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Energetic neutral atom observations and their implications on modeling the heliosheath

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Abstract: Since 1996, energetic hydrogen and helium atoms (ENAs) have been identified and their fluxes are monitored by the High-Energy Suprathermal Time-of-Flight sensor (HSTOF) of the Charge, Element, and Isotope Analysis System (CELIAS) onboard the Solar and Heliospheric Observatory (SOHO) near the Lagrangian point L1. ENAs, neutralized via charge transfer reactions, move along ballistic trajectories unaffected by the interplanetary magnetic field. ENAs originate in the heliosphere from CIRs, solar energetic particle events, pre-accelerated pickup ions and low-energy (up to few hundred keV) anomalous cosmic ray (ACR) ions in the outer heliosphere, in the vicinity and beyond the solar wind termination shock. The observed ENA fluxes set upper limits on the fluxes of energetic particles in the outer heliosphere and on the modeling parameters of the heliospheric plasma simulations.

Introduction

In 2004 VOYAGER 1 crossed the termination shock into the inner heliosheath [1-3]. This heliospheric region is one of the likely sources of the energetic neutral atoms, both H and He, observed from 1996 onwards by CELIAS/HSTOF onboard SOHO [4-7]. These energetic neutral atoms (ENAs) are considered to originate in the heliosheath from energetic ions, neutralized by charge-exchange with the neutral atoms of the local interstellar medium (LISM) and then move on ballistic trajectories, some towards the inner solar system to be detected at 1 AU.

Potential ENA sources in the inner and outer heliosphere are solar energetic particle events, co-rotating interaction regions (CIRs), pre-accelerated pick-up ions and low-energy anomalous cosmic ray (ACR) ions in the outer heliosphere [8,9]. In the following, we will focus on ACRs as potential source of ENAs, following the arguments outlined in [4].

Based on in-situ data of the Low Energy Charged Particle (LECP) sensor onboard VOYAGER 1 and HSTOF measurements of the ENA fluxes onboard SOHO, the thickness of the heliosheath was estimated to be smaller than 75 AU [10].

In the following we present ENA energy spectra as observed between 1996 and 2005 by CELIAS/HSTOF. While ENA data set from SOHO has a counting statistics poorer than that of the ion data sets from Voyager 1, it nevertheless offers the unique opportunity to monitor indirectly the ion flux in time and in regions of the heliosheath inaccessible to the in-situ measurements of VOYAGER 1 now and VOYAGER 2 in the future.

Instrument and data analysis

CELIAS/HSTOF is one of two sections of the Suprathermal Time-of-Flight instrument (STOF) of the CELIAS instrument suite onboard SOHO [11]. The instrument identifies mass and energy of each incident energetic particle by its speed measured by a time-of-fight (TOF) unit and the residual energy deposited in a pixellated solid-state detector (PSSD). In front of the TOF unit is an electrostatic energy/charge (E/Q) filter suppressing ions.

The HSTOF section has its boresight set at 37° west of the Sun-SOHO line. It scans the ecliptic with a field of view (FOV) +/- 2° in and +/- 17° out of the ecliptic plane as SOHO orbits the Sun. However, it must be pointed out, that the positions of both, VOYAGER 1 and 2, are beyond the aperture scanned by HSTOF off the ecliptic plane. HSTOF scanned the entire ecliptic plane once a year (1966-2002) and scans only sections of the ecliptic (2003-present), because SOHO does a 180°-roll twice a year since 2003. Therefore the region near the apex and anti-apex is presently inaccessible to HSTOF's field-of-view.
First detection of the heliospheric ENAs by HSTOF were reported in [5], the ENA flux calibrations quoted were later scaled up after in-flight re-calibration of HSTOF [6]. The ENA fluxes are observed in the energy range 58-88 keV/nuc for H and 28-58 keV/nuc for He. The selected ranges result from the energy/charge entrance filter transmission function for protons and He ions, respectively. ENA observations are carried out during so-called 'quiet times' as ion fluxes in the observation time interval are below a pre-defined threshold (12 counts per day for mass = 1 amu in the energy region 58 to 660 keV, observational 'quiet time' intervals for the years 1996 to 2005 versus the heliocentric coordinates are shown in Figure 1). For ENA flux measurements, the transmitted ion flux was deduced from high energy tail observations with a quiet time power law energy spectra (γ = -2.5). Therefore, most data points are collected in intervals of very low solar activity.
ENA fluxes are calculated from the observed HSTOF events, removing accidental coincidence

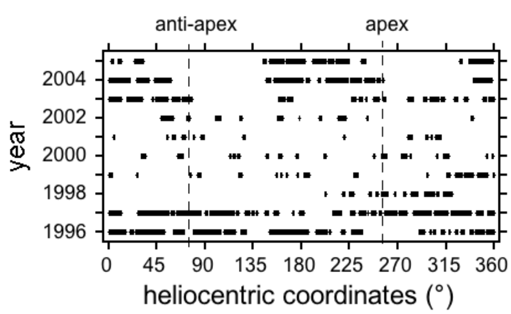

Figure 1: CELIAS/HSTOF "quiet time" observation time intervals between 1996 and 2005.

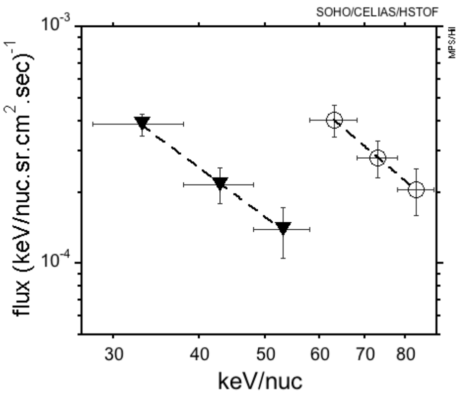

Figure 2: Differential energy spectra of energetic neutral hydrogen (ENH - open circles) and helium (ENHe - filled triangles) integrated over all heliocentric coordinates in the region between 0° and 360° as observed by CELIAS/HSTOF. Bars refer to 1σ statistical flux errors and 10 keV/nuc bins.

background events as well as contributions of ions passing the energy per charge entrance filter according to the methods described in [5,6].

ENA flux observations

ENAs, e.g. energetic neutral hydrogen (ENH) and helium (ENHe) are observed between 1996 and 2005. HSTOF observations were taken in diverse time intervals, adding up to 975 days of so-called "quiet time" observation intervals (Figure 1).
ENH energy spectra between 58 to 88 keV/nuc and ENHe energy spectra between 28 to 58 keV/nuc are shown for the time interval from 1996 to 2005 and integrated over all viewing directions - from the heliospheric tail to the apex direction - in Figure 2. The observed ENH and ENHe fluxes observed with HSTOF in the ecliptic plane in the last decade are statistically significant on a 3σ confidence level in the low energy/nuc bins and on a 1σ confidence level for the plotted higher energy/nuc bins, for ENH and ENHe respectively. This is due to the limited counting statistics as well as the transmission function of the instrument entrance system, i.e. ions with higher energy/charge are less suppressed than ions with low energy/charge.
ENH and ENHe energy spectra are plotted in respect to the viewing direction, binned in 90°

sectors, and shown in Figure 3 to Figure 6. The dotted line is a restricted fit, keeping the power index as in Figure 2 while fitting only the flux intensity. The viewing direction 30° to 120° encloses the tail direction of the heliosphere, the viewing direction of 210° to 300° the apex direction. The counting statistics is much better in the tail direction of the heliosphere, as compared to the other 3 sectors. ENA flux time variations might be comparable to ENA flux spacial variations, but not on a statistical significant level.

Discussion

The ENH and ENHe observations of SOHO/CELIAS/HSTOF do reveal a pattern of variations in the apex and anti-apex direction of the heliosphere, i.e. the ENA flux from the helio tail is higher than the ENA flux from the other heliospheric view directions, including the apex direction [4]. The rebinned CELIAS/HSTOF data, with 90° sectors, should lead to an updated estimatation of the heliosheath thickness, i.e. about half of the previous estimate based on an extended heliospheric apex sector [10]. As the observation of ENAs constitutes an integral observation along the line of sight, one does not expect large variations from year to year, however, the observed fluxes in the ecliptic plane do not support nor exclude the possibility of such variations. If other ENA sources, as outlined above, would have contributed to the observed ENA energy spectra to a different extent than our previous estimates implied, the ENA energy spectra observations would have to be interpreted rather as upper limits for the ACR contribution towards the observed ENA than as ACR- ENA energy spectra. Models of the heliosphere and the heliosheath should subsequently predict heliospheric ACR- ENA fluxes smaller or equal to ENA fluxes observed with SOHO/CELIAS/HSTOF in the last decade.

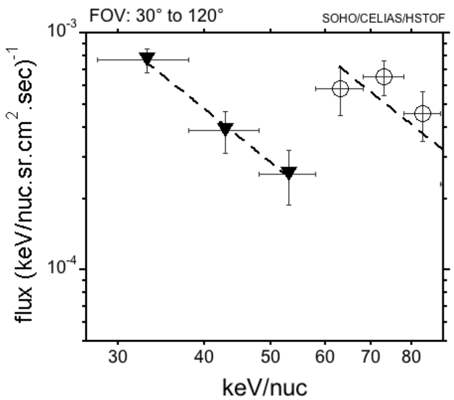

Figure 3: Differential energy spectra of energetic neutral hydrogen (ENH - open circles) and helium (ENHe - filled triangles) integrated over all heliocentric coordinates in the sector between 30° and 120° as observed by CELIAS/HSTOF. Bars refer to 1σ statistical flux errors and 10 keV/nuc bins.

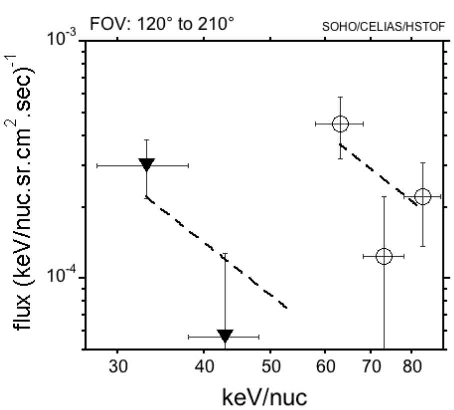

Figure 4: Differential energy spectra of energetic neutral hydrogen (ENH - open circles) and helium (ENHe - filled triangles) integrated over all heliocentric coordinates in the sector between 120° and 210° as observed by CELIAS/HSTOF. Bars refer to 1σ statistical flux errors and 10 keV/nuc bins.

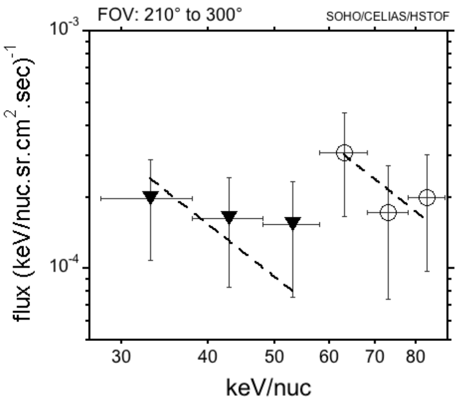

Figure 5: Differential energy spectra of energetic neutral hydrogen (ENH - open circles) and helium (ENHe - filled triangles) integrated over all heliocentric coordinates in the sector between 210° and 300° as observed by CELIAS/HSTOF. Bars refer to 1σ statistical flux errors and 10 keV/nuc bins.

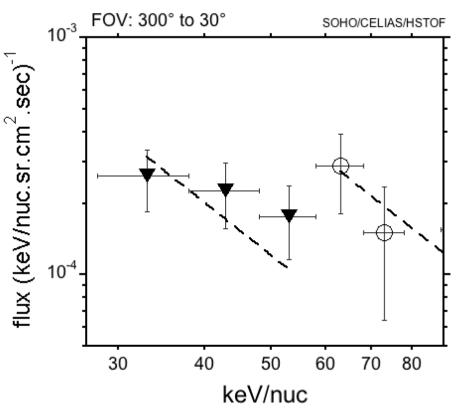

Figure 6: Differential energy spectra of energetic neutral hydrogen (ENH - open circles) and helium (ENHe - filled triangles) integrated over all heliocentric coordinates in the sector between 300° and 30° as observed by CELIAS/HSTOF. Bars refer to 1σ statistical flux errors and 10 keV/nuc bins.

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