What Does Our Heliosphere Look Like in Energetic Neutral Atoms? Some Recommendations for a Low-Energy ENA Camera Onboard the Interstellar Probe

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November 24, 2022

Abstract

The concept of an Interstellar Probe (ISP) offers an intriguing combination of scientific break-throughs in several disciplines. These include a global view of our heliosphere, unperturbed sampling of the interstellar medium, discoveries of Kuiper Belt Objects, and many others. The current mission concept of the ISP aims at reaching a distance of 1000 au away from the Sun within this century, far beyond the heliopause at roughly 100-200 au. In this presentation, we investigate basic requirements for an Energetic Neutral Atom (ENA) instrument onboard the ISP for the energy range between 10 eV and 5 keV. An ENA is produced when a fast ion exchanges its charge with an ambient neutral atom. The resulting ENA leaves the source region on a straight trajectory, no longer influenced by electromagnetic fields. This allows an ENA camera to image the ion distribution of remote plasma regions. We calculate the energy spectrum of heliospheric ENAs an observer would see from a given vantage point inside or outside the heliopause. Since the global shape of the heliosphere is unknown yet, we use two analytical models to derive proton flowlines for two different heliospheric shapes: the Parker model [Parker 1961] modified with a termination shock and the analytical representation of a full MHD model [Röken et al. 2015, Kleimann et al. 2017]. The ENA intensity then is the line-of-sight integral of proton density times the local density of neutral hydrogen times the charge-exchange cross-section. We disregard any other neutral species inside the heliosphere and we only consider protons as source for ENAs. The proton populations included are the supersonic solar wind and pickup ions inside the termination shock and the shocked solar wind and pickup ions between termination shock and heliopause. The calculated ENA intensities are first compared to the globally distributed ENA flux measured by the Interstellar Boundary Explorer and Cassini in the inner solar system in the energy range from 10 eV to 55 keV. We then proceed to calculate the ENA intensity as seen by an observer at other positions near or beyond the heliopause. These predictions can serve as a rough guideline for the mission concept of ISP: which trajectory offers the most interesting view on the heliosphere in ENAs and which technical requirements should a low-energy ENA imager meet?

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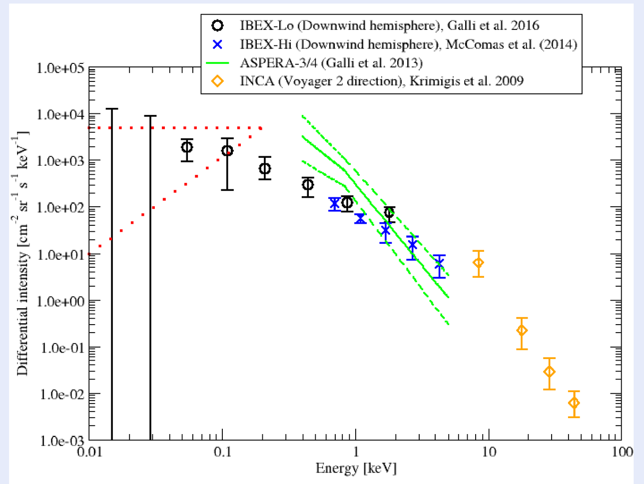
Our empirical ENA model

Use ENA observations (the Globally Distributed Flux from the heliosheath observed with IBEX, INCA, etc. close to 1 au) and uniform neutral hydrogen density n_H to derive proton distribution j_{H+}.

No matter the heliospheric shape or physical processes, the predicted ENA intensity for an observer close to the Sun must agree with these observations.



Physical processes implemented in model so far:

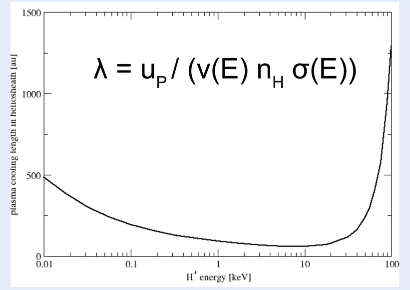
•Charge-exchange between H^+ (supersonic solar wind inside TS, shocked solar wind and pick-up ions in inner heliosheath with isotropic velocity distribution, plasma bulk flow u_p = 100 km/s) and neutral hydrogen. The cross-section σ depends on energy.

•ENA losses outside heliopause (for constant n_{H+} = 0.1 cm^{-3})

•Compton-Getting due to spacecraft motion with $j(E) = j_{in} (1 + 2u_{sc}/v(E) + u_{sc}^2/v(E)^2)^{-(\gamma+1)}$ for u_{sc} = 0...20 au/yr)

•Various heliopause shapes (based on theory or observations)

•Plasma cooling with the following cooling length:



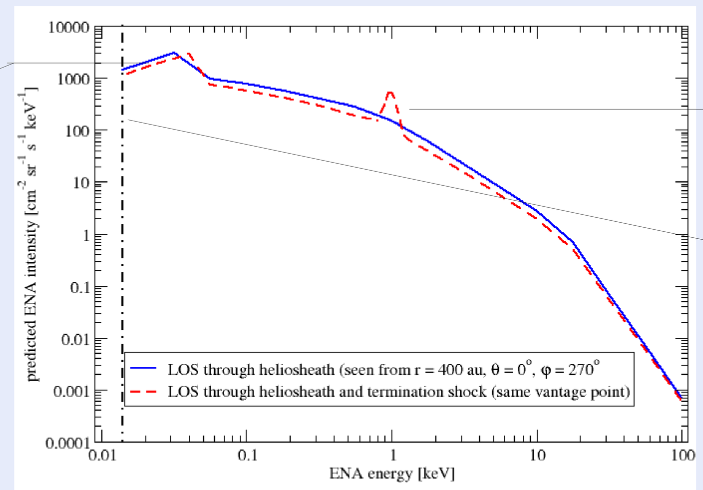
So far missing:

•Outer heliosheath sources or any other ENA sources overlying the globally distributed ENA flux (IBEX Ribbon, INCA Belt etc.)

•H^+ distribution in inner heliosheath derived from first principles

Calculate ENA intensities from the line of sight integral $j_{ENA} = \int dl\, j_{H+}\, \sigma\, n_H$ – losses for energies 10 eV – 100 keV for any vantage point inside or outside heliopause:

Assumed roll-over at 100 eV in solar ref. frame [Galli et al. 2016]. Other low-energy spectra [Zirnstein et al. 2018] can easily be implemented



Neutralized Solar wind

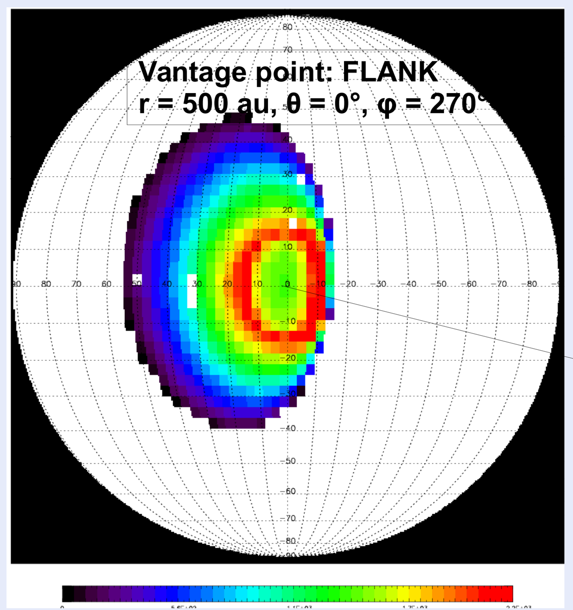
Compton-Getting: Cut-off energy around 14 eV (if u_{sc} = 10 au/yr)

An ENA camera outside the heliosphere... why?

Observing the heliosheath in ENAs from the inner heliosphere (INCA, IBEX, IMAP, ASPERA-3&4 etc.) shows us a 2D projection of a 3D shape from a vantage point that hardly moves compared to the dimensions of the shape (100s of au).

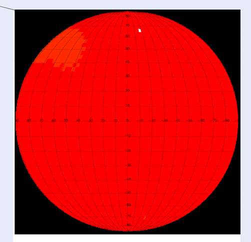
This results in several degeneracies when we try to deduce the shape, the ion distributions, and neutral distributions giving rise to that 2D image. For example, consider two very different kinds of plasma properties in the inner heliosheath:

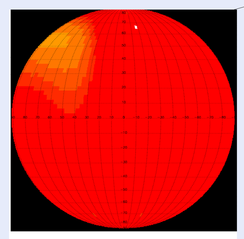
If plasma cools down over expected cooling length:



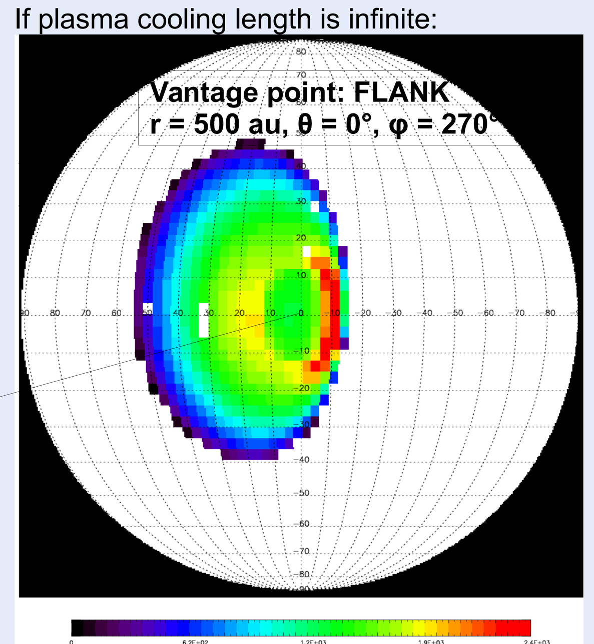
The difference is easy to spot for an observer outside the heliosphere.

But for an ENA camera at 1.1 au, the entire sky looks uniformly bright!

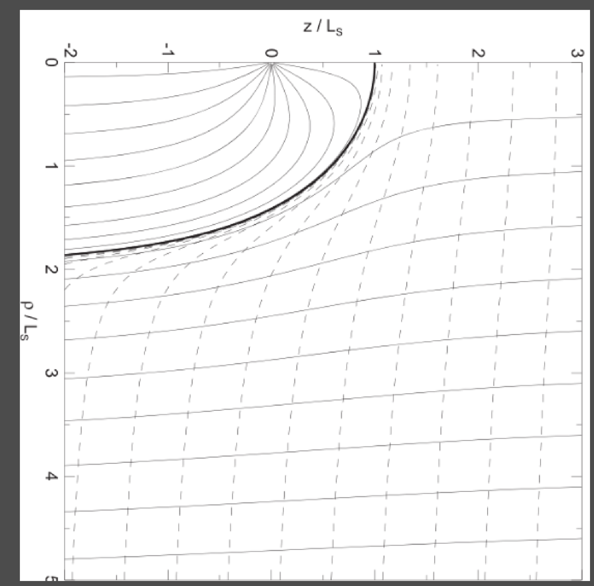




If plasma cooling length is infinite:

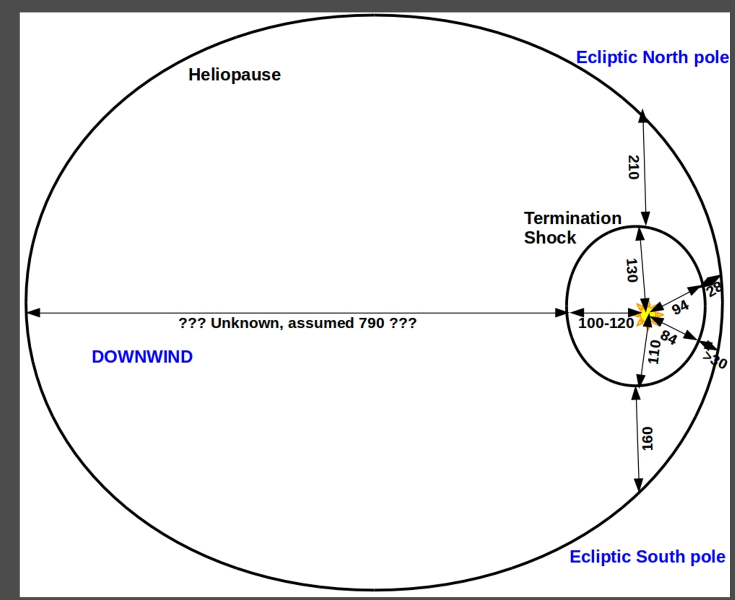


Three different heliopause shapes

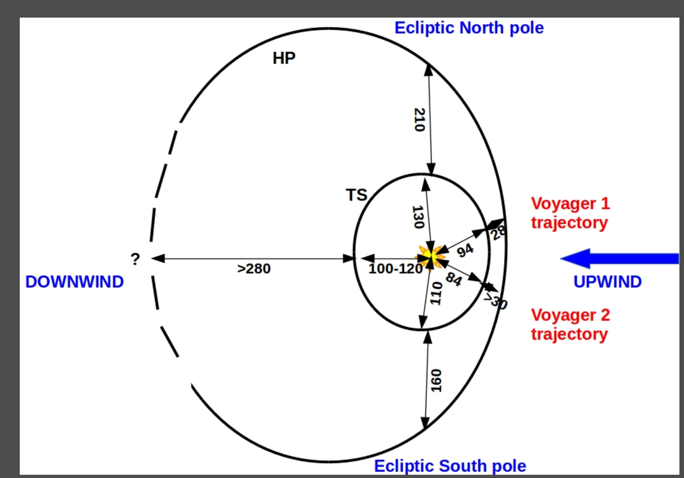


1) Cylindrical shape of heliopause (analytic solution for plasma boundary [Parker 1961]) with an upwind stand-off distance of 115 au (from Voyager measurements) and an infinitely long heliotail.

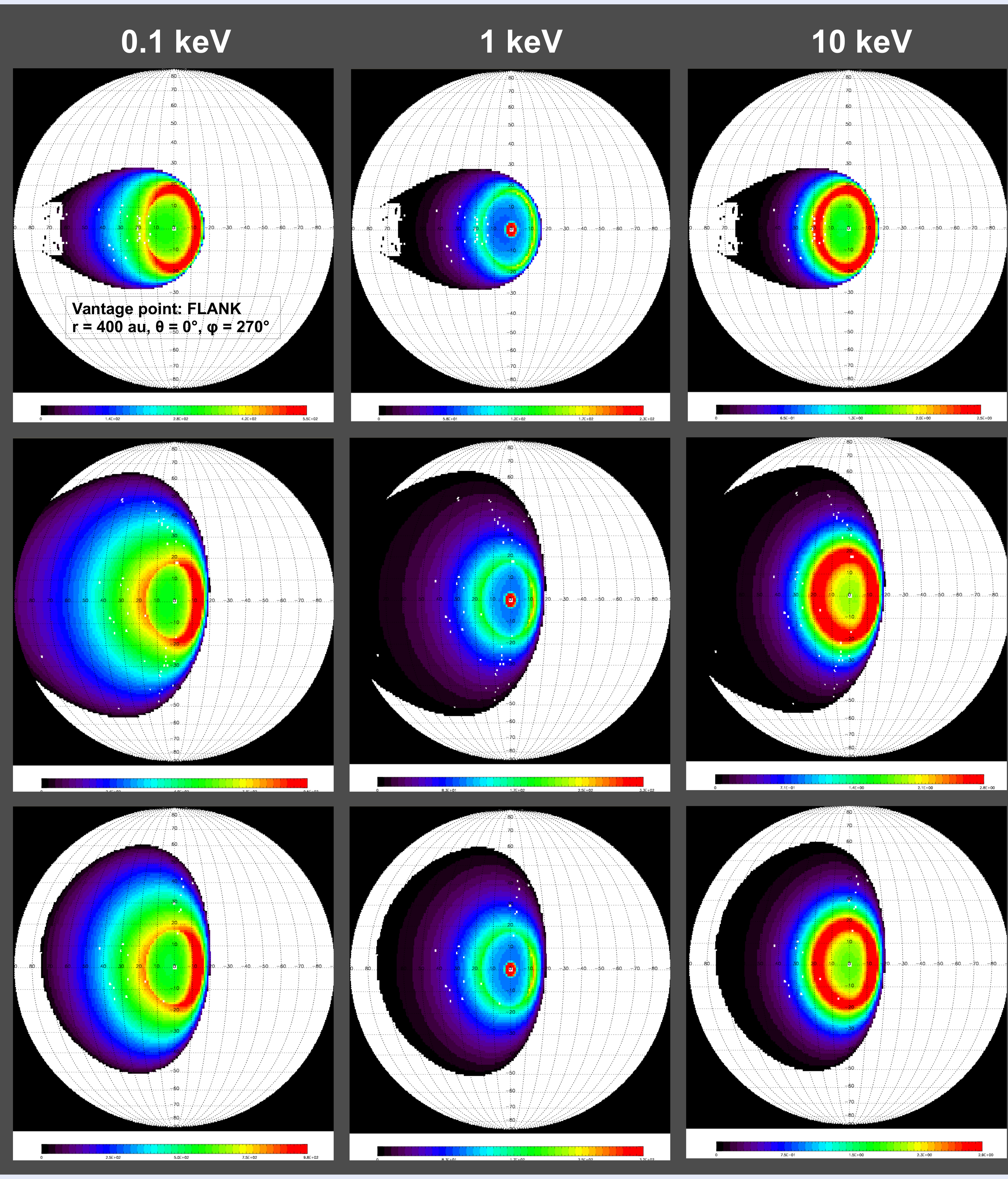
The ENA signal from the tail is finite because the plasma is cooled down as it flows towards the tail by the neutral hydrogen. Plot from Röken et al. [2015]



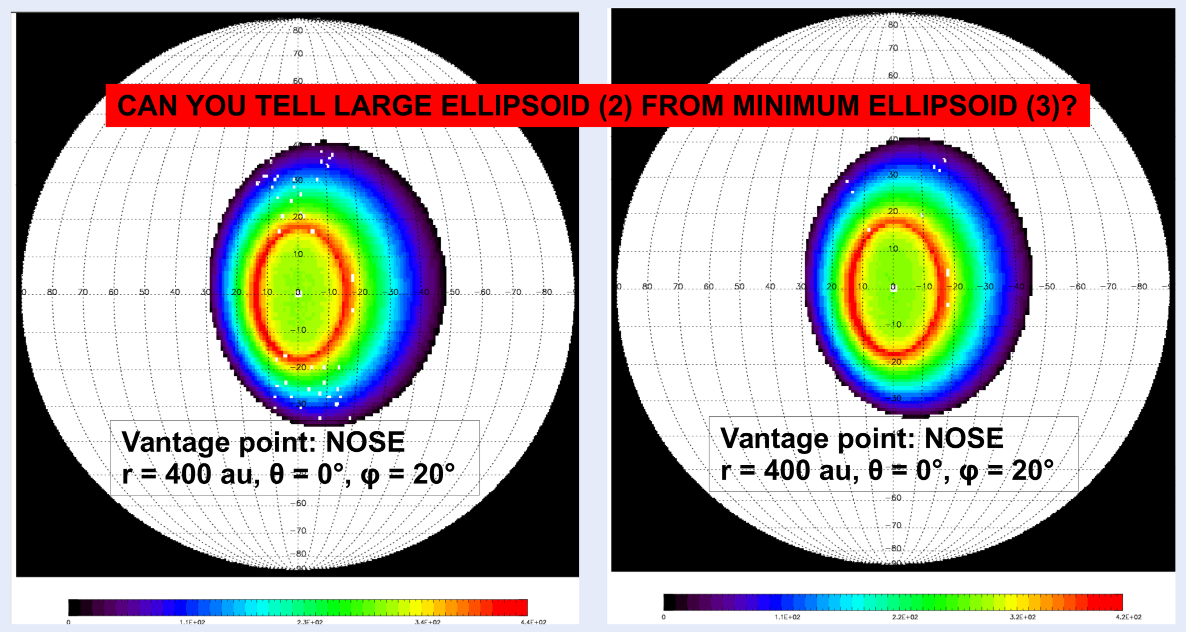
2) Large ellipsoid: the dimensions toward the nose, the poles and the flanks are consistent with ENA observations and Voyager in-situ measurements, 790 au heliosheath thickness toward the downwind hemisphere was assumed as an example.



3) Minimum ellipsoid: also consistent with observations so far. The heliosheath thickness in downwind direction is assumed to be 280 au (minimum distance derived by Galli et al. [2017].



The drawback of a nose vantage point



Preliminary recommendations

•Trajectory through flanks seems more informative in terms of ENA imaging (also keep in mind that we already have Voyager data from the nose region). Definitive answer must also include viewing opportunities of IBEX Ribbon (~1 keV) and INCA Belt (tens of keV).

•ENA energy ranges of interest: Energies around 0.1 keV allow us to determine the shape of the heliosphere and image the protons of the most frequent energies occurring in the heliosheath. The solar wind energy (1 keV ENAs) range must also be covered because of the IBEX Ribbon. The ENA energies around 10 keV are most heavily affected by plasma cooling effects; at ENA energies > tens of keV, heliosheath plasma 100s of au away from the Sun become visible again.

•ENA cameras onboard ISP must be able to detect ~100, 10, 0.1 cm^{-2} sr^{-1} s^{-1} keV^{-1} around 0.1, 1, and 10 keV. Most background sources will be weaker than close to Sun: lower plasma densities and fewer photons, higher cosmic ray flux beyond heliopause less of a nuisance for a low-energy ENA camera.

•Spatial resolution: at least as good as IBEX (6°x6°).

•Spacecraft motion: 10 au/yr = 50 km/s → ENAs down to ~20 eV can be detected. If ISP achieves a radial velocity of 20 au/yr (100 km/s), ENAs below 100 eV (=140 km/s) will be difficult to detect.

•Further physics to be included in model before making more detailed statements: outer heliosheath ENA sources and non-uniform neutral hydrogen density, explicit proton distribution if possible, He ENAs (strong argument for a low energy ENA sensor because charge-exchange He^+ + He has very low cross-section for energies above 10 keV).

SH33C-3663. Display time: Wednesday, 13:40 – 18:00 The Interstellar Probe Mission: Study Findings and Next Steps