Energetic neutral helium atoms as a tool to study the heliosphere and the Local Interstellar Medium

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Paweł Swaczyna, Stan Grzedzielski, and Maciej Bzowski

Space Research Centre of the Polish Academy of Sciences, Warsaw, Poland

1. Introduction

More than 5 years of the **IBEX** observations shows the unique role of **Energetic Neutral Atoms (ENA)** in remote sampling of the plasma in the **heliosphere** and its vicinity (McComas et al. 2014). However, ionization of the hydrogen ENA in the **Local Interstellar Medium (LISM)** make the H ENA fluxes extinct at distances ~1000 AU.

One of the most popular **models of the LISM** suggests coexistence of warm partially ionized clouds embedded in the fully ionized plasma of the bay of the Local Bubble. The two clouds closest to the Sun are probably the **Local Interstellar Cloud (LIC)** and **Galactic (G) Cloud** (Redfield & Linsky 2008, Linsky & Redfield 2014). The structure of the clouds could be resolved using atomic absorption lines in high-resolution spectra of the closest stars. This method requires the minimal thickness of the observed cloud of the order of 0.1 pc, and thus gives only an upper limit for the distance to the LIC boundary (Wood et al. 2000).

Helium due to the **higher ionization energy** could extend the ability of the ENA imaging of the LISM to distances unavailable for the telescopic observations of absorption lines. This, however, requires an ENA detector with mass spectrometer in future missions.

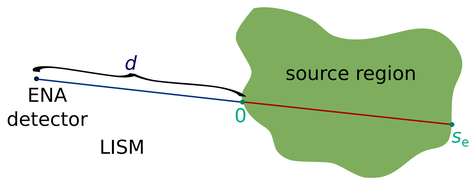
2. He ENA from the heliosphere

The heliospheric H ENA signal observed by the IBEX could be split into two main sources. One is the **inner heliosheath (IHS)**, where Pick-Up Ions (PUI) created in the supersonic solar wind could be neutralized by charge-exchange with interstellar neutrals. The other one is the outer heliosheath (OHS) source due to the **Secondary ENA** Mechanism (Heerikhuisen et al. 2010), in which the neutral solar wind could produce ENA flux backwards into the Sun by two subsequent charge-exchange in the region of the sky where interstellar magnetic field is perpendicular to the line-of-sight.

For simulation of the **IHS signal** we use **axisymmetrical model of incompressible plasma flow** (Suess & Nerney 1990), with parameters reflecting Voyagers results (Grzedzielski et al. 2014). The He ENA fluxes originate from the **He$^+$ PUI** for which we evolve spectra assumed at the termination shock. The expected **Secondary He ENA** fluxes were calculated using generalized analytical model by Möbius et al. (2013) with the heliolatitudial structure of the supersonic solar wind obtained from interplanetary scintillations (Sokół et al. 2013).

3. Extraheliospheric sources

Suprathermal helium ions in the LISM after charge-exchange with the neutrals produce **fluxes of He ENA**. Long mean free path against ionization (Figure 1) makes them observable at distances comparable to the distance to the LIC edge.



$$j_{\mathrm{ENA}}(E) = e^{-\frac{d}{\lambda_{\mathrm{LISM}}}} \int_0^{s_e} e^{-\frac{s}{\lambda_{\mathrm{source}}}} \left\{ j_{\mathrm{He}^+} \left[\sigma^{\mathrm{cx}}_{\mathrm{He}^+\mathrm{H}} n_{\mathrm{H}} + \sigma^{\mathrm{cx}}_{\mathrm{He}^+\mathrm{He}} n_{\mathrm{He}} \right] + j_{\mathrm{He}^{2+}} \sigma^{\mathrm{2cx}}_{\mathrm{He}^{2+}\mathrm{He}} n_{\mathrm{He}} \right\} \mathrm{d}s$$

The expected flux depends on the extinction in the LISM to the edge of the source region and the properties of the source region: extinction, intensities of suprathermal helium ions, distribution of neutrals, and dimension over the line-of-sight.

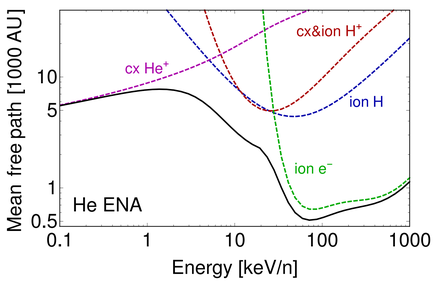


Figure 1. — The He ENA mean free path (m.f.p.) against ionization in the LISM with the densities: H 0.19 cm^{-3}, H$^+$ 0.06 cm^{-3}, He 0.015 cm^{-3}, He$^+$ 0.009 cm^{-3}. The longest m.f.p. (>7000 AU) have He ENA with energies 0.5 – 3 keV/n. Notice that electron impact ionization makes the LISM opaque above a few tens keV/n.

4. Simulated signal from the heliosphere

The simulated **heliospheric He ENA** signal is concentrated in the **heliotail** direction (Figure 2). In the model He$^+$ PUI are distributed almost homogeneously in the IHS, thus the expected signal grows as the IHS thickness grows in the tail direction. This is possible due to lower rate of He$^+$–He charge-exchange in comparison with the rate of H$^+$–H charge-exchange.

The Secondary ENA mechanism provides a signal at most **of the order of the IHS** emission (Figure 3). The peak energy depends on heliolatitude, as observed for H ENA.

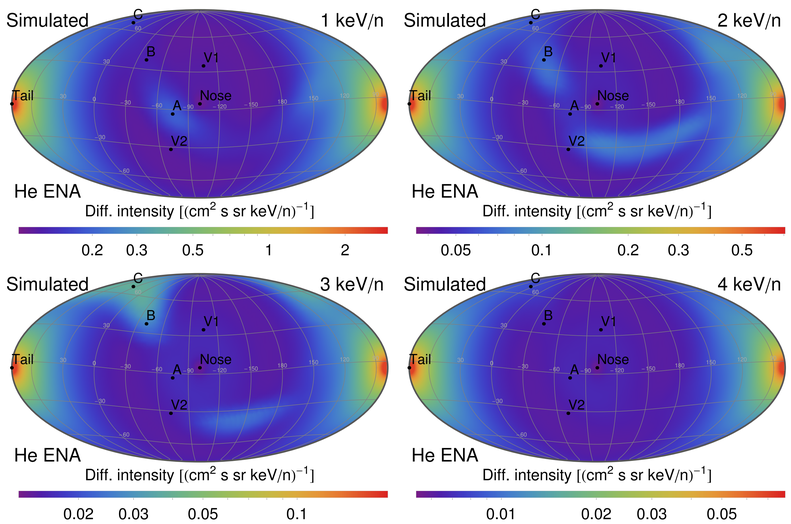


Figure 2. — Maps of simulated He ENA intensities from the heliosphere. Notice the logarithmic scale in the intensities.

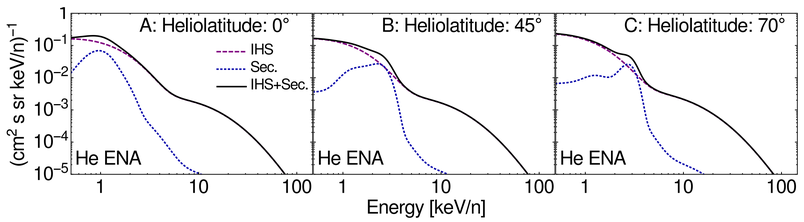
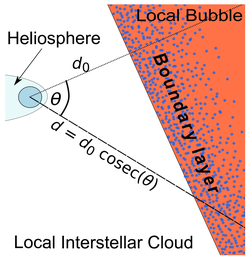


Figure 3. — He ENA spectra of the IBEX Ribbon in three directions decomposed into the IHS and Secondary ENA components.

5. Exemplary model of extraheliospheric source



As an exemplary model we adapt the model of ENA production at **the contact layer between the Local Interstellar Cloud and Local Bubble** originally proposed by Grzedzielski et al. (2010) as the source for the IBEX Ribbon. In the cases considered by Grzedzielski et al. (2010) the expected He ENA fluxes are larger than the heliospheric emission (Swaczyna et al. 2014).

Here we extend the considered **distance** d_0 to the source region **up to ~0.1 pc**. We assume planar interface, thus the closest path define the center of circular symmetry.

We assume that the Local Bubble far away from the interface is filled with hot (10^6 K), low density completely ionized plasma ($n_p = 0.005$ cm^{-3}, $n_\alpha = 0.0005$ cm^{-3}). The ion distribution function is assumed to be κ-distribution with $\kappa = 2$.

The signals obtained from the model are up to **~50 times larger than the heliospheric signal** for energies $\lesssim$10 keV/n (Figure 4). Above few tens of keV/n the fluxes are strongly attenuated by electron impact ionization. The spatial shape of the signal changes with the distance to the interface (Figure 5).

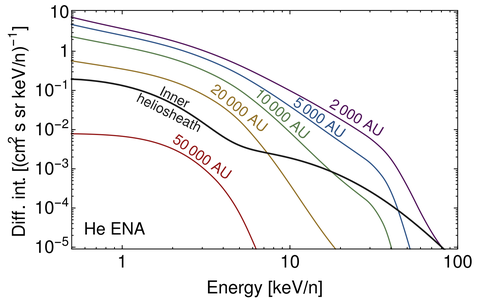


Figure 4. — Simulated He ENA spectra with different distances to the interface in the closest path direction. The IHS signal at 90° from the nose is also plotted for comparison. Notice that for energies 0.5 – 3 keV/n the spectra are shifted only vertically due to almost constant mean free path against ionization in this energy range (Figure 1).

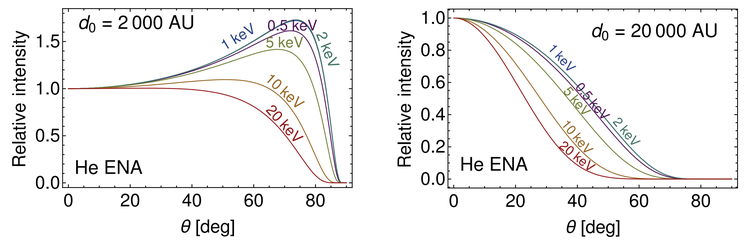
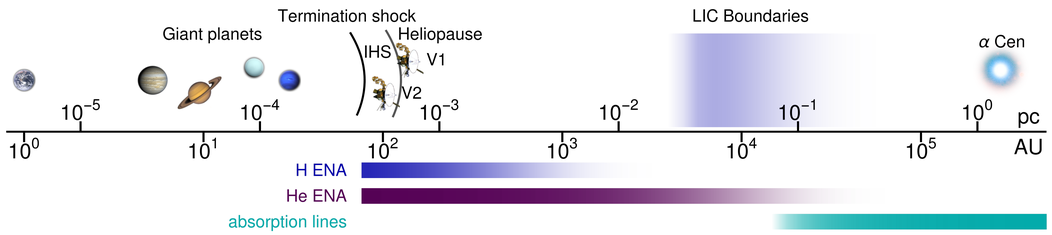


Figure 5. — Relative signal strength as a function of angular distance from the center of symmetry for two selected distances to the interface. Notice the maximum at ~70° for the lowest energies in the left panel.

6. Conclusions & Perspectives



- Expected signal of the **He ENA emission from the heliosphere is small** except for the heliotail.
- The long He ENA m.f.p. against ionization in the LISM makes the **hypothetical extraheliospheric ENA sources detectable** at distances **up to 20 000 AU / 0.1 pc**.
- Successful **observations are most likely for energies $\lesssim$ 50 kev/n**.
- High sensitivity ENA detector with mass spectrometer could make He ENA detection possible.

7. References

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