ICRC'07 Mérida, México

# Comparing the ENA data to Voyager 1 ion measurements in the heliosheath: the puzzle of H/He ratio

A. CZECHOWSKI[1], M. HILCHENBACH[2], K.C. HSIEH[3], J. KOTA[4].
[1] *Space Research Center, Polish Academy of Sciences, Bartycka 18A, PL 00-716 Warsaw, Poland*
[2] *Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse 2, 37191 Katlenburg-Lindau, Germany*
[3] *Physics Department, University of Arizona, Tucson AZ 85721, U.S.A.*
[4] *Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, U.S.A.*
*ace@cbk.waw.pl*

**Abstract:** A comparison of the energetic neutral atom observations by CELIAS/HSTOF with the Voyager 1 measurements of the termination shock particles in the heliosheath shows that the ENA hydrogen flux is consistent with Voyager 1 data. On the other hand, the ENA He flux is much higher than expected from the helium ion fluxes measured by Voyager 1. We discuss possible explanations and implications of this result.

## Introduction

Since year 1996 the instrument HSTOF aboard SOHO has been observing the energetic neutral atoms (ENA), both hydrogen (58-88 keV) and helium (28-58 keV/n) [8, 7, 3]. The outer heliosphere (inner heliosheath) was recognized to be the most probable source of these atoms [8]. Observations of the ENA provide a means of remote sensing of the ion populations in the distant regions of the heliosphere [10]. A clear confirmation of the heliosheath origin of the observed ENA was, however, absent because of lack of knowledge of the heliospheric ion distributions in the HSTOF energy range until the first in situ measurements by Voyager 1 of the ion spectra downstream of the termination shock became available [4, 12]. It is now possible to compare the expected production of the ENA in the heliosheath based on the Voyager 1 ion data with the ENA observations by HSTOF.

In the outer heliosphere the ENA are produced by charge exchange between the energetic ions and the neutral background gas. Assuming that Voyager 1 ion spectrum can be applied in the region of the heliosheath observed by HSTOF, in [2] we have derived the column density $N_{\rm H}$ of the neutral background hydrogen in the ENA source region required to account for the HSTOF ENA data. The average thickness $< L >$ of the source region can then be estimated as $< L >= N_{\rm H}/n_{\rm H}$ where $n_{\rm H}$ is the average neutral hydrogen density in the heliosheath. The result ($< L >\sim$ 75 AU. at $n_{\rm H}$ =0.1 cm$^{-3}$) is consistent with the models of the heliosheath [13].

The HSTOF ENA spectrum used in [2] was, however, an average over a wide range of directions, including the regions of the heliosheath that are distant from Voyager 1 trajectory. For this reason, we have reanalysed the HSTOF data ([6], see also Hilchenbach et al., the present volume) in order to identify the contribution from the sector of the heliosheath close to the Voyager 1 trajectory, which is also close to the apex direction of the interstellar medium (ISM). In this study we use these data to derive the hydrogen column density and estimate the thickness of the heliosheath $L_{apex}$ near the ISM apex direction. Since the models of the heliosphere suggest that this value should be about 3 times less [13] than the average $< L >$ obtained in [2], the result $L_{apex}$ ~20-30 AU at $n_{\rm H}$=0.1 cm$^{-3}$ is close to expectations [13].

However, there is an important difference between the HSTOF ENA data and the estimations based on Voyager 1 ion spectra: the H/He flux ratio mea-

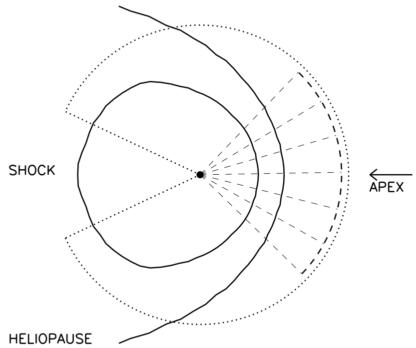


Figure 1: The schematic view of the heliosheath with the direction ranges in the ecliptic plane corresponding to the selected HSTOF ENA data (dashed lines). The HSTOF data used in [2] were averaged over a larger range of directions, shown by the dotted lines.

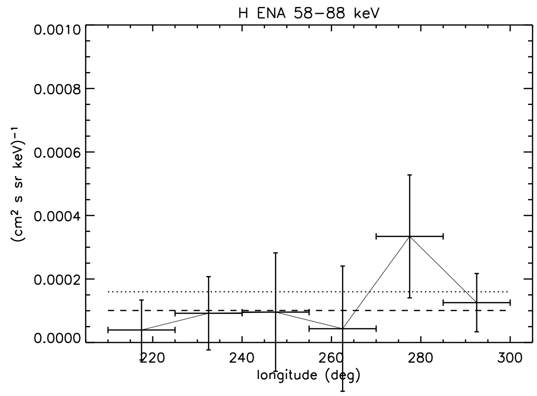


Figure 2: The H ENA flux measured by HSTOF near the ISM apex as a function of direction and the results of the fit based on the Voyager 1 LECP ion data. The ISM apex is at $254^o$ ecliptic longitude.

sured by HSTOF is significantly less (∼5) than the value following from Voyager 1 data (∼25 for termination shock particles). We discuss some possibilities of resolving this discrepancy.

## Observations

The description of the HSTOF instrument is given in [9]. HSTOF field of view is restricted to $\pm 17^o$ from the ecliptic and, in the ecliptic, to $37^o \pm 2^o$ from the sunward direction. Until mid 2003 the orientation of the instrument was unchanged, so that all ecliptic longitudes were scanned once a year. After mid 2003 the orientation of the spacecraft had to be changed, so that the region close to the ISM apex (or anti-apex) could no longer be observed. The ENA observations are only possible during the periods of low ion intensities (the "quiet times"). In result, a large part of the data comes from the periods of low solar activity, in particular the first two years of operation (1996-1997) which were close to solar minimum.

The energy range of the HSTOF ENA data is 58-88 keV for H and 28-58 keV/n for He. This overlaps with the energy range of Voyager 1 LECP Z≥1 data [4]. Voyager 1 ion measurements in the heliosheath correspond to the ecliptic longitude ∼ $253^o$ (close to the ISM apex direction) which is covered also by the HSTOF ENA data. On the other hand, there is a difference between the HSTOF and Voyager 1 data in terms of ecliptic latitude (Voyager 1 crossed the termination shock at the latitude $\sim 34^o$) and the time of measurement (HSTOF data come from the period 1996-2003). For comparison between the HSTOF and Voyager 1 observations one must assume, therefore, that the ion spectrum measured by Voyager 1 downstream of the shock can be applied also to the sector of the heliosheath and the period of the solar cycle corresponding to the HSTOF data.

## The fit

The main source of the ENA in the heliosphere is the neutralization of the energetic ions by charge-exchange with neutral atoms (predominantly hydrogen) which enter the heliosphere from the interstellar medium. For a given line of sight, the flux $J_{\rm ENA,i}(E)$ of the ENA species $i$ ($i$ =H or He) at energy $E$ originating in the heliosheath can then be written as

$$J_{\rm ENA,i}(E) = J_{\rm ion,i}(E)\sigma_{\rm cx,i,H}(E)N_{\rm H} \qquad (1)$$

where $J_{\rm ion,i}(E)$ is the parent ion flux averaged over the line of sight ($i$ =$H^+$ or $He^+$) at the

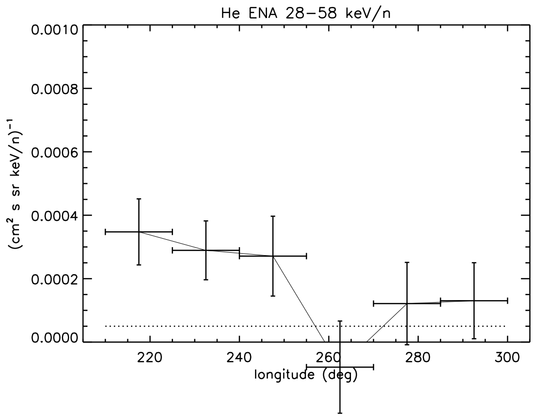


Figure 3: The He ENA flux measured by HSTOF near the ISM apex as a function of direction and the results of the fit based on the Voyager 1 LECP ion data. Note that the helium ENA flux derived from Voyager 1 ion spectrum is lower than the HSTOF observations by a factor of $\sim$5.

same energy $E$ (momentum transfer in the charge-exchange process is small) directed towards the observer, $\sigma_{\rm cx,i,H}(E)$ the charge-exchange cross section of the energetic ion with neutral hydrogen (the cross sections used here are taken from [1]) and $N_{\rm H}$ the column number density of the neutral hydrogen along the line of sight. The losses to the ENA between the source region and the observer are negligible in the HSTOF ENA energy range and therefore omitted in Eq. (1).

Assuming that the average ion spectra in the part of the heliosheath corresponding to the selected HSTOF directions can be approximately described by the $J_{\rm ion,i}(E)$ given by Voyager LECP data, we use Eq. (1) to fit the ENA fluxes measured by HSTOF and determine the best fit value of $N_{\rm H}$ in the heliosheath. $N_{\rm H}$ is the only free parameter in the fit. The HSTOF ENA data to be fitted are shown in Figs. 2 and 3 as functions of direction in the ecliptic plane. All six direction bins are included in the fit. Both the simultaneous fit to hydrogen and helium ENA data and the fit to the hydrogen data only are considered. The Voyager 1 data used in the fit are taken from [4]. We use the power law $E^{-1.67}$ fit of [4] and determine the H and He ion fluxes from Fig. 3 of [4] using the scale factors 1/0.6 for H and 0.672 for He (see [2] for details). Note that in the present fit we disregard the directional dependence of the measured ENA flux as well as of the ion flux and the hydrogen column density in the selected range of directions (210$^o$ to 300$^o$ ecliptic latitude). That is, we assume that the variations seen in Figs. 2 and 3 can be attributed to statistics, and that the average ion flux along the line of sight does not vary significantly in the selected region.

The best fit values are:

$N_{\rm H}$=(4.7±1.4) $10^{13}$ cm$^{-2}$

(H and He simultaneous fit, $\chi^2$=22.8)

$N_{\rm H}$=(3.0±1.5) $10^{13}$ cm$^{-2}$

(H only fit, $\chi^2$=2.0)

The corresponding best fit ENA fluxes are shown in Fig. 2 and Fig. 3 (H and He simultaneous fit: dotted line; H only fit: dashed line).

The thickness of the heliosheath in the forward direction $L_{apex}$ can be estimated as $L_{apex} = N_{\rm H}/n_{\rm H}$. For $n_{\rm H}$=0.1 cm$^{-3}$ it follows that $L_{apex}$=31 AU (H and He fit) and 20 AU (H only fit), with $\sim$30-50% statistical error. Most of the models of the heliosphere suggest the value of $\sim$40-50 AU.

## Discussion

The proton flux intensity downstream of the termination shock measured by Voyager 1 LECP is high enough to account for the hydrogen ENA flux observed by HSTOF. The results of the re-analysis of the HSTOF data that restricts the observed region to the vicinity of the ISM apex direction imply that the thickness of the heliosheath in the forward direction is 2-3 times thinner than the average including both the forward region and the flanks of the heliosheath. This is consistent with expectations based on the models of the heliosphere [13].

The HSTOF ENA data imply that the helium ENA flux is significantly higher than expected on the basis of the presently available Voyager 1 measurements in the heliosheath. This may indicate that the present Voyager 1 data (obtained during the first half year after crossing of the termination shock) do not yet give the complete picture of the ion distribution in the heliosheath. One argument for this possibility is that the H/He flux ratio

($\sim$5) following from the HSTOF measurements is close to the value following from the anomalous cosmic ray (ACR) data [12] This may indicate that the ion spectra further downstream from the shock may evolve towards the form expected for the ACR case. Another point is that the Voyager 1 LECP data do not distinguish between different species in the low energy region: the estimation of the helium flux at low energy can only be obtained by extrapolation.

It is also possible that the HSTOF helium ENA data do not entirely represent the energetic helium flux from the heliosheath, but might be considered to provide an upper limit on this flux. This may be due to ion contamination of the HSTOF ENA data which is more likely to occur in the case of helium than in the case of hydrogen. Another possibility is that a large part of the helium ENA flux originates not in the heliosheath. One candidate could be the region near the Sun, where the $He^+$ pick-up ions dominate over the pick-up protons. This is because the neutral helium (but not hydrogen) atoms from the ISM can penetrate to the region near the Sun. The $He^+$ pick-up ion flux at 1 AU was estimated to be as high as $\sim 10^4$ cm$^{-2}$s$^{-1}$ near the ISM apex direction [11]. The pick-up ion distributions are known to evolve the energetic "tails" [5]. The flux of $He^+$ needed to produce (from the region within $\sim$1 AU) the amount of He ENA comparable to the HSTOF measurements would have to be of the order of 10 (cm$^2$ s sr keV/n)$^{-1}$ at 30 keV/n at 1 AU. The energetic tail in this case would have to be of much larger intensity than the examples shown in [5]. Note that the time periods with high energetic ion intensities are not included in the ENA measurements.

## Acknowledgements

A.C. acknowledges support from the Polish Ministry of Science and Higher Education grant 4T12E 002 30.

## References

[1] C.F. Barnett, H.T. Hunter, M.I. Kirkpatrick, I. Alvarez, and R.A. Phaneuf. *Atomic Data for Fusion. Collisions of H, H2, He and Li Atoms and Ions with Atoms and Molecules*. Oak Ridge Natl. Lab. Report, ORNL-6086-VI, Oak Ridge, Tenn., 1990.

[2] A. Czechowski, M. Hilchenbach, K.C. Hsieh, R. Kallenbach, and J. Kota. *Astrophysical Journal*, 647:L69–L72, 2006.

[3] A. Czechowski, K.C. Hsieh, M. Hilchenbach, J. Kota, and A.W. Shaw. *Advances in Space Research*, 34:104, 2004.

[4] R.B. Decker, S.M. Krimigis, E.C. Roelof, M.E. Hill, T.P. Armstrong, G. Gloeckler, D.C. Hamilton, and L.J. Lanzerotti. *Science*, 309:2020, 2005.

[5] G. Gloeckler and L. Fisk. In *Physics of the Inner Heliosheath: Voyager Observations, Theory and Future Prospects, 5th IGPP International Astrophysics Conference*, 2006.

[6] M. Hilchenbach, A. Czechowski, K.C. Hsieh, and R. Kallenbach. In *Physics of the Inner Heliosheath: Voyager Observations, Theory and Future Prospects, 5th IGPP International Astrophysics Conference*, 2006.

[7] M. Hilchenbach, K.C. Hsieh, D. Hovestadt, R. Kallenbach, A. Czechowski, E. Möbius, and P. Bochsler. In *The Outer Heliosphere: The New Frontiers, COSPAR Colloquium Series, Vol. 11*, page 273, 2001.

[8] M. Hilchenbach, K.C. Hsieh, D. Hovestadt, B. Klecker, H. Grünwaldt, and et al. *Astrophysical Journal*, 503:916, 1998.

[9] D. Hovestadt, M. Hilchenbach, A. Bürgi, B. Klecker, P. Laeverenz, M. Scholer, H. Grünwaldt, W.I. Axford, S. Livi, E. Marsch, and et al. *Solar Physics*, 162:441, 1995.

[10] K.C. Hsieh, K.L. Shih, J.R. Jokipii, and S. Grzedzielski. *Astrophysical Journal*, 393:756, 1992.

[11] D. Rucinski, M. Bzowski, and H.-J. Fahr. *Astronomy and Astrophysics*, 334:337–354, 1998.

[12] E.C. Stone, A.C. Cummings, F.B. McDonald, B. Heikila, N. Lal, and W.R. Webber. *Science*, 309:2017, 2005.

[13] G.P. Zank. *Space Science Reviews*, 89:413, 1999.