Local Interstellar Medium: Six Years of Direct Sampling by the Interstellar Boundary Explorer

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Abstract

The Interstellar Boundary Explorer has been directly observing neutral atoms from the

local interstellar medium for the last six years (2009-2014). This paper ties together the

13 studies in this special issue of the *Astrophysical Journal Supplement*, which

31   collectively describe the IBEX interstellar neutral results from this epoch and provide a

32   number of other relevant theoretical and observational results. Interstellar neutrals

33   interact with each other and with the ionized portion of the interstellar population in the

34   "pristine" interstellar medium ahead of the heliosphere. Then, in the heliosphere's close

35   vicinity, the interstellar medium begins to interact with escaping heliospheric neutrals. In

36   this study we compare the results from two major analysis approaches led by IBEX

37   groups in New Hampshire and Warsaw. We also directly address the question of the

38   distance upstream to the pristine interstellar medium and adjust both sets of results to a

39   common distance of ~1000 AU. The two analysis approaches are quite different, but

40   yield fully consistent measurements of the interstellar He flow properties, further

41   validating our findings. While detailed error bars are given for both approaches, we

42   recommend that for most purposes, the community use "working values" of ~25.5 km s^{-1},

43   ~75.5° ecliptic inflow longitude, ~-5.1° ecliptic inflow latitude, and ~7500 K temperature

44   at ~1000 AU upstream. Finally, we briefly address future opportunities for even better

45   interstellar neutral observations to be provided by the Interstellar Mapping and

46   Acceleration Probe (IMAP) mission, which was recommended as the next major

47   Heliophysics mission by the NRC's 2013 Decadal Survey.

48

49   **1. Introduction**

50   This *Astrophysical Journal Special Supplement* comprises 13 papers that examine the

51   first six years of direct sampling of the local interstellar neutral populations by the

52   Interstellar Boundary Explorer (IBEX), as well as some new analyses of Ulysses/GAS

53   and various related observational and theoretical topics. Collectively, these studies, along

54   with the prior published papers related to the IBEX interstellar neutral observations, open

55   a completely new window on the local interstellar environment, its composition, its

56   properties, and the likely processes at work in the interstellar space around our Sun and in

57   the heliospheric boundary region. These observations also benchmark our understanding

58   of the low density interstellar medium more generally, which is key for stellar and

59   planetary system formation, the formation of astrospheres around other stars, and

60   understanding the tenuous material throughout our galaxy and the many galaxies beyond.

61   The interstellar medium arises from the evolutionary processes associated with star

62   formation, and is refreshed by stellar winds and material ejected from novae and

63   supernovae. IBEX measures the neutral component of the low density interstellar gas that

64   originates in the cloud surrounding the heliosphere. This material is partially ionized and

65   the ions and neutrals interact with each other through charge exchange, recombination,

66   and various forms of ionization. The ionized portion is magnetized and further

67   participates in collective plasma behavior that then couples back into neutral populations

68   producing the complex and fascinating partially ionized medium that dominates the

69   heliosphere's configuration and populates the disk and halo of our galaxy.

70   The local interstellar cloud (LIC) that surrounds the solar system is part of a dynamic

71   system of interstellar clouds, whose column densities, relative speeds and temperatures

72   have been studied on scales of several parsecs through optical and UV line absorption in

73   the light of nearby stars (e.g. see reviews by Cox & Reynolds 1987; Frisch 1995; Frisch

74 et al. 2011). The first *Copernicus* ultraviolet spectra of interstellar nitrogen lines toward

75 alpha Leo (24 pc) revealed roughly equal amounts of neutral and ionized gas that

76 indicated the warm, low density, partially ionized nature of the local interstellar medium

77 (Richardson et al. 1973). Interstellar neutrals inside of the heliosphere are linked to the

78 interstellar gas toward nearby stars by the gas velocities (Adams & Frisch 1977;

79 Lallement & Bertin 1992; Redfield & Linsky 2008; Gry & Jenkins 2014). The LIC is a

80 quite structured cloud, with the Sun apparently close to its boundary, having recently

81 entered it and with the prospect of exiting it within the next 35000 years according to the

82 neutral hydrogen component (Frish 1944; Lallement et al. 1995; Wood et al. 2000; Slavin

83 Frisch 2008). Further, directly around the Sun, the very local interstellar medium is part

84 of an evolved superbubble shell that is a particularly interesting portion of the LIC to be

85 able to directly sample and thereby study in detail.

86 While there have been indirect observations of interstellar neutrals through backscattered

87 solar Lyman-alpha emission [e.g., Bertaux & Blamont 1971; Bertaux et al., 1985; Costa

88 at al., 1999] and even in-situ observations through pickup ions [Möbius et al. 1985;

89 Gloeckler et al. 1992; Gloeckler & Geiss et al. 1998], the only direct sampling of any

90 neutrals from the local interstellar medium prior to 2009 was for Helium (He) by the

91 GAS experiment on the Ulysses spacecraft [Witte et al., 1996; Witte 2004]. Since then,

92 IBEX has been returning new observations of interstellar neutrals from space each year

93 during its interstellar neutral observation season in the winter/spring. IBEX [McComas et

94 al. 2009a] is one of NASA's Small Explorer missions; its objective is to discover the

95 global interaction between the solar wind and the interstellar medium. This has been

96   achieved through a combination of making the first all sky energetic neutral atom (ENA)

97   images and by directly measuring multiple species of interstellar neutrals that transit

98   through the heliosphere to the location of IBEX at 1 AU.

99   IBEX has two high-sensitivity ENA cameras: IBEX-Lo [Fuselier et al., 2009a] and

100   IBEX-Hi [Funsten et al., 2009a], which measure ENAs from ~10-2000 eV and ~300-

101   6000 eV, respectively. At its lower energies, IBEX-Lo also measures interstellar neutrals

102   [Möbius et al. 2009a]. IBEX collects neutral atoms as a function of spacecraft spin phase,

103   which arrive nearly perpendicular to its roughly Sun-pointing spin axis. Each

104   winter/spring season, the Earth is in the part of its orbit where the spacecraft's inertial

105   motion rams into interstellar neutrals, which are gravitationally bent just enough that they

106   enter IBEX's viewing plane. Thus, IBEX's detailed observations of various measured ion

107   species as a function of spacecraft pointing and spin phase contains the information

108   needed to determine these species' inflow properties of direction, speed, and temperature.

109   First results from IBEX, including the discovery of the "IBEX Ribbon" – a long, narrow

110   arc of significantly enhanced ENA emissions that is ordered by the very local interstellar

111   magnetic field – were documented in a special issue of *Science* magazine [McComas et al.

112   2009b; Funsten et al. 2009b; Fuselier et al. 2009b; Schwadron et al. 2009b]. That issue

113   also provided IBEX's first observations of interstellar neutrals [Möbius et al. 2009b].

114   These included the first direct sampling of interstellar Hydrogen (H) and Oxygen (O) and

115   IBEX's first season of interstellar He observations. Subsequent studies showed IBEX's

116   first direct sampling of Neon (Ne) and the Ne/O ratio [Bochsler et al. 2012; Park et al.

117   2014], and the first direct sampling of interstellar deuterium (D) [Rodriquez et al. 2013;

118   2014] in the LISM.

119   A number of the prior IBEX studies on interstellar neutrals were published together in a

120   special *Astrophysical Journal Supplement* in 2012 [Bochsler et al. 2012; Bzowski et al.

121   2012; Hlond et al. 2012; Lee et al. 2012; McComas et al. 2012; Möbius et al. 2012; Saul

122   et al. 2012]; these results were based entirely on data from the 2009 and 2010 viewing

123   seasons. In this new, 2015 Special *Astrophysical Journal Supplement*, we provide 13

124   additional studies (Table 1) that collectively incorporate data from all six years of IBEX

125   observations (2009-2014), update the knowledge gained from IBEX's interstellar neutral

126   data, and examine implications of these unique observations on interstellar gas at a single

127   location in space.

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Table 1. Papers in this special *Astrophysical Journal Supplement* (*ApJS*)	
Title	Lead Author
1. Local Interstellar Medium: Six Years of Direct Sampling by the Interstellar Boundary Explorer	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 the Interstellar Boundary Explorer – beyond closed form approximations	Schwadron
5. Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer observations: I. Uncertainties and backgrounds in the data and parameter determination method	Swaczyna
6. Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer observations: II. The Warsaw Test Particle Model (WTPM)	Sokół

7. Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer 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 - non-dissipative limit	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

129

130   **2. Prior Studies of Interstellar Helium**

131   The IBEX team's approach to analyzing the interstellar He data has been two pronged.

132   First, in the work led by University of New Hampshire (UNH) team members, we used

133   analytic solutions and approximations [Lee et al. 2012] for the hyperbolic orbits of He

134   atoms in the Sun's gravity well (unlike interstellar H and D, radiation pressure is

135   essentially negligible for He). Using these equations and approximations, we then

136   analytically analyzed the IBEX observations [Möbius et al. 2012]. Second, in the work

137   led by our team members from the Space Research Centre of the Polish Academy of

138   Sciences, we used the Warsaw Test Particle Model (WTPM) to simulate the trajectories

139   of test particles, calculate the expected signal for all data points, and then minimize

140   deviations between results for various input parameters and the IBEX observations

141   [Bzowski et al. 2012]. The two approaches are quite different. The Warsaw approach

142   addresses the more complex problem of fitting the full distributions, including all

143   possible contributions from the various populations as well as backgrounds. In contrast,

144   the UNH approach focuses only on the peak of the distribution, which is a simpler

145   problem. The fact that both approaches yield very consistent values lends strong support

146   for the combined results.

147   Because IBEX observes neutrals only when their trajectory is nearly tangential to Earth's

148   orbit (IBEX views perpendicular to its Sun pointed spin axis), there is a very tight

149   coupling between the interstellar He inflow vector: speed ($V_{ISM\infty}$), ecliptic longitude

150   ($\lambda_{ISM\infty}$), ecliptic latitude ($\beta_{ISM\infty}$) and temperature ($T_{He\infty}$) far upstream [Lee et al. 2012].

151   This tight coupling is found in both the analytic analyses [Möbius et al. 2012] and

152   Warsaw test particle results [Bzowski et al. 2012]. These analyses provided nearly

153   identical four dimensional "tubes" of these coupled parameters with a very small

154   uncertainty for any specific location along the tube, but a significant extent of possible

155   coupled parameters along it. McComas et al. [2012] examined a small difference between

156   the Warsaw results, which are calculated to 150 AU ahead of the Sun, and the UNH

157   results, which are theoretically calculated to infinity (Section 4 below takes up this issue

158   in more detail), to combine both sets of results. Equations 1-3 of that study provide the

159   coupling equations among the four observable interstellar parameters in the IBEX data.

160   This 4-D tube comes out naturally without further assumptions in the numerical analysis

161   and remains in all subsequent IBEX interstellar He observations and analyses and we

162   have expended considerable effort to localize the most likely position along the tube.

163   The initial He results [Bzowski et at. 2012; Möbius et al. 2012; McComas et al. 2012]

164   raised interesting questions about the stability of the helium flow direction [Frisch et al.

165   2013] that stimulated active discussions in the community [e.g. Lallement and Bertaux

166   2014; Katushkina et al. 2014, Frisch et al. 2015]. However, criticisms of earlier IBEX

167   work were unfounded as McComas et al. [2012] clearly provided (see their Table 1) a

168   broad range of possible coupled parameters from (21.3 km s^{-1}, 82.0°, –4.84°, 5000 K) to

169   (25.7 km s^{-1}, 75.5°, –5.14°, 8300 K) with 1σ uncertainties of ~(±0.3 km s^{-1}, ±0.5°, ±0.2°,

170   ±400 K) around any consistent set of parameters along the 4-D parameter tube. Clearly,

171   the tube of possible coupled parameters allowed by the IBEX data was inconsistent with

172   the prior Ulysses data (Witte, 2004) and required either a different velocity vector (with

173   slightly lower speed and slightly larger longitude) or a significantly higher temperature. It

174   was also clear that we needed a larger observational baseline to identify a well-

175   constrained location along the tube for the interstellar parameters.

176   IBEX and Ulysses observations both have their advantages and disadvantages for

177   measuring the interstellar neutrals, with Ulysses having a more advantageous orbit and

178   overall viewing geometry and IBEX being able to identify various neutral species

179   uniquely and having a much greater peak signal to noise ratio (~1000 as compared to ~10

180   for Ulysses - see discussion in McComas et al. [2015]). From the smaller 2009-2010 data

181   set and analysis tools available at the time, it appeared that the more likely resolution of

182   the differences between the Ulysses and IBEX results was that the heliosphere could be

183   moving more slowly and in a slightly different direction with respect to the interstellar

184   medium (with the same upstream temperature found by Ulysses) than previously thought

185   [McComas et al. 2012]. If so, then these authors suggested that a fast magnetosonic bow

186   shock ahead of the heliosphere would no longer be expected. Subsequently, Zank et al.

187   [2013] used numerical models to show that even for a faster relative speed, the coupling

188   of the heliosphere and the directly upstream region via charge exchange would "mediate"

189   a bow shock into a more continuous bow wave.

190   Both the UNH analytic and Warsaw models assumed a single Maxwellian distribution for

191   the upstream interstellar He population as a first approximation, even though there was

192   some evidence for deviations in the shape of the distribution [Bzowski et al. 2012].

193   Subsequently, Kubiak et al. [2014] found that these deviations indicated another,

194   secondary, population of He superposed on the primary ISN flow. This "Warm Breeze"

195   population is roughly half as fast, two and a half times warmer, ~7% as dense, and

196   appears to be coming from an inflow direction ~20° offset from the primary He inflow.

197   The discovery of the Warm Breeze is a major accomplishment, but also one that calls into

198   question this population's effect on prior studies, which sought to fit the He inflow with a

199   single Maxwellian population.

200   Since the publication of the early IBEX papers, the Ulysses observations have been

201   reexamined, corrected, and extended. These included improved pointing offsets and

202   addition of Ulysses' final (2006-2007) fast latitude scan data [Bzowski et al. 2014; Wood

203   et al. 2015a], which had not been previously analyzed. Both of these studies returned

204   flow vectors very close to the earlier Ulysses values (the same to within uncertainties),

205 but found significantly higher temperatures of $T_{He\infty}$ = 7500 +1500/-2000 K [Bzowski et al.

206 2014] and 7260±270 K [Wood et al. 2015a] – far above the prior 6300±340 K

207 temperature value [Witte et al. 2004] (see also McComas et al. [2015] for a detailed

208 discussion).

209 Most recently, Leonard et al. [2015] and McComas et al. [2015] examined additional

210 IBEX data and used knowledge of the Warm Breeze to provide updated IBEX results for

211 the interstellar He parameters. Leonard et al. [2015] found inconsistent results for the

212 examined data from 2012-2014 when the IBEX spacecraft spin axis pointing was

213 alternated between essentially in the ecliptic plane and ~5° south of it; comparison of

214 these observations made it clear that the previous analytic approximations [Lee et al.,

215 2012] used were not adequate to handle data taken when IBEX points out of the ecliptic.

216 Those authors then only used the data from these seasons when the IBEX spin axis was

217 pointing nearly in the ecliptic plane.

218 McComas et al. [2015] further combined the Leonard et al. [2015] UNH results with

219 Warsaw model analyses and new, direct numerical integrations of the precise analytic

220 trajectories (see Schwadron et al. [2015]) of the 2012-2014 data for pointing both within

221 and out of the ecliptic plane. These results showed that the solution again laid along the

222 same 4-D parameter tube [e.g., McComas et al., 2012, Bzowski et al., 2012, Möbius et

223 al., 2012] and collectively indicated center values for the flow direction closer to the prior

224 Ulysses flow vector, but with a much higher temperature than Ulysses' earlier value.

225 These authors proposed a combined IBEX/Ulysses set of values of $V_{ISM\infty}$ ~26 km s^{-1},

226   $\lambda_{ISM\infty}$ ~75°, $\beta_{ISM\infty}$ ~ -5°, and $T_{He\infty}$ ~7000-9500 K. They also discussed the important

227   implications of the heliosphere being in a substantially warmer region of the interstellar

228   medium than previously indicated by Ulysses. Because IBEX has a much (~100x) higher

229   signal to noise than Ulysses, it measures much deeper into the tails of the distributions.

230   Clearly IBEX is exposing far more subtle and complex aspects of the interaction than

231   previously observable.

232   **3. Interstellar He Observations in this special *Astrophysical Journal Supplement***

233   In this new *Astrophysical Journal Supplement*, nine studies are devoted to

234   examining interstellar He data over the first six years of IBEX observations. In these,

235   we have made a number of improvements to the data analysis, both in terms of analysis

236   techniques available and instrumental and background effects in order to explore the

237   IBEX interstellar neutral observations much more deeply. These studies include

238   improved analytic approximations for the structure of the helium distribution and the

239   effects of spin axis tilt [Lee et al. 2015]; careful examination of a variety of possible

240   sources of error and new solutions using the analytic approximations [Möbius et al.

241   2015]; a new direct integration of the Keplerian motion and integration through the

242   detailed IBEX-Lo response function [Schwadron et al. 2015]; detailed examination of the

243   uncertainties and backgrounds in the data and their effects on the He parameter

244   determination [Swaczyna et al. 2015]; a thorough discussion and documentation of the

245   Warsaw Test Particle Model [Sokół et al. 2015a]; determination of the He properties

246   using all data and the WTPM [Bzowski et al. 2015]; exploration of the possibilities for

247 IBEX to detect interstellar neutral He (or O) from the anti-ram direction [Sokół et

248 al.2015b, Galli et al. 2015]; an examination of the broad, low flux tails of the interstellar

249 He population [Sokół et al. 2015b]; and an exploration to see if interstellar O or Ne

250 observed by IBEX could be "contaminating" the He peak observed by Ulysses [Wood et

251 al. 2015b]. In addition (see Section 5), several other studies examine other aspects of the

252 IBEX observations and interstellar neutrals: [Katushkina et al. 2015] explore the H ISN

253 flow and effects of radiation pressure using a new self-consistent 3D kinetic-MHD model

254 of the global heliosphere and its interaction with the interstellar wind [Izmodenov and

255 Alexashov 2015] while [Park et al. 2015] provide heavy neutral maps and look for a

256 secondary O component.

257 Lee et al. [2015] improve the analytic work from their previous model [Lee et al. 2012].

258 The new work includes an analytic second order expansion of the peak of the velocity

259 distribution for several small quantities including the ratio of the helium thermal bulk

260 speed, the angle of the bulk velocity out of the ecliptic, both angles of the spin axis

261 pointing away from the Sun, the collimator angular width, and the difference between the

262 observing longitude and the inflow's ecliptic tangent longitude at Earth's orbit. This

263 study shows how the He neutrals evolve into an ellipsoidal distribution as they move

264 along their average hyperbolic orbit.

265 Möbius et al. [2015] use the analytic approximations of Lee et al. [2012; 2015] to

266 examine the accuracy and robustness of the interstellar He flow determination using data

267 from all six spring seasons of IBEX observations with varying viewing strategies. The

268   results reconfirm the narrow 4-D tube in allowable interstellar parameters (inflow speed,

269   latitude, longitude, and temperature) [McComas et al. 2012; 2015]. Möbius et al. [2015]

270   evaluate how the parameters are constrained through the observation geometry and

271   analysis methods used and examine various systematic effects important for determining

272   where along this coupled tube of parameters the actual interstellar values lie. These

273   effects include 1) pointing accuracy, 2) ionization, 3) precision of models, 4) coupling of

274   analysis uncertainties, and 5) the influence of the Warm Breeze. Analyzing the angular

275   width of the ISN flow distributions from all six years, these authors find a substantially

276   higher temperature than the original Ulysses GAS value. They also show that the Warm

277   Breeze, which was not yet discovered at the time of our 2012 studies, most likely affects

278   the temperature determination more than the other parameters. They also conclude that

279   this additional population contributed significantly to indicating a slightly different center

280   value along the 4-D tube in the earlier studies [Bzowski et al. 2012; Möbius et al. 2012;

281   McComas et al. 2012].

282   Using a relatively new analytical tool, Schwadron et al. [2015] numerically integrate

283   trajectory solutions through the detailed IBEX-Lo response function instead of relying on

284   analytic approximations [Lee et al. 2012; 2015]. Then, by varying interstellar parameters

285   along the 4-D parameter tube they minimize the deviations from the IBEX observations.

286   One of the central results of this study is that there can be significant differences in the

287   indicated portion of the 4-D tube from one season to the next owing to the limited data

288   quantity, complicated background, and other effects. On the other hand, by combining the

289   2009 to 2013 data, these authors achieve a robust result with an interstellar He flow

290   longitude of 75.6°$\pm$1.4°, with latitude of -5.12°$\pm$0.27°, speed of 25.4$\pm$1.1 km/s, and

291   temperature of 8000$\pm$1300 K, obtained from the parameter correlation tube found by

292   McComas et al. [2012]. While they provide valuable insight into physical effects at play,

293   with the development of this new tool, analytic approximations are no longer required for

294   the parameter analysis in the UNH approach and Keplerian orbit solutions can be carried

295   out incorporating increasingly detailed instrumental, spacecraft pointing, and other

296   effects.

297   A set of three papers from the Warsaw group independently examines the first six years

298   of interstellar neutral helium observations from IBEX using the Warsaw Test Particle

299   Model (WTPM) [Bzowski et al. 2015; Sokół et al. 2015a; Swaczyna et al. 2015].

300   Swaczyna et al. [2015] provides an in-depth analysis of uncertainties and backgrounds in

301   the IBEX data, works out corrections for the instrument throughput effects, and develops

302   a unified uncertainty system that includes correlations between data points in addition to

303   independent statistical fluctuations. Potentially correlated effects include 1) backgrounds,

304   2) spin pointing knowledge, 3) viewing direction knowledge, 4) data throughput effects,

305   and 5) removal of the signal from the Warm Breeze. Of these, imperfect knowledge, and

306   thus subtraction, of the Warm Breeze is the dominant contributor to the high global chi-

307   squared values in previous analyses and these authors show that, at least for the 2009 data,

308   the new uncertainty scheme can reduce the chi-squared minimum value by a factor of ~4.

309   However, they also note that this value is still above the expected value – the number of

310   degrees of freedom in the analysis – which likely indicates additional unaccounted for

311   uncertainties and/or additional missing aspects in the physical model.

312   The second paper in this set by Sokół et al. [2015a] provides a number of advances and

313   improvements and detailed documentation for the Warsaw Test Particle Model (WTPM),

314   which is based on the "hot model" of interstellar neutral helium in the heliosphere [e.g.,

315   Fahr 1978; Thomas 1978]. This was then initially adapted to model the IBEX-Lo

316   measurements by Bzowski et al. [2012]. This study describes two unique versions of the

317   model: an analytic-based version, aWTPM, and the full numerical version, nWTPM.

318   While based on the same basic approach, the two differ in how ionization losses are

319   included and how quickly they can come to closure. The WTPM model tracks test atoms

320   from the detector backwards to their source region in front of the heliosphere using

321   analytic solutions for the hyperbolic Kepler trajectories. The temporal and spatial

322   variations in the ionization losses due to solar EUV radiation, charge exchange with solar

323   wind ions, and electron impact are taken into account based on a state of the art model of

324   these solar factors developed by Bzowski et al. 2013, Bochsler et al. 2014, and Sokół &

325   Bzowski 2014.

326   Finally for this set of three papers, Bzowski et al. [2015] applies the complete nWTPM

327   [Sokół et al. 2015a] with the data correlation, uncertainty system, and parameter fitting

328   method [Swaczyna et al. 2015] to the first six years of IBEX interstellar neutral

329   observations. These authors examine the data both separately for each year and for all six

330   years together. Separately, the results show significant differences in the most likely set

331   of values, which are highly correlated with each other along the 4-D tube of possible

332   parameters, but, as those authors show, this scatter in the results does not exceed

333   statistical expectations. Thus, the WTPM analysis suggests that ISN He data from all six

334   years are consistent with one parameter set, regardless of observation details such as

335   IBEX spin axis pointing, which may vary between orbits. Analyzing the data from all six

336   years combined, they find the most likely values for the interstellar He neutral speed,

337   latitude, longitude, and temperature as (25.8±0.4 km s^{-1}, 75.8°±0.5°, -5.16°±0.10°,

338   7440±260K) , with highly correlated parameter values and uncertainties. They also find

339   that as the ratio of thermal to bulk velocity, the sonic Mach number of 5.079±0.028 is

340   much less variable than the other parameters. This value is also consistent with both

341   earlier IBEX analyses [Bzowski et al. 2012; Möbius et al. 2012; McComas et al. 2012]

342   and the revised Ulysses values [Bzowski et al. 2014; Wood et al. 2015a], but not with the

343   earlier Ulysses values with a much lower temperature [Witte 2004].

344   In other studies related to the IBEX observations of interstellar He, Sokół et al. [2015b]

345   examined the deep wings of this distribution. This study presents the topic of the fall peak

346   and makes predictions about its location and strength, as well as the dependence of the

347   signal on the sputtering cutoff. In contrast to the peak of the He distribution, which has a

348   signal to noise ratio in IBEX-Lo of >1000, these authors used simulations to examine

349   signals in the range from 0.001 to 0.01 of the peak value. While these lower fluxes have

350   been left out of prior analyses, they may contain some of the most important information

351   about the detailed physics of the He distribution, including its possible departure from

352   equilibrium. These authors examine the possibilities of both a superposition of the

353   Maxwellian primary and Warm Breeze populations and several different kappa

354   distributions and identify the regions of IBEX observations that have the most potential

355   to resolve these important tails of the interstellar He population.

356   Following on the modeling reconnaissance by Sokół et al. [2015b], Galli et al. [2015]

357   made a detailed examination to see if IBEX can possibly detect interstellar neutral He or

358   O in the fall when the Earth (and IBEX) are moving away from the interstellar flow

359   direction. While extremely challenging, such an observation would provide very strong

360   constraints on the interstellar flow vector. These authors examine the times of the lowest

361   possible background rates in IBEX-Lo, but find that even then, it cannot observe

362   interstellar helium from the anti-ram direction. This result is largely because of the low

363   He energy of ~10 eV in the IBEX spacecraft frame because of the velocity subtraction,

364   which is below that required for detection by sputtering off the IBEX-Lo conversion

365   surface (~25–30 eV). In contrast, interstellar O might be detectable, but given the much

366   lower fluxes, the expected signal is close to the detection limit imposed by the

367   magnetospheric foreground and counting statistics. This study also provides an

368   assessment of the minimum energy threshold for sputtering by interstellar He, which was

369   impossible to obtain by ground calibration. The result provides an important confirmation

370   of the data analysis strategy the IBEX team adopted (no need to correct for this effect) on

371   one hand, and on the other hand points out the importance of this threshold for Warm

372   Breeze studies, as inferred already by modeling studies [Kubiak et al. 2014; Sokół et al.

373   2015b].

374 Finally, Wood et al. [2015b] seek a solution for the remaining, albeit much smaller,

375 temperature difference between the warmer IBEX measurements and cooler Ulysses ones.

376 These authors examine whether "contamination" by interstellar O and Ne could

377 artificially reduce the width of the interstellar He distributions in the Ulysses observations.

378 In particular, the Ulysses GAS experiment cannot distinguish between neutral species as

379 IBEX-Lo can, so it is possible that heavier neutrals could be contributing to the putative

380 He signal on Ulysses. Such contamination would contribute a narrower superposed peak

381 and manifest itself as an apparently lower temperature for the combined distribution. This

382 study finds that while this effect cannot produce a 1000 K difference, it can easily

383 account for an apparent 100 K difference, and possibly as much as several hundred K

384 artificial reduction in the Interstellar He temperature.

385 **4. How far upstream is the "pristine" local interstellar medium?**

386 Table 2 shows the interstellar He parameters from both approaches taken in this special

387 *Supplement*: The UNH analytic method [Lee et al. 2015; Möbius et al. 2015], culminating

388 in the new UNH trajectory numerical integration method [Schwadron et al. 2015] and the

389 Warsaw WTPM method [Sokół et al. 2015a; Swaczyna et al. 2015; Bzowski et al. 2015].

390 The first of these is based on hyperbolic, Keplerian motion around the Sun and calculates

391 trajectories in principle "from infinity." In contrast, the WTPM calculates particle

392 trajectories only out to 150 AU from the Sun. While the error bars are such that the two

393 results are already consistent, the difference in how far upstream the two methods are

394 calculated is not a residual statistical error, but a systematic effect that should be

395   calculated and corrected for. McComas et al. [2012] took a first cut at this for the 2012

396   studies [Mobius et al. 2012; Bzowski et al. 2012]; here we examine this issue more

397   carefully and suggest a better compromise solution.

Table 2. Interstellar He values derived from the independent UNH and Warsaw analysis methods for determining these parameters.

	$V_{ISM\infty}$ (km s^{-1})	$\lambda_{ISM\infty}$ (^{o})	$\beta_{ISM\infty}$ (^{o})	$T_{He\infty}$ (K)
UNH ("infinity")*	25.4±1.1	75.6±1.4	-5.12±0.27	8000±1300
WTPM (150 AU)*	25.8±0.4	75.8±0.5	-5.16±0.10	7440±260
* Uncertainties are dependent on one another and lay along the 4-D parameter tube.				

398

399   For any of the test particle [Bzowski et al. 2012, Sokół et al. 2015a] or even MHD

400   simulations [e.g., e.g. Izmodenov et al. 2009; Zank et al. 2013; Heerikhuisen et al. 2014;

401   Izmodenov & Alexashov, 2015], calculations begin at some finite distance upstream

402   where the gas is presumed to be in equilibrium and thus represented by a spatially

403   homogeneous Maxwellian distribution, flowing with a relative velocity with respect to

404   the Sun called the "velocity at infinity". However, this is not precisely correct. Here, we

405   seek to determine as accurately as possible where we can best assume a Maxwellian or at

406   least stationary state (kappa distribution) [Livadiotis and McComas 2009; 2013] where

407   the upstream neutral population is unaffected by interactions with the Sun or heliosphere.

408   At such an upstream distance, this distribution can be assumed to be flowing with a fixed

409   velocity, from a region that is beyond both nearly all of the 1) Sun's gravitational

410   influence and 2) coupling to the heliosphere and its separate particle and field

411   environment, both of which produce systematic effects. At least on the 100s AU scale

412   size of the heliosphere, we should be able to assume that this flow is homogeneous with

413   the same flow vector, a necessary assumption when we combine observations from

414   different vantage points.

415   Collisions and charge exchange between ions and neutrals in the interstellar medium

416   knock some of the atoms onto the trajectories that ultimately enter the IBEX-Lo

417   collimator. The distance of this last collision before heliospheric influences set in is

418   certainly finite, not known precisely, and is basically stochastic, since collisions are

419   stochastic in the interstellar medium. Thus, the individual dynamical histories of the

420   atoms are not needed – all that counts is the trajectory of each atom after its last

421   interaction. Collisions in the outer heliosheath are quite frequent and, for example, for a

422   population with a density of ~0.2 cm^{-3} at ~ 7000 K, the collisional Mean Free Path (MFP)

423   is only ~100-200 AU [Kubiak et al. 2014]. For particles approaching the heliosphere, the

424   populations are moving together, so the mean relative speed relevant for the calculation

425   of collisional rates is the thermal speed, which can lead to MFPs several times larger.

426   In the pristine interstellar medium is not important whether an interaction is charge

427   exchange between He and He$^+$ or elastic He – He or He – proton collision, or even a He –

428   H collision. What matters is that the trajectories are changed and in fact randomized in

429   the combined upstream interstellar population. So long as these interactions are between

430   members of the pristine interstellar flow populations, they fundamentally don't matter as

431   IBEX measures an ensemble of atoms from the LIC. The key point in the interaction

432   occurs when unaffected interstellar neutral atoms begin to interact with atoms that have

433   already been influenced by the heliosphere. At some distance the heliosphere begins to

434   perturb the medium as neutrals that start within the heliospheric interaction region travel

435   far upstream into the inflowing LIC. One of the advantages of measuring He from the

436   LIC is that He atoms interact less than other species in the outer heliosheath. However,

437   they still do at least a little, likely producing the Warm Breeze and possibly even other

438   smaller populations; fortunately, with the extremely large signal to noise of IBEX-Lo, we

439   are able to see deeply into the tails of the interstellar He population and discover and

440   separate such populations. The bottom line is that there is a finite, surprisingly small, and

441   currently unknown distance for the source of pristine He atoms. This contributes a small

442   extra systematic uncertainty to the results of both the Ulysses and IBEX analyses.

443   There are two primary and independent effects relevant to how far upstream the "pristine"

444   interstellar medium might be thought to begin, and hence how far upstream IBEX (and

445   other) interstellar neutral observations should be calculated to. These are based on 1) the

446   Sun's gravity and 2) coupling of information about the presence of the heliosphere to the

447   interstellar gas upstream of it in the interstellar medium. The first, gravitational

448   considerations are more straightforward. The Sun's Hill Sphere, or region where its

449   gravitational influence is dominant, extends out to ~5000 AU, where the net collective

450   forces of the gravitational field of the Galactic disk begin to become larger than that of

451   the Sun [Chebotarev 1964]. Without collisions, at approximately this distance, the

452 concept of Keplerian motion about the Sun breaks down. Fortunately, the difference in

453 the analytic trajectory solutions between 5000 AU and infinity is <0.05° and is thus

454 effectively negligible. Therefore, this distance sets an upper bound on where it might be

455 reasonable to consider the interstellar medium as actually pristine.

456 Analyses by the UNH group invoke hyperbolic equations of Keplerian motion to

457 calculate trajectories of neutrals observed by IBEX "to infinity" either using analytic

458 approximations [Lee et al. 2012; 2015; Möbius et al. 2012, 2015; Leonard et al. 2015] or

459 numerical integration of the equations [Schwadron et al. 2015; McComas et al. 2015]. In

460 contrast, the Warsaw group calculates particle motions out to 150 AU ahead of the Sun

461 [Bzowski et al. 2012, 2015], well within the region where there is still some bending of

462 the trajectories from the Sun's gravity as well as coupling of the interstellar and

463 heliospheric neutral and plasma populations. For the 2012 round of IBEX papers in

464 *Astrophys. J. Supplements* [Bzowski et al. 2012; Möbius et al. 2012], McComas et al.

465 [2012] proposed a resolution where the values at 150 AU were "corrected" to infinity for

466 comparison, using the analytic equations [Lee et al. 2012; Möbius et al. 2012]. McComas

467 et al. [2012] found that the differences from 150 AU to infinity were mainly in the flow

468 longitude and speed. Starting from the IBEX observations at 1 AU in the spring season,

469 the longitude at infinity was calculated to be 0.75° larger (i.e. 76.15° versus 75.4°) than

470 reported at 150 AU. Likewise, the speed is lower by 0.3 km s^{-1} at infinity versus 150 AU.

471 This leads to a noticeable difference in the results of the two different techniques that is

472 based entirely on where each sets its starting distance.

473   Here, we further examine the underlying physics and propose another definition of the

474   appropriate upstream distance to consider as "pristine" local interstellar medium. This

475   requires both a reexamination of the residual gravitational effects beyond 150 AU and an

476   assessment of how far upstream interactions between the heliosphere and the inflowing

477   very local interstellar medium exist. The effects of the heliosphere's coupling with the

478   upstream interstellar medium are complex [e.g., Izmodenov et al., 2009; Zank et al. 2014].

479   On the one hand, collisions, charge exchange, and other internal interactions between

480   pristine interstellar neutrals and charged particles are simply processes that maintain the

481   particle distributions in the partially ionized interstellar medium; we assume interactions

482   keep this medium in a state of equilibrium at sufficiently large distances from the Sun.

483   On the other hand, as soon as the interstellar medium reaches the vicinity of the Sun, the

484   coupling starts to include collisions, charge exchange, and other interactions with

485   heliospheric particles, effectively sharing information about the presence of the

486   heliosphere with the inflowing material ahead of it.

487   An important aspect of the heliosphere's interstellar interaction is the coupling between

488   the magnetic fields and charged particles of the plasma inside and surrounding the

489   heliosphere with the neutral component of the local interstellar medium. This coupling

490   occurs through charge exchange, ionization, and recombination, where ions and neutral

491   atoms pass back and forth between the ionized and neutral distributions. The creation of a

492   "Hydrogen Wall" ahead of the heliopause [Baranov et al., 1991; Linsky & Wood, 1996]

493   is the best known example of this coupling. More recently, IBEX data were used to

494   discover a secondary neutral He population, dubbed the "Warm Breeze" [Kubiak et al.

495   2014], which is most likely also explained by such coupling. The overall coupling clearly

496   affects the analysis and interpretation of interstellar neutral observations from Ulysses

497   and IBEX.

498   While the Warm Breeze appears to form over a surprisingly small distance from the Sun,

499   the primary interstellar flow is probably only minimally affected by its passage through

500   the outer heliosheath. The largest effect on it is probably just losing a small percentage of

501   its members to charge exchange and thus to the heliosheath plasma. In addition, rare non-

502   charge exchanging collisions could have a small, but noticeable effect on the interstellar

503   flow proper. This could produce non-thermal features in the wings of the distribution.

504   Again, however, we would expect only a very minor influence on the bulk parameters of

505   the primary interstellar flow.

506   To further examine how the implied upstream parameters change with increasing

507   distance in the Warsaw modeling, we calculated three chi-squared minimizations for the

508   2013 season for various upstream distances. For this study we included orbits 193a-198a,

509   which is just slightly broader than used in Bzowski et al. [2015]. In order to ensure that

510   the broadest range of the distribution is included, we also use a slightly broader range of

511   spin angles (246°-288°). For all optimizations, we use the same data and correlation

512   matrix of uncertainties. Figure 1 plots various implied upstream inflow parameters out at
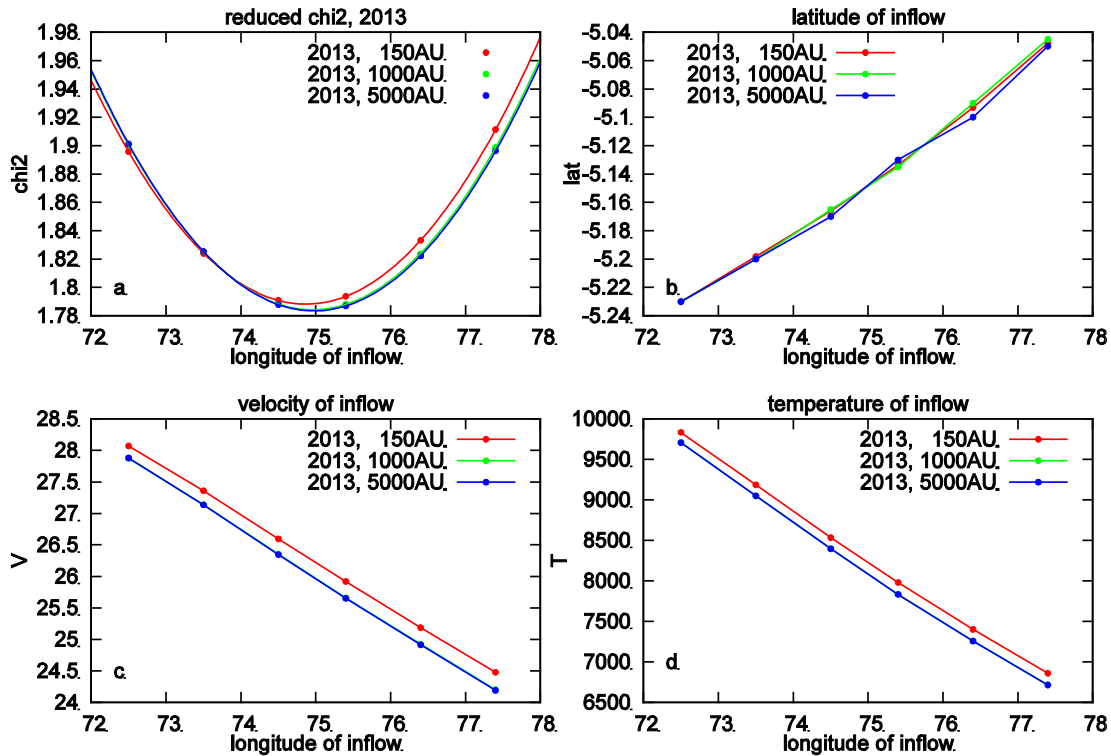
513   150, 1000, and 5000 AU.

514

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 out at 150 AU (red), 1000 AU (green),

and 5000 AU (blue).

Differences between the three distances are small, but systematic with a significant

difference from 150-1000 AU and very little difference from there out to 5000 AU. From

150AU to 1000AU the differences are ~0.1° in the reduced chi-squared minimum inflow

longitude and ~200 K lower temperature, and ~0.4 km s^{-1} smaller inflow speed. There is

525   essentially no difference in inflow latitude, indicating that the inflow latitude is not

526   sensitive to the tracking distance of the atoms. Perhaps most interesting is the very small

527   difference in inflow longitude, which varies from 74.87^o, 74.96^o, 74.97^o for 150 AU,

528   1000 AU, and 5000 AU, respectively. These small differences, and similarly small

529   changes in the temperature and inflow speed, occur as the optimum solution moves

530   slightly along the 4-D tube of correlated parameters. The differences between 1000AU

531   and 5000AU are all extremely small, and in the case of temperature and speed the blue

532   curve actually covers the green one. The differences between the speed and temperature

533   at 150 AU and 1000 AU are a consequence of the acceleration due to Sun's gravity and

534   resulting increase in kinetic energy of ISN He atoms. Heliosphere models provide an

535   alternative way of assessing the region of the solar influence on the interstellar medium.

536   Only for a very strong external magnetic field of ~4 μG, is the influence of the

537   heliosphere even barely evident in the plasma component at 1000 AU (Zank et al. 2013),

538   but such a strong field is not consistent with other information on the LIC properties from

539   IBEX (Schwadron et al. 2011) and theoretical LIC models (Slavin & Frisch 2008).

540   In balance, we recommend a reasonable distance to consider the upstream interstellar

541   medium to be "essentially pristine" is 1000 AU, and we adopt that distance in this study.

542   Beyond 1000 AU, the gravitational bending calculated from the analytic solutions is

543   <0.1^o and MHD simulations even for the no Bow Shock case [Zank et al. 2013] show

544   essentially no perturbation by the heliosphere on the LIC. For stronger interactions where

545   a Bow Shock does exist, the distance range covered by the Hydrogen Wall, and in fact

546   the entire scale of the heliosphere's interaction, extends even less far upstream. Using

547   1000 AU as the baseline distance to track neutral atoms to and compare between the

548   WTPM and UNH calculations, Table 3 includes both sets of values corrected to 1000 AU.

549   For the UNH values, we used the analytic calculation as McComas et al. [2012] did, but

550   this time to take UNH values at "infinity" and bring them back in to 1000 AU. These

551   modifications were tiny and only added 0.04 km s^{-1}, reduced the inflow longitude by 0.1^{o},

552   and increased the temperature by 25 K, which is so much smaller than the error bars that

553   it is ignored in the table. For the Warsaw values, we include the offsets found above for

554   the 2013 data along the coupled parameter tube, but have simply retained the error bars

555   from the uncorrected values. In both cases, the corrections to 1000 AU are very small.

Table 3. Interstellar He parameters adjusted to an upstream source at ~1000 AU.				
	$V_{ISM\infty}$ (km s^{-1})	$\lambda_{ISM\infty}$ (^{o})	$\beta_{ISM\infty}$ (^{o})	$T_{He\infty}$ (K)
UNH (1000 AU)*	25.44±1.1	75.5±1.4	-5.12±0.27	8000±1300
WTPM (1000 AU)*	25.4±0.4	75.9±0.5	-5.16±0.10	7240±260
"Working values" (1000 AU)	**25.5**	**75.5**	**-5.1**	**7500**
* Uncertainties are dependent on one another and lie along the 4-D parameter tube.				

556

557   Finally, we sought to combine both sets of values into a single "best" set for our current

558   knowledge of the pristine interstellar He properties around the heliosphere as we did in

559 2012 [McComas et al. 2012]. However, given the differences in the analysis approaches

560 used, largely overlapping error bars, and difficulty in assigning quantitatively exactly the

561 correlation or independence of the various uncertainties in the two techniques, we

562 decided not to attempt this. Rather, we return to the concept of McComas et al. [2015],

563 that it may be best to simply provide good "working values" for the community to use,

564 that by their very lack of specificity, avoid implying more accuracy than is really known.

565 Thus, we suggest working values of $V_{ISM\infty}$ ~25.5 km s^{-1}, $\lambda_{ISM\infty}$ ~75.5°, $\beta_{ISM\infty}$ ~ -5.1°, and

566 $T_{He\infty}$ ~7500 K at ~1000 AU upstream as shown in Table 3. These values are within the

567 one sigma error bars of both of the new IBEX analyses and also in good agreement with

568 the revised Ulysses values [Bzowski et al. 2014; Wood et al. 2015a], especially when the

569 possibility of ~100 K reduction in the apparent temperature is added back onto the

570 Ulysses values [Wood et al. 2015b].

571 **5. Other Interstellar Neutral Atom Observations and Analyses**

572 Izmodenov & Alexashov [2015] describe the latest version of 3D kinetic-MHD model of

573 the solar wind/LISM interaction. Both heliospheric and interstellar magnetic fields are

574 included in the model as well as heliolatitudinal variations of the solar wind mass flux.

575 Interstellar hydrogen atoms are treated kinetically and a Monte-Carlo method is used for

576 calculations of the hydrogen parameters in the heliosphere. The Hydrogen Wall appears

577 in the model due to charge-exchange between H atoms and interstellar protons outside

578 the heliopause. The hydrogen distribution obtained at 90 AU from the Sun is used as a

579 boundary condition for study of Katushkina et al. [2015].

580   Katushkina et al. [2015] use the Moscow model described by Izmodenov and Alexashov

581   [2015], to simulate interstellar hydrogen fluxes at one AU. The study focuses on a

582   specific IBEX orbit from 2009, which was part of interstellar H observations from 2009-

583   2011 examined by Schwadron et al. [2013]. The model includes solar radiation pressure

584   and solar wind ionization as functions of time and heliolatitude and charge exchange in

585   the outer heliosphere, which leads to non-Maxwellian distributions. Differences between

586   the observations and model are most strongly affected by solar radiation pressure, and a

587   best fit between the model and data requires a ratio of radiation pressure to gravity (μ)

588   ~1.26, which is significantly larger than the value derived from independent solar

589   Lyman-alpha flux observations for this time.

590   The study by Park et al. [2015] examines IBEX observations of interstellar O and Ne for

591   the 2009-2011 seasons. These observations have quite low counting statistics, so these

592   authors employ three independent statistical methods to determine the statistical

593   significance of individual pixels. Together, the results from these complimentary methods

594   build confidence in the detection of heavy neutral atoms and resultant sky maps of these

595   neutral atoms. The sky maps in turn inform the spatial distribution of heavy neutral atoms

596   in the heliosphere. The emission feature extends toward both lower longitude and higher

597   latitude from the interstellar neutral O+Ne inflow peak; this feature may be exposing a

598   secondary oxygen distribution, produced by charge exchange between interstellar neutral

599   hydrogen atoms and oxygen ions in the outer heliosheath. Its offset from the primary O

600   and Ne ISN flow is in the same direction as that of the He Warm Breeze from the He ISN

601   flow.

602   **6. Interstellar Mapping and Acceleration Probe – IMAP**

603   In 2012-2013, the National Research Council (NRC) of the United Stated National

604   Academies carried out the latest Heliophysics Decadal Survey, which culminated in the

605   Decadal Survey report entitled *Solar and Space Physics: A Science for a Technological*

606   *Society* (2013). As a part of the survey, over 180 white papers were submitted as input to

607   the process. Of these, a small number of mission concepts were analyzed in detail,

608   including one named the Interstellar Mapping Probe or IMaP [McComas et al., white

609   paper 2012]. This white paper laid out a mission concept to follow on from IBEX as a

610   Heliophysics Solar-Terrestrial Probe (STP) mission.

611

612   IMaP was conceived to take the next quantum leap forward from IBEX, both pushing

613   forward IBEX's groundbreaking Energetic Neutral Atom (ENA) observations with

614   ~100x better combined sensitivity and resolution and an extended energy range and

615   directly sampling the interstellar neutral populations with decades better statistics. The

616   suggested payload also included all other samples of interstellar matter including pickup

617   ions (generated from interstellar neutrals), ACRs and GCRs, and interstellar dust. Finally,

618   the suggested payload also included solar wind observations from L1, including solar

619   wind plasma electrons and ions, energetic particles, and interplanetary magnetic field, as

620   well as Ly-α photometry; all of these are needed to characterize and remove backgrounds

621 from the primary observations and could also be used for upstream, real time solar wind

622 observations if desired. The mission concept provided by the IMaP white paper was for a

623 Sun pointed spinning spacecraft in orbit around the Earth-Sun L1 Lagrangian point,

624 roughly 1.5 million km sunward of the Earth. This allowed for a very simple spacecraft,

625 like the Advanced Composition Explorer (ACE), and a minimum cost but extremely

626 robust mission. McComas et al. [2011] argued that IMaP would be an analogous step

627 forward for heliophysics that WMAP was from COBE.

628

629 After significant study, the Decadal Survey committee returned a very similar Interstellar

630 Mapping and Acceleration Probe (IMAP) that largely reflected the IMaP white paper, but

631 also expanded the energetic particle observations into a much more capable instrument

632 that not only provided background and real time solar wind information, but also enabled

633 detailed analysis of particle acceleration in the solar wind, and thus required the expanded

634 name Interstellar Mapping and Acceleration Probe (IMAP).

635

636 IMAP will provide the next giant step forward in the direct measurement of interstellar

637 neutral atoms. In particular, an even more capable low energy interstellar neutral atom

638 camera is envisaged to measure atoms from ~10-1000 eV with a pointing knowledge of

639 better than 0.05°. This will provide the capability to measure the precise abundances and

640 independent flow parameters of H, He, O, and Ne, and accurately measure the D/H ratio.

641 These observations will have much higher sensitivity and angular resolution than the

642 current IBEX-Lo observations. The high-precision flow vector and temperature

643   measurements of He and O will strongly constrain models of the ionization state and

644   radiation environment of the LISM. Further, detailed observations of secondary O and He

645   will inform the very local interstellar magnetic field and the detailed structure of the outer

646   heliosheath, as well as the expected departures of the local interstellar gas from

647   equilibrium. Key isotope ratios (D/H, ^{3}He/^{4}He, ^{22}Ne/^{20}Ne), obtained through pickup ions,

648   will provide strong constraints on big bang cosmology and the evolution of matter.

649   Surely, IMAP promises to push discoveries and understanding of the heliosphere's

650   interstellar environment even far beyond the great leaps currently being taking with

651   IBEX!

652   **7. Conclusions**

653   IBEX is truly a remarkable mission of exploration and discovery. Over its first six years

654   of observations IBEX has generated a broad range of important scientific firsts and

655   discoveries (see Table 1 in McComas et al. [2014]). In the 13 studies in this special

656   *Astrophysical Journal Supplement*, we significantly push forward the analysis and

657   interpretation of the interstellar neutral observations from IBEX, using its six first years

658   of data.

659   For the interstellar He, which is the primary focus of this *Supplement*, we rely on two

660   independent and quite different analysis schemes led by IBEX team members in Warsaw

661   and at UNH. Both approaches are used to solve for interstellar parameters by minimizing

662   the difference between simulations and observations. The basis for comparison comes

663   from the observed spin-phase distribution of counts as a function of the 6° spin sector,

664   collected over a series of spins of the spacecraft. However, the analyses differ

665   significantly in how spin-phase distributions are analyzed. In the case of the UNH model,

666   only the peak location in spin-phase is used for further analysis to deduce the ISN flow

667   latitude and longitude. The sectored counts are fit to a smooth function (a Gaussian

668   distribution so far) and the peak of that distribution provides a single spin-phase with

669   which to compare to the distribution peak returned by simulations. Since the peak in the

670   distribution is mostly sensitive to the changes in the primary component over the

671   observer longitude through the ISN flow observation season and the data selection is

672   restricted in longitude and latitude coverage very close to the peak, this method almost

673   eliminates the sensitivity to the secondary component or background. Möbius et al.

674   [2015] detail the residual uncertainty from the presence of the secondary component.

675   In the case of the Warsaw model, the deviation is calculated over the spin-phase

676   distribution. The Warm Breeze from Kubiak et al. [2014] is subtracted from the observed

677   spin-angle count distribution and the residual distribution is fit to a background and the

678   primary distribution by minimizing the difference between the residual distribution and

679   simulated distribution. The Warsaw model is therefore somewhat sensitive to residuals

680   from the Warm Breeze.

681   In addition, in a supplementary analysis, the Warsaw model is used to calculate the

682   expected Gaussian parameters of the ISN beam, which are subsequently compared with

683   the observed one. In this analysis, the Warsaw and UNH analyses come the closest

684   together in their assumptions, since adopting the Gaussian function as an approximation

685   of the signal forces symmetry in spin angle about the peaks. Results of this analysis,

686   shown by Bzowski et al. [2015], are essentially identical with the results from their

687   baseline analysis, with a temperature that is somewhat higher (~8150 K versus 7440 K).

688   Another difference in the two analyses is in time resolution of the data used. The UNH

689   approach uses data collected in five groups of equal time length per orbital arc, while in

690   the Warsaw treatment the signal is integrated over the entire duration of the clean ISN

691   observing times, and the simulation reproduces this integration.

692   In any case, the UNH and Warsaw analysis methods differ significantly in their approach,

693   assumptions, and what aspects of the observations they are most sensitive to. The fact

694   that both methods lead to completely consistent values (within their one sigma errors)

695   lends significant credibility to these combined solutions.

696   Together, the interstellar He studies in the *Supplement* provide a major step forward in

697   the analysis of the IBEX interstellar neutral He observations and in the understanding of

698   the local interstellar medium more generally. Future work will need to simultaneously fit

699   the primary and Warm Breeze He components using all of the data currently available

700   along with new data from the 2015 season, which includes spin axis pointing 5° north of

701   the ecliptic. While analytic approximations may not be up to this even harder task, the

702   two models with direct integrations of the analytic trajectories (WTPM [Sokół et al.

703   2015a]) and the newly-developed UNH response function integration [Schwadron et al.

704   2015] are suitable for this problem. In this way, we seek to maintain two parallel analysis

705   paths as a cross check to ensure the most careful analysis and absolutely most accurate

706   scientific results from these challenging but extremely critical observations.

707   In this study we also examined the systematic effects of gravitation and the coupling of

708   the heliosphere and interstellar medium. Here we propose a working definition of an

709   essentially "pristine" interstellar medium ahead of the heliosphere at ~1000 AU. By this

710   distance, 1) the gravitational effects produce <0.1° and 0.05 km s^{-1} difference compared

711   to infinity, and 2) the coupling with the heliosphere is essentially negligible even for the

712   larger interaction in the case where there is no bow shock ahead of the heliosphere [Zank

713   et al. 2013]. Thus, we recommend that for most purposes, the community use the

714   "working values" of $V_{ISM\infty}$ ~25.5 km s^{-1} , $\lambda_{ISM\infty}$ ~75.5°, $\beta_{ISM\infty}$ ~ -5.1°, and $T_{He\infty}$ ~7500 K

715   for the interstellar He inflow at ~1000 AU upstream; these values are consistent with both

716   approaches used for the IBEX data analysis and the recent reanalysis of the Ulysses

717   observations.

718   Finally, the ongoing IBEX observations and two-point Voyager ground truth

719   measurements in the inner and outer heliosheath, along with even better observations

720   from the planned IMAP mission, will further challenge us and require extensive theory

721   and modeling efforts to reconcile our evolving understanding of the local interstellar

722   medium, outer heliosphere, and their critical interaction. Surely this is an incredibly

723   exciting time for the study of our heliosphere, the very local interstellar medium, and

724   their complicated and delicate interactions.

731

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