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ENERGETIC NEUTRAL ATOM SPECTRA AT THE ECLIPTIC POLES*

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EXPLORING THE TIME DISPERSION OF THE *IBEX*-HI ENERGETIC NEUTRAL ATOM SPECTRA AT THE ECLIPTIC POLES

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ABSTRACT

The *Interstellar Boundary Explorer* (*IBEX*) has observed energetic neutral atom (ENA) hydrogen emissions from the edge of the solar system for more than three years. The observations span energies from 0.01 to 6 keV FWHM. At energies greater than 0.5–6 keV, and for a travel distance of ~ 100 AU, the travel time difference between the slowest and the fastest ENA is more than a year. Therefore, we construct spectra including the effect that slower ENAs left the source at an earlier time than faster ones. If the source produces a steady rate of ENAs and the extinction does not vary, then we expect that the spectral shape would be time independent. However, while the extinction of ENAs has been fairly constant during the first two and a half years, the source appears to have changed, and thus the spectra at a single time may not represent the conditions at the source. *IBEX*'s viewing allows continuous sampling of the ecliptic poles where fluxes can be continuously monitored. For a given source distance we construct spectra assuming that the measured ENAs left the source at roughly the same time. To accomplish this construction, we apply time lag corrections to the signal at different ENA energies that take into account the travel time difference. We show that the spectral shape at the poles exhibits a statistically significant change with time.

Key word: Sun: heliosphere

1. INTRODUCTION

The *Interstellar Boundary Explorer* (*IBEX*) was launched in 2008 October to study the global interaction between the heliosphere and the local interstellar medium (McComas et al. 2009a, and references therein). *IBEX* measures energetic neutral atoms (ENAs) from ~ 10 eV up to 6 keV with two very sensitive single-pixel (~ 6.5 FWHM) ENA sensors (Funsten et al. 2009a; Fuselier et al. 2009b). Its very elliptical Earth orbit allows for long integration times away from the radiation belts with more than half the time outside Earth's magnetosphere (see, e.g., Schwadron et al. 2009b). *IBEX*'s spin axis is repointed every orbit (~ 7.6 days until 2011 June, ~ 9 days since then; McComas et al. 2011a) such that its field of view is roughly perpendicular to the Sun–Earth line. After six months, *IBEX* sees the entire sky and a set of energy-resolved ENA maps are produced. So far, *IBEX* has produced five sets of maps of the global interaction and is accumulating observations for the sixth set.

The first maps (McComas et al. 2009b; Fuselier et al. 2009a; Funsten et al. 2009b) revealed a bright feature, the “*IBEX* ribbon,” that was not predicted by models at the time (Schwadron et al. 2009a). The ribbon lies on top of a more diffuse emission that is called the globally distributed flux (McComas et al. 2009b; Schwadron et al. 2011). The energy-resolved maps were used to derive ENA spectra (McComas et al. 2009b; Funsten et al. 2009b) at different longitudes and latitudes. One of the main results is that the spectral shape is ordered by latitude, but largely independent of longitude. Spectra from the polar regions show a flattening of their slopes for energies > 1 keV.

The ENAs measured by *IBEX* are created in the outer heliosphere, most likely beyond the termination shock in the inner and/or outer heliosheath (see different possible scenarios in McComas et al. 2009b, 2010, 2011b). Therefore, ENAs that leave the source region at the same time will arrive at different times in the inner heliosheath with the fastest arriving first and the slowest last. For instance, for 0.5 and 6 keV ENAs traveling 100 AU the time travel difference is roughly 13 months. The spectra are like a snapshot over such a timescale because data for a single pixel are collected over the time of an orbit (~ 7.6 days).

If the source does not vary with time and if ENAs at different energies are attenuated the same way from the source to *IBEX*, then spectra collected from a single map (or orbit) should represent spectra at the source. However, if either of these conditions changes significantly over time, then the spectral shape derived at 1 AU is no longer a good representation of the spectral shape at the source.

McComas et al. (2010) compared the second set of maps to the first in order to assess the possibility of temporal changes over the six months between views. They reported significantly lower (10%–15%) emissions from both the north and the south poles in the second map compared to the first. Moreover, Reisenfeld et al. (2012) studied the variations of ENA emission at the ecliptic poles and found that the intensity decreased with time, with the largest change (70%) at 1.1 keV. Given those results, a spectrum derived from a single time (or orbit, or pixel) at *IBEX* probably does not accurately represent conditions at the source.

IBEX's unique pointing and instrument mounting provides continuous sampling of ENAs from the ecliptic poles. The 6° pixels from the north and south ecliptic poles are sampled

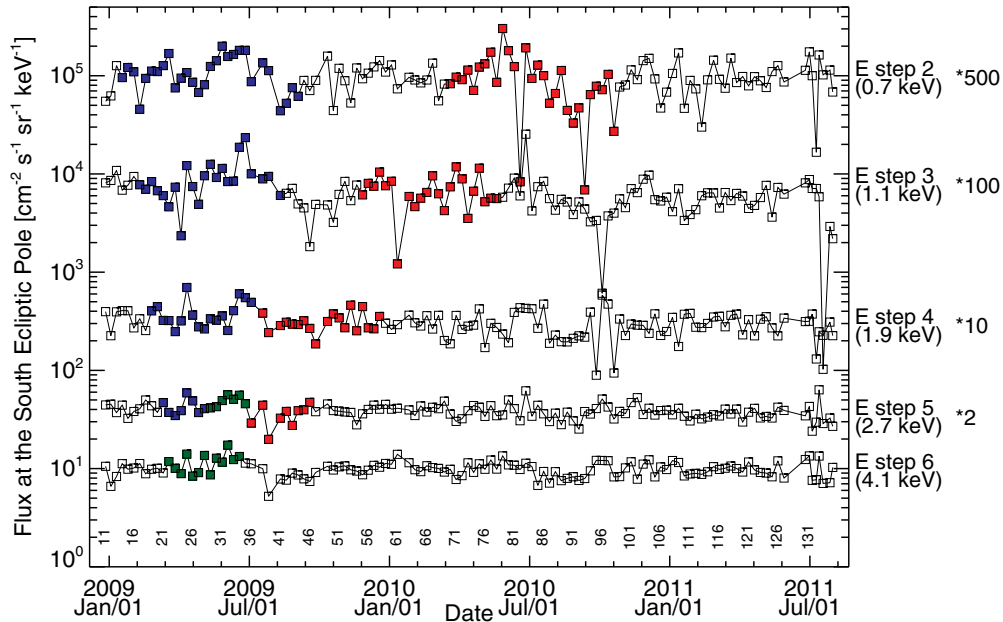


Figure 1. Orbit averages of H ENA fluxes corrected for extinction measured for passbands centered on energies from 0.7 to 4.1 keV (at the center of the passband) for the 12° FWHM around the south ecliptic pole. Also indicated on the bottom are the orbit numbers (no data were obtained for orbits 40, 62, 128, and 129). See the text for the filled symbols.

every spin during every orbit. Because of the low ENA fluxes, however, we typically integrate over many days or orbits in order to get good statistics. Still, the sampling rate is much faster at the poles than the six-month resampling for the rest of the sky. Using continuous observations and faster cadence at the poles, we apply a time shift correction to the ENA flux according to travel time in order to compensate for time dispersion in the *IBEX* spectra.

2. OBSERVATIONS

The data used for this study were collected by the *IBEX*-Hi sensor (Funsten et al. 2009a) from 2009 December to 2011 July. *IBEX*-Hi has six energy passbands of roughly 65% FWHM. The lowest energy step often has significant background and is not used in this study. For the other energy channels, all the identified backgrounds (from cosmic rays and from solar wind and magnetospheric ions) were removed to the maximum extent possible. More detailed discussions on the backgrounds are given in Reisenfeld et al. (2012) and D. J. McComas et al. (2012, in preparation).

ENAs on their journey to *IBEX* can experience charge exchange with solar wind ions or be ionized by solar radiation. The survival probability of an ENA between the termination shock and *IBEX* was calculated using a model (Bzowski 2008). For this study we used the two-dimensional extinction model that combines solar wind observations and radiation pressure as described by McComas et al. (2010); this data set matches the one used by Reisenfeld et al. (2012).

Because we examine only fluxes at the poles, there is no need to account for the Compton-Getting effect, which has no effect in these directions. However, because of the Earth's motion around the Sun there is an aberration effect. This effect is small (4:5 for energy step 2, 1:9 for step 6; Reisenfeld et al. 2012) and neglected in this study.

In order to improve statistics, counts are integrated over a 12° pixel centered on the ecliptic poles. Figure 1 shows the average fluxes calculated for each orbit as a function of time for the five

energy steps centered at 0.71, 1.08, 1.85, 2.70, and 4.09 keV at the south ecliptic pole.

3. RESULTS

If we were to construct a spectrum from a single orbit we would take average fluxes in each of the five energy steps and plot them versus energy, more precisely, versus the central energy of the energy passband. However, it would not take into account time dispersion because the slowest ENAs would have left the source region much earlier than the fastest in order to arrive at the same time at *IBEX*.

To correct for time dispersion, we need to know the time when the ENAs at different energies arrive at *IBEX* assuming that they left the source at the same time. In principle, knowing the distance and the speed is sufficient. However, there are two complications. First, because the energy passbands of *IBEX*-Hi are $\sim 65\%$ FWHM, ENAs in a wide range of energies can be detected in a single energy step. Therefore, we cannot use a unique ENA speed for a given energy step. Second, the source is likely to be spread out rather than a point source. In the following, we describe how to address these complications and how we define our time dispersion correction.

For the distance to the source we use the estimates from Reisenfeld et al. (2012) who inferred the distance to the termination shock and the heliosheath thickness using the pressure balance between ENAs and the solar wind. They found that the termination shock was at 110 AU in the south and 134 AU in the north pole directions and the heliosheath thickness was 55 AU (south) and 82 AU (north). Note that these values agree well with the latest models quoted in their paper. For simplicity and for the sake of describing the method, let us say that the ENAs travel from the middle of the heliosheath, i.e., they travel 137.5 AU from the south and 175 AU from the north, and that they travel at a speed corresponding to the central energy of the passband. The ENA travel times for the central energies as well as those for energies at the lower and upper end of the FWHM are given in Table 1.

Table 1
Travel Times for H ENAs at Different Energies (E = Central Energy of the Passband,
HW = Half Width at Half-maximum of the Passband) for Two Different Distances

Distance	Travel Time in Days at Energies	Step 2 $E = 0.71$ keV	Step 3 $E = 1.08$ keV	Step 4 $E = 1.85$ keV	Step 5 $E = 2.70$ keV	Step 6 $E = 4.09$ keV
137.5 AU (South)	E–HW	754	593	466	386	307
	E	646	523	400	331	269
	E+HW	558	437	344	281	222
175 AU (North)	E–HW	960	755	594	491	391
	E	822	666	509	421	342
	E+HW	710	556	438	357	283

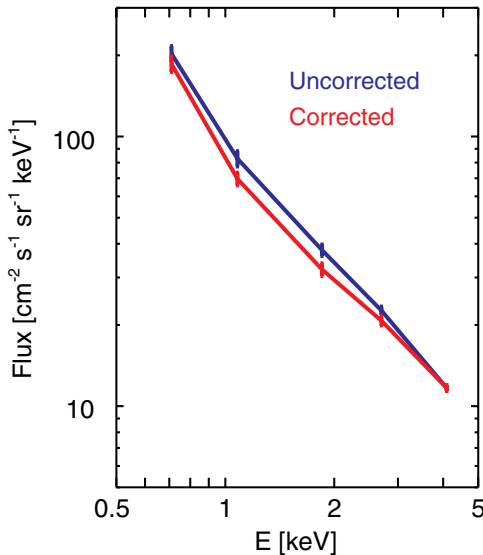


Figure 2. Example of a spectrum with and without time dispersion correction.

We note that for a given energy step the range of travel times is rather wide. For example, in energy step 2, an ENA with energy at the lower end of the FWHM of the passband takes ~ 196 more days to travel from a source at 137.5 AU when compared with an ENA with energy at the corresponding upper end. This is for a point source while the source is most likely spread out over a larger area. For comparison, an ENA with energy 0.71 keV (central energy of step 2) travels 110 and 165 AU (estimates of the inner and outer boundaries of the heliosheath) in 516 and 775 days (259 days difference), respectively. Thus, these travel time differences due to the width of the energy passbands and the spread of the source determine the minimum time resolution for observing time variations. Because of these two effects and also to improve statistics, we average the fluxes over many orbits. The spread of the source is presently unknown, hence, we define the averaging time interval in our analysis based on the first of the above-mentioned effects, i.e., 196 days for ESA step 2, 156 days for E step 3, 122 days for E step 4, 105 days for E step 5, and 85 days for E step 6, in the south. We demonstrate in Section 4 that changing this parameter does not change the results of this study much.

By and large, the ENAs detected in energy step 6 are the first to arrive at *IBEX* if they all left at the same time from the source. Thus, to construct a time-dispersion corrected spectrum, we start with energy step 6 at a given orbit and define the arrival time as $t = 0$. We calculate a time-exposure weighted average of the flux and its uncertainty in this energy step over a period of 85 days (cf. previous paragraph) centered on $t = 0$. Then, since the travel time difference between an ENA at energy step 6 and energy

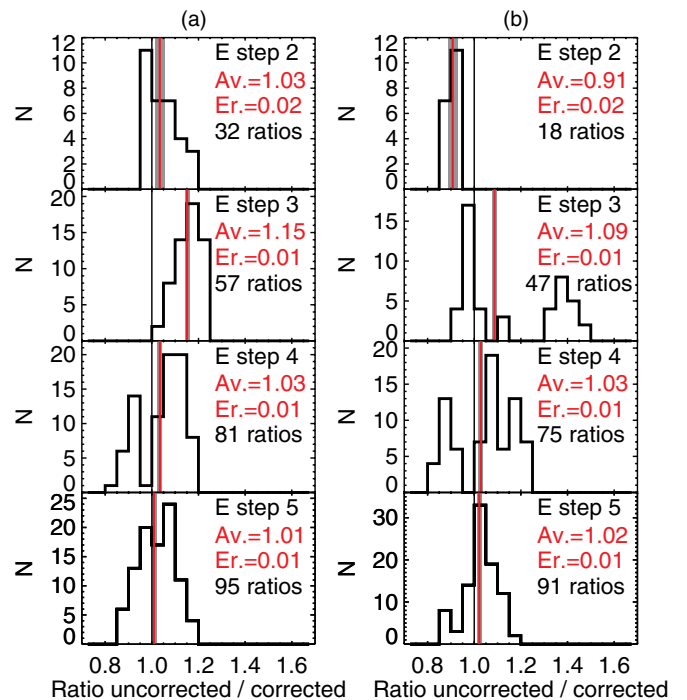


Figure 3. Occurrences (N) of the ratio between the uncorrected and the corrected (time-dispersion removed) spectra for the south (a) and the north (b). There is no correction to energy step 6 because it is used as the starting point to build the spectra (ratio = 1). The thin black line shows a ratio of 1 and the red line shows the average ratio (also given in red). The gray areas represent the uncertainties of the average ratios.

step 5 is 66 days for the central energies in the south (cf. Table 1), we calculate the average flux in energy step 5 for a period of 105 days centered on $t = 66$ days. We repeat the same process for the lower energy steps until we produce a spectrum over all five energies. The red-filled symbols in Figure 1 illustrate the method and show the time periods over which the averages are calculated for the different energy steps. In order to examine the effects of the correction, we also calculate a spectrum using the same averaging time periods but without time dispersion correction. The blue-filled symbols in Figure 1 show the averaging time periods without time dispersion. The green-filled symbols show when the averaging periods for the corrected and uncorrected spectra overlap.

Figure 2 examines the differences between the uncorrected spectrum (blue) and the time-dispersion corrected spectrum (red). We have repeated this analysis for all orbits and determined the ratios between the corrected and uncorrected spectra at all energies. Figure 3 shows histograms of these ratios.

The corrected and uncorrected intensities for all orbits in energy step 6 are identical and hence not shown in Figure 3.

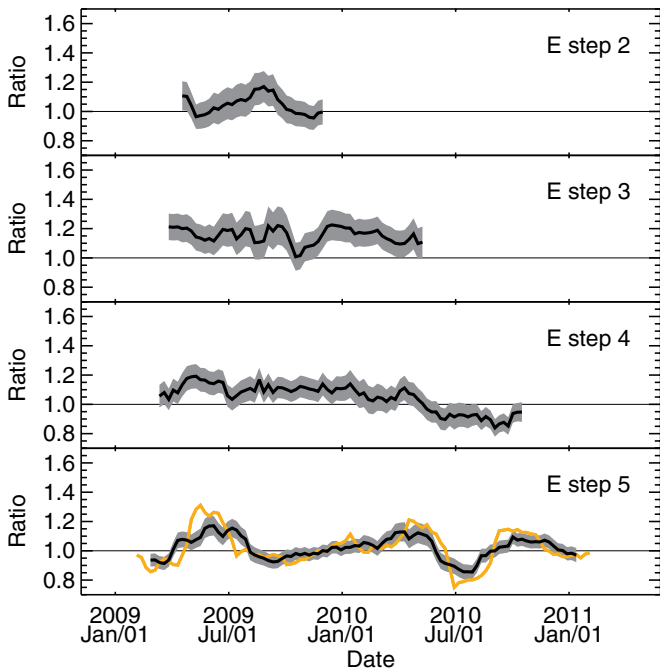


Figure 4. Ratios of corrected to uncorrected spectra for energy steps 2–5 as a function of ENA arrival time at *IBEX*. The black curves and gray areas represent the ratios and their uncertainties for an averaging time interval corresponding to the travel time difference between ENAs from the two ends of the energy passbands. See the text for the orange curve.

Averages (red vertical lines) and uncertainties (gray bars) of the ratio are calculated using a weighted average of all the ratios from the spectra. The average ratio is always larger than 1 except for energy step 2 in the north. The north pole region may be contaminated by contributions from the nearby *IBEX* ribbon. We remark that the ribbon exhibits significant differences between maps 1 and 2 in this part of the sky (McComas et al. 2010), and its effects on our analysis are uncertain. Therefore, here we focus only on observations from the south pole.

To investigate how ratios vary over time we plot them versus time in Figure 4. The time corresponds to the time when the ENAs in energy step 6 arrived at *IBEX*. The black curves represent the same data as in Figure 3, i.e., the fluxes were averaged over an interval equivalent to the travel time difference between ENAs at the central energy plus or minus the half-width at half-maximum of the energy passband. When comparing the flux at energy step 5 between corrected and uncorrected spectra, there is a slight overlap of the averaging intervals between the two. The reason is that the time shift correction (66 days) is smaller than the averaging interval (105 days). This overlap does not occur at lower energies because the time shift correction is larger than the averaging time interval. We show in the bottom panel the effect on the time shift correction by reducing the averaging time interval such that there is no overlap between the corrected and uncorrected averaged fluxes at energy step 5 (orange curve). The trends are very similar between the two curves and the average ratio is the same.

4. DISCUSSION

In this study, we showed that applying a time dispersion correction changes the spectral shape. The simple fact that there is change indicates that the source is indeed varying over time. Moreover, a ratio greater than 1 of the uncorrected to the

corrected spectra (except for the lowest energy in the north pole) implies that the ENA flux is decreasing over time. This result is consistent with previous reports of flux decreases at the poles (McComas et al. 2010; Reisenfeld et al. 2012), but was arrived at independently.

The ratio of corrected to uncorrected spectra indicates how much the flux at a given energy is overestimated by simply using a single time spectra. For example, a ratio of 1.15 (energy step 3, south) indicates that the flux should be 13% lower ($0.87 = 1/1.15$); the largest difference appears for energy step 3 (at ~ 1.1 keV). We normalized our time dispersion correction with energy step 6. Thus, we must take into account the travel time of ENA in energy step 6 (~ 269 days for 137.5 AU) to obtain the time when the ENAs that make the corrected spectrum left the source at ~ 137.5 AU. Note that we would arrive at the same conclusion if we had normalized to another energy step. In the end, it does not matter which energy step is chosen for the normalization, and the result is that the corrected spectra are harder than the uncorrected ones.

These results have two distinct consequences. On the one hand, the differences between the corrected and uncorrected spectra are modest (at most $\sim 13\%$) but significantly larger than the uncertainties. Nonetheless, the slight hardening of the corrected spectrum should be taken into account in models that seek to reproduce conditions in the heliosheath and infer the parent ion populations that produce the ENAs. Clearly, if changes on the order of a few percent are relevant for such models, then the correction is needed. Our results also indicate that time dispersion corrections to the ENA spectra are likely to be more significant and should be thoroughly characterized when comparing with lower-energy or higher-energy ENA measurements from *IBEX*-Lo or the Cassini INCA data, respectively. On the other hand, our results clearly indicate that studies of the global properties of ENAs, which have revealed differences much larger than a few percent, are essentially unaffected by the time-dispersion effects (e.g., McComas et al. 2010).

In order to assess how the travel distance affects results presented here, we ran the same analysis with a travel distance of 110 AU and 165 AU for the south pole. This is the range of distances obtained by Reisenfeld et al. (2012) for the boundaries of the heliosheath at the south pole. Again, the largest difference is attributed to the ratio at energy step 3 where it decreased to 1.12 for 110 AU and increased to 1.19 for 165 AU. All other ratios changed by no more than 0.03. Even with some error in the travel distance, this method gives a systematic shift toward lower fluxes with the most pronounced effect at ~ 1.1 keV.

When referring to the central (or average) energy of an ESA passband, a uniform energy distribution is often assumed as input to the sensor. However, ENA spectra observed by *IBEX* resemble a power law with negative power index rather than a uniform distribution. This causes the average energy for a passband to shift toward lower values. We calculated the average energy for each passband assuming a power-law spectrum with power index -1.5 . Then we applied the time dispersion correction with these new average energies. We found that the ratios did not change by more than 0.01.

In order to account for the fairly broad energy passbands and the spread of the source, we averaged the fluxes over a time interval. Note that changing the time intervals does not change the average ratios much. We ran the same analysis for the south pole with a shorter (by $\sim 40\%$) and a longer (by $\sim 30\%$) interval and found that in both cases the largest difference was at most

0.05 in the average ratios for energy step 2, and less than 0.02 for energy steps 3, 4, and 5.

The time-averaging interval can be converted to a distance using the measured ENA speeds. The average travel distance is ~ 43 AU for energy steps 2–6. It is interesting to note that this distance is comparable to the inner heliosheath thickness of ~ 55 AU (south pole) derived by Reisenfeld et al. (2012). If the ENAs measured by *IBEX* are indeed produced between the termination shock and the heliopause, then a fast ENA for a given energy step leaving from the furthest parts of the IHS will arrive at about the same time as the slow one leaving from the closest parts of the IHS.

Note that because the north pole pixels may contain some of the ribbon ENAs, there is a possibility that variability of the ribbon is superposed on variability of the distributed flux at the north pole. It is therefore difficult to draw conclusions from north polar data.

In summary, the time-dispersion correction of the *IBEX*-Hi spectra at the ecliptic poles shows that fluxes have decreased since the first orbits and that spectra are generally harder around 1 keV than when no time dispersion correction is applied. Differences up to $\sim 13\%$ (at 1.1 keV) are observed. For detailed studies where small changes of this order are important the time-dispersion correction is necessary. From a more global perspective where differences of more than $\sim 13\%$ are observed, the time dispersion correction can be neglected because it will probably not affect the end results much.

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