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The inner heliosheath source for keV energetic neutral atoms (ENAs)

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IBEX – the Interstellar Boundary EXplorer

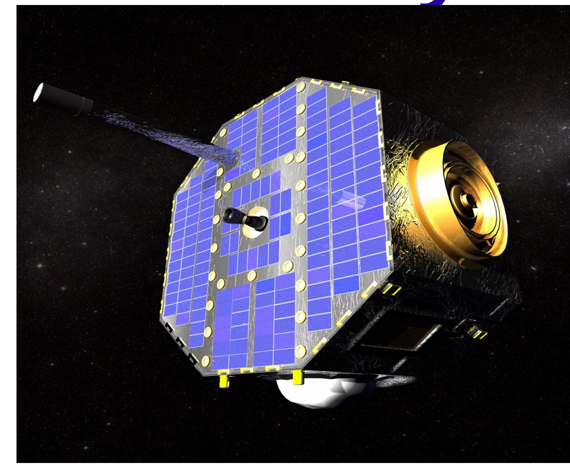
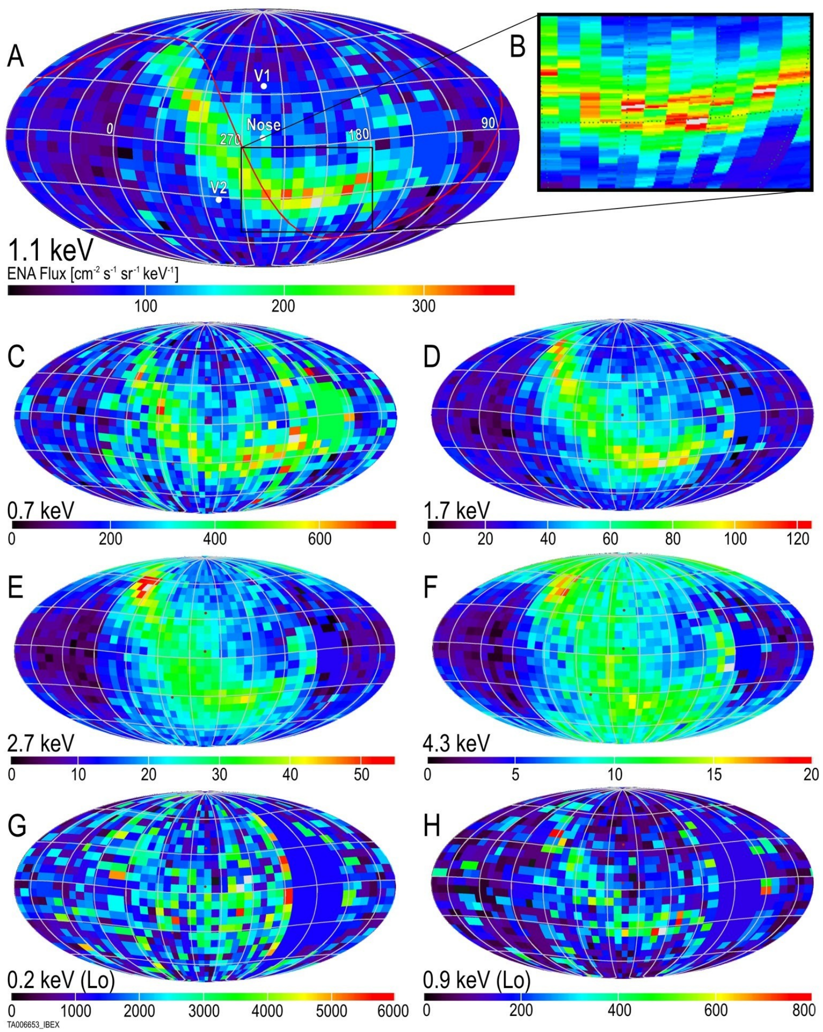


Image: NASA

- IBEX is a detector for neutral particles between 0.01 and 6 keV
- Neutral particles are produced primarily in charge-exchange processes
  - Allows to get an almost unperturbed image of distant distribution functions
  - Allows access to a broad area of energy regions
- Spatial distance that can be resolved: o(100 AU)
  - Allows to trace remotely the heliospheric boundary layer
  - Allows to test models for microphysical processes dominating the outer heliosphere

Surprising results: the “ribbon”

(McCom as et al, Nature, 2009)



Where a smooth and mostly continuous ENA flux image was expected...

… people found a pronounced “ribbon” structure, where much more ENAs are produced than expected

- ribbon ≃ 2*background
- Ribbon has a detailled substructure (“knots”)
- Ribbon appears almost exclusively at high energies (i.e. > 1 keV)

ENA production

- The primary microphysical source for keV ENAs is resonant charge exchange with energetic ions.

$$p^* + n \to n + p^*$$

$$f_{ENA}(v) \propto n_p^*(v) n_n(v) \sigma(v)$$

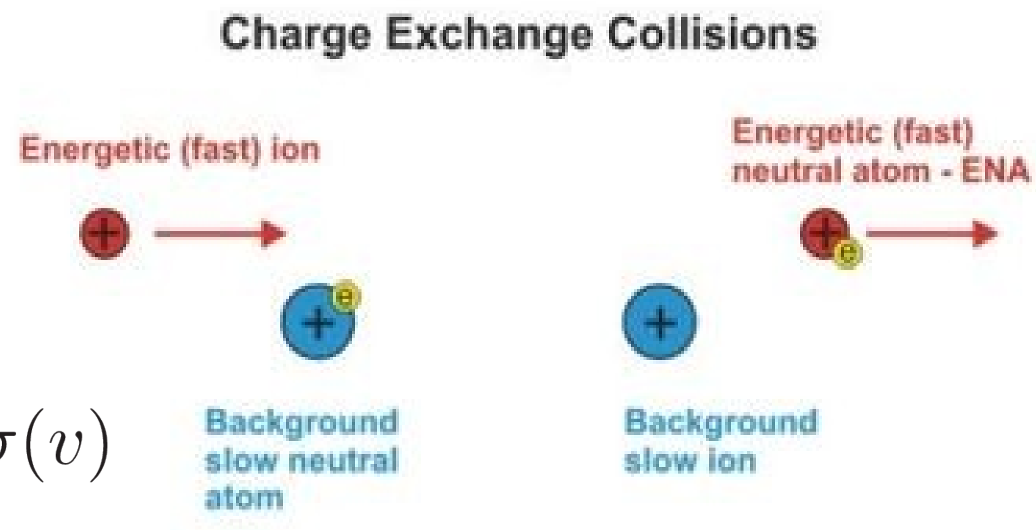


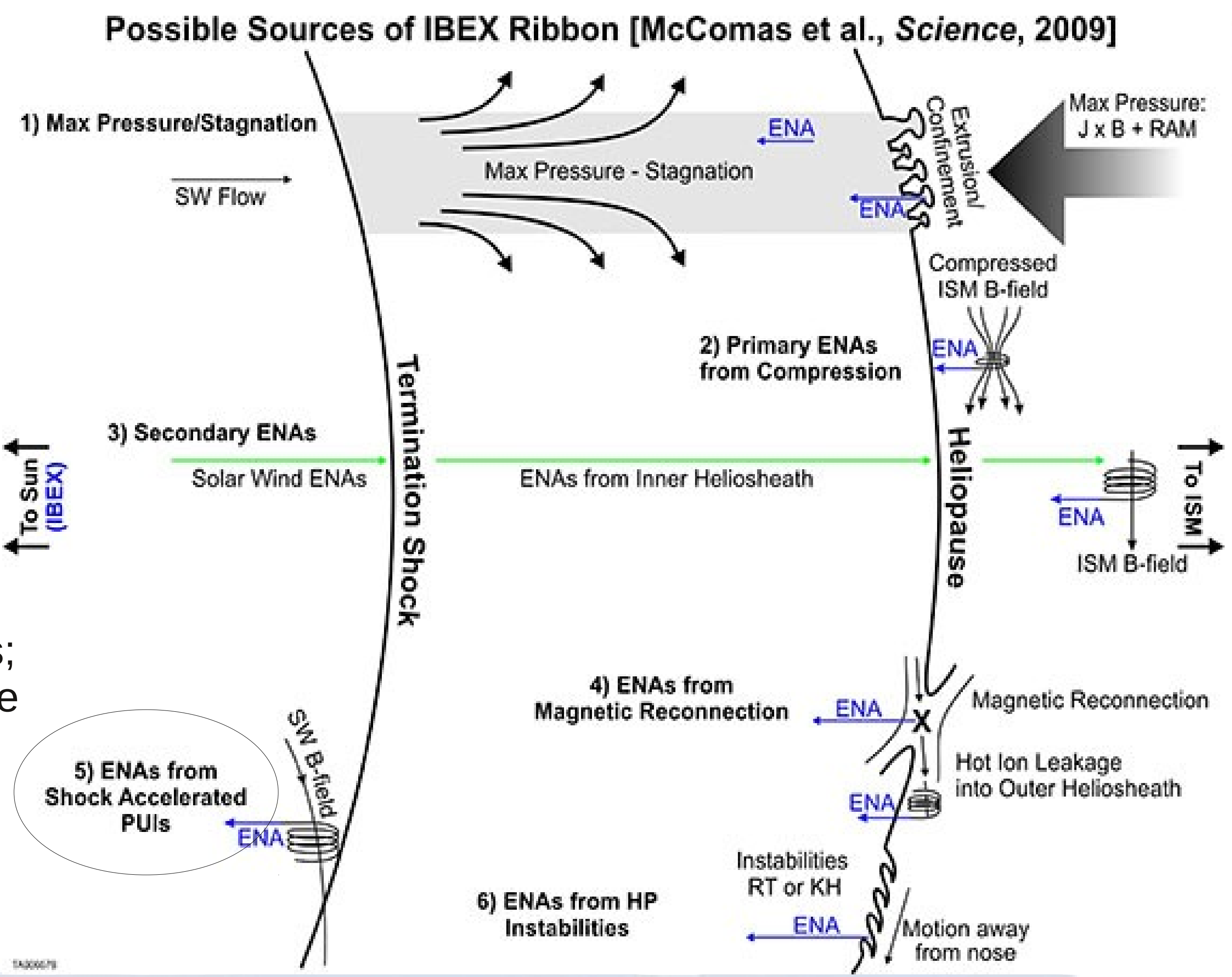
Image: Wikipedia/M. Gruntmann

- Energy and momentum are essentially conserved, so we need keV energetic ions to produce keV ENAs (experimentally not well covered)

Pick-up ions

There are many ideas how to explain the “ribbon” feature.

We study pick-up ions, since they do not need any complicated physics; they just happen to come at the right energies



Direct and indirect pickup ions

Fahr et al., 2009

- There are two different contributions to the PUI regime on the upstream side:
  - direct/”native” PUIs
  - Indirect PUIs, produced from cooled down ACRs

$$f_{pui}(v,r) = \frac{\Lambda}{2\pi} n_{p,E} U^2 (\frac{r_E}{r}) v^{-5} H(U-v) + \frac{1}{9\pi} p_{pui}^3 f_{const}^{ACR} v_{pui} v^{-4}$$

- direct PUIs are never faster than the solar wind → **upstream** PUIs do not contribute to the ribbon due to a frame-of-reference effect
- Indirect PUIs follow from ACRs that have cooled down

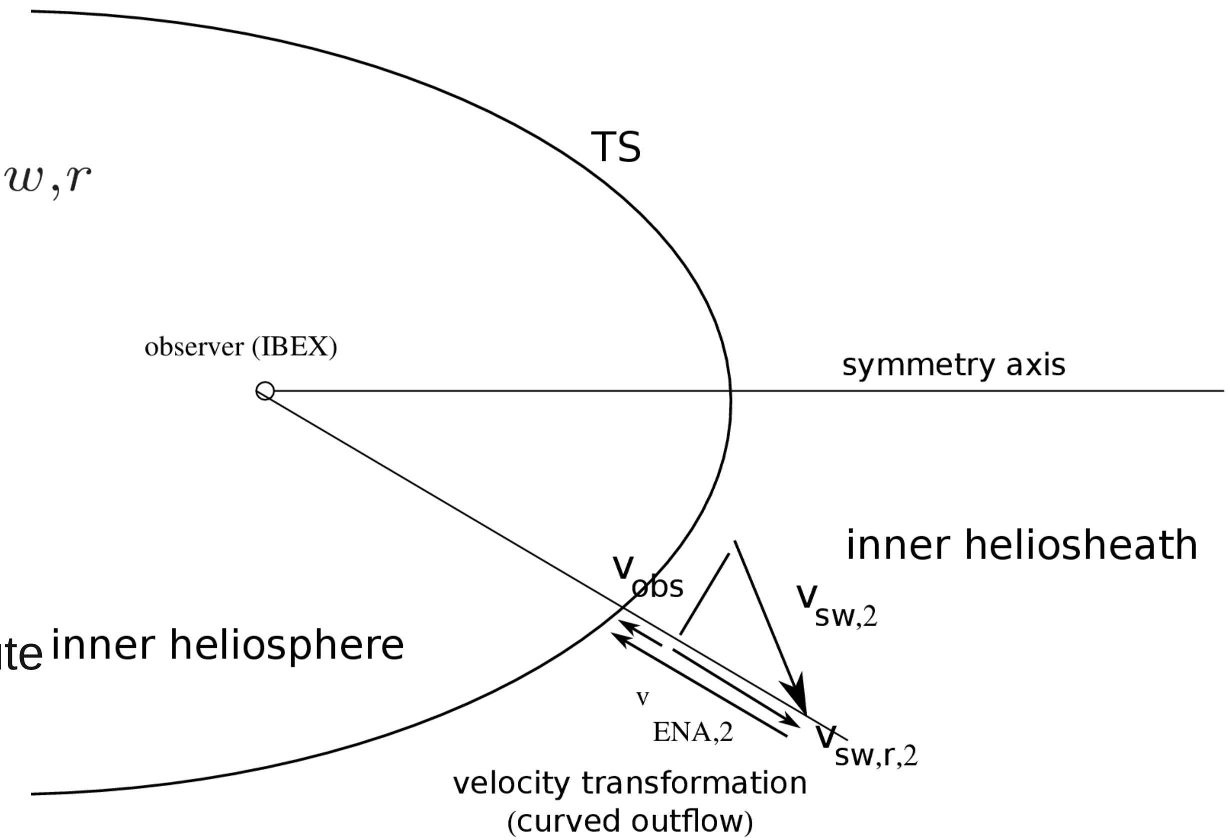
The frame-of-reference effect

- The distribution funtion is derived in the rest frame co-convected with the solar wind, and velocities need to be transformed into the observers rest frame

$$v_{obs} = v_{ENA} - v_{sw,r}$$

...so, between the upstream and downstream sides, the ENAs originate in different regions of the distribution function.

→ direct PUIs do conbtribute to ENA fluxes (and indeed, they **dominate** the fluxes)



The downstream distribution function

- We need a way to transform the upstream function into a downstream one (see Siewert & Fahr 2008, Fahr & Siewert 2010):

$$f_2(v_2) = sC^{-3/2}(s,\theta) f_1\left(\frac{v_2}{\sqrt{C(s,\theta)}}\right)$$

$$C(s,\theta) = \frac{2}{3}\sqrt{G(s,\theta)} + \frac{1}{3}\frac{s^2}{G(s,\theta)}$$

$$G(s,\theta) = \cos^2\theta + s^2\sin^2\theta$$

This is based on a conservative kinetic model for the shock, assuming that:
- Most stochastic processes are not significant
- The magnetic moment is conserved during the shock passage
- The system is always isotropic (i.e. pitchangle isotropisation is sufficiently fast)

Result: downstream ions are heated strongly enough to overcome the frame-of-reference effect, and thus contribute to ENA fluxes.

The line-of-sight integral

- Within the framework of this process, energetic ENA intensities follow from a line-of-sight integral between the termination shock and the heliopause:

$$I_{tot} \propto \int_{r_{TS}}^{r_{HP}} v^2 f_{ENA} dr$$

  - We need a model for the termination shock geometry and the heliopause geometry

    → Borrmann & Fichtner (2005), Fahr, Scherer & Potgieter (2008) for the termination shock

    → Fahr & Fichtner (1991) for the heliopause, and the radial solar wind speed

Properties of the integral

- For the -5 power law, an analytical solution of the integral exists (but it is quite non-nice; Siewert et al. 2011, under review)

$$I \propto \left[\bar{r} \frac{(3a\bar{r}^2 + 4b)^2 - (a\bar{r}^2 - b)^2 - ab\bar{r}^2}{8a^3(a\bar{r}^2 + b)^2} \right]_{\bar{r}_1}^{\bar{r}_2}$$

$$- \frac{15\sqrt{\frac{b}{a}}}{8a^3} \arctan\left(\sqrt{\frac{a}{b}} \frac{\bar{r}_2 - \bar{r}_1}{1 + \frac{a}{b}\bar{r}_1\bar{r}_2} \right)$$

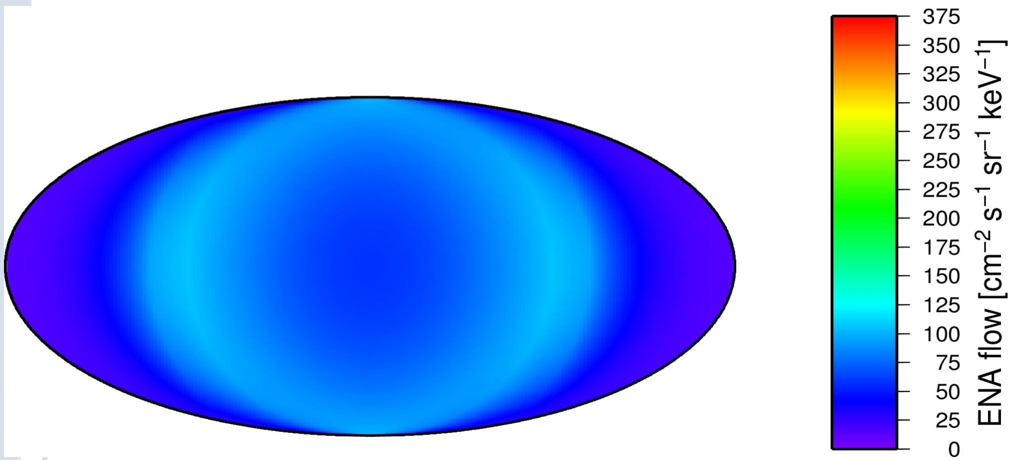
In first order, this integral is proportional to the length of the line-of-sight, i.e. the distance between the TS and the HP.

$$I \approx \alpha(r_2 - r_1) + \beta$$

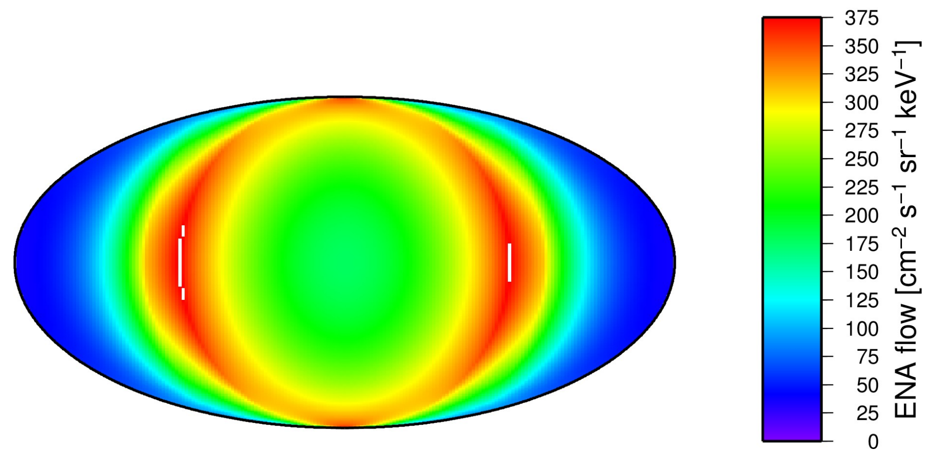
$$a = a(v_{sw}, v_{obs}) \qquad b = b(v_{sw})$$

ENA fluxes from the downstream side of the TS (1 keV)

- For constant solar wind speed, this results in a ring-like feature at the boundary between the nose and the tail.
- The order of magnitude is correct; for the fast solar wind, we reach the observed fluxes within a factor of 2.
- The relative size between the feature and the “background” is also very close to observations

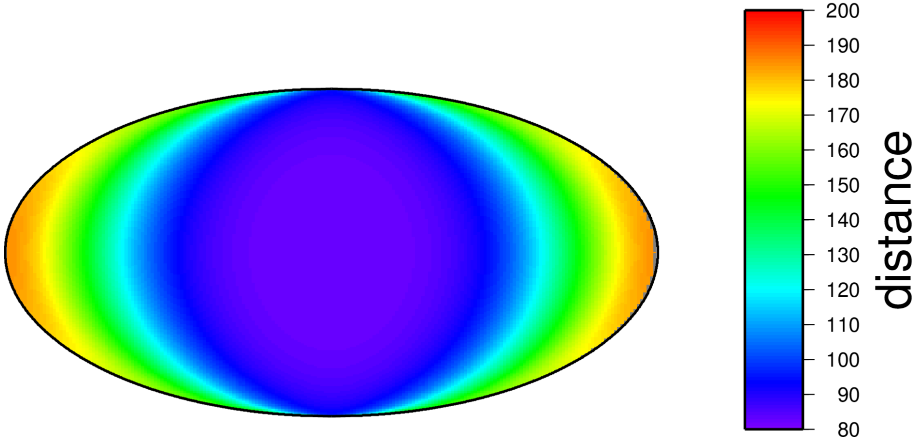


Slow solar wind

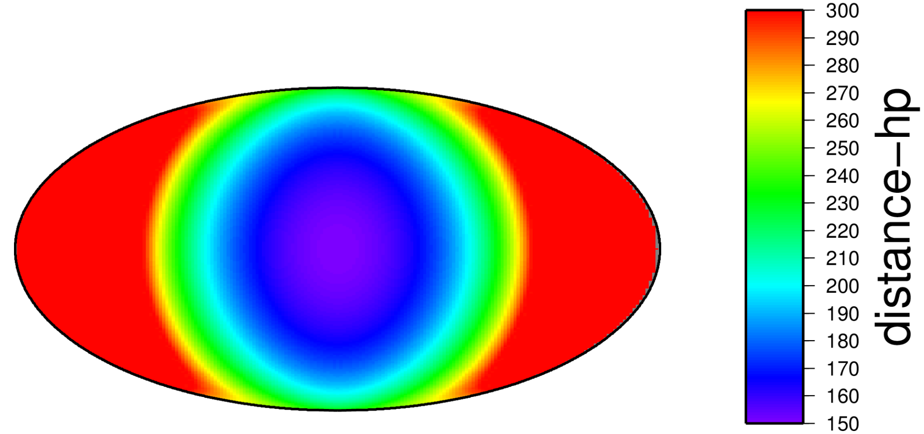


Fast solar wind

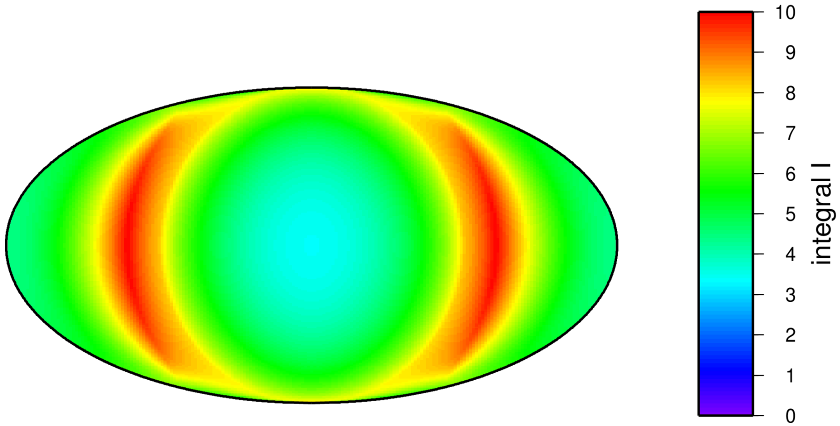
Can we understand this behavior?



Distance to the TS



Distance to the HP



Contribution due to the line-of-sight integral

Conclusion: There is a narrow, ring-like region where the heliospheric model strongly favors an enhanced ENA production.

This correlates to a region of a locally thicker inner heliosheath.

Conclusions and outlook

- There is an encouragingly good match between our model (shock-heated pick-up ions) and the ENA fluxes observed by IBEX.
- More work is required to refine the heliospheric models used in this prediction.
- Spectral properties of the ENA flux spectra are currently under investigation
- The model is quite sensitive to heliospheric parameters, such as the solar wind speed and the location (and stationarity) of the termination shock.
- Maybe it is possible to trace the precise shape of the outer heliosphere using ENAs. This would allow to test existing (and partially conflicting) models of the outer heliosphere using real-world data. (Work in progress/Proposal under constructuion)

Thank you for your attention!