# Proton Velocity Distributions in the Inner Heliosheath Derived from Energetic Hydrogen Atoms Measured with Cassini and IBEX

G. Gloeckler and L. A. Fisk

[1]*Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan*
*2455 Hayward St., Ann Arbor, MI 48109-2143, USA, e-mail gglo@umich.edu*

**Abstract** Recent definitive observations of Energetic Hydrogen Atoms (EHAs) with IBEX [1] and *Cassini* [2] allow us to deduce the proton velocity distribution in the region of EHA production, assumed to be the inner heliosheath (HS). We consider four separate components, (a) the solar wind, (b) heliosheath pickup protons, (c) heliosphere pickup protons and (d) the -5 power law suprathermal tails that combine to produce the composite IBEX-LO, IBEX-HI and Cassini INCA EHA spectrum. We find that (1) the total particle pressure is $(1.2 \pm 0.15)\bullet 10^{-12}$ dyne/cm$^2$, remaining constant throughout the HS, although contributions from individual components vary with heliocentric distance from the termination shock (TS), (2) the heliocentric distance of the heliopause (HP) in the *Voyager-1* direction, $R_{HS}$, is $148^{+10}_{-6}$ AU using the interstellar neutral H density at the TS of $(0.1\pm0.015)$ cm$^{-3}$, (3) in order to explain the lowest energy published IBEX ENA flux the amplitude of compressional turbulence starts to increase at $\sim(R_{HS} - 10)$ AU, reaching $(155\pm5)$ km/s, and (4) near the HP, the –5 tail pressure rises, while the heliosphere pickup proton pressure falls. The Fisk and Gloeckler model for ACR acceleration near the heliopause [3] requires (3) and (4).

**Keywords:** Heliosphere, Heliosheath, Energetic Neutral Atoms

**PACS:** 96.50Pw, 96.50.Fm, 96.50Ek, 94.05.Ya

## INTRODUCTION

The most dominant sources of energetic neutral atoms (ENAs) in the inner heliosphere are the ENAs created in the inner heliosheath (HS) by charge exchange of ions with the ambient neutral gas. Recent measurements of the EHA differential intensities in the *Voyager-1* (*V-1*) direction by IBEX [1] and *Cassin*-INCA [2,4] allow us to deduce the velocity distributions (or the differential intensities) of protons in the HS in the critical energy range not measured with *Voyagers* and thus obtain fundamental properties of the HS plasma parameters, and constrain the value of the thickness of the heliosheath in the *V-1* direction. Downstream of the termination shock (TS), the dominant particle population consists of four components. The HS solar wind, pickup ions created in the heliosphere and heated by the termination shock (we will refer to these pickup ions as 'heliosphere' pickup ions), the –5 suprathermal tails with a rollover at around several MeV and the modulated anomalous cosmic rays (ACRs) that roll over at ~200 MeV. Deeper into the HS another plasma component becomes important, namely pickup ions created in the HS (we call these heliosheath pickup ions) by charge exchange of the solar wind with the same neutral gas that interacts with the HS plasma to create the ENAs. *Voyagers* measure all of these components (including galactic cosmic rays not considered here) except the heliosphere pickup ions that carry most of the plasma pressure and the HS pickup ions [6-8]. Ordinarily, ENAs produced from the HS solar wind and HS pickup ions would not have sufficient energy to flow back towards the sun. However, if there were a large random component, $\delta u$ added to the average radial solar wind flow speed, than ENAs from these two low-energy plasma components would be observed deep inside the heliosphere. We will demonstrate that the IBEX EHA measurements indeed require a large $\delta u$ component that increases with distance and becomes comparable to the solar wind speed near the heliopause. We will also show that the simplest explanation of the IBEX and Cassini higher energy EHA observations and *Voyager* measurements of suprathermal tails (sometimes called the TSP population) and modulated ACRs is to assume a radial dependence of the distribution functions of heliosphere pickup ions and of suprathermal tails.

## OBSERVATIONS AND MODEL ASSUMPTIONS

Observations of EHAs coming from the *V-1* directions and of HS particles (protons) measured *in situ* by *Voyagers* relevant to the topic discussed here are shown in Fig. 1. The EHA differential intensities [1,2,4] are in the energy range from ~ 1 to ~50 keV, while the *in situ V-1* proton spectrum at ~110 AU is measured by LECP [2,4] above ~40 keV. At the same time The LECP *V-2* spectrum is observed to be identical (within uncertainties) even though the two spacecraft are over 100 AU apart and at different heliocentric distances ($r$) from the termination shock [2,4]. There are no measurements of particles below ~40 keV on *V-1* and from ~0.2 to 35 keV from *V-2*. Thus, the EHA spectrum nicely bridges the gap in energies not measure *in situ* and allows us to reconstruct the HS proton spectrum from ~0.1 to ~100 keV as a function of heliocentric distance $r$. The averages HS plasma parameters measured by V-2 [6] and the HS magnetic field strength observed by V-1 [9] are given in column 2 of Table 1.

Table 1. Heliosheath measured and model parameters

| Physical Quantity | Value | Component | Parameter† | | | | |
|---|---|---|---|---|---|---|---|
| | | | $\kappa$ | $w_0$ | $s_1$ | $s_2$ | $\eta$ |
| SW speed (km/s) | 145 | Solar Wind | ***50*** | ***0*** | ***0.25*** | — | — |
| SW density (cm$^{-3}$) | 0.00133 | Sheath pickup $H^+$ | ***50*** | ***1*** | 0.68 | — | — |
| SW thermal speed (km/s) | 36 | Sphere pickup $H^+$ | 4.65 | 12.42 | 20 | 1.4 | 2.5 |
| Magnetic Field strength (nT) | 0.14 | –5 Tail $H^+$ | ***5*** | 250 | 2 | 20 | 7.5 |

†Values in bold italic were fixed. All other values in columns 4-7 were adjusted to fit the EHA spectrum

We make the following simplifying assumptions in our present model. (I) The observed EHAs in the *V-1* direction come predominantly from the inner heliosheath. (II) Steady-state conditions apply and adiabatic cooling is negligible. (III) The radial component of the solar wind speed, $V_r(r)$, decreases with $r$ as observed by LECP [10] and approaches zero at the heliopause. (IV) There is a turbulent component to the radial speed, $\delta u_r(r)$, whose amplitude increases with $r$ beyond $r_C$ (where $r_C$ is about 10 AU upstream of the heliopause), becoming comparable to the solar wind speed. Only by invoking (IV) can we explain the IBEX 0.16 keV EHA differential intensity.

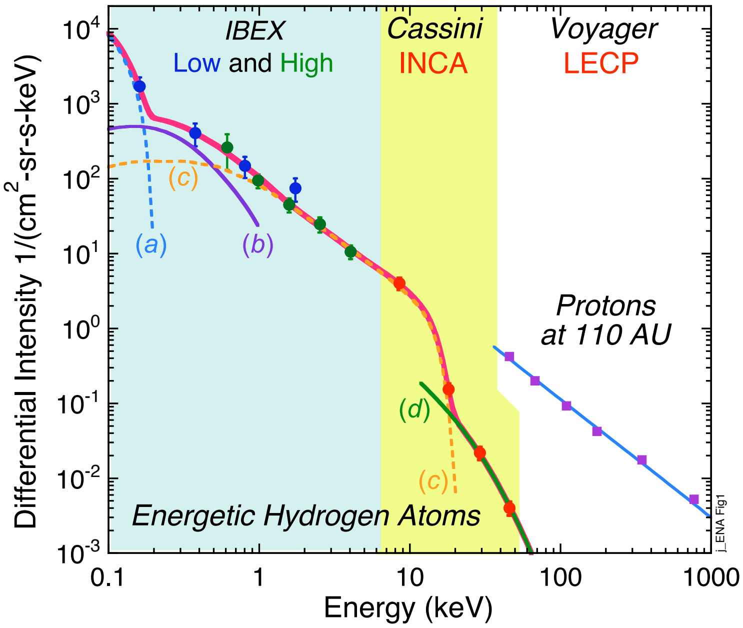


**Figure 1**. Differential intensity of protons in the heliosheath at 110 AU measured with LECP on Voyager-1 [2,4] and energetic hydrogen atoms in the *V-1* direction observed with IBEX [1] (corrected for extinction [5]) and Cassini [2]. The Cassini spectrum shown is taken from [4]. Four model EHA spectra are computed (see text) from four HS proton populations: (*a*) HS solar wind, (*b*) heliosheath pickup $H^+$ (*c*) heliosphere pickup $H^+$, and (*c*) –1.5 power law tail protons. The sum of all four model spectra (bold red curve) matches the entire observed EHA spectrum well within the primarily systematic errors of the measurements.

## METHODOLOGY

The energetic hydrogen atoms (EHAs) measured by IBEX-LO, IBEX-HI and Cassini INCA shown in Fig. 1 are created from energetic protons in the heliosheath by charge exchange with the interstellar hydrogen gas that permeates the HS. The governing equation for the production of EHAs is

$$j_{\mathrm{EHA}}(E_{\mathrm{EHA}}) = \int_{\mathrm{TS}}^{\mathrm{HP}} j_{\mathrm{P}}(E_{\mathrm{P}}, r)\,\sigma(E_{\mathrm{EHA}})\, N(r)\mathrm{d}r, \tag{1}$$

where $j_{\mathrm{EHA}}(E_{\mathrm{EHA}})$ is the differential intensity of energetic hydrogen atoms at energy $E_{\mathrm{EHA}} = (2.28 \bullet 10^{-8} v_{\mathrm{EHA}})^2$, $j_{\mathrm{P}}(E_{\mathrm{P}}, r)$ is the differential intensity of heliosheath protons at energy $E_{\mathrm{P}} = (2.28 \bullet 10^{-8} v_{\mathrm{P}})^2$, $j_{\mathrm{P}}(E_{\mathrm{P}}, r) = 1.83\, E_{\mathrm{P}} f_{\mathrm{P}}(E_{\mathrm{P}}, r)$, $f_{\mathrm{P}}(E_{\mathrm{ION}}, r)$ is the phase space density of HS protons at energy $E_{\mathrm{P}}$ and distance $r$, and $\sigma(E_{\mathrm{EHA}})$ is the charge exchange cross section at energy $E_{\mathrm{EHA}}$. We neglect the small speed of the interstellar hydrogen gas and use the Lindsay and Stebbings [11] expression for the $H^+$ on H charge exchange cross section. The density of interstellar hydrogen, $N(r)$, is calculated to increase slightly with $r$ and we take its value at the termination shock ($r_{\mathrm{TS}}$= 90 AU) to be (0.10±0.015) $\mathrm{cm}^{-3}$. The heliocentric distance of the heliopause, $R_{\mathrm{HP}}$, is a free parameter. Its value in the *V-1* direction will be constrained by the published average EHAs differential intensity spectrum.

The speed of the EHA, $v_{\mathrm{EHA}}$, that is observed in the inner heliosphere is related to the speed in the solar wind frame of the proton from which it was produced, $v_{\mathrm{P}}$, by

$$v_{\mathrm{EHA}} = \sqrt{v_{\mathrm{P}}^2 + V_{\mathrm{r}}(r)^2 - V_{\mathrm{SW}}(r)^2} - u_{\mathrm{r}}(r), \tag{2}$$

where $u_{\mathrm{r}}(r) = V_{\mathrm{r}}(r) + \delta u_{\mathrm{r}}(r)$ and $V_{\mathrm{SW}}(r)$ is the bulk speed of the HS solar wind which increases slowly with $r$, $V_{\mathrm{SW}}(r) = 145[0.15\{g(r) - 1\} + 1]$, and the function $g(r)$ is shown in Fig. 2a. The radial component of the turbulent speed has the form $\delta u_{\mathrm{r}}(r) = 30[\alpha\{g(r) - 1\} + 1]\cos(\pi[r - 90])$, with $\alpha$ a free parameter adjusted to best fit the EHA spectrum at 160 eV.

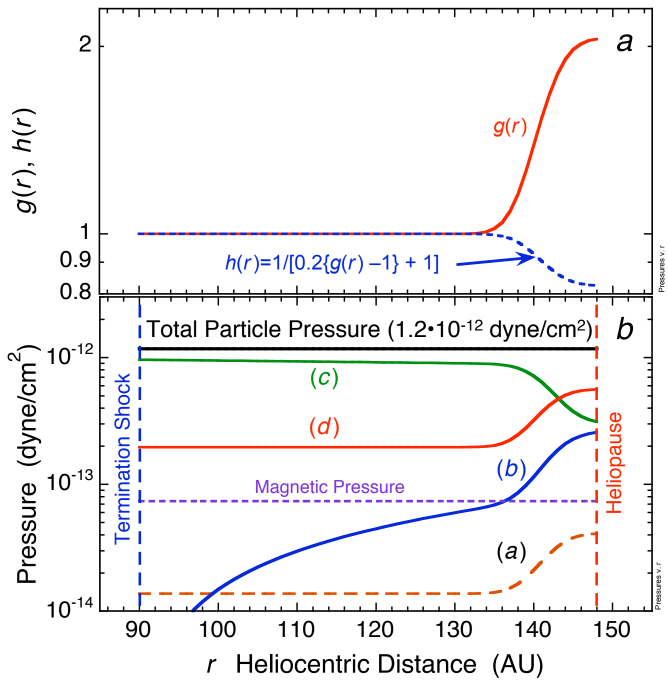


**Figure 2**. Dependence on heliocentric distance of (*a*) $g(r)$ and $h(r)$ (see text), and (*b*) pressure of four proton populations (see text) in the HS, and magnetic pressure (assumed to be constant throughout the HS). For $r <$ ~136 AU heliosphere pickup protons (*c*) provide ~80% of the total pressure, while near the heliopause the –1.5 tail-ACR protons (*d*) carry most of the pressure (48%) with the heliosphere pickup ions (*c*) contributing ~27% of the total. The solar wind (*a*) and magnetic pressure are small, only ~1% to 4% and ~6%, respectively, of the total. The pressure of component (*b*) increase with *r* from zero at the TS to ~27% of the total particle pressure near the termination shock.

We consider four proton populations from which EHAs are produced, each dominating the EHA spectrum at progressively increasing energies: (*a*) HS solar wind, (*b*) HS pickup protons (pickup $H^+$ created in the HS), (*c*) heliosphere pickup protons (pickup $H^+$ created in the heliosphere, convected towards the termination shock where they are heated by the shock according to Rankine-Hugoniot conditions, and then further convected radially toward the heliopause, and (*d*) the suprathermal tail protons whose differential intensity is observed to be a power law with spectral index –1.5 throughout most of the HS, especially away from the TS. For each population we choose a simple spectral shape for the phase space density (assumed to be isotropic in the HS solar wind frame) *versus* $w$, the proton speed, $v_P$, divided by $V_{SW}$. For populations (*a*) and (*b*) we use a kappa (maxwellian when $\kappa > 20$) function

$$f_{a,b}(w,r) = f_0(r)(1 + \kappa^{-1}[w - w_0]^2 s_1^{-2})^{-\kappa}, \tag{3}$$

with values of the parameters $\kappa$, $w_0$ and $s_1$ given in rows 2 and 3 of columns 4-8, respectively of Table 1. For populations (*c*) and (*d*) we use

$$f_{c,d}(w,r) = f_0(r) w^{-\kappa} \exp(-[w/\{w_0\rho(r)\}]^{-s_1}) \exp(-[\eta/w]^{-s_2}), \tag{4}$$

with values of the parameters $\kappa$, $w_0$, $s_1$, $s_2$ and $\eta$ and given in rows 4 and 5 of columns 4-8, respectively of Table 1.

## RESULTS

The model EHA differential intensities for HS proton populations (*a*) and (*b*) are computed using eqs. (1), (2) and (3) with parameter values listed in Table 1. For (*a*) $f_0(r)$ is a constant $f_0$ whose value we compute by setting the phase space integral of $f_a(w,r)$ equal to the HS solar wind density, $n_{SW} = 0.0012\ \text{cm}^{-3}$ [6]. For (*b*) $f_0(r)$ is computed such that the integral of $f_b(w,r)$ over phase space equals $n_{HS}(r)$, the density of heliosheath pickup protons at distance $r$ that is readily computed to be

$$n_{HS}(r) = n_{SW}\sigma_{SW}V_{SW}\int_{TS}^{r} N(r)v_r(r)^{-1}\mathrm{d}r, \tag{5}$$

where $\sigma_{SW}$= 2.8•10$^{-15}$ cm$^2$ is the charge exchange cross section at the solar wind speed, $N(r)$ is the slowly increasing (with increasing $r$) interstellar H density and $v_r(r)$ = 0.7•$|V_r(r) + \delta u_r(r)|$. Solar wind and heliosheath pickup protons would produce few EHAs without a sizeable turbulent velocity component $\delta u_r(r)$. We iteratively adjust $\alpha$, and thus the amplitude of $\delta u_r(r)$, as well as $R_{HP}$, until the model EHA differential intensity spectra (*a*) and (*b*) shown in Fig. 1 match the IBEX observations. With spectrum (*a*) most sensitive to $\delta u_r(r)$ and (*b*) most sensitive to $R_{HP}$ the best values for $R_{HP}$ is $148^{+10}_{-6}$ AU, where the upper and lower limits are for values of the interstellar neutral hydrogen density of 0.085 cm$^{-3}$ and 0.115 cm$^{-3}$, respectively. The best value for $\alpha$ is 3.95±0.15, which corresponds to an amplitude for $\delta u_r(r)$ at $r$ =148 AU of (155 ± 5) km/s, compared to the observed value of ~30 km/s near the TS [6]. The relevant parameter values given in Table 1 provided the best spectral shape match to the lower energy EHA observations.

The model EHA differential intensities for HS proton populations (*c*) and (*d*) are computed using eqs. (1), (2) and (4) with parameter values listed in Table 1, $R_{HP}$ held at 148 AU and $\delta u_r(r) = 30[3.95\{g(r) - 1\}+1]\cos(\pi[r - 90])$. For population (*d*) we used the proton spectrum measured by LECP on *V-1* (see Fig. 1). However, it was necessary to introduce a radial dependence in $f_0(r)$ in eq. (4). With $f_0(r)$ = 1.4•10$^4$$g(r)$ for (*d*) and relevant parameter values from Table 1 we obtained the best fit to both the *in situ* tail spectrum measured at 110 AU [2] and the Cassini high energy EHA differential spectrum (model curve (*d*) in Fig. 1). For completeness, we also introduced a dependence in the rollover e-folding speed with heliocentric distance r, $\rho(r) = [2g(r) - 1] + 1$. This was done to be consistent with *Voyager* ACRs measurements [7,8]. We note that ENAs provide no information on the rollover speed because very few are created and none are currently measured in this high-energy range.

We know least about population (*c*), the heliosphere pickup ions in the HS. This ion population, which carries most of the particle pressure [12,6] is not measured *in situ* by *Voyagers*, nor will it be observed *in situ* in the foreseeable future. However, with observations in the inner heliosphere [e.g.13] and modeling we can obtain reasonable estimates of their density, $n_C$ = (6 ± 3)•10$^{-4}$ cm$^{-3}$ and pressure, $p_C$ = (1.0 ± 0.5)•10$^{-12}$ dyne/cm$^2$, as well as their approximate spectral shapes just downstream of the TS. Using eq. (4) for the spectrum of (*c*) with relevant parameter values given in Table 1, $R_{HP}$ = 148 AU and $\delta u_r(r) = 30[3.95\{g(r) - 1\}+1]\cos(\pi[r - 90])$, we find it necessary to introduce a radial dependence on the rollover e-folding energy, $\rho(r) = [2\{h(r) - 1\} + 1]^{-1}$ with $h(r) = [0.2\{g(r) - 1\} + 1]^{-1}$ (see Fig. 2a) in order to fit the EHA spectrum in the steep rollover region of the spectrum just below onset of the tail. The constant value of $f_0(r)$ is computed by requiring that the phase space integral of $f_C(w,r)$ equals 6•10$^{-4}$ cm$^{-3}$, the best fit value of the density of heliosphere pickup protons just downstream of the TS at 90 AU, introducing a slight decrease in the density with $r$ to keep the total pressure constant.

The sum of the best model spectra of all four populations (bold red curve in Fig. 1) is an excellent fit to the entire currently measured average EHA spectrum. The pressure of each population *versus r* is shown in Fig. 2b along with the magnetic pressure [9]. Fig. 3 shows the HS differential intensity at 115 AU and near the heliopause.

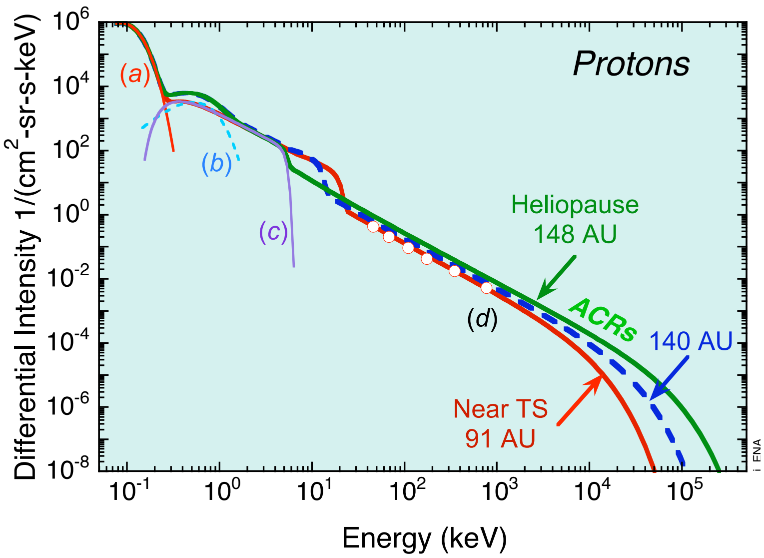


**Figure 3**. Model differential intensities for four heliosheath proton populations as would be measured with a large field-of-view particle detector in the heliosheath near the termination shock at ~91 AU (red curve), in the transition region at ~140 AU (dashed blue curve) and near the heliopause at ~148 AU (green curve): Populations (*a*), (*b*), (*c*) and (*d*) are described in the text. Open circles are LECP data [2,4] Modulated ACRs and GCRs are not shown. Populations (*b*) and (*c*) are not measured by *Voyagers*.

## CONCLUSIONS AND PREDICTIONS

Based on current knowledge of physical properties of the heliosheath from *in situ* measurements by *Voyagers* and reasonable assumptions we constructed model EHA differential spectra for four HS proton populations. By matching the model spectrum of each component to the measured EHA differential intensity in the *V-1* direction we obtained the total HS model proton spectrum as a function heliocentric distance. We constrained the heliopause heliocentric radial distance in the *V-1* direction to be between 142 AU and 158 AU, consistent with the value of Opher et al. [14]. We find the total particle (proton) pressure to be $(1.2 \pm 0.15) \bullet 10^{-12}$ dyne/cm$^2$ throughout the HS. We predict significant changes in several properties of the HS and proton spectra that the *Voyagers* should begin to observe in the transition region beyond about 140 AU: (i) the amplitude of the turbulent (on a scale of ~ 1 AU) speed should start to increase from its current value of ~30 km/s, to reach (155±5) km/s near the heliopause, (ii) the density of the –1.5 suprathermal tail should approximately double, and (iii) the –1.5 power law proton spectrum (i.e. the ACR spectrum at its source) should be observed up to ~100 MeV at which energy it will begin to roll over. It remains for *Voyagers* to tell us over the next 5 to 10 years how true these predictions are.

## ACKNOWLEDGEMENTS

This research benefited greatly from discussions that were held at the meetings of the International Team devoted to understanding the -5 tails and ACRs that has been sponsored by the International Space Science Institute in Bern, Switzerland, and has been supported in part by the Voyager Guest Investigation grant NNX07AH, by NASA/LWS grant NNX07AC14G, by NSF grant ATM0632471, and by SwRI as a part of the IBEX Explorer mission (GG).

# REFERENCES


1. D. J. McComas et al., *Science* **326**, 959, 2009.
2. S. M. Krimigis et al., *Science* **326**, 971, 2009.
3. L. A. Fisk and G. Gloeckler, *Adv, Space Res*. **43**, 1471, 2009.
4. S. M. Krimigis et al., this volume.
5. M. Gruntman et al., *J. Geophys. Res*. **106**, 15,767, 2001.
6. J. D. Richardson et al., *Nature* **454**, 63-66, 2008.
7. R. B. Decker et al., *Nature* **454**, 67-70, 2008.
8. E. C. Stone et al., *Nature* **454**, 71-74, 2008.
9. L. F. Burlaga et al., *Nature* **454**, 75-77, 2008.
10. R. B. Decker, private communication.
11. B. G. Lindsay and R. F. Stebbings, *J. Geophys. Res*. **110**, A12213, 2005.
12. G. Gloeckler, L. A. Fisk, G. M. Mason and M. E. Hill, *AIP Conf. Proceedings*, **1039**, 367-374, 2008.
13. G. Gloeckler et al., *Space Sci. Rev.* **143**: 163–175, 2009.
14. M. Opher, E. C. Stone and P. C. Liewer, *Astrophys. J*. **640**, L71, 2006.