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INTERSTELLAR NEUTRAL ATOMS AT 1 AU OBSERVED BY THE *IMAGE*/LENA IMAGER

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ABSTRACT

Observations from the *Imager for Magnetopause to Aurora: Global Exploration* (*IMAGE*) Low Energy Neutral Atom (LENA) imager from 2005 are used to investigate characteristics of interstellar neutrals in the inner solar system. The LENA imager detected an interstellar neutral signal starting in 2004 December and extending to early 2005 April. Using the orientation of the field of view of the imager and the date of the loss of the interstellar neutral signal, it is concluded that the signal is consistent with a relatively compact (several degrees wide in ecliptic latitude and longitude) source of neutral helium and/or energetic (>150 eV) hydrogen originating from the solar apex direction. Observations later in 2005 are used to distinguish the composition and conclude that the relatively compact source likely contains some energetic hydrogen (in addition to the helium).

Key words: ISM: structure – interplanetary medium – space vehicles: instruments

1. INTRODUCTION

Because of the motion of the Sun through the local interstellar cloud, neutral hydrogen and helium atoms flow into the heliosphere. These neutrals interact gravitationally with the Sun and, for low-energy hydrogen, are affected significantly by radiation pressure and resonant charge exchange. Radiation pressure and charge exchange effects on hydrogen are significant enough that, for most of the solar cycle, low-energy (less than ∼150 eV) hydrogen atoms are excluded from the inner solar system (Bzowski 2008). In contrast, interstellar helium neutrals are much less affected and have ready access to the inner solar system.

Interstellar neutral helium has been observed in the inner solar system directly (Witte et al. 2004) and through indirect means, i.e., by pickup ion measurements (Möbius et al. 1985; Gloeckler & Geiss 1998) and EUV measurements (Vallerga et al. 2004). The properties of these neutrals are reasonably well understood. They appear as a relatively compact (∼few degrees wide) source arriving from $\lambda = 74\overset{\circ}{.}5$, $\beta = -5\overset{\circ}{.}5$ (i.e., very near the apex direction) with a speed of approximately 26 km s^{-1} (14.5 eV), a temperature of ∼6300 K, and a density of 1.5×10^{-2} cm^{-3} (Möbius et al. 2004). These parameters represent the unperturbed flow of neutrals into the heliosphere. Interstellar neutral hydrogen with nearly the same speed (i.e., with an energy of a few eV) has been inferred from a variety of measurements (e.g., Lallement et al. 1996; Gloeckler & Geiss 1998).

As interstellar helium neutrals approach the inner solar system, their trajectories are deflected by the Sun's gravity. Their velocities are comparable to the Earth's velocity around the Sun (29.5 km s^{-1}). Thus, in the Earth's frame of reference, their energy and apparent arrival direction change substantially over a year. From December 2–3 to June 4, interstellar helium neutrals are moving opposite the Earth's velocity vector. In the Earth's frame of reference, they have higher energy and a smaller apparent deflection angle than in the Sun's frame of reference. From June 4 to December 2–3, the opposite is true and, in the Earth's frame, helium neutrals have much lower energy and larger deflection angles. The angle deflections are largest around the anti-apex position of the Earth (i.e., the Earth's location around December 2–3). At this location, the neutrals appear to arrive from a direction almost 90° off the apex direction. This angle decreases until, after March 21, when the Earth is in the "upwind" direction (i.e., the apex–Sun–Earth angle is less than 90°), the neutrals appear to arrive from close to the apex direction.

In addition to the primary, low-energy, compact source of interstellar neutrals from the apex direction, other neutral sources both inside and outside the solar system have been suggested. One of these sources is at the outer edge of the solar system. The heliospheric termination shock and other outer boundaries produce neutral hydrogen over a wide range of energies and from essentially all directions in the sky. Models suggest that the neutral flux varies with the direction and that this variation depends on the details of the interaction of the heliosphere with the interstellar medium (Gruntman et al. 2001). For example, recent models of the neutral flux produce a broad (∼30°–45° wide) region of neutral hydrogen flux centered on the apex direction and extending over energies from several hundred eV to several keV (e.g., Heerikhuisen et al. 2007, 2008; Prested et al. 2008). Recent observations at lower energies (Galli et al. 2006; Wurz et al. 2008) are consistent with this extended heliospheric neutral source.

Besides this extended source, another, compact source was inferred from measurements from the *Imager for Magnetopause to Aurora Global Exploration* (*IMAGE*) Low-Energy Neutral Atom (LENA) imager. This secondary stream of neutrals was assumed to be ∼1 keV hydrogen originating from $\lambda \sim 104°$, $\beta \sim 0°$ (i.e., 30° off the apex direction; Collier et al. 2004; Wurz et al. 2004).

Previous studies (Collier et al. 2004; Wurz et al. 2004) used data from 2000 December through 2001 February to infer properties of the secondary stream. In particular, the neutral atom count rate, measured from 2000 December to the end of 2001 February, showed a distinct peak around 2001 January 10. If this count rate profile were due to interstellar neutral helium from the apex direction, then models predicted a peak count rate in the interstellar neutral helium-focusing cone around December 5–10. The peak in the count rate profile that occurred nearly 30 days later (around January 10) was interpreted as evidence for a second source of energetic (∼1 keV) hydrogen from ∼30° from the apex direction (i.e., 30 days after the predicted helium-focusing cone; Wurz et al.

2004). The hydrogen neutral energy was not measured, but it was inferred to be high because energetic hydrogen atoms are not adversely affected by radiation pressure and/or charge exchange as they approach the inner solar system.

This paper focuses on observations from the *IMAGE*/LENA imager obtained from later periods in the mission. Analysis of data from 2005 is presented. The results of the analysis are not consistent with a secondary stream from off the apex direction. Instead, the observations appear to be consistent with a mixture of two relatively compact sources from the apex direction. The first source is the familiar interstellar neutral helium and the second source appears to be energetic (>150 eV) hydrogen.

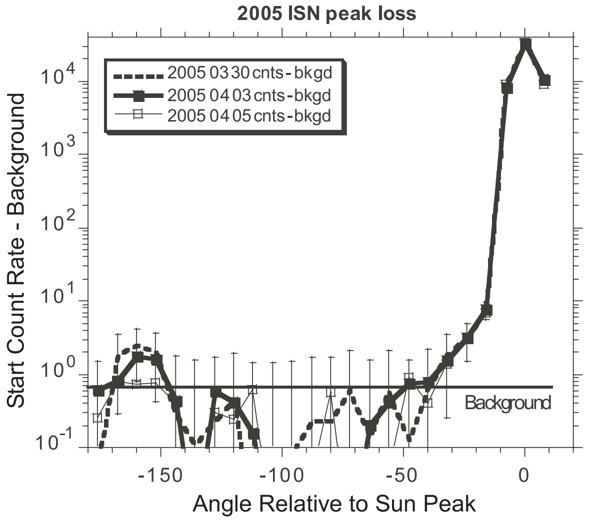

Figure 1. LENA 4 hr averaged count rate vs. spin angle for three different days around the time that the interstellar neutral signal was lost from the FOV of the imager. The peak at 0° is the Sun (primarily solar photon response) and the peak at about 160° is the interstellar neutral signal. From March 3 to March 5, the neutral signal decreases to background.

2. INSTRUMENTATION

Observations in this paper are from the *IMAGE*/LENA imager (Moore et al. 2000). This imager determined the neutral atom flux in a ~8° × ~90° field of view (FOV). The center of the FOV was oriented perpendicular to the *IMAGE* spacecraft spin axis. During a 2 minute spacecraft spin, the imager swept out a 360° × ~90° band in the sky. The *IMAGE* spacecraft was in a polar orbit around the Earth, the spacecraft spin axis was perpendicular to the orbit plane, and the orbit had a nominal right ascension of ascending node (RAAN) of 192° (at the time of launch). Thus, the imager swept out a band 360° × ~90° band in the sky that was tilted 23°.5 from the perpendicular to the ecliptic. Initially, the *IMAGE* apogee (8 Earth radii or R_E) was at high northern latitudes. This high-latitude apogee was nearly ideal for observing interstellar neutrals because the orbit was well outside the Earth's radiation belts (which create background in the imager).

The LENA imager was designed to detect magnetospheric neutrals with energies from 10 to 300 eV using conversion of neutrals to negative ions off a polycrystalline tungsten conversion surface. The imager was also sensitive to more energetic neutrals (e.g., hydrogen up to several keV) that created sputtered negative ions (Collier et al. 2004). The LENA imager used a double coincidence time-of-flight mass spectrometer to determine the negative ion mass. Because of sputtering and low double coincidence rates for the interstellar neutral signal, mass analysis is not used in this paper. The imager also divided the ~8° × ~90° FOV into 11 ~8° × ~7° pixels. However, determining the pixel location requires using double coincidence measurements. For the weak interstellar neutral signal, the double coincidence count rates were not high enough for this determination. For this paper, single rates (in particular, the "start" singles) are used.

3. 2005 OBSERVATIONS

Interstellar neutrals were observed from early December through at least late February for three of the five years of *IMAGE* spacecraft operations. Observations from 2000 December through 2001 February (when the *IMAGE* apogee was at high northern latitudes) were discussed in the introduction. Unfortunately, after 2001 February, the interstellar neutral arrival direction coincided with the direction to the Earth. Significant background from neutrals in the Earth's magnetosphere and ultraviolet light from the Earth did not allow observations of interstellar neutrals after February. From 2001 December, through 2002 February, (the second interstellar neutral observing interval), a similar neutral signal, with a peak count rate on 2002 January 10 was observed. Again, interference from the Earth did not permit observations after 2002 February. From 2002 December through the beginning of 2004, the spacecraft apogee was near the equatorial plane and background from energetic particles in the radiation belts inhibited interstellar neutral observations. However, from 2004 December through 2005, the apogee was at high (southern) latitudes and, for the springtime part of this interval, the Earth did not interfere with interstellar neutral observations.

Figure 1 shows observations from the LENA imager on 2005 March 30, April 3 and 5. Plotted are the LENA start signal count rate minus the background count rate as a function of spin angle (with zero spin angle toward the Sun). These data represent the count rates in each 8° × 80° angular spin bin averaged over 4 hr while the spacecraft was near apogee. The interstellar neutral signal is apparent at about 160° from the Sun signal, and its angular extent is similar to that of the Sun signal (that is, it is spread over about three 8° wide spin bins). Although the angular extent of the Sun at the Earth orbit is 0°.5, solar photons generate significant counts in adjacent spin bins through internal scattering in the imager. Comparing the angular extent of the Sun and interstellar neutral signals, it is concluded that, in the direction approximately perpendicular to the ecliptic, the interstellar neutral signal cannot subtend an angle of more than a few degrees.

The interstellar neutral signal is above the background from March 30 to April 3, but it is below the background on April 5. Simulations (described below) indicate that between April 3 and 5, the interstellar neutral helium flow moves outside the FOV of the imager. The signal cutoff by the edge of the FOV occurs over one day and is similar in duration to the signal cutoff observed when the Sun moves out of the FOV. (Although not shown in Figure 1, the signal does not return above the background later). Thus, in the ecliptic, the angular extent of the neutral signal must be small, of the order of 1°–2°. Combining this result with the spin angle information (out of the ecliptic extent of the signal), it is concluded that the neutral source is compact, having an angular extent of at most a few degrees in the ecliptic, and perpendicular to the ecliptic.

Figure 2 shows a schematic of the LENA FOV in the ecliptic plane for different times of the year. In 2005 January, a peak in

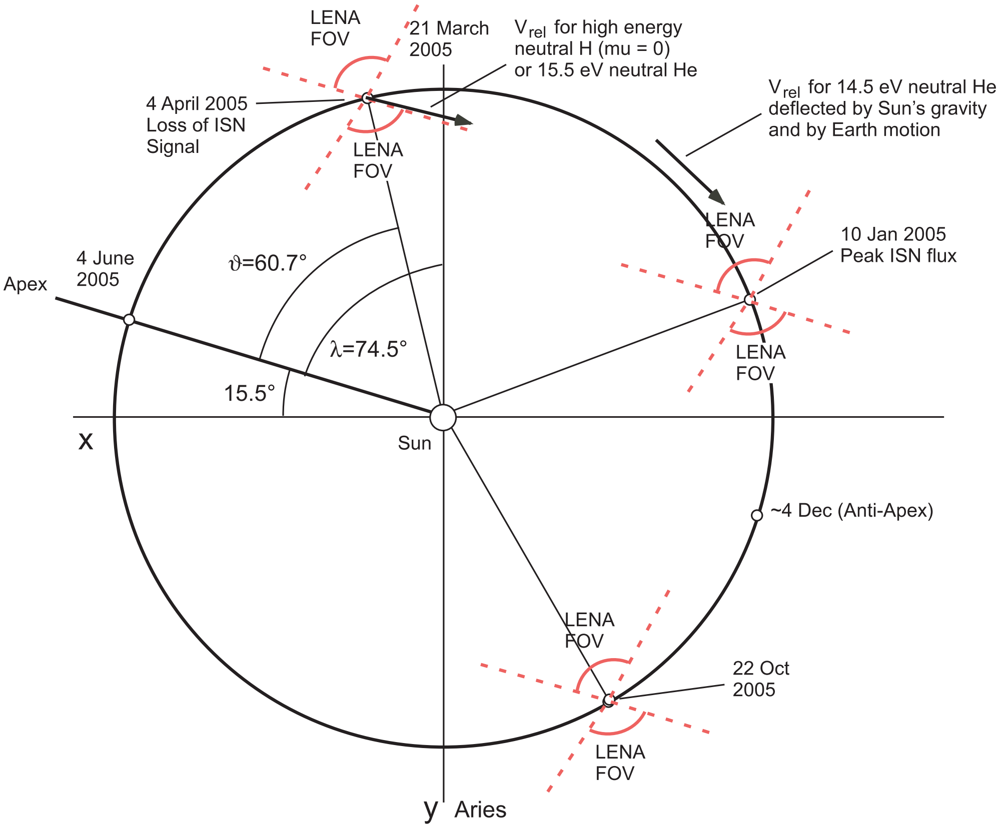

Figure 2. Schematic of the Earth's orbit and the LENA imager FOV in the ecliptic plane. The imager sweeps out a band that is ∼90° × 360° in one spacecraft spin. On 2005 January 10, the peak in the interstellar neutral flux was observed. From the orientation of the FOV, this peak is consistent with either Helium neutrals that are highly deflected by the Sun's gravity (and the Earth's velocity vector in the Earth frame of reference) or neutrals that have little deflection from the apex direction. On April 4, when the neutral signal was lost, the edge of the FOV provides an accurate measure of the flow direction of the fairly compact neutral flux. This direction is consistent with either high energy hydrogen or 15.5 eV helium (or some combination of both species) from the apex direction.

the interstellar neutral signal was observed similar to the peak observed in 2001 January, (not shown). At this time of year, the LENA FOV was centered almost along the Earth's velocity vector, pointing away from the apex direction at an angle of about 45°. Thus, considering a neutral flux that is near the center of the FOV of the imager, the peak interstellar neutral signal is consistent with a source of low-energy interstellar neutrals (like the low-energy helium source) that are deflected considerably. This deflection is due to the Sun's gravity and also due to the addition of the Earth's velocity vector to the total velocity measured in the Earth's frame of reference. However, Figure 2 shows that one edge of the LENA FOV is also directed within a few degrees of the apex direction. Thus, a second possible interpretation is that the peak flux signal observed in 2005 January is caused by higher energy interstellar neutrals (e.g., >150 eV hydrogen) that are deflected only by a small angle (i.e., a few degrees) from near the apex direction.

As discussed above, the interstellar neutral signal was cutoff by the edge of the LENA FOV on 2005 April 4, when the Earth was in the upwind direction (Figure 2). On that day, the edge of the FOV serves as an accurate indication of the direction of motion of the interstellar neutrals at that location in the Earth's orbit. In the upwind direction, the interstellar neutrals are not deflected significantly by the Sun's gravity. Because the Earth's velocity vector is directed almost opposite to the neutral flow direction, the apparent arrival direction of the neutral flow in the Earth's frame must be close to the point of origin of the neutrals. As is evident in Figure 2, this direction is within a few degrees of the apex direction. Thus, the cutoff in the interstellar neutral signal on April 4 indicates that these neutrals are a rather compact source (at most a 1°–2° wide in the sky) of either helium or energetic (>150 eV) hydrogen (or a mixture of both) originating from the apex direction. These results are not consistent with a source that is 30° off the apex direction. Modeling (not shown here) indicates that energetic neutral flow from 30° off the apex direction would exit the LENA FOV approximately 30 days earlier.

The loss of the ISN signal on April 4, combined with earlier *IMAGE*/LENA observations, is inconsistent with detection of a background X-ray source. First, X-rays are not known to produce significant negative ions on the imager's tungsten conversion surface. Second, even if there were a mechanism for producing negative ions, the cutoff of the signal is inconsistent with a source fixed in the sky. There are several strong and variable X-ray sources near the ecliptic plane (e.g., Wood et al. 1984; Hsieh et al. 2009). Notably, Scorpio X-1 is nearly in the ecliptic and at $\lambda \sim 66°$ and there are a number of sources at $\lambda > 74°$ in the general direction of the galactic center. However, these X-ray sources would need very unusual properties to be consistent with the *IMAGE*/LENA observations. In particular, since Scorpio X-1 is always in the *IMAGE*/LENA FOV, its flux would need to increase above detection threshold in 2000 December, December 2001, and December 2004 and then decrease below detection threshold in 2001 February–March, 2002 February–March, and 2004 April. Furthermore, fluxes would need to remain below detection threshold for the remainder of 2001, 2002, and most of 2005. X-ray sources near the galactic center are mostly outside of the *IMAGE*/LENA

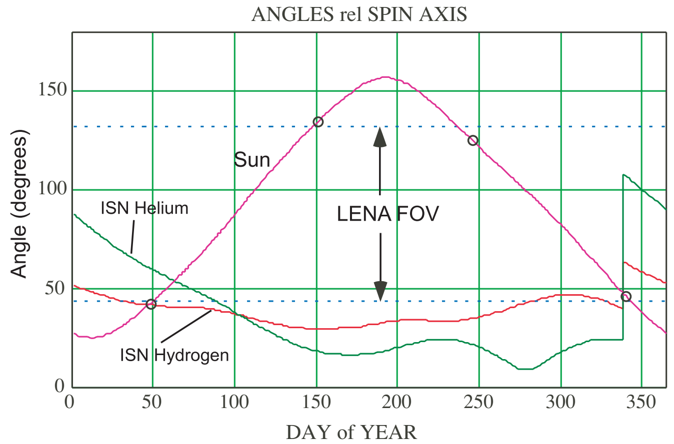

Figure 3. Predicted angles relative to the LENA spin axis for the Sun (purple), neutral helium (green), and neutral hydrogen with $E > 150$ eV (red) as a function of day of the year starting 2004 December and ending 2005 November. The Sun is in the LENA FOV (between the dashed lines) from day 50 to day 150 and from day 249 to day 345. Actual Sun entry and exit points are shown by the circles on the purple line. Interstellar neutrals snap into the FOV at the anti-apex location (~December 4) and remain in the FOV until about day 95 (for helium) and day 50 (for hydrogen). Around day 300, there is a unique period where the energetic neutral hydrogen is in the FOV but the neutral helium is not.

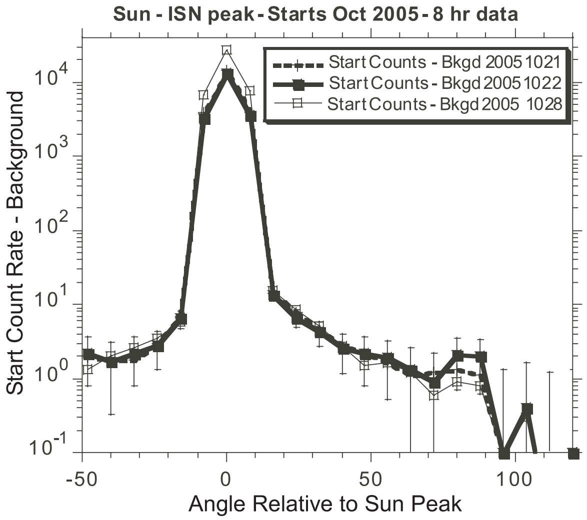

Figure 4. LENA average count rate as a function of spin angle relative to the Sun for three days in 2005 October. The Sun peak occurs at 0° and a peak above background occurs about 80° from the Sun. Based on the prediction in Figure 3, this peak is likely a compact source of energetic (>150 eV) neutral hydrogen coming from the apex direction.

FOV, so they are also inconsistent with the *IMAGE*/LENA observations.

Additional *IMAGE*/LENA observations in 2005 help distinguish between interstellar neutral helium and energetic hydrogen. Figure 3 shows a plot of the predicted angle between the spacecraft spin axis and the Sun direction (purple), interstellar helium (green), and interstellar energetic (150 eV) hydrogen (red) vectors. The x-axis is time of year in 2005 from January through December. The LENA FOV is between the horizontal dashed lines (angles between ~40° and ~130°). The angle between the Sun and the spacecraft spin axis (in purple) has a fairly uniform, cyclic variation through the year. The Sun is predicted to be in the FOV from day 50 to about day 150 and from day 240 to about day 340. The observed entries and exits of the Sun in the LENA FOV are shown by the circles on the purple curve. Predictions and observations agree reasonably well (to within a few degrees).

The predicted angle between the interstellar neutral helium and the spin axis (green curve) has a more complicated variation over the year. The angle was determined by first assuming that interstellar helium, upon entry into the solar system, was propagating at 26 km s^{-1}, had zero temperature, and was arriving from $\lambda = 74\overset{\circ}{.}5$, $\beta = -5\overset{\circ}{.}5$ (i.e., most of the properties discussed in the introduction, excluding temperature effects). Then, effects of the Sun's gravity and the addition of the Earth's velocity vector were accounted for at each point along the Earth's orbit (radiation pressure was assumed to be negligible for helium). Starting on day 337 (December 3), the neutral helium snaps into the LENA FOV. This rapid change in the angle occurs at the anti-apex location. At this location, the neutral flow component along the tangent to the Earth's orbit changes from parallel to antiparallel to the Earth's velocity vector. This rapid change in the angle illustrates the strong influence the Earth's motion has on observing low-energy interstellar neutrals in the Earth frame of reference.

After December 3, the angle between the helium velocity and the spacecraft spin axis slowly decreases. At about day 93 (April 3), the interstellar helium moves outside the LENA FOV. After that date, interstellar helium remains well outside of the LENA FOV for most of the year, until December 3, when the pattern is repeated.

The red curve in Figure 3 shows the angle between the spacecraft spin axis and an interstellar neutral hydrogen flux originating from the apex direction with an initial energy of 150 eV. The profile is similar to that of the helium in that it snaps into the LENA FOV on December 3 and slowly moves out of the FOV, exiting around day 45 (February 14) but staying close to the FOV up to about day 93 (April 3). Given the uncertainty in the predicted angles (approximately ±3°), the hydrogen could remain in the FOV up to day 93. Although the helium and 150 eV hydrogen exit the LENA FOV about the same time, there are differences between the helium and hydrogen angles attributable to the different energies of the species. Because the energy of the hydrogen is much higher, the Earth's velocity vector has less effect on the motion of the hydrogen neutrals in the Earth's reference frame.

The profiles of both the helium and 150 eV hydrogen angles also have significant variations that are associated with changes in the orientation of the spacecraft spin axis. In 2005, five years after the launch of the *IMAGE*, torques on the spinning spacecraft caused the spin axis to precess at several different rates. The largest precession period was several months with an amplitude of almost 10° (M. Tapley 2008, private communication). Figure 3 shows that during one of these precessions, centered around day 305 (November 1), there was a unique occurrence where 150 eV hydrogen is predicted to be in the LENA FOV, while lower energy helium is predicted to be well outside the FOV.

Figure 4 shows LENA observations from October 21 through 2005 October 28 (day 294 through day 301). Plotted are the start counts (averaged over eight hours of data near apogee) versus spin angle relative to the Sun direction. The format is similar to that in Figure 1. There is a small peak in the count rate about 80° from the Sun direction. This weak signal extends over two spin bins, indicating that, at least perpendicular to the ecliptic plane, the source is compact (probably no more than a few degrees in the sky).

The peak in Figure 4 is observed from about day 294 to day 300. That is, it is observed near the time predicted in Figure 3 where the energetic neutral hydrogen is in the LENA FOV but the lower energy neutral helium is not in the FOV. For other years, the precession of the spin axis was not large enough to bring the 150 eV hydrogen neutrals into the LENA FOV and no signal was observed around day 300. These observations and predictions indicate that, in addition to the helium interstellar neutrals, there is a second, compact source of interstellar neutral hydrogen in the apex direction.

4. DISCUSSION

Some neutral atoms from the apex direction enter the inner solar system. Neutral helium has been observed in the inner solar system while low-energy neutral hydrogen is excluded due to charge exchange and radiation pressure effects. The *IMAGE*/LENA imager observed interstellar neutrals from December through February for three of the five years of spacecraft operations (for two of the years, the spacecraft was in the radiation belts and high background made these observations difficult).

In addition to these sources, observations in the inner solar system have been interpreted as evidence for other neutral sources. These include a fairly broad source of heliospheric neutrals centered on the apex direction (Galli et al. 2006; Wurz et al. 2008). In addition, the count rate profiles from the *IMAGE*/LENA imager were interpreted as evidence for a secondary stream of neutrals from 30° off the apex direction (Collier et al. 2004; Wurz et al. 2004). The count rate profile showed a peak around 2001 January 10, 30 days after the expected peak for interstellar neutrals in the focusing cone (Wurz et al. 2004).

In this paper, the cutoff of the interstellar neutral signal by the edge of the LENA FOV, observed in the upwind direction on 2005 April 4 (see Figure 1), was used to determine the direction of the propagation of interstellar neutrals. Figures 2 and 3 show that this cutoff is consistent with sources arriving from the apex direction. The slightly deflected arrival of neutrals in the imager on 2005 April 4 is consistent with lower energy neutral helium and higher energy (>150 eV) neutral hydrogen, both from near the apex direction. Sources 30° off the apex direction would be cutoff by the edge of the LENA FOV approximately one month earlier.

Later in 2005, precession of the spacecraft spin axis created a unique opportunity to distinguish between the two possible neutral sources from the apex direction. Observations of neutrals in late October (Figure 4) are consistent with a higher energy neutral hydrogen source from the apex direction.

The observations are not consistent with a fixed, but variable X-ray source. The brightest X-ray source near the ecliptic plane, Scorpio X-1, is always in the *IMAGE*/LENA FOV. Therefore, to be consistent with the *IMAGE*/LENA observations, the X-ray source flux would need to be seasonally dependent, increasing in December and decreasing in February, March, or April. Other X-ray sources are weaker and most are always outside of the *IMAGE*/LENA FOV.

These observations indicate that, in addition to the well-known, compact, low-energy interstellar neutral hydrogen and helium, a third higher energy population enters the solar system from near the apex direction. The energy of this population is not measured directly. However, it can be inferred to of the order of 1 to a few hundred eV because, to be observed in late 2005 October, these neutrals must be essentially unaffected by the Earth's velocity vector. The value of 150 eV was chosen as the lowest energy of this population because, below that energy, charge exchange and radiation pressure begin to exclude these neutrals from the inner solar system (Wood et al. 2007). The upper energy is somewhat hard to determine. An upper bound of the energy is estimated from the following. At energies ~1 keV, the deflection from the apex direction decreases to a point where the neutrals are in the LENA FOV for a longer period of time around day 300. In contrast, neutrals were observed in the FOV for only a few days (Figure 4), suggesting that the neutral energy was <1 keV. Also, the LENA imager was designed to detect neutrals with energies from 10 eV to 300 eV. Thus, the imager is more sensitive to direct detection of a lower energy population (below 300 eV), although a higher energy population may be also present. The higher energy population would be largely outside the *IMAGE*/LENA FOV because it would be essentially undeflected from the apex direction.

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