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LOCAL INTERSTELLAR HYDROGEN'S DISAPPEARANCE AT 1 AU: FOUR YEARS OF *IBEX* IN THE RISING SOLAR CYCLE

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ABSTRACT

NASA's *Interstellar Boundary Explorer* (*IBEX*) mission has recently opened a new window on the interstellar medium (ISM) by imaging neutral atoms. One "bright" feature in the sky is the interstellar wind flowing into the solar system. Composed of remnants of stellar explosions as well as primordial gas and plasma, the ISM is by no means uniform. The interaction of the local ISM with the solar wind shapes our heliospheric environment with hydrogen being the dominant component of the very local ISM. In this paper, we report on direct sampling of the neutral hydrogen of the local ISM over four years of *IBEX* observations. The hydrogen wind observed at 1 AU has decreased and nearly disappeared as the solar activity has increased over the last four years; the signal at 1 AU has dropped off in 2012 by a factor of ~8 to near background levels. The longitudinal offset has also increased with time presumably due to greater radiation pressure deflecting the interstellar wind. We present longitudinal and latitudinal arrival direction measurements of the bulk flow as measured over four years beginning at near solar minimum conditions. The H distribution we observe at 1 AU is expected to be different from that outside the heliopause due to ionization, photon pressure, gravity, and filtration by interactions with heliospheric plasma populations. These observations provide an important benchmark for modeling of the global heliospheric interaction. Based on these observations we suggest a further course of scientific action to observe neutral hydrogen over a full solar cycle with *IBEX*.

Key words: ISM: general – Sun: heliosphere

1. IBEX-Lo

NASA's *Interstellar Boundary Explorer* (*IBEX*) is a small explorer class mission (SMEX) consisting of an Earth-orbiting satellite launched in the fall of 2008. The *IBEX* spacecraft is on a highly elliptic orbit and has two energetic neutral atom sensors covering overlapping energy ranges (McComas et al. 2009). The interstellar neutral wind is in the energy range of the *IBEX-Lo* sensor (Fuselier et al. 2009; Möbius et al. 2008). To observe and characterize neutral atoms in this energy range a surface conversion system is necessary because the atoms are not energetic enough to pass through the thin foils used in most time-of-flight (TOF) mass spectrometers (Wurz 2000). Surfaces suitable for such neutral to negative ion conversion were tested at the University of Bern in Switzerland and are described by Scheer et al. (2006) and Wurz et al. (2006). The surface chosen for the *IBEX-Lo* instrument was chemical-vapor-deposited diamond-like carbon. This material is pure carbon, however, at the surface where there are open chemical bonds it is hydrogen-terminated, and so energetic neutral atoms incident on the surface produce a signal of sputtered hydrogen ions. While this is an important feature for the detection of noble gases such as helium, it presents a background for our hydrogen measurement. The backgrounds present in the *IBEX-Lo* measurements from various sources are described by Wurz et al. (2009).

IBEX-Lo is designed to maximize the observed signal of ENAs by using a large geometric factor, which enables mass-, energy-, and angle-resolved measurements and the ability to measure very small fluxes. The *IBEX-Lo* sensor incorporates a number of innovations that optimize the signal-to-noise ratio and reduce the background count rate. Most importantly, *IBEX-Lo*, like *IBEX-Hi* (Funsten et al. 2009), is based on a "Bundt-Pan"-type electrostatic analyzer, which focuses a very large circular aperture onto a much smaller, central mass spectrometer, providing a largely enhanced signal-to-noise (Fuselier et al. 2009; McComas et al. 2009). In addition, the mass spectrometer in *IBEX-Lo* is a TOF system that uses a triple coincidence detection system, which measures the TOF of an atom in the mass spectrometer three ways to verify a valid detection and eliminate background. For the purposes of this paper we only use fully qualified triple coincidence counts, i.e., counts in which all three TOF measurements agree for the mass of the particle, to reduce background rates as described by Wurz et al. (2009).

To determine the flux of interstellar hydrogen from the local interstellar medium (ISM) entering the *IBEX-Lo* sensor and converted to negative ions on the conversion surface, it is necessary to separate the background hydrogen due to surface sputtering by ISM helium. Two approaches to statistically separating the converted hydrogen component from the sputtered component are outlined in Saul et al. (2012). For this work we use the energy analysis method to separate the converted interstellar hydrogen component. This method relies on the difference of the energy spectrum for hydrogen produced by sputtering from that of converted hydrogen (Möbius et al. 2012). The raw energy spectra taken during the interstellar helium peak as well as the interstellar hydrogen peak are shown in Figure 1.

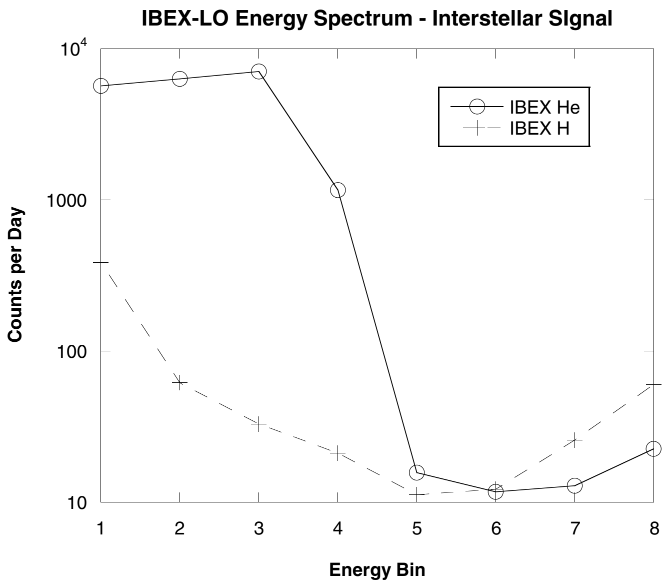

Figure 1. A comparison of *IBEX-Lo* sensor hydrogen, during one orbit produced by interstellar helium wind sputtering (orbit 18) and in the other mostly by converted interstellar hydrogen wind (orbit 23). Shown are raw triple coincidence H^0 events, which come from the 1/10 of spin phase range (36°) bracketing the maximum interstellar flow.

The energy spectrum of the sputtered component taken during the peak of interstellar He wind observation matches very well to the calibration measurements taken at the University of Bern using a low energy neutral helium beam to simulate the incoming interstellar matter. In contrast to the He wind observation we can see that the H interstellar signal is peaked at the lowest energy bin, with some flux in the second bin. The increase in flux in bins 7 and 8 is due to omnidirectional background of high energy ions which increases during the times when the spacecraft is in Earth's magnetotail and is unrelated to the interstellar flow.

We found that the results using the TOF spectrum to separate the species are generally the same as for using this energy method (Saul et al. 2012). However, we caution that improvements need be made in this methodology in order to carry out detailed analysis of the low-energy wings of the hydrogen distribution. In particular, our method for separation relies on certain assumptions about the incoming energy of the interstellar helium and hydrogen. In fact, there are unique distributions of energies for each species. A more complete analysis will take this into account. For this paper we use a simple energy analysis as outlined in our previous paper; this method is adequate for determining bulk parameters.

2. LOCAL INTERSTELLAR MEDIUM

By observing absorption lines in the light of nearby stars one can determine many line-of-sight integrated properties of the surrounding interstellar medium (Frisch et al. 2002, 2011; Redfield & Linsky 2008). Some indirect local measurements of this material have also been made. Solar radiation scatters from the neutral component of the interstellar gas, which has been observed for hydrogen (Lallement et al. 2004) and helium (Vallerga et al. 2004; Chassefiere et al. 1986). It is the very local interstellar medium and magnetic field that combined with the solar wind determine the size and shape of the heliosphere (Baranov et al. 1981; Zank & Müller 2003; Izmodenov et al. 2003). Therefore observations of the boundaries of the heliosphere also constitute an indirect measurement of the local interstellar medium. More recent models of the heliosphere have been made that include *IBEX* measurements (such as interstellar magnetic field direction) as constraints (Pogorelov et al. 2011; Opher et al. 2011; Ratkiewicz et al. 2012). In the present work, we offer further *IBEX* measurements that can constrain models of the heliospheric interaction with the local interstellar medium.

Ionization processes erode the neutral interstellar wind on its passage through the heliosphere, and only a small fraction survives into the inner heliosphere. As a result, the composition of the wind at 1 AU (where *IBEX* resides) is mostly helium, and measurements of the helium wind by *IBEX* give us our best determination of the local interstellar parameters (Möbius et al. 2012; Lee et al. 2012; Bzowski et al. 2012; McComas et al. 2012). The hydrogen component was first observed by *IBEX* in 2009 as reported by Möbius et al. (2008). Later, a more detailed investigation of the hydrogen component showed some variation over the first two years of operation (Saul et al. 2012). The variation we report here over the last two years is much larger, and forms a strong test for global models of the heliosphere, in particular our models of ionization rates and radiation pressure.

3. LONGITUDINAL STRUCTURE OF LISM H WIND AT 1 AU

As the Earth (and *IBEX*) moves around the Sun, the instrument aperture views successively higher ecliptic longitudes. This change of pointing direction is not uniform, but is carried out by discrete orbital adjustments, which maintain the spacecraft attitude to maintain a nearly Sun-pointing spin axis. Between the orbital adjustments, the orientation of *IBEX*'s viewing is inertially fixed while the position of the spacecraft continues to move about the Sun, creating a "sawtooth" shape of the resulting time series (Saul et al. 2012). The vertical discontinuities correspond to the orbital adjustments of the *IBEX* spacecraft attitude (Figure 2).

For a colder distribution of neutral interstellar atoms, this sawtooth structure will be more pronounced, as there will be a larger difference between the flux from two nearby directions. For hydrogen, the sawtooth structure is barely visible (Figures 2 and 3). This is in part due to lower statistics but also suggests that the hydrogen distribution observed at 1 AU appears hotter than the helium distribution, which serves as the reference for the physical conditions in the local interstellar medium (Möbius et al. 2012; Bzowski et al. 2012; McComas et al. 2012). In Figure 3 we show the longitudinal profile of interstellar hydrogen observed by *IBEX-Lo* over the first four years of observation, where the spread in angular space is larger than for helium. To improve the statistics required to perform the separation of converted H from sputtered H, we use three-hour averages (Figure 3) in contrast to the overview plot (Figure 2).

As *IBEX* observed the interstellar hydrogen in 2009 and 2010, the Sun was still in an extended solar minimum. The reduction in the LISM H flux observed over these years was quite small (see Figure 3 and Table 1). However, as the Sun began to increase its activity and the extreme ultraviolet flux increased accordingly, leading directly to a dramatic decrease in the observed interstellar hydrogen. To derive the peak rate, the center position, and the width of the distribution we fit a Gaussian distribution and additive flat background. Table 1 provides the peak rate (in counts/3 hr) integrated over the entire range of heliospheric latitudes. The observed center of the H

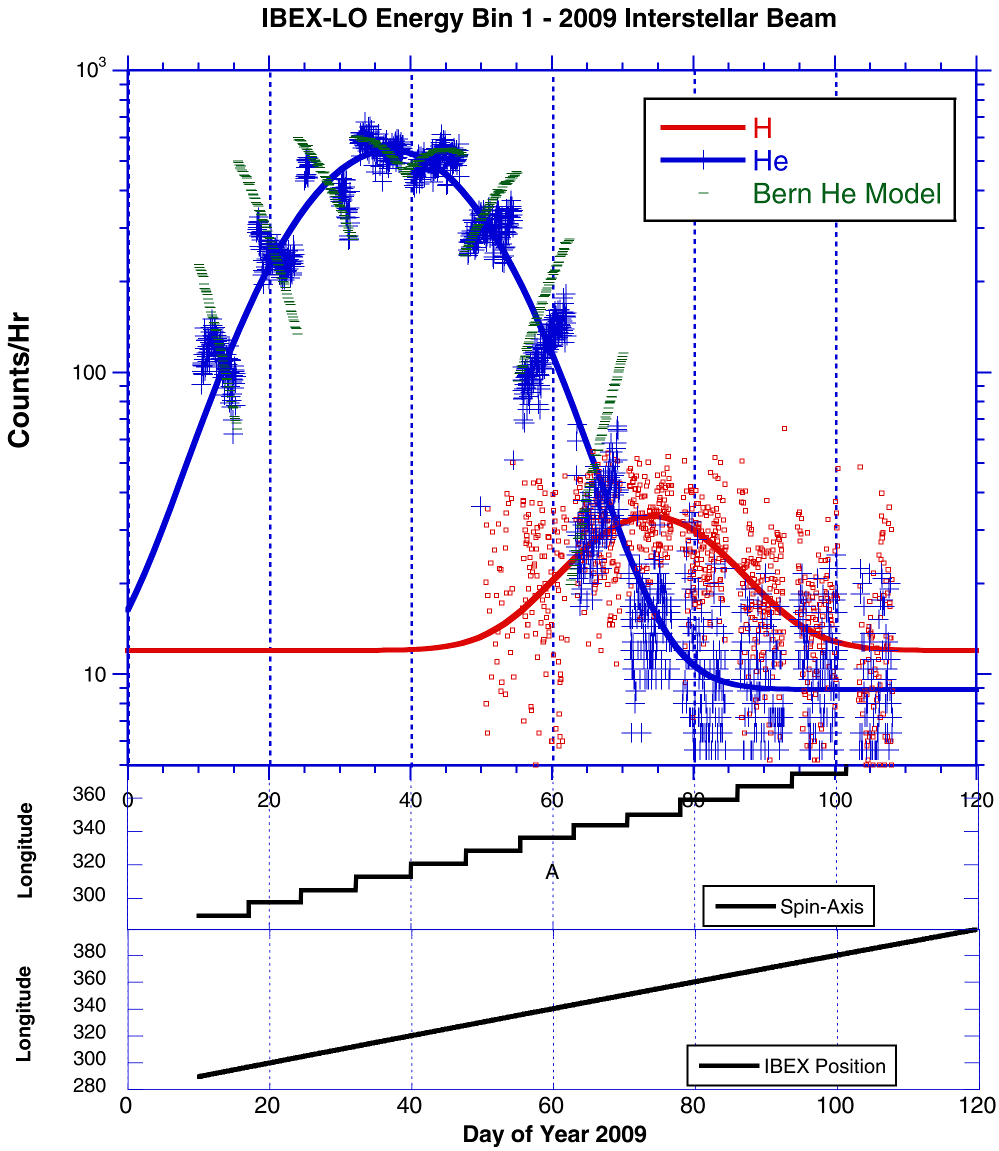

Figure 2. Overview plot for showing the hourly count rates in *IBEX-Lo*'s first energy channel. Counts are separated into converted H atoms (red) and H atoms sputtered from the conversion surface by incident He (blue). A simulation (green) is based on the real pointing and position of the spacecraft (lower panels). Note the logarithmic scale. Gaussian fits are drawn to guide the eye.

Table 1
Best Gaussian Fit to *IBEX-Lo* Measurements of Interstellar Hydrogen Flux

	Peak Rate (counts)	Background Rate (counts)	Flow Center (Ecl. Lat, deg)	Width (σ) (deg)
2009	90.1 (1.8)	10.4 (1.6)	82.9 (0.3)	19.4 (0.7)
2010	85.0 (1.7)	6.1 (1.7)	78.1 (0.4)	25.0 (0.9)
2011	38.2 (1.1)	5.2 (1.1)	86.1 (0.5)	21.4 (1.1)
2012	8.6 (0.6)	3.4 (0.5)	97.6 (1.2)	16.5 (2.6)

Notes. The flux is measured as counts per three hours in the first energy bin, while the center is given as the flow direction of the peak flux in heliospheric longitude. The width is the standard deviation of the distribution given in degrees. The background rate is calculated as a best fit from the data and so indicates not only real background but also deviation from the Gaussian fit. Statistical errors are given in parentheses.

wind or the peak direction is given as the flow direction in heliospheric longitude. The background rate is included as a "best" parameter in the least squares fitting procedure, which is also listed in Table 1. The width is the standard deviation of the peak in degrees. It can be seen that the center of the peak moves to a later observation date with increasing solar activity. The position of the peak is in qualitative agreement with the result that the radiation pressure on hydrogen exceeds the gravitational force (Fahr 1979; McComas et al. 2004). The motion of this observed peak is in qualitative agreement with one driver: an increased radiation pressure as solar activity rises. We return to a more detailed discussion of comparing these observations to the modeled distribution of interstellar hydrogen in the heliosphere in Section 5.

4. LATITUDINAL PROFILE OF LISM H WIND AT EARTH ORBIT

IBEX is a Sun-pointed spinner and thus provides a latitude profile as a function of spin phase. The aperture of *IBEX-Lo* in the low angular resolution mode (used for these observations) is ~7° FWHM (Fuselier et al. 2009). We report here on the latitudinal profile of the interstellar H wind averaged over

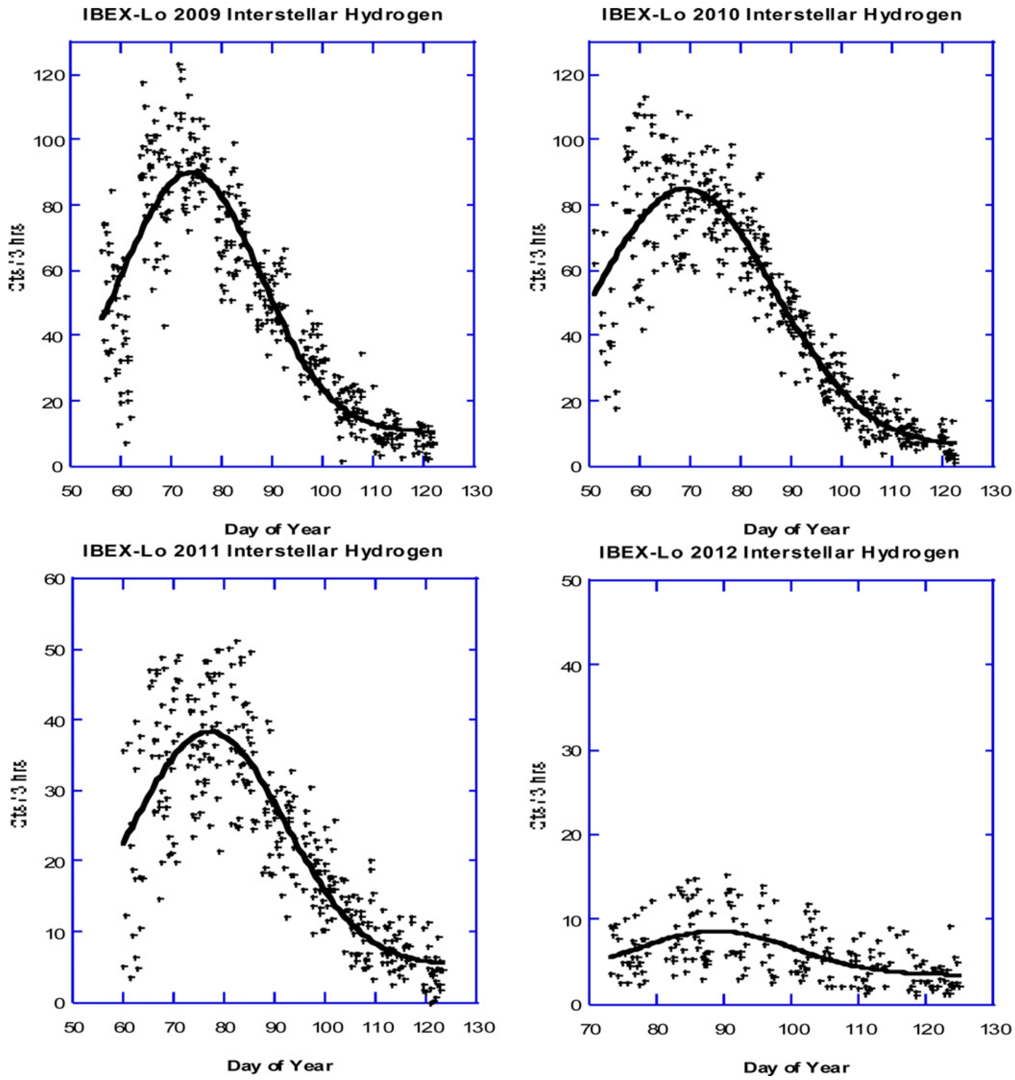

Figure 3. *IBEX-Lo* observations of interstellar hydrogen over the first four years of operation, shown as accumulated counts per 3 hr, as a function of day of year, for the lowest energy channel. Gaussian best fits are shown as solid lines; parameters with error bars are given in Table 1.

the peak orbit of H observation. The number of the *IBEX* orbit as well as the Gaussian fit characteristics are shown in Table 2.

By taking 2° bins in the spacecraft spin phase and summing over the good observations of the orbit at maximum LISM H viewing, we produce the latitude profiles shown in Figure 4. Again, these profiles show the reduction in H flux over the rising phase of the solar cycle. The differences in the center position (the flow direction in heliospheric latitude) are not as pronounced as those in heliospheric longitude. This is because the flow direction in latitude is close to the ecliptic plane and so radiation pressure does not have a chance to strongly deflect this component of the flow.

The width of the latitudinal profile also changes (Table 2), as the distribution appears to get cooler with increasing solar activity, a statistically significant variation. This may in part be due to filtering effects in the outer heliosphere as the higher energy and more direct trajectories have a higher survival probability in the ionizing field of the Sun. However, the effects of filtering mechanisms on the distribution of H atoms at 1 AU must be more fully modeled to quantitatively understand the implications.

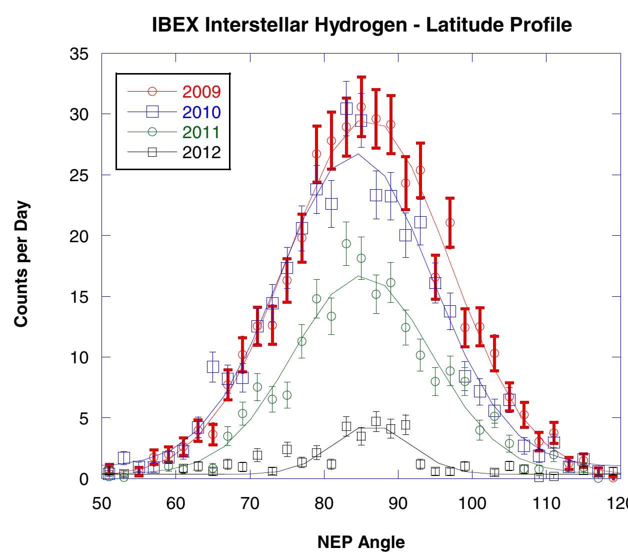

Figure 4. *IBEX* observations of interstellar hydrogen over the first four years of operation, shown as spin phase or latitudinal profiles as north ecliptic polar angle during the maximum LISM H flux orbits. Gaussian fits are shown as solid lines, parameters given in Table 2.

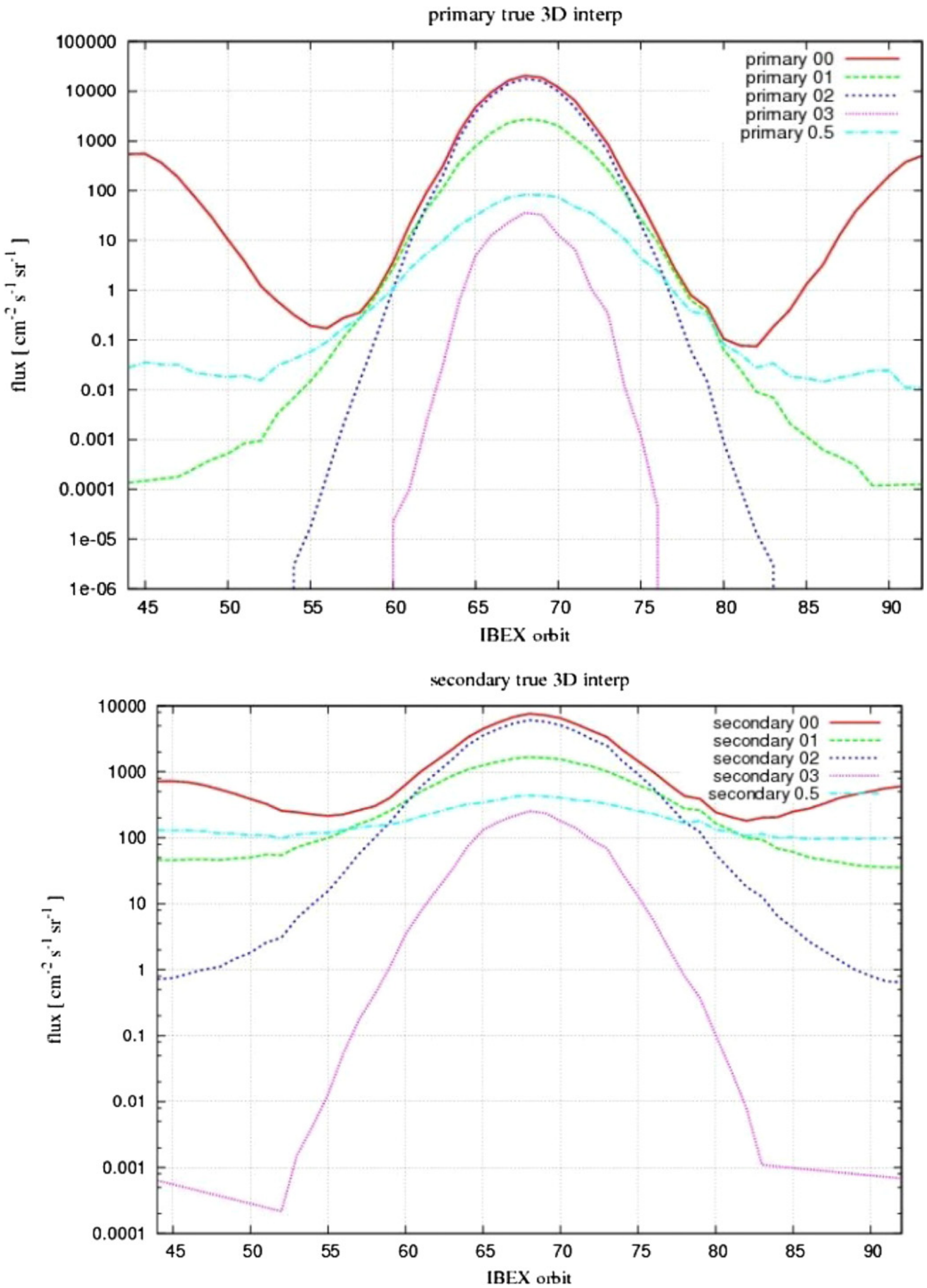

Figure 5. Model of expected H flux. Primary and secondary interstellar H populations based on simulations of the Warsaw Group (Bzowski 2008; Bzowski et al. 2012). The red line is the integral of all particles in the interstellar wind, while the other lines show fluxes in the energy range of the first three *IBEX-Lo* energy bins.

5. DISCUSSION AND FUTURE OBSERVATIONS

Our observations show clearly that the interstellar hydrogen wind in the vicinity of the Earth has drastically reduced in the rising phase of the solar cycle. The precise amounts of this reduction, and the associated angular shifts in position (Tables 1 and 2), provide important information to test our knowledge of transport and loss of the interstellar atoms on their way in from the interstellar medium to Earth's orbit. While changes in the angular directions and flux are qualitatively consistent with those expected from the rising solar activity, the details lead to several questions: once these observations are deconvolved with well-measured ionization rates and radiation pressure will they allow us to determine the density of protons in the heliosheath? Can we explain the observed "cooling" of the latitudinal angular distribution of the LISM H wind with velocity dependent filtration by ionizing alone? Do our ionization models account for these dramatic changes, and what do they predict for the coming solar maximum and the declining phase? Is the radiation pressure calculated based on direct observations of the Sun's Lyα line profile and flux consistent with the radiation pressure needed to explain the interstellar hydrogen wind observations?

We have presented the interstellar hydrogen observed with *IBEX-Lo* in the lowest energy channel, which is centered

Table 2
IBEX-Lo Observations of Interstellar Hydrogen over the First Four Years of Operation, Shown as Spin Phase or Latitudinal Profiles during the Maximum LISM H Flux Orbits

	Orbit (Number)	Apogee (mon:d:h:min)	Peak Rate (counts)	Center (Ecl. Lat., deg)	Width (σ) (deg)
2009	23	03:30:14:33	29.43 (0.37)	−4.10 (0.15)	15.47 (0.22)
2010	71	03:31:12:55	25.76 (0.56)	−5.76 (0.25)	14.55 (0.37)
2011	119	03:31:16:28	16.32 (0.57)	−4.73 (0.57)	13.27 (0.82)
2012	161	04:02:16:12	4.04 (1.02)	−3.55 (1.52)	7.36 (2.18)

Notes. The orbit number and date of apogee are given in the table as well as the peak rate in the angle bin (in counts per day) the flow direction center (in heliospheric latitude) and the standard deviation of the best fit Gaussian. Statistical errors are given in parentheses.

at 14 eV in the spacecraft frame of reference. This is near to the expected energy of unmodified interstellar hydrogen entering the heliosphere. While this is the energy channel where we observed the maximum H flux, there is also some hydrogen observed in energy channel 2, which is centered at 28 eV (Figure 2). Understanding the small additional H flow at higher energies will need detailed modeling. We present here (Figure 5) preliminary results of the Warsaw group to model these observations using the heliospheric parameters and ionization models which include heliospheric filtration presented in Bzowski 2008; Bzowski et al. 2012).

The most striking difference between these model results (Figure 5) and our observations is that they predict a peak signal in *IBEX-Lo* energy bin 2, whereas in our observations the peak is located in energy bin 1 (Figures 1 and 6). The reason the models show the peak in bin 2 is in part due to heavy ionization loses experienced by lower energy hydrogen entering the heliosphere. To emphasize this energy distribution we show in Figure 6 the same data from orbit 23 that was used to produce Figure 1. In this case we plot the flux of interstellar hydrogen observed at the spacecraft rather than the count rate. We also do a background subtraction in which the average signal from the area of the sky not containing the LISM wind is subtracted from our signal (as carried out in Rodríguez et al. 2012). It can be seen that the higher energy background is removed and the enhancement in the low energy is accentuated after the instrument efficiencies are taken into account.

This energy discrepancy could mean that some assumptions in the ionization model need new attention, including our estimates of hydrogen densities in the outer heliosphere. Further modeling efforts underway are likely to test these assumptions against the time variability and the latitude distribution as well as the ecliptic longitude dependence of the interstellar H signal shown here.

Finally, the nature of these observations in the rising solar cycle underline the importance of continued observations to separate the effects on the observed flow by the Sun from actual variations at the heliospheric interface. From our observations we can extrapolate over the rising solar activity and say that interstellar hydrogen will almost certainly not be visible during the solar maximum. Therefore we suggest an intense viewing strategy centered on the observing times available to *IBEX* during the falling solar cycle. Some improvements can be made to the observing strategy to increase our knowledge of interstellar hydrogen during that time. The simplest way to increase observing statistics will be to spend more time in the first energy bin of *IBEX-Lo*, rather than performing the nominal eight energy steps.

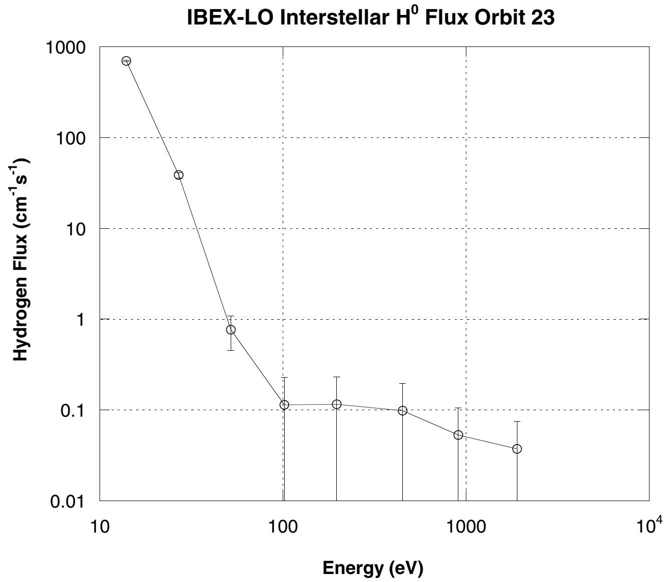

Figure 6. Flux of interstellar hydrogen during orbit 23 is shown as measured at 1 AU by *IBEX-Lo* (spacecraft reference frame). Omnidirectional background has been subtracted.

In combination with direct ENA measurements from *IBEX* and in situ measurements from *Voyager*, the neutral H wind distribution variations reported here add another way to test our knowledge of the outer heliosphere.

We acknowledge the entire *IBEX* team for their great work and dedication to this successful mission. Work carried out in the United States was supported by the *IBEX* mission, which is a part of NASA's Explorer program. The financial support of the Swiss National Foundation and hospitality and work from the University of Bern team is also acknowledged. Participants of a scientific meeting on the very local interstellar medium led by Dimitra Koutroumpa at the International Space Science Institute in Bern are acknowledged for useful discussion. Finally our reviewer is acknowledged for useful discussion and advice to improve this manuscript.

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