraints may have different sensitivities to $T_\perp$ and $T_\parallel$. It is perhaps worrisome that the inferred $(\lambda_{axis}, b_{axis})$ direction is very close to the ecliptic where IBEX is observing, and is also close to the flow direction, $(\lambda_{flow}, b_{flow})$. With this geometry, the $T_\perp$ parameter will primarily define the latitudinal scan width. Both $T_\parallel$ and $T_\perp$ will influence the peak-flux-versus-orbit width, the former through the distribution of angular particle directions in the ecliptic, and the latter through the difference in degree of
and similar rates for the last orbits. All deviations are between 1.5% and 4%. A similar pattern is seen in other years.

The Astrophysical Journal, 881:55 (16pp), 2019 August 10
Wood, Müller, & Möbius

Figure 6. Using the 2012 orbits as an example, we plot the count rate differences predicted by the best-fit bi-Maxwellian and single-Maxwellian fits. Specifically, the single-Maxwellian count rates are subtracted from the bi-Maxwellian rates. The bi-Maxwellian fit predicts lower rates at early orbits, higher rates for the middle orbits, and similar rates for the last orbits. All deviations are between 1.5% and 4%. A similar pattern is seen in other years.

gravitational deflection for particles of different energies directed along the central flow direction.

We have made an effort to change our analysis in various ways to see how sensitive the results in Figure 3 are to various assumptions that have to be made. We increased the number of orbits considered in the fit, and also considered a broader latitudinal range. We considered an analysis in which the secondary He component contribution was allowed to be a free parameter of the fit, and an analysis that makes no correction for secondaries at all. None of these experiments yielded any significant change to the maps in Figure 3. They still suggest a preferred fit with \( \lambda_{axis}, b_{axis} = (57^\circ, -2^\circ) \), and \( T_\parallel/T_\perp < 1 \).

Our analysis follows the practice of most past IBEX analyses in assuming no energy dependence for the He detection efficiency. However, we now briefly explore how our results might be affected by an energy-dependent sensitivity function, following the example of Swaczyna et al. (2018). Swaczyna et al. (2018) assume a sensitivity function, \( S_{PV} \), that is linearly dependent on particle velocity,

\[
S_{PV} \propto 1 + b_p(v - v_0),
\]

where \( v_0 = 78 \text{ km s}^{-1} \) is an arbitrary reference velocity, which is a typical speed for He particles when they reach IBEX (see Figure 2). We assume a value of \( b_p = -0.05 \text{ km s}^{-1} \), a typical value found by Swaczyna et al. (2018) when they allow \( b_p \) to vary in fits to data, implying a higher sensitivity to slower He particles. We then repeat the bi-Maxwellian fit, leading to the new maps in Figure 8, which can be compared with our baseline results in Figure 3.

With this assumed energy dependence for the detector sensitivity we still find a best-fit bi-Maxwellian with \( T_\parallel/T_\perp < 1 \), where \( \chi^2 \) is minimized. However, the longitude of the minimum region, \( \lambda_{axis} \), is shifted. It is important to note that none of the other bi-Maxwellian fit parameters listed in Table 1 are significantly affected at all. This is consistent with the results of Swaczyna et al. (2018), who found no significant change in best-fit He flow direction or magnitude when the detector sensitivity was allowed to depend on particle velocity, as in Equation (4). However, in our bi-Maxwellian analysis, we find that \( \lambda_{axis} \) decreases from \( \lambda_{axis} = 57^\circ 2 \pm 8^\circ 9 \) to \( \lambda_{axis} \approx 30^\circ \). Although this exercise demonstrates that it is possible that \( \lambda_{axis} \) in a bi-Maxwellian analysis could be affected by an energy sensitivity in particle detection, we note that the quality of the best fit within Figure 8 (\( \chi^2 = 3.35 \)) is significantly worse than the best fit in Figure 3 assuming no energy sensitivity (\( \chi^2 = 1.83 \)). Further work allowing a variable \( b_p \) would be required to demonstrate that an assumed energy dependence of instrument sensitivity is statistically justified in the context of a bi-Maxwellian fit, which is outside the scope of our current analysis.

The one experiment we tried that showed potential for yielding truly fundamental changes to our bi-Maxwellian fit results was to vary the assumed photoionization rates. Our first experiment was to remove the loss rate correction entirely. This not only did not change the basic character of Figure 3, but it also greatly worsened the quality of fit to \( \chi^2 \sim 5 \). However, when we go the opposite direction and arbitrarily increase the photoionization loss rates by 50%, we have more promising results, which are shown in Figure 9. The appearance of the maps in Figure 9 is curiously similar to those for 2011 in Figure 7, suggesting similar systematic uncertainties may be coming into play here. Could this mean that the photoionization rate assumed for 2011 is significantly too high? In Figure 9, with the 50% increase in photoionization, the \( \chi^2 \) minimum near \( (\lambda_{axis}, b_{axis}) = (57^\circ, -2^\circ) \) disappears entirely. The \( T_\parallel/T_\perp \) minimum at that location fades as well, although it is still visible. Furthermore, the \( \chi^2 \) values found for these fits do not indicate any dramatic degradation in fit quality like we see when photoionization rates are arbitrarily decreased instead of increased.

Thus, our best bi-Maxwellian fit with \( T_\parallel/T_\perp < 1 \) and \( (\lambda_{axis}, b_{axis}) = (57^\circ, -2^\circ) \) could in principle be an artifact of underestimated photoionization loss rates, but it is questionable
Figure 7. Analogous to Figure 3, but for the four considered years of IBEX data analyzed separately. All 4 years show the same $T_{\perp}/T_{||}$ minimum region seen in Figure 3, although in 2011 this minimum is much less pronounced and there is no $\chi^2$ minimum at that location.
whether the rates could really be systematically that far off. We use a simplified treatment of the loss rates here, where a single constant rate is used for all particles in an observing season, with no attempt to account for rate variation during the He atoms’ slow journey to 1 au. Sokół et al. (2015) studied the effects of loss rate assumptions in great detail, including the effects of secondary loss processes such as electron impact ionization and charge exchange near the Sun, and including the effects of latitudinal variation. Their analysis implies that our assumption of constant loss rates could lead to loss estimates being of order 7% off for a given observing season. However, this is still much lower than the ~50% error needed to affect our analysis. Furthermore, such errors should not be consistent from year to year, so the persistence of the $T_{\perp}/T_{\parallel}$ minimum region for all 4 years in Figure 7 implies that the effects of loss rate variability are not significant factors. Only a latitude dependence issue would likely lead to a systematic error in the same direction every year, but the analysis of Sokół et al. (2015) implies that errors introduced by that effect are less than 1%.

Our preferred interpretation remains that the bi-Maxwellian results in Figure 3 are truly indicative of VDF asymmetries in the He flow that exist far from the Sun, but there is clearly value in looking for independent support for these asymmetries elsewhere. With that in mind, we turn our attention to Ulysses.

2.2. Ulysses Data Analysis

The GAS instrument on the Ulysses spacecraft (Witte et al. 1992) conducted episodic observations of the ISN He flow between the 1990 launch date and the end of the mission in 2007. The primary observations were made from Ulysses’s operational orbit roughly perpendicular to the ecliptic plane, with an aphelion near 5 au and a perihelion near 1 au. The He observations could only be made during the fast latitude scans near perihelion, with the spacecraft moving fast enough for He particles to be entering the GAS detector with sufficient energy for detection. Thus, the observations are limited to three periods from 1994–1996, 2000–2002, and 2006–2007.

When the He flow was observable, the GAS instrument could make a scan across the He beam in a 2–3 day period, so the Ulysses database consists of hundreds of separate He beam maps from many different places in Ulysses’s orbit. Based on a set of 238 of these maps, we have previously inferred He flow properties assuming a Maxwellian VDF (Wood et al. 2015). Our analysis procedures here are essentially identical to this previous work, only with the Maxwellian VDF replaced with a bi-Maxwellian. We refer the reader to Wood et al. (2015) for details. Before fitting the data, we subtract the secondary He contribution reported by Wood et al. (2017).

Figure 10(a) shows an example of a Ulysses He beam map, from 2001 February 4, and the best fit to this data from...
Wood et al. (2015) in Figure 10(b), with the residuals in Figure 10(c). In order to illustrate the effects of a bi-Maxwellian distribution with a large temperature anisotropy, in Figure 10(d) we simulate a beam map assuming the best-fit He flow vector, but with the temperature changed so that \( T_{\perp}/T_{\parallel} = 2 \). Specifically, we replaced the best-fit single-Maxwellian \( T = 7260 \) K with \( T_{\perp} = 7500 \) K and \( T_{\parallel} = 3750 \) K. For this purely illustrative test, we used the \( B_{\text{SM}} \) direction suggested by the IBEX ribbon as the bi-Maxwellian axis, \( (\lambda_{\text{axis}}, b_{\text{axis}}) = (39^\circ 2, -39^\circ 9) \) (Funsten et al. 2013). The residuals in Figure 10(e) are naturally much worse than those in Figure 10(c).

As was the case in the IBEX analysis, it is necessary to do a full search through the \( (\lambda_{\text{axis}}, b_{\text{axis}}) \) parameter space to look for \( \chi^2 \) minima. The resulting maps of \( \chi^2 \) and best-fit \( T_{\perp}/T_{\parallel} \) are shown in Figure 11. Unlike IBEX, the Ulysses map in Figure 11 shows two distinct \( \chi^2 \) minima, one at \( (\lambda_{\text{axis}}, b_{\text{axis}}) \approx (60^\circ, 15^\circ) \) with \( T_{\perp}/T_{\parallel} < 1 \), and one at \( (\lambda_{\text{axis}}, b_{\text{axis}}) \approx (10^\circ, -30^\circ) \) with \( T_{\perp}/T_{\parallel} > 1 \). At the \( \chi^2 \) minima the best-fit temperature values are: \( T_{\perp} = 6930 \) K, \( T_{\parallel} = 7440 \) K, and \( T_{\perp}/T_{\parallel} = 0.93 \); at \( (\lambda_{\text{axis}}, b_{\text{axis}}) \approx (60^\circ, 15^\circ) \); and \( T_{\perp} = 7280 \) K, \( T_{\parallel} = 6760 \) K, and \( T_{\perp}/T_{\parallel} = 1.08 \) at \( (\lambda_{\text{axis}}, b_{\text{axis}}) \approx (10^\circ, -30^\circ) \). Using the same 3\( \sigma \) thresholds used in the IBEX analysis in Figure 4, we compute a \( \chi^2 \) threshold for acceptable fits, which is indicated as a dashed line in Figure 11. Both \( \chi^2 \) minima regions are statistically acceptable fits to the data, and the regions around each minimum where the fits are acceptable are quite large. This is indicative of the low S/N of the Ulysses data, compared to that of IBEX.

By itself, the Ulysses analysis provides only marginal evidence that a bi-Maxwellian assumption yields an improvement in quality of fit relative to a Maxwellian assumption, with two rather broad \( (\lambda_{\text{axis}}, b_{\text{axis}}) \) regions where the fits are acceptable. The best-fit bi-Maxwellian fit has \( \chi^2 \approx 1.497 \), compared with \( \chi^2 = 1.524 \) for the best Maxwellian fit (Wood et al. 2015). This improvement is much less than that seen for IBEX (see Section 2.1). The temperature anisotropy is not quite as large as we find for IBEX, but perhaps this is also a manifestation of the lower statistical significance of the improvement in fit quality provided by the bi-Maxwellian assumption.

The most important aspect of Figure 11 to note is that the \( \chi^2 \) minimum region of Ulysses with \( T_{\perp}/T_{\parallel} < 1 \) does overlap with the bi-Maxwellian fit of IBEX, which also has \( T_{\perp}/T_{\parallel} < 1 \). Thus, we conclude that the Ulysses data do provide independent support for the reality of the best-fit solution to the IBEX data in Figure 3. Furthermore, the Ulysses analysis is insensitive to assumptions about photoionization loss rates (Wood et al. 2015), so the potential dependence of the IBEX bi-Maxwellian results on the assumed loss rates (see Figure 9) does not exist for Ulysses.
2.3. Interpretation of the Bi-Maxwellian Results

We have found evidence that the ISN neutral He flow through the inner heliosphere exhibits a non-Maxwellian character, with the IBEX data being fit better with a bi-Maxwellian VDF instead of a Maxwellian, with an orientation of \((\lambda_{\text{axis}}, b_{\text{axis}}) = (57^\circ 2 \pm 8^\circ 9, -1^\circ 6 \pm 5^\circ 9)\) and a temperature anisotropy of \(T_{\perp}/T_\parallel = 0.62 \pm 0.11\). As noted at the beginning of Section 2, a bi-Maxwellian VDF model makes the most physical sense if oriented about the magnetic field. Thus, the case for the He flow being truly bi-Maxwellian would be particularly strong if the best-fit \((\lambda_{\text{axis}}, b_{\text{axis}})\) orientation had ended up close to the \(B_{\text{ISM}}\) direction.

The IBEX ribbon observations imply a \(B_{\text{ISM}}\) direction at or near \((39^\circ 2, -39^\circ 9)\) (Funsten et al. 2013), a direction explicitly indicated in both Figures 3 and 11. However, this direction is \(41^\circ 6\) from the best-fit \((\lambda_{\text{axis}}, b_{\text{axis}})\) direction. The Ulysses results in Figure 11 do show an acceptable fit with \((\lambda_{\text{axis}}, b_{\text{axis}})\) near the \(B_{\text{ISM}}\) direction, with \(T_{\perp}/T_\parallel > 1\), but IBEX provides no support for this solution. Thus, the actual He VDF implied by our results may not be truly bi-Maxwellian, but instead simply asymmetric to an extent that it is significantly better represented by a bi-Maxwellian model than a symmetric Maxwellian one.

The \((\lambda_{\text{axis}}, b_{\text{axis}})\) direction implied by IBEX may not be very close to the \(B_{\text{ISM}}\) direction, but it is only \(18^\circ 7\) from the He flow direction, \((\lambda_{\text{flow}}, b_{\text{flow}})\), as shown explicitly in Figures 3 and 11. A direction picked at random has only a 5.3% chance of being this close to \((\lambda_{\text{flow}}, b_{\text{flow}})\), so the proximity of \((\lambda_{\text{axis}}, b_{\text{axis}})\) and \((\lambda_{\text{flow}}, b_{\text{flow}})\) is likely not accidental. The heliocentric rest frame in which \((\lambda_{\text{flow}}, b_{\text{flow}})\) is computed has no relevance for the VLISM in general, so the proximity between \((\lambda_{\text{axis}}, b_{\text{axis}})\) and \((\lambda_{\text{flow}}, b_{\text{flow}})\) implies that the VDF asymmetry that we are sensing is not intrinsic to the VLISM, but is instead induced in the VDF somewhere in the outer heliosphere.

One possible cause of the VDF asymmetry is suggested by the existence of the secondary He neutrals discovered by IBEX, which are likely produced by charge exchange in the outer heliosheath (Kubiak et al. 2014, 2016). Given that for He the primary charge exchange reaction should be \(\text{He}^0 + \text{He}^+ \rightarrow \text{He}^+ + \text{He}^0\), the primary He flow population that we are studying here represents the neutral charge exchange partners for the \(\text{He}^+\) that becomes the secondary neutral population after charge exchange. This outer heliosheath charge exchange therefore represents a loss process for the primary neutral He flow. If the charge exchange losses are isotropic throughout the VDF, then there would be no effect on the VDF shape. But if the charge exchange losses are preferentially extracted from certain parts of the VDF, then this would introduce asymmetries into the VDF, which could be what we are detecting.

Accounting for the secondary ISN He population itself remains a concern as well. Charge exchange adds a population to the overall He VDF that is generally slower and hotter than the primary ISN He, but subtracting the secondary He signal from the data is very difficult. Our subtraction is based on an analysis that treats the secondaries as a homogeneous, laminar, Maxwellian flow from infinity (Kubiak et al. 2016), much as the primary neutrals are generally treated. But this is a poor approximation for the secondary population, which is created in a region of divergent flow in the outer heliosheath, a region that is likely not very homogeneous.

Additional theoretical work is needed to assess whether the outer heliosheath charge exchange involving He should be expected to introduce VDF asymmetries into the primary ISN He population consistent with those we infer here. The suggestion of non-Maxwellian ISN VDFs also provides motivation for future investigations with more advanced observing capabilities, such as those that will be available on the proposed Interstellar Mapping and Acceleration Probe mission.

3. Assuming a Kappa Distribution

In addition to the bi-Maxwellian VDF assumption discussed in the previous section, we also experiment with a kappa distribution. A kappa distribution has been a common way to describe space plasmas that are not in equilibrium, such as the solar wind (Pierrard & Lazar 2010; Livadiotis & McComas 2012). Observational evidence for turbulence exists in the ISM (Redfield & Linsky 2008), and this turbulence could in principle lead to VDFs that are best described with kappa distributions (Fisk & Gloeckler 2006).

A kappa distribution can be expressed as

\[
F(v) = \frac{n \Gamma(\kappa + 1)}{\omega_p \pi^{3/2} \kappa^{3/2} \Gamma(\kappa - 1/2)} \left(1 + \frac{(v - U)^2}{k \omega_p^2}\right)^{-\kappa-1},
\]

where \(\omega_p\) is the plasma frequency, \(U\) is some reference velocity, and \(\kappa\) is the kappa parameter that determines the shape of the distribution.
where

\[ w_\nu = \frac{2kT \kappa - 3/2}{m \kappa}, \quad (6) \]

with \( T \) defined in the limit \( \kappa \to \infty \). This distribution has a thermal core and a power-law tail, reducing to a Maxwellian as \( \kappa \to \infty \). The lower limit for \( \kappa \) is \( \kappa = 1.5 \), where the kappa distribution becomes ill-defined.

Replacing a Maxwellian with a kappa distribution and reanalyzing the IBEX and Ulysses data is significantly simpler than the bi-Maxwellian analysis in Section 2, because the kappa distribution only introduces one extra free parameter (\( \kappa \)), compared to the three introduced by the bi-Maxwellian assumption. The fitting process is therefore relatively straightforward.

However, for IBEX we believe it is necessary to expand the range of orbits and latitudes considered in order to properly test the kappa distribution. This is because the kappa distribution is most distinct from a Maxwellian in its extended power-law tail. Thus, in addition to the orbit selection illustrated in Figure 5, which was originally defined by Bzowski et al. (2015), we add up to two earlier orbits and up to two later orbits for each considered year (2011–2014), with the precise additions each year depending on the availability of good time intervals for each orbit. We also increase the latitude range considered from \( \pm 25^\circ \) to \( \pm 45^\circ \) from the ecliptic.

Analogous to the bi-Maxwellian analysis in Figure 4, we measure the \( \kappa \) parameter and its uncertainty by conducting a sequence of fits with different assumed \( \kappa \) values held constant, but all other parameters allowed to vary. The results are shown in red in the top panel of Figure 12. We quickly conclude that the kappa distribution does not provide an improvement in fits to the data compared to a Maxwellian, as the best fits are for the Maxwellian-like high-\( \kappa \) models, with the \( \chi^2 \) value increasing greatly as \( \kappa \) is decreased. Using a 3\( \sigma \) \( \Delta \chi^2 \) threshold, as in Section 2, we find an upper limit of \( \kappa > 17.0 \) based on this initial analysis. Figure 12 also illustrates the variation of best-fit temperature as a function of \( \kappa \), with \( T \) decreasing monotonically as \( \kappa \) is increased. This relation is very similar to that found by Swaczyna et al. (2019), who have also investigated the implications of a kappa distribution assumption for analyses of IBEX data.

In order to illustrate the problems with the low-\( \kappa \) fits, Figure 5 shows the residuals of the best \( \kappa = 3 \) fit. There are clear, systematic discrepancies that are consistent from year to year. For example, for the last orbits of each year shown in Figure 5 (116, 158a, 197b, and 238a), the \( \kappa = 3 \) fit systematically underpredicts fluxes near peak center at latitudes in the range \([0^\circ, 10^\circ]\), and overpredicts fluxes in the near wings, at \([-15^\circ, -5^\circ]\) and \([15^\circ, 25^\circ]\). This is clear evidence that the extended power-law nature of the wings of the low-\( \kappa \) VDFs is not consistent with the data.

Perhaps the biggest systematic uncertainty in the kappa distribution analysis concerns the effects of the secondary He neutrals. The hotter, slower secondary He population yields a signal observed by IBEX over a broad distribution of latitudes and orbits, stretching well beyond the orbits where the primary He neutrals dominate. The secondary component therefore acts as a sort of broad background under the primary component, the effects of which mimic the effects that should be produced by a kappa distribution with broad power-law wings. We have to consider the possibility that when we correct for the secondary neutral contribution (see Section 2.1), some of the counts that we are assigning to the secondaries may in fact be primary neutrals in the wings of a kappa distribution.

For this reason, we perform a second IBEX analysis in which we still assume the Kubiak et al. (2016) flow parameters to correct for the secondaries, but we allow the contribution fraction of the secondary population to vary from the \( n(\text{He}_2)/n(\text{He}_1) = 0.057 \) ratio measured by Kubiak et al. (2016). The results are shown in green in Figure 12. Unlike for the original fit sequence, for this new sequence each year depending on the availability of good time intervals for each orbit. We also increase the latitude range considered from \( \pm 25^\circ \) to \( \pm 45^\circ \) from the ecliptic.

It should be noted that if we considered even earlier orbits for each year, where the secondary neutrals completely dominate the IBEX signal, the \( \chi^2 \) improvement for the variable \( n(\text{He}_2)/n(\text{He}_1) \) model in Figure 12 would likely decrease, as the low \( n(\text{He}_2)/n(\text{He}_1) \) values would probably lead to a failure to account for the observed counts in those earlier orbits. However, this only emphasizes that our approach for assessing the systematic errors introduced by uncertainties in the secondary He contribution should be a fairly conservative one.
Finally, we also repeat our analysis of the *Ulysses* data, but assuming a kappa distribution instead of a Maxwellian or bi-Maxwellian. The initial results are shown in red in Figure 13. We once again find no evidence that a kappa distribution yields better fits than a simple Maxwellian. We find a lower limit of $\kappa > 6.3$.

Analogous to the *IBEX* analysis, we assess the systematic errors introduced into the *Ulysses* analysis by uncertainties in the He secondary subtraction. For *Ulysses*, we address this by conducting a second sequence of fits in which we simply do not correct for secondaries at all. In principle, this should free up extra counts in the wings of the observed He beam for the kappa distributions to account for, allowing low-$\kappa$ models to fit the data better. In practice, however, the change in $\chi^2$ is minimal. The results, shown in green in Figure 13, yield only a tiny downward adjustment to the $\kappa$ lower limit, $\kappa > 6.0$, which is nevertheless what we choose to report as our final measurement. Given the lower $S/N$ of the *Ulysses* data relative to *IBEX*, it is not a surprise that its limits on $\kappa$ are less restrictive.

We find no evidence that a kappa distribution provides better fits to either the *IBEX* or *Ulysses* data, compared to a simple Maxwellian VDF. This suggests that the VLISM may be very close to thermal equilibrium, despite the apparent presence of turbulence. Although densities in the VLISM are very low, and collisional timescales are therefore very long, the perturbation timescale in the VLISM may also be very long, possibly providing sufficient time for collisional equilibrium to be reached. This would happen first for the plasma component of the VLISM, which could then imprint its properties onto the neutral component through charge exchange.

### 4. Summary

We have reanalyzed *IBEX* and *Ulysses* observations of ISN He atoms flowing through the inner solar system. Our primary goal has been to assess whether fits to the data can be improved by assuming non-Maxwellian VDFs for the flow, as opposed to the usual Maxwellian assumption. Our findings are summarized as follows:

1. We first experiment with a bi-Maxwellian VDF. In fits to *IBEX* data from 2011–2014 we find a very clear preferred fit with $T_{\perp}/T_\parallel = 0.62 \pm 0.11$ oriented about an axis with ecliptic coordinates $(\lambda_{\text{axis}}, b_{\text{axis}}) = (57.2 \pm 8.9, -17.6 \pm 5.9)$. This result seems fairly robust to most assumptions made in the analysis. However, we find some evidence that the $\lambda_{\text{axis}}$ parameter is curiously dependent on assumptions about the energy dependence of particle detection. We also find some sensitivity of our results to the assumed photoionization loss rates, though it is questionable whether our assumed rates could be off by enough for this to be a major issue. The $(\lambda_{\text{axis}}, b_{\text{axis}})$ location right on the ecliptic is also cause for concern, as this is in *IBEX*’s orbital plane around the Sun. This could in principle be indicative of some unknown systematic error affecting the *IBEX* data or the assumptions involved in our analysis of it.

2. A bi-Maxwellian analysis is also performed on *Ulysses* data. The lower $S/N$ of the data leads to the existence of two rather large, separate $(\lambda_{\text{axis}}, b_{\text{axis}})$ regions of acceptable fit, but one of them is consistent with the *IBEX* result, and it also has $T_{\perp}/T_\parallel < 1$. Thus, the *Ulysses* analysis provides independent support for the best-fit *IBEX* bi-Maxwellian solution, and unlike *IBEX*, the *Ulysses* analysis will not be sensitive to photoionization assumptions.

3. The axis of symmetry implied by the best bi-Maxwellian fit to the data, $(\lambda_{\text{axis}}, b_{\text{axis}})$, is not very close to the $B_{\text{ISM}}$ direction, but it is only $18.7^\circ$ from the He flow direction in a heliocentric rest frame. This implies that we are detecting VDF asymmetries that are introduced in the outer heliosphere rather than VDF asymmetries that are intrinsic to the VLISM. Perhaps charge exchange processes in the outer heliosheath are responsible for these asymmetries.

4. We also experiment with a kappa distribution, but we find that a kappa distribution does not lead to better fits to the data for either *IBEX* or *Ulysses*, compared to a Maxwellian. Based on these analyses, we find lower limits of $\kappa > 6.0$ and $\kappa > 12.1$ based on *Ulysses* and *IBEX*, respectively.

5. The kappa distribution results emphasize that a simple Maxwellian VDF is actually quite successful at fitting the *IBEX* and *Ulysses* data, implying that the VLISM is close to thermal equilibrium.

6. Replacing the Maxwellian VDF with a bi-Maxwellian or kappa distribution does not lead to any significant change in the best-fit ISN He flow vector, for either *IBEX* or *Ulysses*.

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