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LOCAL INTERSTELLAR MEDIUM: SIX YEARS OF DIRECT SAMPLING BY *IBEX*

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ABSTRACT

The *Interstellar Boundary Explorer* (*IBEX*) has been directly observing neutral atoms from the local interstellar medium for the last six years (2009–2014). This paper ties together the 14 studies in this *Astrophysical Journal Supplement Series* Special Issue, which collectively describe the *IBEX* interstellar neutral results from this epoch and provide a number of other relevant theoretical and observational results. Interstellar neutrals interact with each other and with the ionized portion of the interstellar population in the "pristine" interstellar medium ahead of the heliosphere. Then, in the heliosphere's close vicinity, the interstellar medium begins to interact with escaping heliospheric neutrals. In this study, we compare the results from two major analysis approaches led by *IBEX* groups in New Hampshire and Warsaw. We also directly address the question of the distance upstream to the pristine interstellar medium and adjust both sets of results to a common distance of ~1000 AU. The two analysis approaches are quite different, but yield fully consistent measurements of the interstellar He flow properties, further validating our findings. While detailed error bars are given for both approaches, we recommend that for most purposes, the community use "working values" of ~25.4 km s^{-1}, ~75$^\circ\!\!.$7 ecliptic inflow longitude, ~ $-5^\circ\!\!.1$ ecliptic inflow latitude, and ~7500 K temperature at ~1000 AU upstream. Finally, we briefly address future opportunities for even better interstellar neutral observations to be provided by the Interstellar Mapping and Acceleration Probe mission, which was recommended as the next major Heliophysics mission by the NRC's 2013 Decadal Survey.

Key words: interplanetary medium – ISM: general – local interstellar matter – Sun: heliosphere

1. INTRODUCTION

This *Astrophysical Journal Supplement Series* Special Issue comprises 14 papers that examine the first six years of direct sampling of the local interstellar neutral populations by the *Interstellar Boundary Explorer* (*IBEX*), as well as some new analyses of *Ulysses*/*GAS* and various related observational and theoretical topics. Collectively, these studies, along with the previously published papers related to the *IBEX* interstellar neutral observations, open a completely new window on the local interstellar environment, its composition, its properties, and the likely processes at work in the interstellar space around our Sun and in the heliospheric boundary region. These observations also benchmark our understanding of the low density interstellar medium more generally, which is key for stellar and planetary system formation, the formation of astrospheres around other stars, and understanding the tenuous material throughout our galaxy and the many galaxies beyond.

The interstellar medium arises from the evolutionary processes associated with star formation, and is refreshed by stellar winds and material ejected from novae and supernovae. *IBEX* measures the neutral component of the low density interstellar gas that originates in the cloud surrounding the heliosphere. This material is partially ionized and the ions and neutrals interact with each other through charge exchange, recombination, and various forms of ionization. The ionized portion is magnetized and further participates in collective plasma behavior which then couples back into neutral populations producing the complex and fascinating partially ionized medium that dominates the heliosphere's configuration and populates the disk and halo of our galaxy.

The local interstellar cloud (LIC) that surrounds the solar system is part of a dynamic system of interstellar clouds, whose column densities, relative speeds, and temperatures have been studied on scales of several parsecs through optical and UV line absorption in the light of nearby stars (e.g., see reviews by Cox & Reynolds 1987; Frisch 1995; Frisch et al. 2011). The first *Copernicus* ultraviolet spectra of interstellar nitrogen lines toward alpha Leo (24 pc) revealed roughly equal amounts of neutral and ionized gas which indicated the warm, low density, partially ionized nature of the local interstellar medium. Interstellar neutrals inside of the heliosphere are linked to the interstellar gas toward nearby stars by their gas velocities (Adams & Frisch 1977; Lallement & Bertin 1992; Redfield & Linsky 2008; Gry & Jenkins 2014). The LIC is quite structured, with the Sun apparently close to its boundary, having recently entered it and with the prospect of exiting it within the next 35,000 years according to the neutral hydrogen component

Table 1
Papers in this *Astrophysical Journal Supplement Series* (ApJS) Special Issue

Title	Lead Author
1. Local Interstellar Medium: Six Years of Direct Sampling by *IBEX*	McComas
2. The Analytical Structure of the Primary Interstellar Helium Distribution Function in the Heliosphere	Lee
3. Interstellar Flow and Temperature Determination with *IBEX*: Robustness and Sensitivity to Systematic Effects	Möbius
4. Determination of Interstellar He Parameters Using 5 Years of Data From *IBEX*: Beyond Closed-form Approximations	Schwadron
5. Interstellar Neutral Helium in the Heliosphere from *IBEX* Observations. I. Uncertainties and Backgrounds in the Data and Parameter Determination Method	Swaczyna
6. Interstellar Neutral Helium in the Heliosphere from *IBEX* Observations. II. The Warsaw Test Particle Model (WTPM)	Sokół
7. Interstellar Neutral Helium in the Heliosphere from *IBEX* Observations. III. Mach Number of the Flow, Velocity Vector, and Temperature from the First Six Years of Measurements	Bzowski
8. The Interstellar Neutral He Haze in the Heliosphere: What Can We Learn?	Sokół
9. Can *IBEX* Detect Interstellar Neutral Helium or Oxygen from Anti-ram Directions?	Galli
10. Exploring the Possibility of O and Ne Contamination in Ulysses Observations of Interstellar Helium	Wood
11. 3D Kinetic-MHD Model of the Global Heliosphere with the Heliopause-surface Fitting	Izmodenov
12. Impact of the Solar Radiation Pressure on Fluxes of Interstellar Hydrogen Atoms Measured by *IBEX*	Katushkina
13. Statistical Analysis of the Heavy Neutral Atoms Measured by *IBEX*	Park
14. Impact of Planetary Gravitation on High-precision Neutral Atom Measurements	Kucharek

(Frish 1994; Lallement et al. 1995; Wood et al. 2000; Slavin & Frisch 2002). Furthermore, directly around the Sun, the very local interstellar medium (LISM) is part of an evolved superbubble shell that is a particularly interesting portion of the LIC to be able to directly sample and thereby study in detail.

While there have been indirect observations of interstellar neutrals through backscattered solar Lyα emission (e.g., Bertaux & Blamont 1971; Bertaux et al. 1985; Costa et al. 1999), and even in situ observations through pickup ions (Möbius et al. 1985; Gloeckler et al. 1992; Gloeckler & Geiss 1998), the only direct sampling of any neutrals from the local interstellar medium prior to 2009 was for helium (He) by the *GAS* experiment on the *Ulysses* spacecraft (Witte et al. 1992; Witte 2004). Since then, *IBEX* has been returning new observations of interstellar neutrals from space each year during its interstellar neutral observation season in the winter/spring. *IBEX* (McComas et al. 2009a) is one of NASA's Small Explorer missions; its objective is to discover the global interaction between the solar wind and the interstellar medium. This has been achieved through a combination of making the first all-sky energetic neutral atom (ENA) images and by directly measuring multiple species of interstellar neutrals that transit through the heliosphere to the location of *IBEX* at 1 AU.

IBEX has two high-sensitivity ENA cameras: *IBEX*-Lo (Fuselier et al. 2009a) and *IBEX*-Hi (Funsten et al. 2009a), which measure ENAs in the ranges of ~10–2000 eV and ~300–6000 eV, respectively. At its lower energies, *IBEX*-Lo also measures interstellar neutrals (Möbius et al. 2009a). *IBEX* collects neutral atoms as a function of spacecraft spin-phase, which arrive nearly perpendicular to its roughly Sun-pointing spin axis. Each winter/spring season, the Earth is in the part of its orbit where the spacecraft's inertial motion rams into interstellar neutrals, which are gravitationally bent just enough that they enter *IBEX*'s viewing plane. Thus, *IBEX*'s detailed observations of various measured neutral atom species as a function of spacecraft pointing and spin-phase contain the information needed to determine these species' inflow properties of direction, speed, and temperature.

First results from *IBEX*, including the discovery of the "*IBEX* Ribbon"—a long, narrow arc of significantly enhanced ENA emissions that is ordered by the very local interstellar magnetic field—were documented in a special issue of *Science* magazine (Funsten et al. 2009b; Fuselier et al. 2009b; McComas et al. 2009b; Schwadron et al. 2009). That issue also provided *IBEX*'s first observations of interstellar neutrals (Möbius et al. 2009b). These included the first direct sampling of interstellar hydrogen (H) and oxygen (O) and *IBEX*'s first season of interstellar He observations. Subsequent studies showed *IBEX*'s first direct sampling of neon (Ne) and the Ne/O ratio (Bochsler et al. 2012; Park et al. 2014), and the first direct sampling of interstellar deuterium (D) (Rodriquez Moreno et al. 2013, 2014) in the LISM.

A number of the prior *IBEX* studies on interstellar neutrals were published together in a special *Astrophysical Journal Supplement* in 2012 (Bochsler et al. 2012; Bzowski et al. 2012; Hlond et al. 2012; Lee et al. 2012; McComas et al. 2012; Möbius et al. 2012; Saul et al. 2012); these results were based entirely on data from the 2009 and 2010 viewing seasons. In this new, 2015 *Astrophysical Journal Supplement Series* Special Issue, we provide 14 additional studies (Table 1) that collectively incorporate data from all six years of *IBEX* observations (2009–2014), update the knowledge gained from *IBEX*'s interstellar neutral data, and examine the implications of these unique observations on interstellar gas at a single location in space.

2. PRIOR STUDIES OF INTERSTELLAR HELIUM

The *IBEX* team's approach to analyzing the interstellar He data has been two pronged. First, in the work led by University of New Hampshire (UNH) team members, we used analytic solutions and approximations (Lee et al. 2012) for the hyperbolic orbits of He atoms in the Sun's gravity well (unlike interstellar H and D, radiation pressure is essentially negligible for He). Using these equations and approximations, we then analyzed the *IBEX* observations (Möbius et al. 2012). Second, in the work led by our team members from the Space Research Centre of the Polish Academy of Sciences, we used the Warsaw Test Particle Model (WTPM) to simulate the trajectories of test particles, calculate the expected signal for all data points, and then minimize the deviations between the results for various input parameters and the *IBEX* observations (Bzowski et al. 2012). The two approaches are quite different. The Warsaw approach addresses the more complex problem of fitting the full distributions, including all of the possible contributions from the various populations and backgrounds. In contrast, the UNH approach focuses only on the peak of the distribution, which is a simpler problem. The fact that both approaches yield very consistent values lends strong support to the combined results.

Because *IBEX* observes neutrals only when their trajectory is nearly tangential to Earth's orbit (*IBEX* views perpendicular to its Sun pointed spin axis), there is a very tight coupling between the interstellar He inflow vector: speed ($V_{\mathrm{ISM}\infty}$), ecliptic longitude[11] ($\lambda_{\mathrm{ISM}\infty}$), ecliptic latitude[11] ($\beta_{\mathrm{ISM}\infty}$), and temperature ($T_{\mathrm{He}\infty}$) far upstream (Lee et al. 2012). This tight coupling is found in both the analytic analyses (Möbius et al. 2012) and Warsaw test particle results (Bzowski et al. 2012). These analyses provided nearly identical four-dimensional (4D) "tubes" of these coupled parameters with a very small uncertainty for any specific location along the tube, but a significant extent of possible coupled parameters along it. McComas et al. (2012) examined a small difference between the Warsaw results, which are calculated to 150 AU ahead of the Sun, and the UNH results, which are theoretically calculated to infinity (Section 4 below takes up this issue in more detail), to combine both sets of results. Equations (1)–(3) of that study provide the coupling equations among the four observable interstellar parameters in the *IBEX* data. This 4D tube emerges naturally without further assumptions in the numerical analysis and remains in all subsequent *IBEX* interstellar He observations and analyses, and we have expended considerable effort to localize the most likely position along the tube.

The initial He results (Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012) raised interesting questions about the stability of the helium flow direction (Frisch et al. 2013) that stimulated active discussions in the community (e.g., Katushkina et al. 2014; Lallement & Bertaux 2014; Frisch et al. 2015). However, criticisms of earlier *IBEX* work were unfounded as McComas et al. (2012) clearly provided (see their Table 1) a broad range of possible coupled parameters from (21.3 km s^{-1}, 82°.0, −4°.84, 5000 K) to (25.7 km s^{-1}, 75°.5, −5°.14, 8300 K) with 1σ uncertainties of $\sim$(±0.3 km s^{-1}, ±0°.5, ±0°.2, ±400 K) around any consistent set of parameters along the 4D parameter tube. Clearly, the tube of possible coupled parameters allowed by the *IBEX* data was inconsistent with the prior *Ulysses* data (Witte 2004) and required either a different velocity vector (with slightly lower speed and slightly larger longitude) or a significantly higher temperature. It was also clear that we needed a larger observational baseline to identify a well-constrained location along the tube for the interstellar parameters.

IBEX and *Ulysses* observations both have their advantages and disadvantages for measuring the interstellar neutrals, with *Ulysses* having a more advantageous orbit and overall viewing geometry and *IBEX* being able to identify various neutral species uniquely and having a much greater peak signal-to-noise ratio ($\sim$1000 as compared to $\sim$10 for *Ulysses*—see the discussion in McComas et al. 2015). From the smaller 2009–2010 data set and analysis tools available at the time, it appeared that the more likely resolution of the differences between the *Ulysses* and *IBEX* results was that the heliosphere could be moving more slowly and in a slightly different direction with respect to the interstellar medium (with the same upstream temperature found by *Ulysses*) than previously thought (McComas et al. 2012). If so, then these authors suggested that a fast magnetosonic bow shock ahead of the heliosphere would no longer be expected. Subsequently, Zank et al. (2013) used numerical models to show that even for a faster relative speed, the coupling of the heliosphere and the region directly upstream via charge exchange would "mediate" a bow shock into a more continuous bow wave.

Both the UNH analytic model and the Warsaw model assumed a single Maxwellian distribution for the upstream interstellar He population as a first approximation, even though there was some evidence for deviations in the shape of the distribution (Bzowski et al. 2012). Subsequently, Kubiak et al. (2014) found that these deviations indicated another, secondary, population of He superposed on the primary ISN flow. This "Warm Breeze" population is roughly half as fast, two and a half times warmer, $\sim$7% as dense, and appears to be coming from an inflow direction $\sim$20° offset from the primary He inflow. The discovery of the Warm Breeze is a major accomplishment, but also one that calls into question this population's effect on prior studies, which sought to fit the He inflow with a single Maxwellian population.

Since the publication of the early *IBEX* papers, the *Ulysses* observations have been reexamined, corrected, and extended. These included improved pointing offsets and the addition of *Ulysses*' final (2006–2007) fast latitude scan data (Bzowski et al. 2014; Wood et al. 2015a), which had not been previously analyzed. Both of these studies returned flow vectors very close to the earlier *Ulysses* values (the same to within uncertainties), but found significantly higher temperatures of $T_{\mathrm{He}\infty} = 7500 + 1500/-2000$ K (Bzowski et al. 2014) and 7260 ± 270 K (Wood et al. 2015a)—far above the prior 6300 ± 340 K temperature value (Witte 2004; see also McComas et al. 2015 for a detailed discussion).

Most recently, Leonard et al. (2015) and McComas et al. (2015) examined additional *IBEX* data and used knowledge of the Warm Breeze to provide updated *IBEX* results for the interstellar He parameters. Leonard et al. (2015) found inconsistent results for the examined data from 2012 to 2014 when the *IBEX* spacecraft spin axis pointing was alternated between essentially in the ecliptic plane and $\sim$5° south of it; comparison of these observations made it clear that the previously used analytic approximations (Lee et al. 2012) were not adequate to handle data taken when *IBEX* points out of the ecliptic. Those authors then only used the data from these seasons when the *IBEX* spin axis was pointing nearly in the ecliptic plane.

McComas et al. (2015) further combined the Leonard et al. (2015) UNH results with Warsaw model analyses and new, direct numerical integrations of the precise analytic trajectories (see Schwadron et al. 2015) of the 2012–2014 data for pointing both within and out of the ecliptic plane. These results showed that the solution again lay along the same 4D parameter tube (e.g., Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012) and collectively indicated center values for the flow direction closer to the prior *Ulysses* flow vector, but with a much higher temperature than *Ulysses*' earlier value. These authors proposed a combined *IBEX*/*Ulysses* set of values of $V_{\mathrm{ISM}\infty} \sim 26$ km s^{-1}, $\lambda_{\mathrm{ISM}\infty} \sim 75°$, $\beta_{\mathrm{ISM}\infty} \sim -5°$, and $T_{\mathrm{He}\infty} \sim$ 7000–9500 K. They also discussed the important implications of the heliosphere being in a substantially warmer region of the

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[11] All angles in this study are given in ecliptic J2000 coordinates.

interstellar medium than previously indicated by *Ulysses*. Because *IBEX* has a much (∼100x) higher signal to noise than *Ulysses*, it measures much deeper into the tails of the distributions. Clearly *IBEX* is exposing far more subtle and complex aspects of the interaction than previously observable.

3. INTERSTELLAR He OBSERVATIONS IN THIS ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES SPECIAL ISSUE

In this new *Astrophysical Journal Supplement Series* Special Issue, nine studies are devoted to examining interstellar He data over the first six years of *IBEX* observations. In these studies, we have made a number of improvements to the data analysis, both in terms of the analysis techniques available and the instrumental and background effects in order to explore the *IBEX* interstellar neutral observations much more deeply. These studies include the following: improved analytic approximations for the structure of the helium distribution and the effects of spin axis tilt (Lee et al. 2015); careful examination of a variety of possible sources of error and new solutions using the analytic approximations (Möbius et al. 2015); a new direct integration of the Keplerian motion and integration through the detailed *IBEX*-Lo response function (Schwadron et al. 2015); detailed examination of the uncertainties and backgrounds in the data and their effects on the He parameter determination (Swaczyna et al. 2015); a thorough discussion and documentation of the WTPM (Sokół et al. 2015a); determination of the He properties using all of the data and the WTPM (Bzowski et al. 2015); exploration of the possibilities for *IBEX* to detect interstellar neutral He (or O) from the anti-ram direction (Galli et al. 2015; Sokół et al. 2015a); an examination of the broad, low flux tails of the interstellar He population (Sokół et al. 2015b); and an exploration to see if interstellar O or Ne observed by *IBEX* could be "contaminating" the He peak observed by *Ulysses* (Wood et al. 2015b). In addition (see Section 5), several other studies examine other aspects of the *IBEX* observations and interstellar neutrals: Katushkina et al. (2015) explore the H ISN flow and the effects of radiation pressure using a new self-consistent three-dimensional (3D) kinetic-MHD model of the global heliosphere and its interaction with the interstellar wind (Izmodenov & Alexashov 2015), while Park et al. (2015) provide heavy neutral maps and look for a secondary O component.

Lee et al. (2015) improve the analytic work from their previous model (Lee et al. 2012). Their new work includes an analytic second-order expansion of the peak of the velocity distribution for several small quantities including the ratio of the helium thermal bulk speed, the angle of the bulk velocity out of the ecliptic, both angles of the spin axis pointing away from the Sun, the collimator angular width, and the difference between the observing longitude and the inflow's ecliptic tangent longitude at Earth's orbit. This study shows how the He neutrals evolve into an ellipsoidal distribution as they move along their average hyperbolic orbit.

Möbius et al. (2015) use the analytic approximations of Lee et al. (2012, 2015) to examine the accuracy and robustness of the interstellar He flow determination using data from all six spring seasons of *IBEX* observations with varying viewing strategies. The results reconfirm the narrow 4D tube in allowable interstellar parameters (inflow speed, latitude, longitude, and temperature; McComas et al. 2012, 2015). Möbius et al. (2015) evaluate how the parameters are constrained through the observation geometry and analysis methods used and examine various systematic effects important for determining where along this coupled tube of parameters the actual interstellar values lie. These effects include (1) pointing accuracy, (2) ionization, (3) precision of models, (4) coupling of analysis uncertainties, and (5) the influence of the Warm Breeze. Analyzing the angular width of the ISN flow distributions from all six years, these authors find a substantially higher temperature than the original *Ulysses GAS* value. They also show that the Warm Breeze, which was not yet discovered at the time of our 2012 studies, most likely affects the temperature determination more than the other parameters. They also conclude that this additional population contributed significantly to indicating a slightly different center value along the 4D tube in the earlier studies (Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012).

Using a relatively new analytical tool, Schwadron et al. (2015) numerically integrate trajectory solutions through the detailed *IBEX*-Lo response function instead of relying on analytic approximations (Lee et al. 2012, 2015). Then, by varying interstellar parameters along the 4D parameter tube, they minimize the deviations from the *IBEX* observations. One of the central results of this study is that there can be significant differences in the indicated portion of the 4D tube from one season to the next due to the limited data quantity, complicated background, and other effects. On the other hand, by combining the 2009–2013 data, these authors achieve a robust result with an interstellar He flow longitude of $75^{\circ}.6 \pm 1^{\circ}.4$, with latitude of $-5^{\circ}.12 \pm 0^{\circ}.27$, speed of $25.4 \pm 1.1\ \mathrm{km\ s^{-1}}$, and temperature of 8000 ± 1300 K, obtained from the parameter correlation tube found by McComas et al. (2012). While they provide valuable insight into the physical effects at play, with the development of this new tool, analytic approximations are no longer required for the parameter analysis in the UNH approach and Keplerian orbit solutions can be carried out incorporating increasingly detailed instrumental, spacecraft pointing, and other effects.

A set of three papers from the Warsaw group independently examines the first six years of interstellar neutral helium observations from *IBEX* using WTPM (Bzowski et al. 2015; Sokół et al. 2015a; Swaczyna et al. 2015).

Swaczyna et al. (2015) provides an in-depth analysis of the uncertainties and backgrounds in the *IBEX* data, works out corrections for the instrument throughput effects, and develops a unified uncertainty system that includes correlations between data points in addition to independent statistical fluctuations. Potentially correlated effects include (1) backgrounds, (2) spin pointing knowledge, (3) viewing direction knowledge, (4) data throughput effects, and (5) removal of the signal from the Warm Breeze. Of these, imperfect knowledge, and thus subtraction, of the Warm Breeze is the dominant contributor to the high global chi-squared values in previous analyses, and these authors show that, at least for the 2009 data, the new uncertainty scheme can reduce the chi-squared minimum value by a factor of ∼4. However, they also note that this value is still above the expected value—the number of degrees of freedom in the analysis—which likely indicates additional unaccounted for uncertainties and/or additional missing aspects in the physical model.

Table 2
Interstellar He Values Derived from the Independent UNH and Warsaw Analysis Methods for Determining These Parameters

	$V_{\mathrm{ISM}\infty}$ (km s^{-1})	$\lambda_{\mathrm{ISM}\infty}$ (°)	$\beta_{\mathrm{ISM}\infty}$ (°)	$T_{\mathrm{He}\infty}$ (K)
UNH ("infinity")[a]	25.4 ± 1.1	75.6 ± 1.4	−5.12 ± 0.27	8000 ± 1300
WTPM (150 AU)[a]	25.8 ± 0.4	75.8 ± 0.5	−5.16 ± 0.10	7440 ± 260

Note.
[a] Uncertainties are dependent on one another and lay along the 4D parameter tube.

The second paper in this set by Sokół et al. (2015a) provides a number of advances and improvements and detailed documentation for WTPM, which is based on the "hot model" of interstellar neutral helium in the heliosphere (e.g., Fahr 1978; Thomas 1978). This was then initially adapted to model the *IBEX*-Lo measurements by Bzowski et al. (2012). This study describes two unique versions of the model: an analytic-based version (aWTPM) and the full numerical version (nWTPM). While based on the same basic approach, the two differ in how ionization losses are included and how quickly they can come to closure. The WTPM model tracks test atoms from the detector backwards to their source region in front of the heliosphere using analytic solutions for the hyperbolic *Kepler* trajectories. The temporal and spatial variations in the ionization losses due to solar EUV radiation, charge exchange with solar wind ions, and electron impact are taken into account based on a state-of-the-art model of these solar factors developed by Bzowski et al. (2013), Bochsler et al. (2014), and Sokół & Bzowski (2014).

Finally, for this set of three papers, Bzowski et al. (2015) applies the complete nWTPM (Sokół et al. 2015a) with the data correlation, uncertainty system, and parameter fitting method (Swaczyna et al. 2015) to the first six years of *IBEX* interstellar neutral observations. These authors examine both the data separately for each year and for all six years together. Separately, the results show significant differences in the most likely set of values, which are highly correlated with each other along the 4D tube of possible parameters, but, as those authors show, this scatter in the results does not exceed statistical expectations. Thus, the WTPM analysis suggests that ISN He data from all six years are consistent with one parameter set, regardless of observation details such as the *IBEX* spin axis pointing, which may vary between orbits. Analyzing the data from all six years combined, they find the most likely values for the interstellar He neutral speed, latitude, longitude, and temperature to be (25.8 ± 0.4 km s^{-1}, 75$^\circ\!\!.$8 ± 0$^\circ\!\!.$5, −5$^\circ\!\!.$16 ± 0$^\circ\!\!.$10, 7440 ± 260 K), with highly correlated parameter values and uncertainties. They also find that as the ratio of thermal to bulk velocity, the sonic Mach number of 5.079 ± 0.028 is much less variable than the other parameters. This value is also consistent with both earlier *IBEX* analyses (Bzowski et al. 2012; McComas et al. 2012; Möbius et al. 2012) and the revised *Ulysses* values (Bzowski et al. 2014; Wood et al. 2015a), but not with the earlier *Ulysses* values with a much lower temperature (Witte 2004).

In other studies related to the *IBEX* observations of interstellar He, Sokół et al. (2015b) examined the deep wings of this distribution. This study presents the topic of the fall peak and makes predictions about its location and strength, as well as the dependence of the signal on the sputtering cutoff. In contrast to the peak of the He distribution, which has a signal-to-noise ratio in *IBEX*-Lo of >1000, these authors used simulations to examine signals in the range from 0.001 to 0.01 of the peak value. While these lower fluxes have been left out of prior analyses, they may contain some of the most important information about the detailed physics of the He distribution, including its possible departure from equilibrium. These authors examine the possibilities of both a superposition of the Maxwellian primary and Warm Breeze populations and several different kappa distributions and identify the regions of *IBEX* observations that have the most potential to resolve these important tails of the interstellar He population.

Following the initial modeling by Sokół et al. (2015b), Galli et al. (2015) performed a detailed examination to see if *IBEX* can possibly detect interstellar neutral He or O in the fall when the Earth (and *IBEX*) are moving away from the interstellar flow direction. While extremely challenging, such an observation would provide very strong constraints on the interstellar flow vector. These authors examine the times of the lowest possible background rates in *IBEX*-Lo, but find that, even then, it cannot observe interstellar helium from the anti-ram direction. This result is largely because of the low He energy of ∼10 eV in the *IBEX* spacecraft frame because of the velocity subtraction, which is below that required for detection by sputtering off the *IBEX*-Lo conversion surface (∼25–30 eV). In contrast, interstellar O might be detectable, but given the much lower fluxes, the expected signal is close to the detection limit imposed by the magnetospheric foreground and counting statistics. This study also provides an assessment of the minimum energy threshold for sputtering by interstellar He, which was impossible to obtain by ground calibration. The result provides important confirmation of the data analysis strategy which the *IBEX* team adopted (no need to correct for this effect) on one hand, and on the other hand points out the importance of this threshold for Warm Breeze studies, as inferred already by modeling studies (Kubiak et al. 2014; Sokół et al. 2015b).

Finally, Wood et al. (2015b) seek a solution for the remaining, albeit much smaller, temperature difference between the warmer *IBEX* measurements and cooler *Ulysses* ones. These authors examine whether "contamination" by interstellar O and Ne could artificially reduce the width of the interstellar He distributions in the *Ulysses* observations. In particular, the *Ulysses GAS* experiment cannot distinguish between neutral species in the same way that *IBEX*-Lo can, so it is possible that heavier neutrals could be contributing to the putative He signal on *Ulysses*. Such contamination would contribute a narrower superposed peak and manifest itself as an apparently lower temperature for the combined distribution. This study finds that while this effect cannot produce a 1000 K difference, it can easily account for an apparent 100 K difference, and possibly as much as several 100 K artificial reduction in the interstellar He temperature.

4. HOW FAR UPSTREAM IS THE "PRISTINE" LOCAL INTERSTELLAR MEDIUM?

Table 2 shows the interstellar He parameters from both approaches taken in this special *Supplement*: the UNH analytic method (Lee et al. 2015; Möbius et al. 2015), culminating in the new UNH trajectory numerical integration method (Schwadron et al. 2015), and the Warsaw WTPM method (Bzowski et al. 2015; Sokół et al. 2015a; Swaczyna et al. 2015). The first of these is based on hyperbolic, Keplerian motion around the Sun and calculates trajectories in principle "from infinity." In contrast, WTPM calculates particle trajectories only out to 150 AU from the Sun. While the error bars are such that the two results are already consistent, the difference in how far upstream the two methods are calculated is not a residual statistical error, but rather a systematic effect that should be calculated and corrected for. McComas et al. (2012) made a first attempt at this for the 2012 studies (Bzowski et al. 2012; Möbius et al. 2012); here, we examine this issue more carefully and suggest a better compromise solution.

For any of the test particle (Bzowski et al. 2012; Sokół et al. 2015a) or even MHD simulations (e.g., Izmodenov et al. 2009; Zank et al. 2013; Heerikhuisen et al. 2014; Izmodenov & Alexashov 2015), calculations begin at some finite distance upstream where the gas is presumed to be in equilibrium, and thus represented by a spatially homogeneous Maxwellian distribution, flowing with a relative velocity with respect to the Sun called the "velocity at infinity." However, this is not precisely correct. Here, we seek to determine as accurately as possible where we can best assume a Maxwellian or at least stationary state (kappa distribution; Livadiotis & McComas 2009, 2013) where the upstream neutral population is unaffected by interactions with the Sun or heliosphere. At such an upstream distance, this distribution can be assumed to be flowing with a fixed velocity from a region that is beyond both nearly all of the (1) Sun's gravitational influence and (2) coupling to the heliosphere and its separate particle and field environment, both of which produce systematic effects. At least on the 100s AU scale size of the heliosphere, we should be able to assume that this flow is homogeneous with the same flow vector; a necessary assumption when we combine observations from different vantage points.

Collisions and charge exchange between ions and neutrals in the interstellar medium knock some of the atoms onto the trajectories that ultimately enter the *IBEX*-Lo collimator. The distance of this last collision before heliospheric influences set in is certainly finite, not known precisely, and is basically stochastic, since collisions are stochastic in the interstellar medium. Thus, the individual dynamical histories of the atoms are not needed—all that counts is the trajectory of each atom after its last interaction. Collisions in the outer heliosheath are quite frequent and, for example, for a population with a density of $\sim 0.2\ \mathrm{cm}^{-3}$ at ~ 7000 K, the collisional mean free path (MFP) is only ~ 100–200 AU (Kubiak et al. 2014). For particles approaching the heliosphere, the populations are moving together, and so the mean relative speed relevant for the calculation of collisional rates is the thermal speed, which can lead to MFPs several times larger.

In the pristine interstellar medium, it is not important whether an interaction is charge exchange between He and He^+ or elastic He–He or He–proton collision, or even an He–H collision. What matters is that the trajectories are changed and in fact randomized in the combined upstream interstellar population. So long as these interactions are between members of the pristine interstellar flow populations, they fundamentally do not matter as *IBEX* measures an ensemble of atoms from LIC. The key point in the interaction occurs when unaffected interstellar neutral atoms begin to interact with atoms that have already been influenced by the heliosphere. At some distance, the heliosphere begins to perturb the medium as neutrals that start within the heliospheric interaction region travel far upstream into the inflowing LIC. One of the advantages of measuring He from LIC is that He atoms interact less than other species in the outer heliosheath. However, they do still interact at least a little, likely producing the Warm Breeze and possibly even other smaller populations; fortunately, with the extremely large signal to noise of *IBEX*-Lo, we are able to see deeply into the tails of the interstellar He population and discover and separate such populations. The bottom line is that there is a finite, surprisingly small, and currently unknown distance for the source of the pristine He atoms. This contributes a small extra systematic uncertainty to the results of both the *Ulysses* and *IBEX* analyses.

There are two primary, independent effects relevant to how far upstream the "pristine" interstellar medium might be thought to begin, and hence how far upstream *IBEX* (and other) interstellar neutral observations should be calculated to. These are based on (1) the Sun's gravity and (2) the coupling of information about the presence of the heliosphere to the interstellar gas upstream of it in the interstellar medium. The first, gravitational considerations are more straightforward. The Sun's Hill Sphere, or region where its gravitational influence is dominant, extends out to ~ 5000 AU where the net collective forces of the gravitational field of the Galactic disk begin to become larger than that of the Sun (Chebotarev 1964). Without collisions, at approximately this distance, the concept of Keplerian motion about the Sun breaks down. Fortunately, the difference in the analytic trajectory solutions between 5000 AU and infinity is $< 0\overset{\circ}{.}05$, and is thus effectively negligible. Therefore, this distance sets an upper bound on where it might be reasonable to consider the interstellar medium as actually pristine.

Analyses by the UNH group invoke hyperbolic equations of Keplerian motion to calculate the trajectories of neutrals observed by *IBEX* "to infinity" either using analytic approximations (Lee et al. 2012, 2015; Möbius et al. 2012, 2015; Leonard et al. 2015) or numerical integration of the equations (McComas et al. 2015; Schwadron et al. 2015). In contrast, the Warsaw group calculates particle motions out to 150 AU ahead of the Sun (Bzowski et al. 2012, 2015), which is well within the region where there is still some bending of the trajectories from the Sun's gravity as well as coupling of the interstellar and heliospheric neutral and plasma populations. For the 2012 round of *IBEX* papers in the *Astrophysical Journal Supplement Series* (Bzowski et al. 2012; Möbius et al. 2012), McComas et al. (2012) proposed a resolution where the values at 150 AU were "corrected" to infinity for comparison, using the analytic equations (Lee et al. 2012; Möbius et al. 2012). McComas et al. (2012) found that the differences from 150 AU to infinity were mainly in the flow longitude and speed. Starting from the *IBEX* observations at 1 AU in the spring season, the longitude at infinity was calculated to be $0\overset{\circ}{.}75$ larger (i.e., $76\overset{\circ}{.}15$ versus $75\overset{\circ}{.}4$) than reported at 150 AU. Likewise, the speed is lower by $0.3\ \mathrm{km\ s}^{-1}$ at infinity versus 150 AU. This leads to a noticeable difference in the results of the two different techniques that is based entirely on where each sets its starting distance.

Here, we further examine the underlying physics and propose another definition for the appropriate upstream distance to consider as "pristine" local interstellar medium. This requires both a reexamination of the residual gravitational effects beyond 150 AU and an assessment of how far upstream interactions between the heliosphere and the inflowing very local interstellar medium exist. The effects of the heliosphere's coupling with the upstream interstellar medium are complex (e.g., Izmodenov et al. 2009; Zank et al. 2014). On the one hand, collisions, charge exchange, and other internal interactions between pristine interstellar neutrals and charged particles are simply processes that maintain the particle distributions in the partially ionized interstellar medium; we assume that interactions keep this medium in a state of equilibrium at sufficiently large distances from the Sun. On the other hand, as soon as the interstellar medium reaches the vicinity of the Sun, the coupling starts to include collisions, charge exchange, and other interactions with heliospheric particles, effectively sharing information about the presence of the heliosphere with the inflowing material ahead of it.

An important aspect of the heliosphere's interstellar interaction is the coupling between the magnetic fields and the charged particles of the plasma inside and surrounding the heliosphere with the neutral component of the local interstellar medium. This coupling occurs through charge exchange, ionization, and recombination, where ions and neutral atoms pass back and forth between the ionized and neutral distributions. The creation of a "Hydrogen Wall" ahead of the heliopause (Baranov et al. 1991; Linsky & Wood 1996) is the best known example of this coupling. More recently, *IBEX* data were used to discover a secondary neutral He population, dubbed the "Warm Breeze" (Kubiak et al. 2014), which is most likely also explained by such coupling. The overall coupling clearly affects the analysis and interpretation of interstellar neutral observations from *Ulysses* and *IBEX*.

While the Warm Breeze appears to form over a surprisingly small distance from the Sun, the primary interstellar flow is probably only minimally affected by its passage through the outer heliosheath. The largest effect on it is probably just losing a small percentage of its members to charge exchange, and thus to the heliosheath plasma. In addition, rare non-charge exchanging collisions could have a small, but noticeable effect on the interstellar flow proper. This could produce non-thermal features in the wings of the distribution. Again, however, we would expect only a very minor influence on the bulk parameters of the primary interstellar flow.

To further examine how the implied upstream parameters change with increasing distance in the Warsaw modeling, we calculated three chi-squared minimizations for the 2013 season for various upstream distances. For this study, we included orbits 193a-198a, which is just slightly broader than the extent used in Bzowski et al. (2015). In order to ensure that the broadest range of the distribution is included, we also use a slightly broader range of spin angles (246°–288°). Figure 1 plots various implied upstream inflow parameters at 150, 1000, and 5000 AU. For all optimizations, we use the same data and correlation matrix of uncertainties and note that the deduced chi-squared (panel a) is slightly greater than one, indicating that that there are still likely some unaccounted for uncertainties or missing aspects in the physical model (see detailed discussion in Bzowski et al. 2015 and Swaczyna et al. 2015).

Differences between the three distances are small, but systematic with a significant difference from 150 to 1000 AU and very little difference from there out to 5000 AU. From 150 to 1000 AU, the differences are ~0°.1 in the reduced chi-squared minimum inflow longitude, ~200 K lower temperature, and ~0.4 km s^{-1} smaller inflow speed. There is essentially no difference in inflow latitude, indicating that the inflow latitude is not sensitive to the tracking distance of the atoms. Perhaps most interesting is the very small difference in inflow longitude, which varies from 74°.87, 74°.96, to 74°.97 for 150 AU, 1000 AU, and 5000 AU, respectively. These small differences, and similarly small changes in the temperature and inflow speed, occur as the optimum solution moves slightly along the 4D tube of correlated parameters. The differences between 1000 and 5000 AU are all extremely small, and in the case of temperature and speed, the blue curve actually covers the green one. The differences between the speed and temperature at 150 and 1000 AU are a consequence of the acceleration due to Sun's gravity and the resulting increase in the kinetic energy of ISN He atoms. Heliosphere models provide an alternative method of assessing the region of solar influence on the interstellar medium. Only for a very strong external magnetic field of ~4 μG is the influence of the heliosphere even barely evident in the plasma component at 1000 AU (Zank et al. 2013), but such a strong field is not consistent with other information on the LIC properties from *IBEX* (Schwadron et al. 2011) and theoretical LIC models (Slavin & Frisch 2008).

Overall, we recommend that a reasonable distance to consider the upstream interstellar medium to be "essentially pristine" is 1000 AU, and we adopt that distance in this study. Beyond 1000 AU, the gravitational bending calculated from the analytic solutions is <0°.1 and MHD simulations, even for the no Bow Shock case (Zank et al. 2013), show essentially no perturbation by the heliosphere on the LIC. For stronger interactions where a Bow Shock does exist, the distance range covered by the Hydrogen Wall, and in fact the entire scale of the heliosphere's interaction, extends even less far upstream. Using 1000 AU as the baseline distance to track neutral atoms to and compare between the WTPM and UNH calculations, Table 3 includes both sets of values corrected to 1000 AU. For the UNH values, we used the same analytic calculation as in McComas et al. (2012), but this time to take UNH values at "infinity" and bring them back in to 1000 AU. These modifications were tiny and only added 0.04 km s^{-1}, reduced the inflow longitude by 0°.1, and increased the temperature by 25 K, which is so much smaller than the error bars that it is ignored in the table. For the Warsaw values, we include the offsets found above for the 2013 data along the coupled parameter tube, but have simply retained the error bars from the uncorrected values. In both cases, the corrections to 1000 AU are very small.

Finally, we sought to combine both sets of values into a single "best" set for our current knowledge of the pristine interstellar He properties around the heliosphere as we did in 2012 (McComas et al. 2012). However, given the differences in the analysis approaches used, the largely overlapping error bars, and the difficulty in quantitatively assigning exactly the correlation or independence of the various uncertainties in the two techniques, we decided not to attempt this. Rather, we

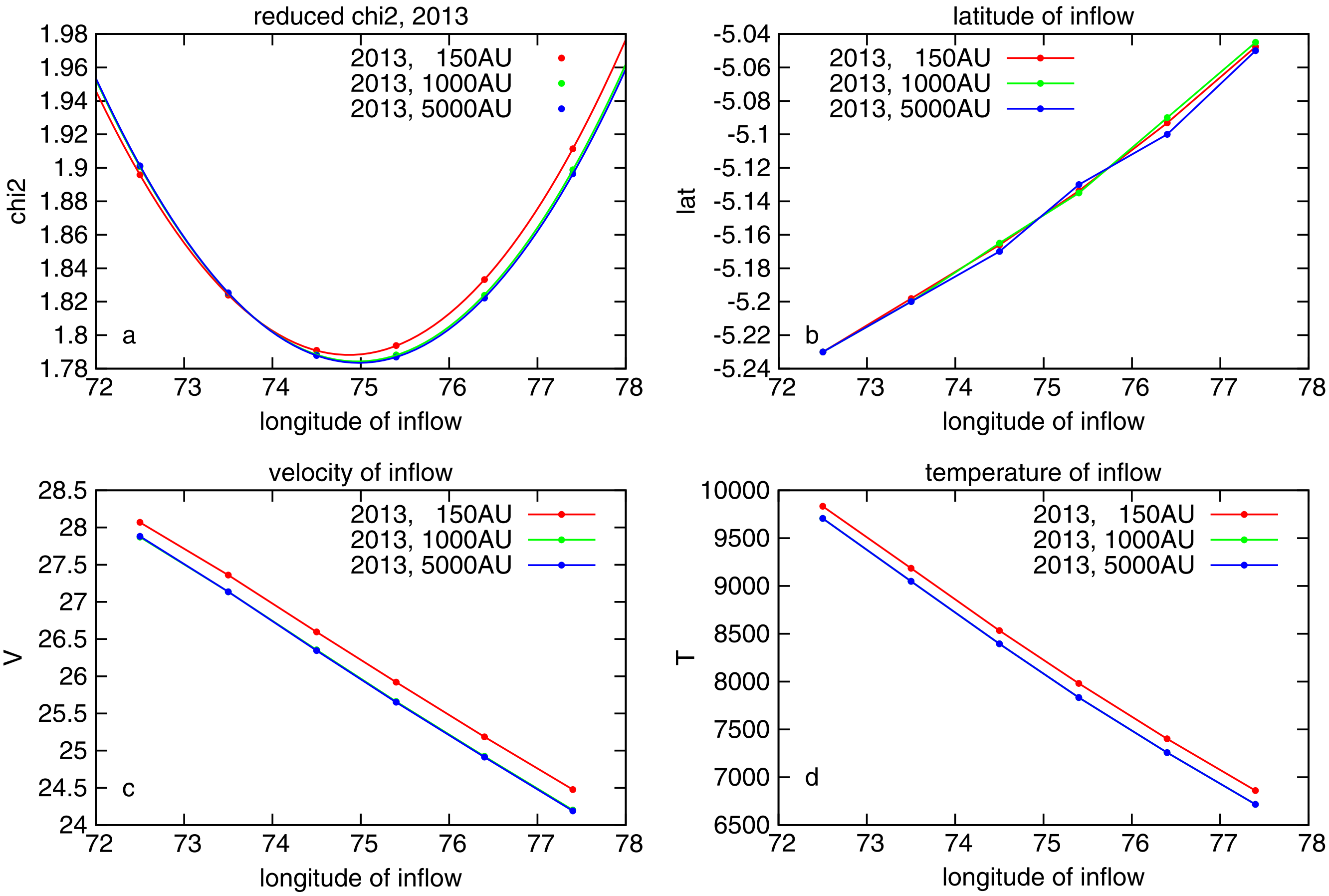

Figure 1. Calculated reduced chi-squared (chi-squared divided by number of degrees of freedom, (a), inflow latitude (b), inflow speed (c), and upstream temperature (d) as functions of inflow longitude for 2013 data using the Warsaw Test Particle Model). The implied upstream inflow parameters are calculated at 150 AU (red), 1000 AU (green), and 5000 AU (blue).

Table 3

Interstellar He Parameters Adjusted to an Upstream Source at ~1000 AU

	$V_{\mathrm{ISM}\infty}$ (km s^{-1})	$\lambda_{\mathrm{ISM}\infty}$ (°)	$\beta_{\mathrm{ISM}\infty}$ (°)	$T_{\mathrm{He}\infty}$ (K)
UNH (1000 AU)[a]	25.44 ± 1.1	75.5 ± 1.4	−5.12 ± 0.27	8000 ± 1300
WTPM (1000)[a]	25.4 ± 0.4	75.9 ± 0.5	−5.16 ± 0.10	7240 ± 260
“Working values” (1000 AU)	**25.4**	**75.7**	**−5.1**	**7500**

Note.

[a] Uncertainties are dependent on one another and lie along the 4D parameter tube.

return to the concept of McComas et al. (2015), that it may be best to simply provide good “working values” for the community to use, which by their very lack of specificity avoid implying more accuracy than is really known. Thus, we suggest working values of $V_{\mathrm{ISM}\infty} \sim 25.4\,\mathrm{km\,s^{-1}}$, $\lambda_{\mathrm{ISM}\infty} \sim 75\overset{\circ}{.}7$, $\beta_{\mathrm{ISM}\infty} \sim -5\overset{\circ}{.}1$, and $T_{\mathrm{He}\infty} \sim 7500$ K at ~1000 AU upstream, as shown in Table 3. These values are within the 1σ error bars of both of the new *IBEX* analyses and are also in good agreement with the revised *Ulysses* values (Bzowski et al. 2014; Wood et al. 2015a), especially when the possibility of ~100 K reduction in the apparent temperature is added back onto the *Ulysses* values (Wood et al. 2015b).

5. OTHER INTERSTELLAR NEUTRAL ATOM OBSERVATIONS AND ANALYSES

Izmodenov & Alexashov (2015) describe the latest version of the 3D kinetic-MHD model of the solar wind/LISM interaction. Both heliospheric and interstellar magnetic fields are included in the model as well as heliolatitudinal variations of the solar wind mass flux. Interstellar hydrogen atoms are treated kinetically and a Monte-Carlo method is used for calculations of the hydrogen parameters in the heliosphere. The Hydrogen Wall appears in the model due to charge exchange between H atoms and interstellar protons outside the heliopause. The hydrogen distribution obtained at 90 AU from the Sun is used as a boundary condition for the study of Katushkina et al. (2015).

Katushkina et al. (2015) use the Moscow model described by Izmodenov & Alexashov (2015) to simulate interstellar hydrogen fluxes at 1 AU. The study focuses on a specific *IBEX* orbit from 2009, which was part of the interstellar H observations from 2009 to 2011 examined by Schwadron et al. (2013). The model includes solar radiation pressure and solar wind ionization as functions of time, heliolatitude, and charge exchange in the outer heliosphere, leading to non-Maxwellian distributions. Differences between the observations and the model are most strongly affected by solar radiation pressure, and a best fit between the model and data requires a ratio of radiation pressure to gravity of (μ) $\sim$ 1.26, which is significantly larger than the value derived from independent solar Lyα flux observations for this time.

The study by Park et al. (2015) examines *IBEX* observations of interstellar O and Ne for the 2009–2011 seasons. These observations have quite low counting statistics, and so these authors employ three independent statistical methods to determine the statistical significance of individual pixels. Together, the results from these complimentary methods build confidence in the detection of heavy neutral atoms and the resultant sky maps of these neutral atoms. The sky maps in turn inform the directional distribution of heavy neutral atoms. The emission feature extends toward both lower longitude and higher latitude from the interstellar neutral O+Ne inflow peak; this feature may be exposing a secondary oxygen distribution, produced by charge exchange between interstellar neutral hydrogen atoms and oxygen ions in the outer heliosheath. Its offset from the primary O and Ne ISN flow is in the same direction as that of the He Warm Breeze from the He ISN flow.

6. INTERSTELLAR MAPPING AND ACCELERATION PROBE (IMAP)

In 2012–2013, the National Research Council (NRC) of the United States National Academies carried out the latest Heliophysics Decadal Survey, which culminated in the Decadal Survey report entitled *Solar and Space Physics: A Science for a Technological Society* (2013). As a part of the survey, over 180 white papers were submitted as input to the process. Of these, a small number of mission concepts were analyzed in detail, including one named the Interstellar Mapping Probe or IMaP (McComas et al. 2012, white paper). This white paper laid out a mission concept to follow up on *IBEX* as a Heliophysics Solar-Terrestrial Probe (STP) mission.

IMaP was conceived to take the next quantum leap forward from *IBEX*, both pushing forward *IBEX*'s groundbreaking ENA observations with ~100× better combined sensitivity and resolution and an extended energy range, and directly sampling the interstellar neutral populations with decades better statistics. The suggested payload also included all other samples of interstellar matter including pickup ions (generated from interstellar neutrals), ACRs and GCRs, and interstellar dust. Finally, the suggested payload also included solar wind observations from L1, including solar wind plasma electrons and ions, energetic particles, and the interplanetary magnetic field, as well as Lyα photometry; all of these are needed to characterize and remove backgrounds from the primary observations and could also be used for upstream, real-time solar wind observations if desired. The mission concept provided by the IMaP white paper was for a Sun-pointed spinning spacecraft in orbit around the Earth–Sun L1 Lagrangian point, roughly 1.5 million km sunward of the Earth. This allowed for a very simple spacecraft, like the *Advanced Composition Explorer* (*ACE*), and a minimum cost but extremely robust mission. McComas et al. (2011) argued that IMaP would be an analogous step forward for heliophysics as *WMAP* was from COBE.

After significant study, the Decadal Survey committee returned a very similar IMAP that largely reflected the IMaP white paper, but also expanded the energetic particle observations into a much more capable instrument that not only provided background and real-time solar wind information, but also enabled detailed analysis of particle acceleration in the solar wind, and thus required the expanded name IMAP.

IMAP will provide the next giant step forward in the direct measurement of interstellar neutral atoms. In particular, an even more capable low energy interstellar neutral atom camera is envisaged to measure atoms from ~10 to 1000 eV with a pointing knowledge of better than 0°.05. This will provide the capability to measure the precise abundances and independent flow parameters of H, He, O, and Ne, and accurately measure the D/H ratio. These observations will have much higher sensitivity and angular resolution than the current *IBEX*-Lo observations. The high-precision flow vector and temperature measurements of He and O will strongly constrain models of the ionization state and radiation environment of LISM. Furthermore, detailed observations of secondary O and He will inform the very local interstellar magnetic field and the detailed structure of the outer heliosheath, as well as the expected departures of the local interstellar gas from equilibrium. Key isotope ratios (D/H, ^{3}He/^{4}He, ^{22}Ne/^{20}Ne), obtained through pickup ions, will provide strong constraints on Big Bang cosmology and the evolution of matter.

Surely, IMAP promises to push discoveries and understanding of the heliosphere's interstellar environment far beyond the great leaps currently being taking with *IBEX*!

7. CONCLUSIONS

IBEX is truly a remarkable mission of exploration and discovery. Over its first six years of observations, *IBEX* has generated a broad range of important scientific firsts and discoveries (see Table 1 in McComas et al. 2014). In the 14 studies in this *Astrophysical Journal Supplement Series* Special Issue, we significantly push forward the analysis and interpretation of the interstellar neutral observations from *IBEX*, using its six first years of data.

For interstellar He, which is the primary focus of this *Supplement*, we rely on two independent and quite different analysis schemes led by *IBEX* team members in Warsaw and at UNH. Both approaches are used to solve for interstellar parameters by minimizing the difference between simulations and observations. The basis for comparison comes from the observed spin-phase distribution of counts as a function of the 6° spin sector, collected over a series of spins of the spacecraft. However, the analyses differ significantly in how spin-phase distributions are analyzed. In the case of the UNH model, only the peak location in spin-phase is used for further analysis to deduce the ISN flow latitude and longitude. The sectored counts are fit to a smooth function (a Gaussian distribution so far) and the peak of that distribution provides a single spin-phase with which to compare to the distribution peak returned by simulations. Since the peak in the distribution is mostly sensitive to the changes in the primary component over the observer longitude through the ISN flow observation season and the data selection is restricted in longitude and latitude coverage very close to the peak, this method almost eliminates the sensitivity to the secondary component or background. Möbius et al. (2015) detail the residual uncertainty from the presence of the secondary component.

In the case of the Warsaw model, the deviation is calculated over the spin-phase distribution. The Warm Breeze from Kubiak et al. (2014) is subtracted from the observed spin-angle count distribution and the residual distribution is fit to a background and the primary distribution by minimizing the difference between the residual distribution and the simulated distribution. The Warsaw model is therefore somewhat sensitive to residuals from the Warm Breeze.

In addition, in a supplementary analysis, the Warsaw model is used to calculate the expected Gaussian parameters of the ISN beam, which are subsequently compared with the observed ones. In this analysis, the Warsaw and UNH analyses come the closest together in their assumptions, since adopting the Gaussian function as an approximation of the signal forces symmetry in spin-angle about the peaks. The results of this analysis, shown by Bzowski et al. (2015), are essentially identical with the results from their baseline analysis, with a temperature that is somewhat higher (~8150 versus 7440 K). Another difference in the two analyses is in the time resolution of the data used. The UNH approach uses data collected in five groups of equal time length per orbital arc, while in the Warsaw treatment the signal is integrated over the entire duration of the clean ISN observing times, and the simulation reproduces this integration.

In any case, the UNH and Warsaw analysis methods differ significantly in their approach, assumptions, and what aspects of the observations they are most sensitive to. The fact that both methods lead to completely consistent values (within their one sigma errors) lends significant credibility to these combined solutions.

Together, the interstellar He studies in the *Supplement* provide a major step forward in the analysis of the *IBEX* interstellar neutral He observations and in the understanding of the local interstellar medium more generally. Future work will need to simultaneously fit the primary and Warm Breeze He components using all of the data currently available along with new data from the 2015 season, which includes spin axis pointing 5° north of the ecliptic. While analytic approximations may not be up to this even harder task, the two models with direct integrations of the analytic trajectories (WTPM; Sokół et al. 2015a) and the newly developed UNH response function integration (Schwadron et al. 2015) are suitable for this problem. In this way, we seek to maintain two parallel analysis paths as a cross check to ensure the most careful analysis and absolutely most accurate scientific results from these challenging but extremely critical observations.

In this study, we also examined the systematic effects of gravitation and the coupling of the heliosphere and interstellar medium. Here, we propose a working definition of an essentially "pristine" interstellar medium ahead of the heliosphere at ~1000 AU. By this distance, (1) the gravitational effects produce $<0\overset{\circ}{.}1$ and $0.05\ \mathrm{km\ s^{-1}}$ difference compared to infinity, and (2) the coupling with the heliosphere is essentially negligible even for the larger interaction in the case where there is no bow shock ahead of the heliosphere (Zank et al. 2013). Thus, we recommend that for most purposes, the community use the "working values" of $V_{\mathrm{ISM}\infty} \sim 25.4\ \mathrm{km\ s^{-1}}$, $\lambda_{\mathrm{ISM}\infty} \sim 75\overset{\circ}{.}7$, $\beta_{\mathrm{ISM}\infty} \sim -5\overset{\circ}{.}1$, and $T_{\mathrm{He}\infty} \sim 7500\ \mathrm{K}$ for the interstellar He inflow at ~1000 AU upstream; these values are consistent with both approaches used for the *IBEX* data analysis and the recent reanalysis of the *Ulysses* observations.

Finally, the ongoing *IBEX* observations and two-point Voyager ground truth measurements in the inner and outer heliosheath, along with even better observations from the planned IMAP mission, will further challenge us and require extensive theory and modeling efforts to reconcile our evolving understanding of the local interstellar medium, outer heliosphere, and their critical interaction. Surely this is an incredibly exciting time for the study of our heliosphere, the very local interstellar medium, and their complicated and delicate interactions.

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