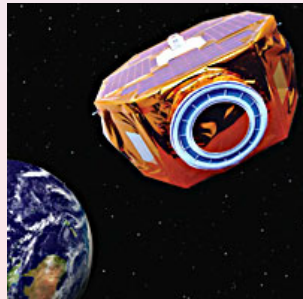


# IBEX - The Heliosphere at Solar Minimum

Horst Fichtner and Hans Fahr



# The Interstellar Boundary EXplorer

Horst Fichtner and Hans Fahr





# IBEX Team: USA, SWI, GER, POL, RUS

**PI:** Dave McComas

<b>Co-I's:</b>	Peter Bochsler	Maciej Bzowski	Hans Fahr
	Horst Fichtner	Priscilla Frisch	Herb Funsten
	Steve Fuselier	Mike Gruntman	Vlad Izmodenov
	Paul Knappenberger	Marty Lee	Stefano Livi
	Don Mitchell	Eberhard Möbius	Tom Moore
	Ed Roelof	Nathan Schwadron	Peter Wurz
	Gary Zank		

<b>Collab.:</b>	Frederic Allegrini	Mike Collier	George Gloeckler
	David Hollenbach	Dan Reisenfeld	Martin Wieser
	Manfred Witte		

# What the talk is (not) about

This talk...

... is about particles with less than 6 keV

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So, one question to be answered is:

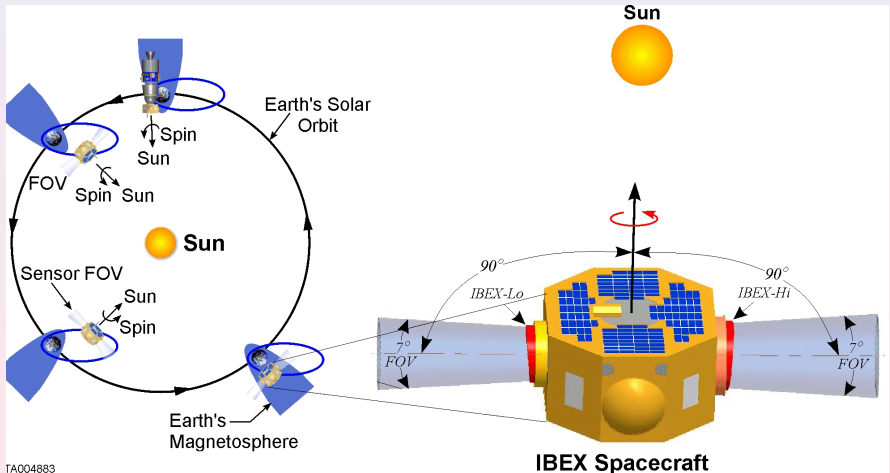
**What is the relevance for cosmic ray physics?**

# Outline

- Mission Overview
- Energetic Neutral Atoms
- Pre-launch Modelling: Predictions
- The Real World: IBEX Observations!
- Post-Launch Modelling: Explanations...?
- Summary

# *Mission Overview*

# The IBEX Orbit

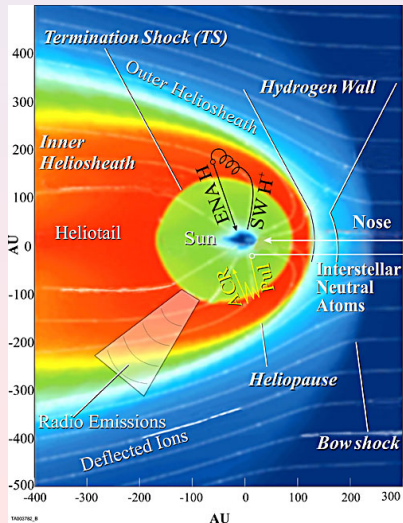


*Measurements of Energetic Neutral Atoms (ENAs) with 0.01 – 6 keV*

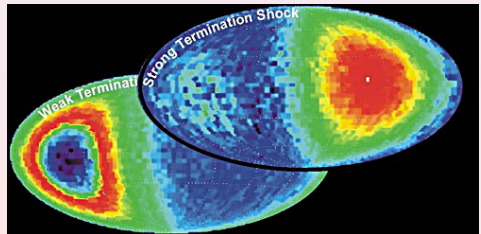


# The IBEX Measurements - Here: ENAs

**Idea:** Measurements of Energetic Neutral Atoms (ENAs) originating in the outer heliosphere...



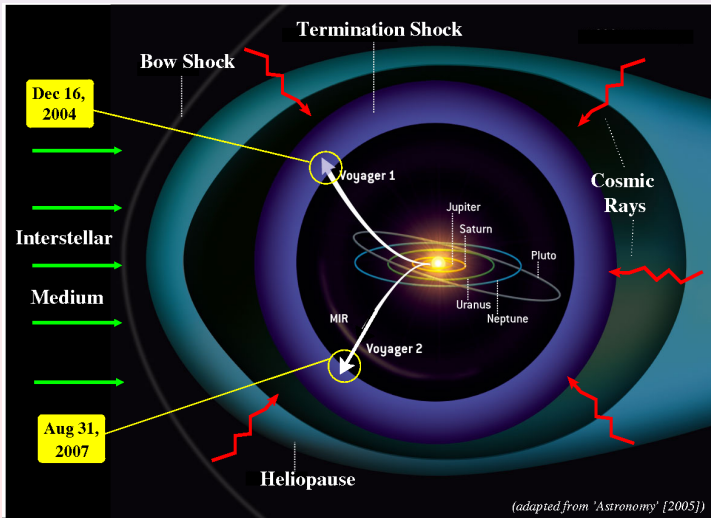
... arriving at Earth from all directions result in all-sky flux maps:



NAs not covered in this talk.

# Why IBEX...

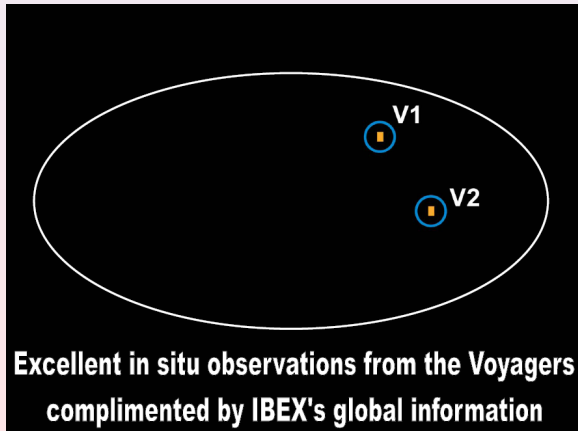
... while the Voyager twins are not only 'alive' but are presently even located within the (inner) heliosheath?



Voyager 1 & 2 have reached the boundary region of the heliosphere...

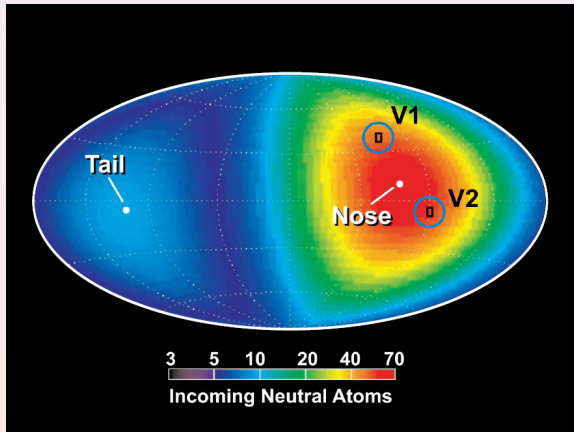
# Why IBEX...

... while the Voyager twins are not only 'alive' but are presently even located within the (inner) heliosheath?



# Why IBEX...

... while the Voyager twins are not only 'alive' but are presently even located within the (inner) heliosheath?



IBEX provides the first maps of the entire (!) outer heliosphere over (hopefully) many years



IBEX measurements are not localized in space and time

# The IBEX Science Objectives

**General:** (Remote) Exploration of the global interaction between the solar wind and the interstellar medium

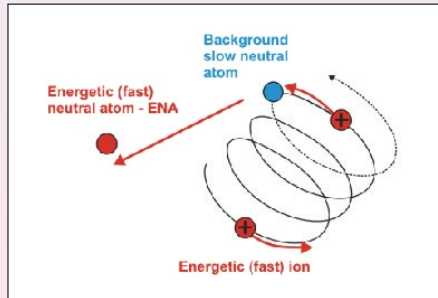
***Specific Questions:***

- What is global strength and structure of the termination shock?
- How are energetic protons accelerated at the termination shock?
- What are the global properties of the solar wind flow beyond the termination shock and in the heliotail?
- How does the interstellar flow interact with the heliosphere beyond the heliopause?

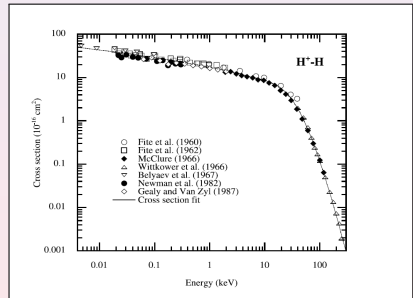
# *Energetic Neutral Atoms (ENAs)*

# Energetic Neutral Atoms (ENAs)

Charge transfer process:

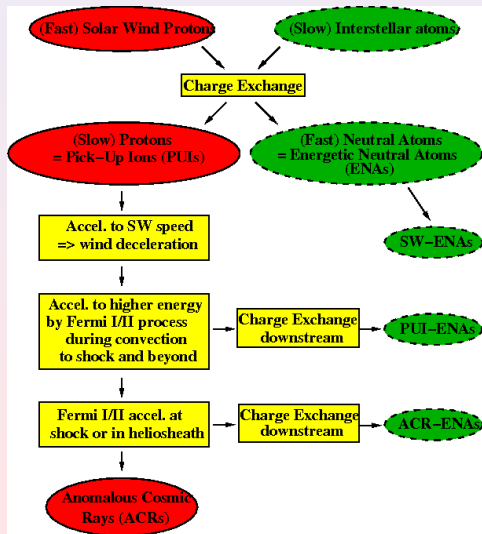
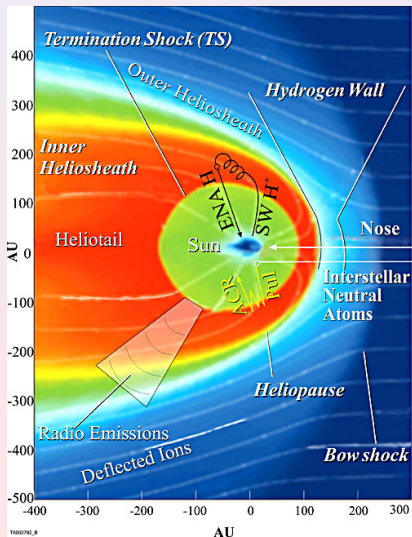


Cross sections (laboratory):



*Lindsay & Stebbings [2005]*

# Heliospheric ENAs





# Heliospheric ENAs: Theoretical Description

**Differential production rate:**

$$\Psi_{\text{ENA},p}(\mathbf{r}, v_{\text{ENA}}, \tau) = \left( n_p f_p(v_p) n_H \sigma_{\text{ex}}(v_{\text{rel}}) v_{\text{rel}} \right) \Big|_{\mathbf{r}, \tau}$$

**SW velocity  $\kappa$ -distribution: (= Maxwellian for  $\kappa = \infty$ ):**

$$f_p(\mathbf{v}) = \frac{n_p}{\pi^{3/2} \Theta_p^3} \frac{1}{\kappa^{3/2}} \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \left[ 1 + \frac{1}{\kappa} \frac{(\mathbf{v} - \mathbf{u}_p)^2}{\Theta_p^2} \right]^{-(\kappa+1)}$$

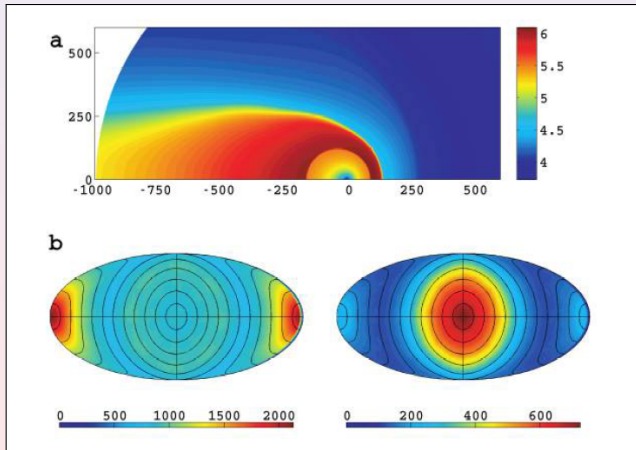
**Differential ENA flux:**

$$\Phi_{\text{ENA},p}(v_{\vartheta,\varphi}, \vartheta, \varphi, t) = \frac{1}{4\pi} \int_{\text{IB}}^{\text{OB}} \Psi_{\text{ENA},p}(\mathbf{r}, v_{\text{ENA}}, \tau) \, ds$$

(to be corrected for losses, see, e.g., Bzowski [2008])

# *Pre-Launch Modelling: Predictions*

# SW-ENA Fluxes: Axisymmetric 2-D Heliosphere



*Heerikhuisen  
et al. [2007]*

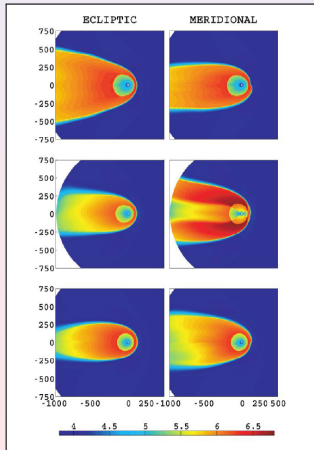
(Aitoff-Hammer  
projection)

50 eV

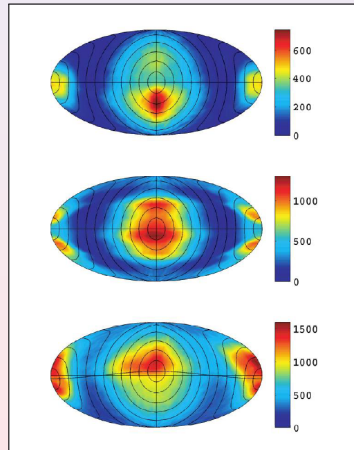
200 eV

# SW-ENA Fluxes: 3-D Heliosphere

... shaped by the (local) interstellar magnetic field:



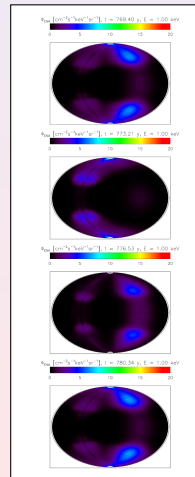
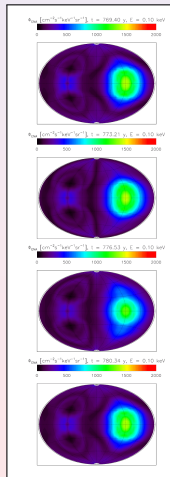
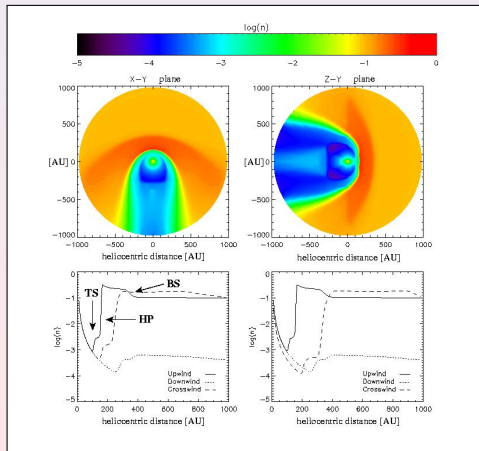
*Heerikhuisen et al. [2007]*



200 eV

# SW-ENA Fluxes: Time-dependent 3-D Heliosphere

*Scherer & Fahr [2003]* – due to solar activity  
*Borrmann & Fichtner [2005]*



100 eV

1 keV

*Sternal et al. [2008]*

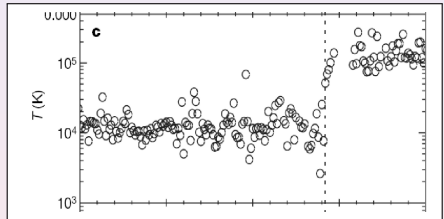
# ENA Fluxes: Post-V2 Shock Encounter Era

## *V2 measurements suggest:*

- SW temperature by a factor of  $\sim 10$  lower than expected
- PUIs 'absorbing' 80% of converted kinetic SW energy

## *Then:*

- SW-ENA fluxes should be lower than computed so far
- ENA fluxes above 1 keV clearly dominated by PUIs

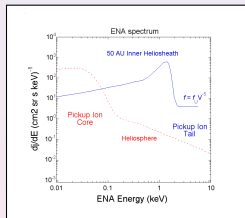


## *However:*

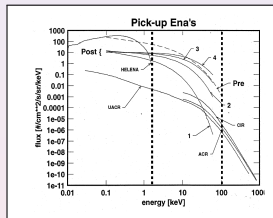
- no self-consistent model for this case yet
- heliospheric structure, particularly thickness of heliosheath unknown

# ENA Spectra: Numerous Predictions...

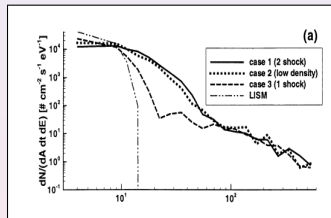
Gloeckler et al. [????]



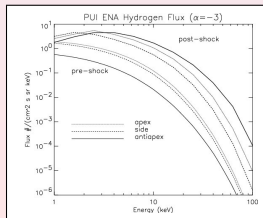
Fahr et al. [2000]



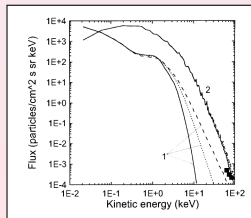
Müller et al. [2000]



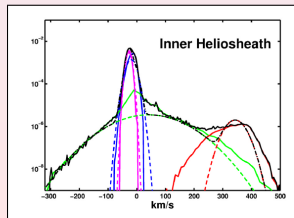
Czechowski et al. [2001]



Chalov et al. [2004]

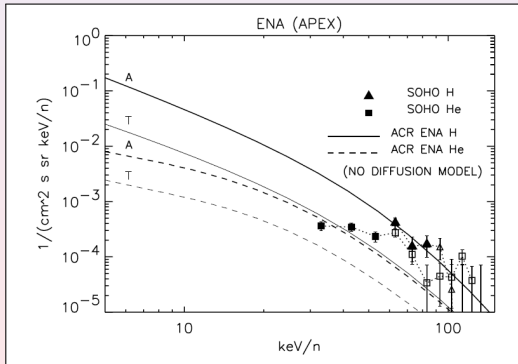


Heerikh. et al. [2007]

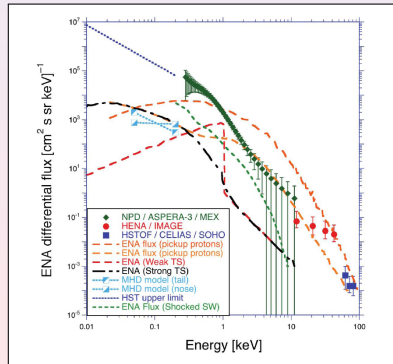


# ... and a few Pre-IBEX Measurements

Czechowski et al. [2005]: SOHO



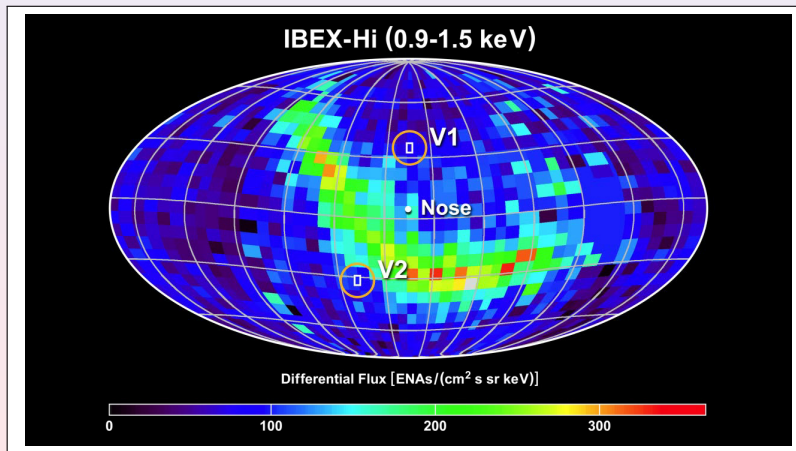
Wurz et al. [2008]: ASPERA





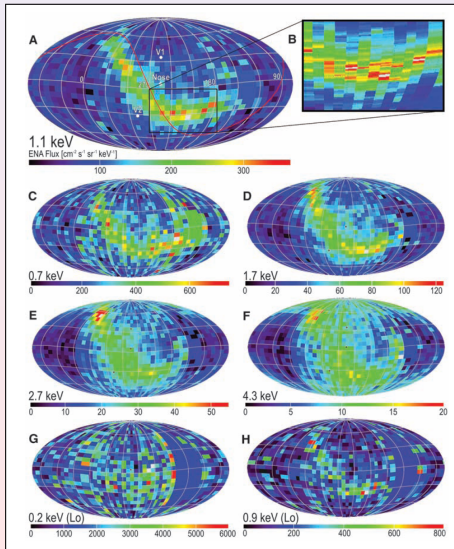
# *The Real World: IBEX Observations!*

# ENA Fluxes: An Unexpected 'Ribbon'



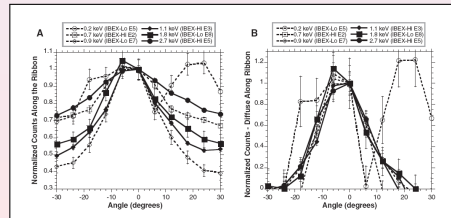
*McComas et al. [2009]*

# ENA Fluxes: An Unexpected 'Ribbon'



the ribbon's

- intensity is energy-dependent
- width is not:

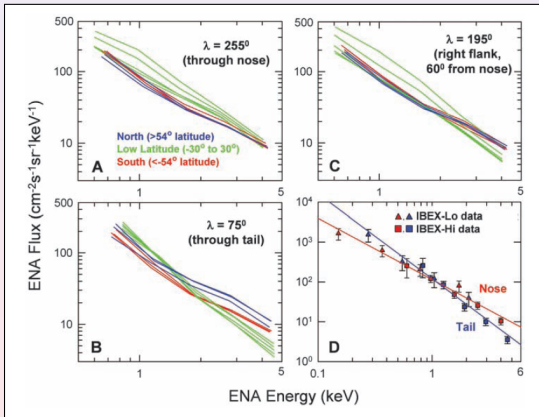


*Fuselier et al. [2009]*

*McComas et al. [2009]*

# ENA Spectra: An Expected Behaviour

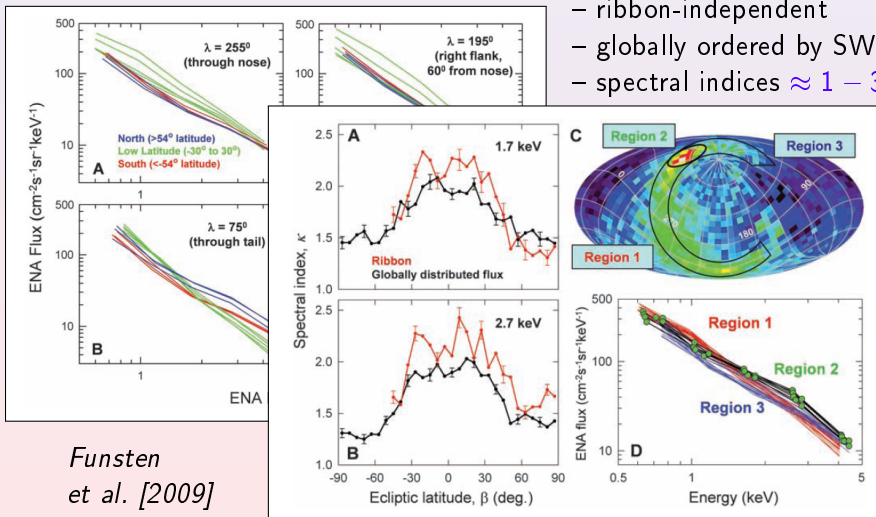
- ribbon-independent
- globally ordered by SW
- spectral indices  $\approx 1 - 3$



*Funsten  
et al. [2009]*

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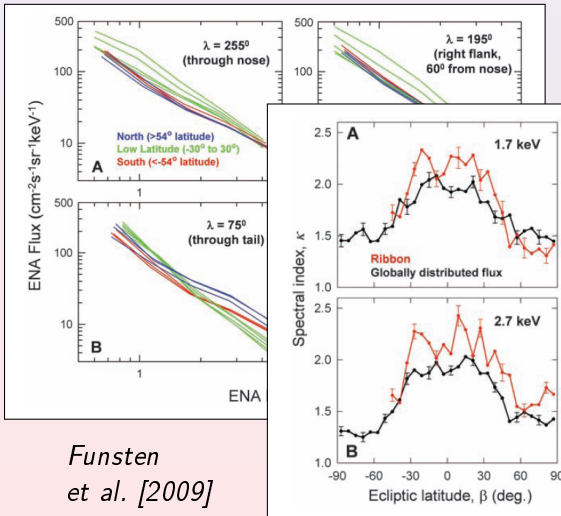
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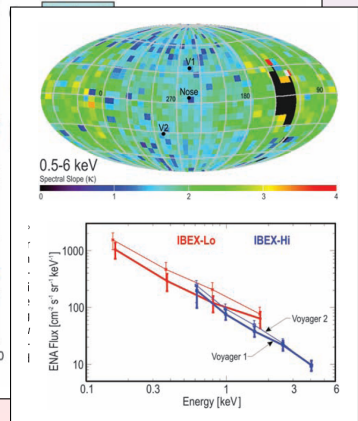
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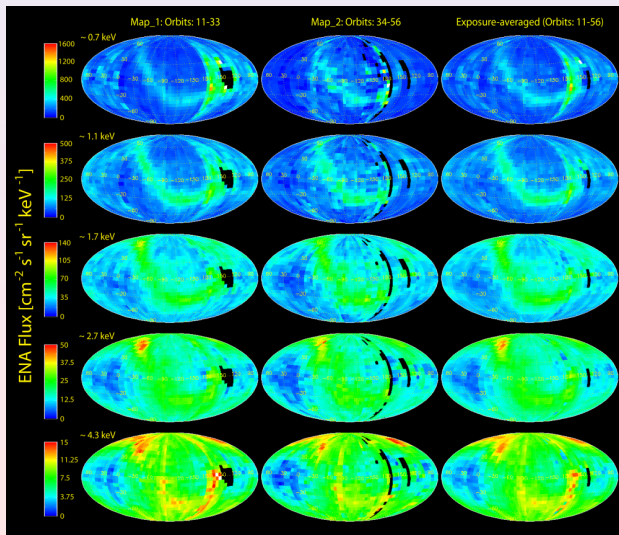


Funsten  
et al. [2009]



# Time-Dependence of the ENA fluxes?

first 6 months  $\approx$  second 6 months combined



0.7 keV

1.1 keV

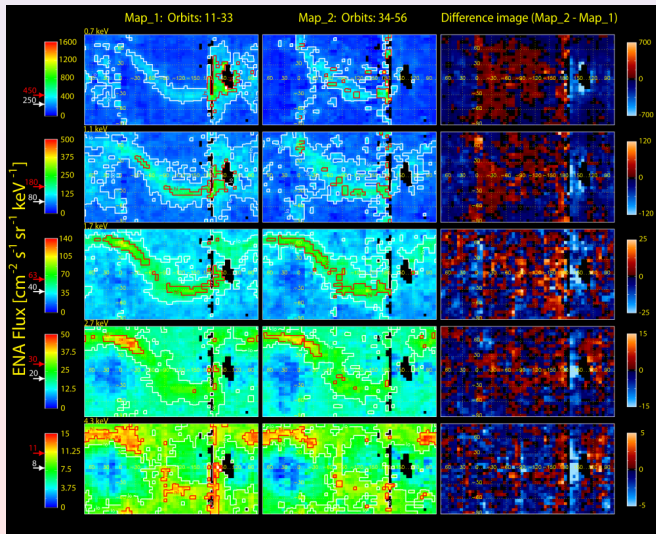
1.7 keV

2.7 keV

4.3 keV

# Time-Dependence of the ENA fluxes?

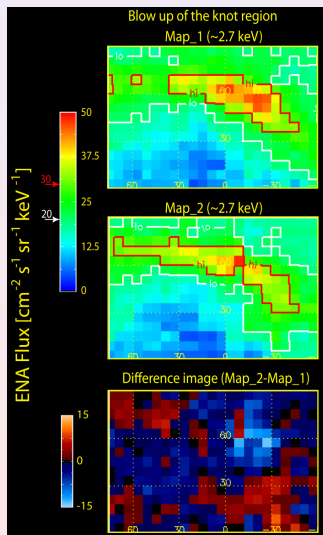
first 6 months  $\neq$  second 6 months      difference



- 'global' time dependence?
- small-scale fluctuations
- motion of ribbon?



# Time-Dependence of the ENA fluxes?



first 6 months

second 6 months

- 'local' time dependence:  
knot region fading

# Summary of Observations

- general 'background' variation of flux and spectra as expected:
  - latitudinal ordering by solar wind ↔ 'minimum' heliosphere
  - longitudinal ordering by heliospheric geometry ↔ heliotail

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  - thickness of heliosheath 15–36 AU ↔ asymmetric heliosphere  
(Cassini ENA measurements indicate greater thickness)

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- 'ribbon' of increased ENA fluxes: ↔ interstellar magnetic field
  - energy-dependent intensity
  - energy-independent width

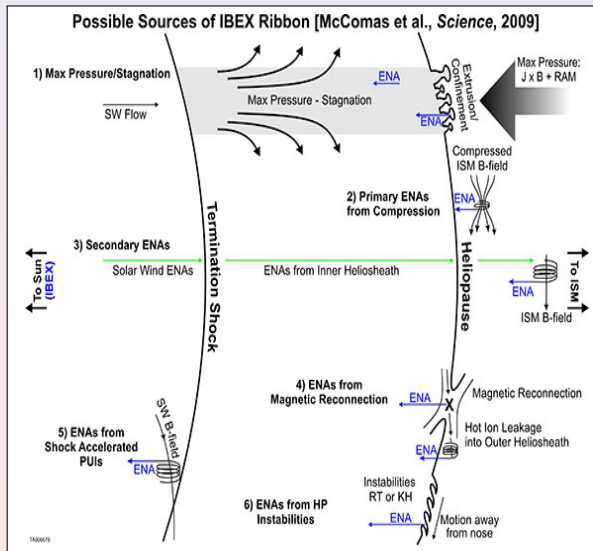
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(Cassini ENA measurements indicate greater thickness)
- 'ribbon' of increased ENA fluxes: ↔ interstellar magnetic field
  - energy-dependent intensity
  - energy-independent width
- (so far weak) time-dependence:
  - of 'global' ENA fluxes (?) ↔ solar activity
  - of 'local' structures ↔ interstellar turbulence/inhomogeneities

# *Post-Launch Modelling: Explanations...*

# First Ideas to Explain the Ribbon

- effect of interstellar magnetic field
- Rayleigh-Taylor-like instabilities of heliopause
- ENA source inside/outside term. shock/heliopause
- reconnection at the heliopause
- ribbon = string of localized, overlapping ENA emission 'knots'
- slow and fast solar wind interaction
- ENA source in Galaxy
- 'cloudlets' in the local interstellar medium

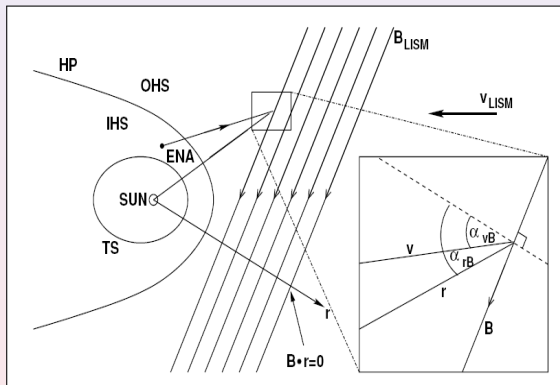


*McComas et al. [2009]; Schwadron et al. [2009]*





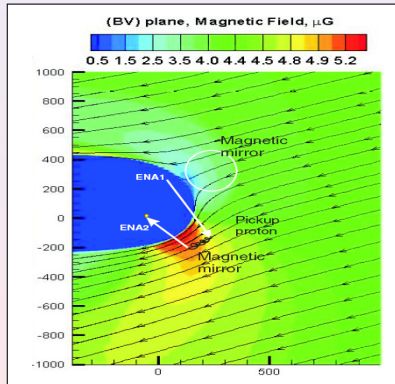
# Interstellar MF & ENA Source Outside Heliosphere



- primary ENA from inner heliosheath
- ionization to interstellar pick-up ion
- re-neutralization to secondary ENA
- formation of ribbon if...
- ... pick-up ions exhibit shell distribution

*Heerikhuisen et al. [2010]*

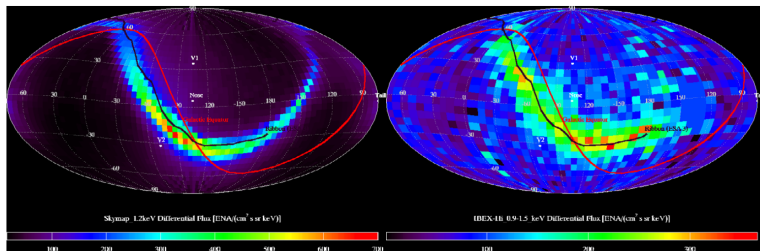
# Interstellar MF & ENA Source Outside Heliopause



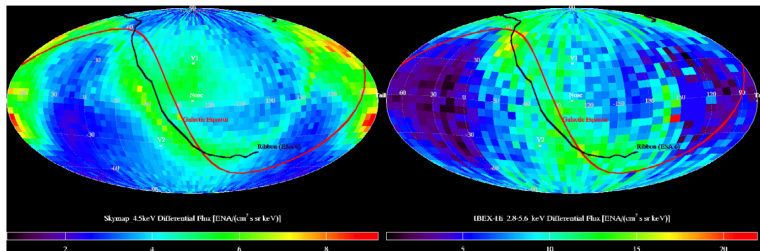
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*Heerikhuisen et al. [2010] – refinement by Chalov et al. [2010]*

# Interstellar MF & ENA Source Outside Heliopause



1.2 keV

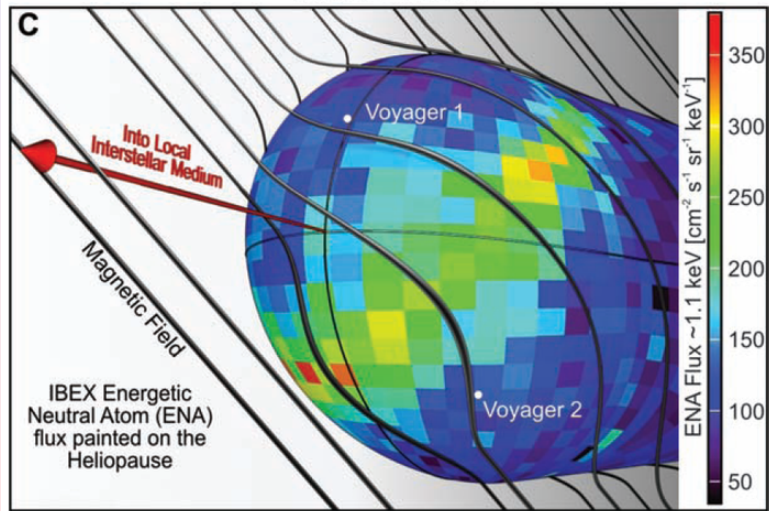


4.5 keV

simulations

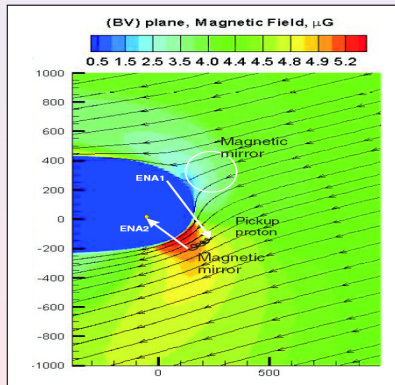
observations

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*McComas et al. [2009]*

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*Heerikhuisen et al. [2010]* – refinement by *Chalov et al. [2010]*

- interstellar turbulence might explain the time-dependence of the ENA fluxes (*Jokipii, private communication, this conference*)

# 'Cloudlets' in the Local Interstellar Medium

Bow Shock Around LL Orionis



Hubble  
Heritage

small-scale  
inhomogeneities  
in the local  
interstellar  
medium...

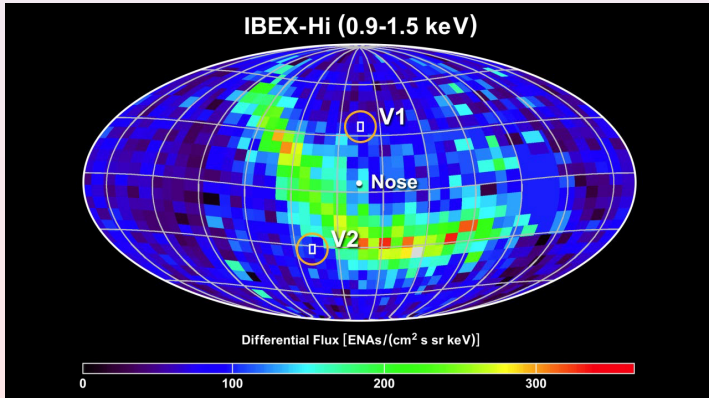
... increase  
neutral density

# *Summary*

# Summary

The IBEX mission provides

- with the ENA all-sky flux maps the first maps of the global (outer) heliosphere

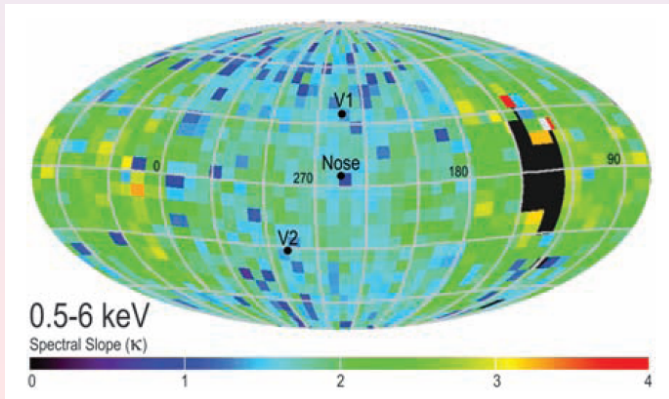




# Summary

The IBEX mission provides

- with the ENA energy spectra detailed information about the suprathermal proton population in the heliosheath



# Summary

The IBEX mission provides

- the structure of the heliosphere, including its variation in time and, thus, valuable implications for astrospheres



# Relevance for Cosmic Ray Physics

The IBEX measurements provide

- significant constraints on the structure of the heliosphere
  - input for cosmic ray modulation & CR-climate connection
- particularly information about the heliosheath
  - input for cosmic ray acceleration processes
- insight into the nature of the (local) interstellar turbulence
  - input for cosmic ray transport