What is New in the Outer Heliosphere?: Voyager and IBEX

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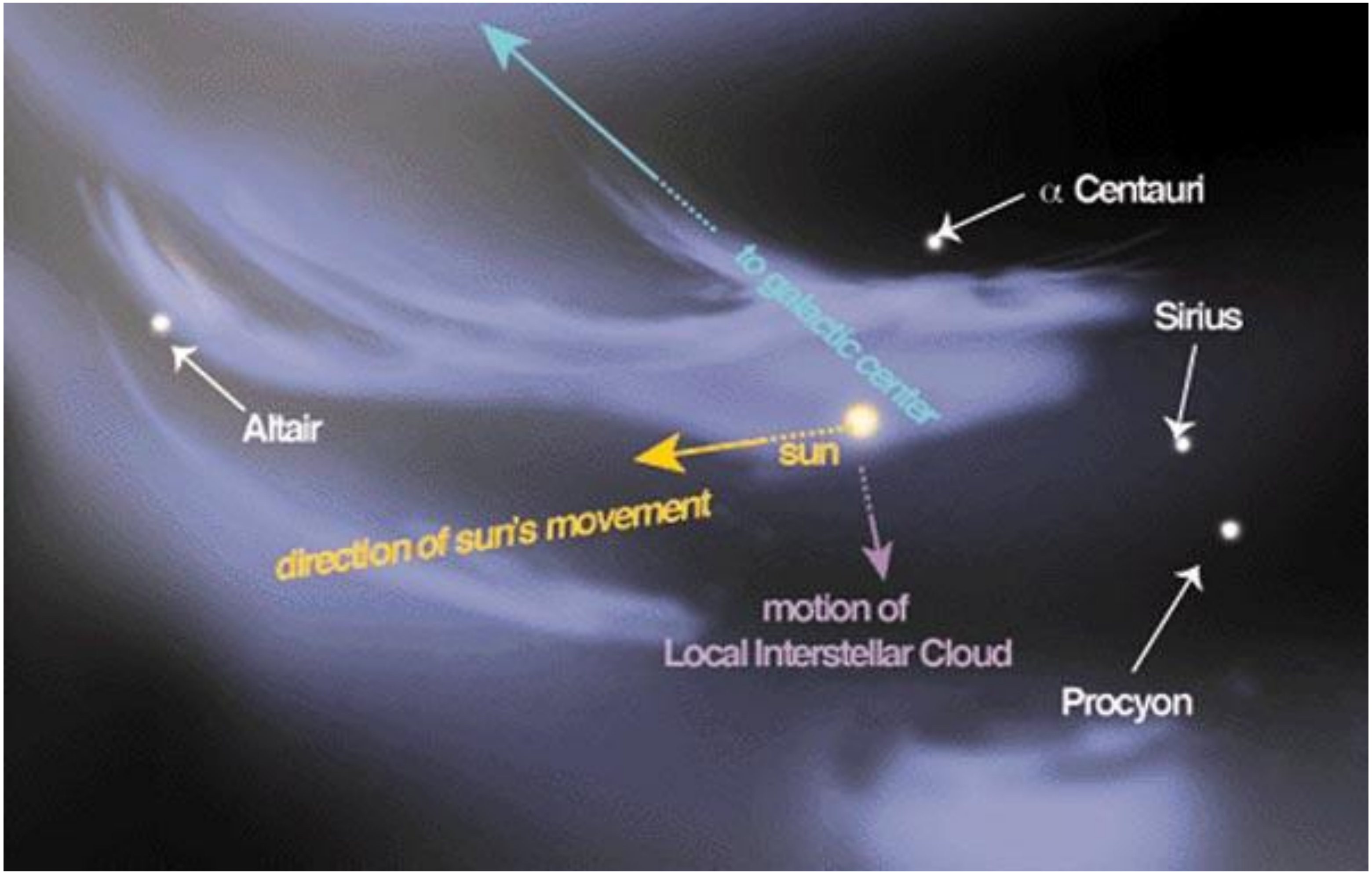
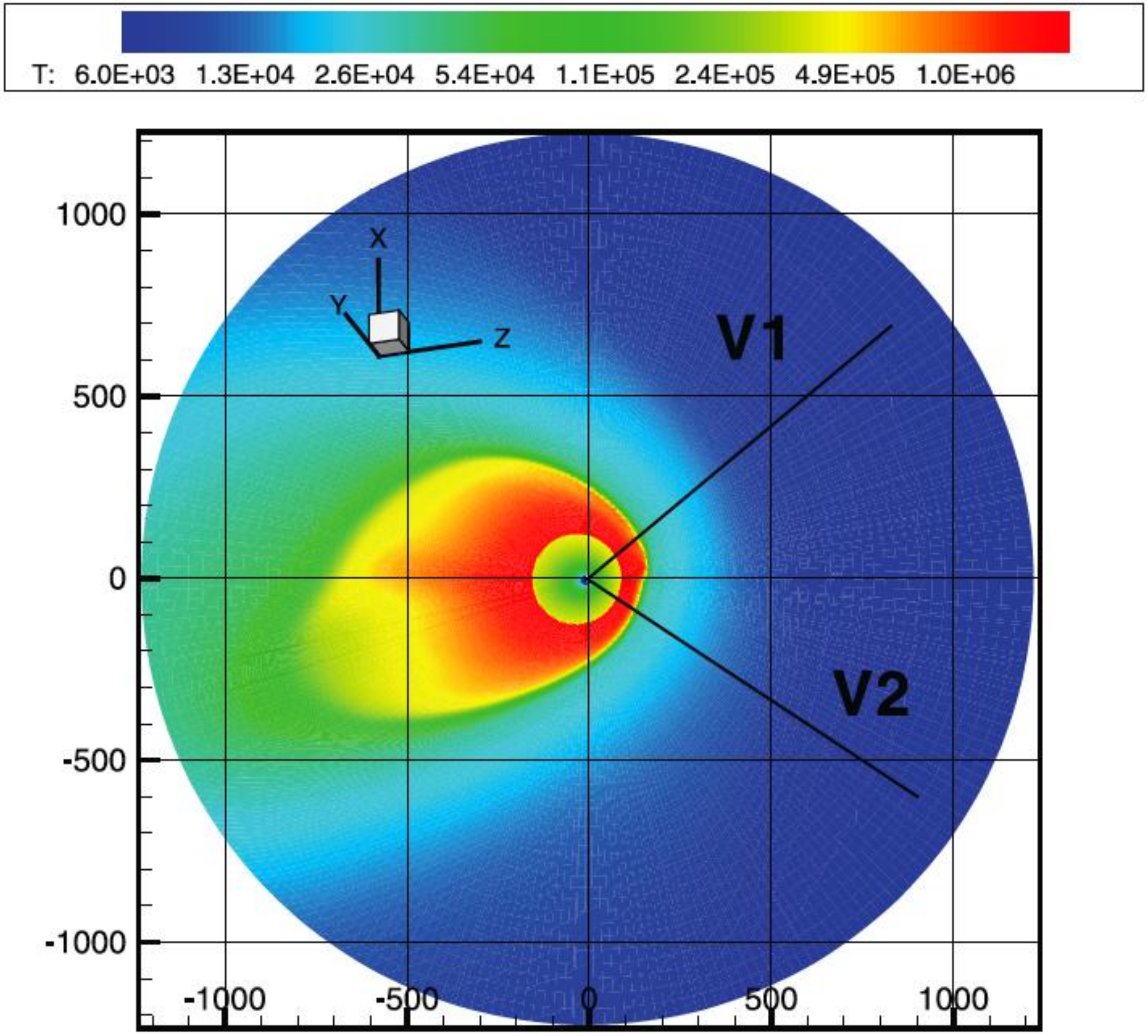
USA

Our Local Interstellar Environment



From E. Möbius

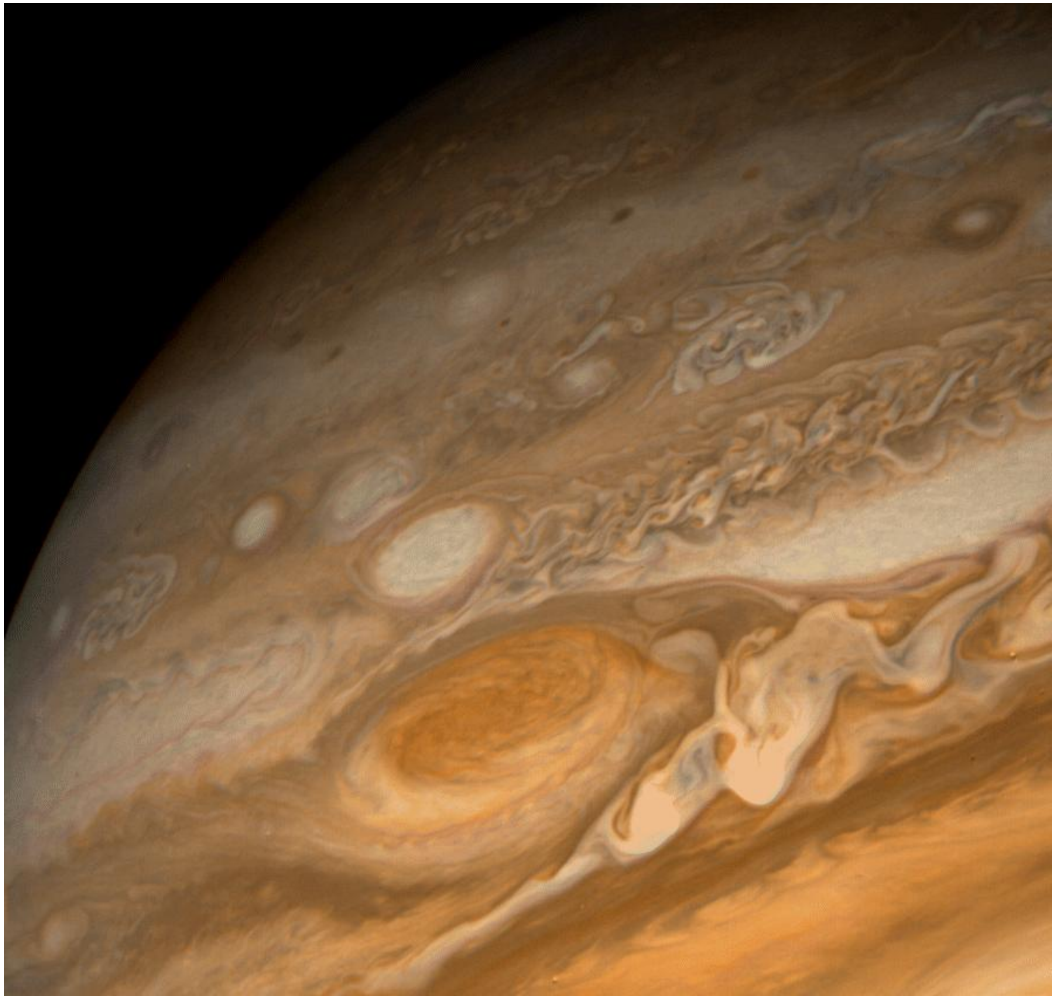


Pogorelov et al., 2008

Plasma & Neutral Parameters

R = 1 AU	R = 100 AU	LISM
$n_p = 5\ \text{cm}^{-3}$	$n_p = 1 \times 10^{-3}\ \text{cm}^{-3}$	$n_p = 0.05\ \text{cm}^{-3}$
$V_{sw} = 400\ \text{km/s}$	$V_{sw} = 300\ \text{km/s}$	$V_{ISM} = 23(?)\ \text{km/s}$
$B_0 = 5 \times 10^{-5}\ \text{G}$	$B_0 = 0.3 \times 10^{-6}\ \text{G}$	$B_0 = 3 \times 10^{-6} (?) \text{G}$
$V_A = 40\ \text{km/s}$	$V_A = 20\ \text{km/s}$	$V_A = 22(?)\ \text{km/s}$
	$n_H = 0.1\ \text{cm}^{-3}$	$n_H = 0.2\ \text{cm}^{-3}$
$n_{He} = 0.015\ \text{cm}^{-3}$	$n_{He} = 0.015\ \text{cm}^{-3}$	$n_{He} = 0.015\ \text{cm}^{-3}$

Voyagers 1&2: Still Exploring!



Voyager Trajectories

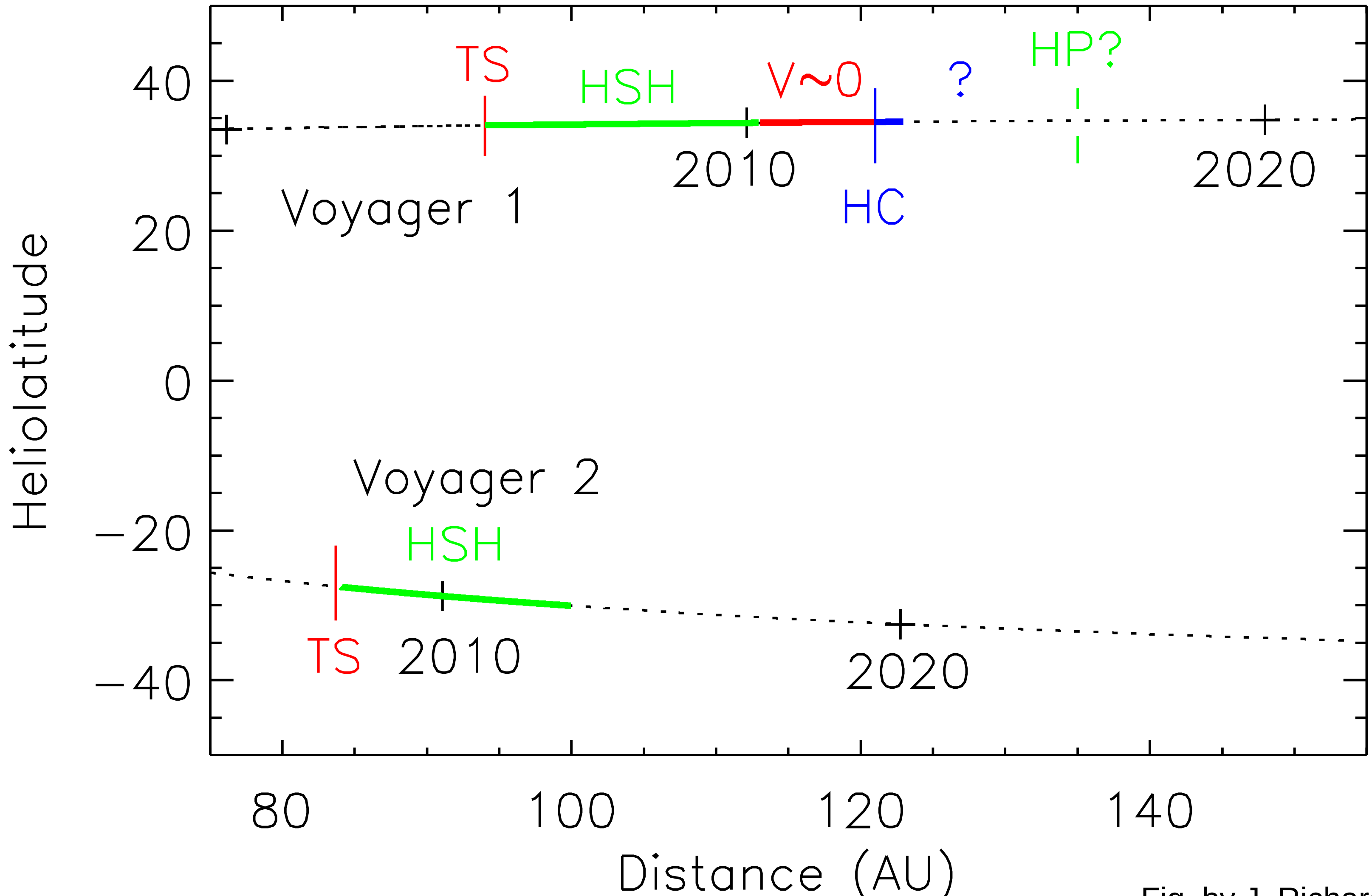
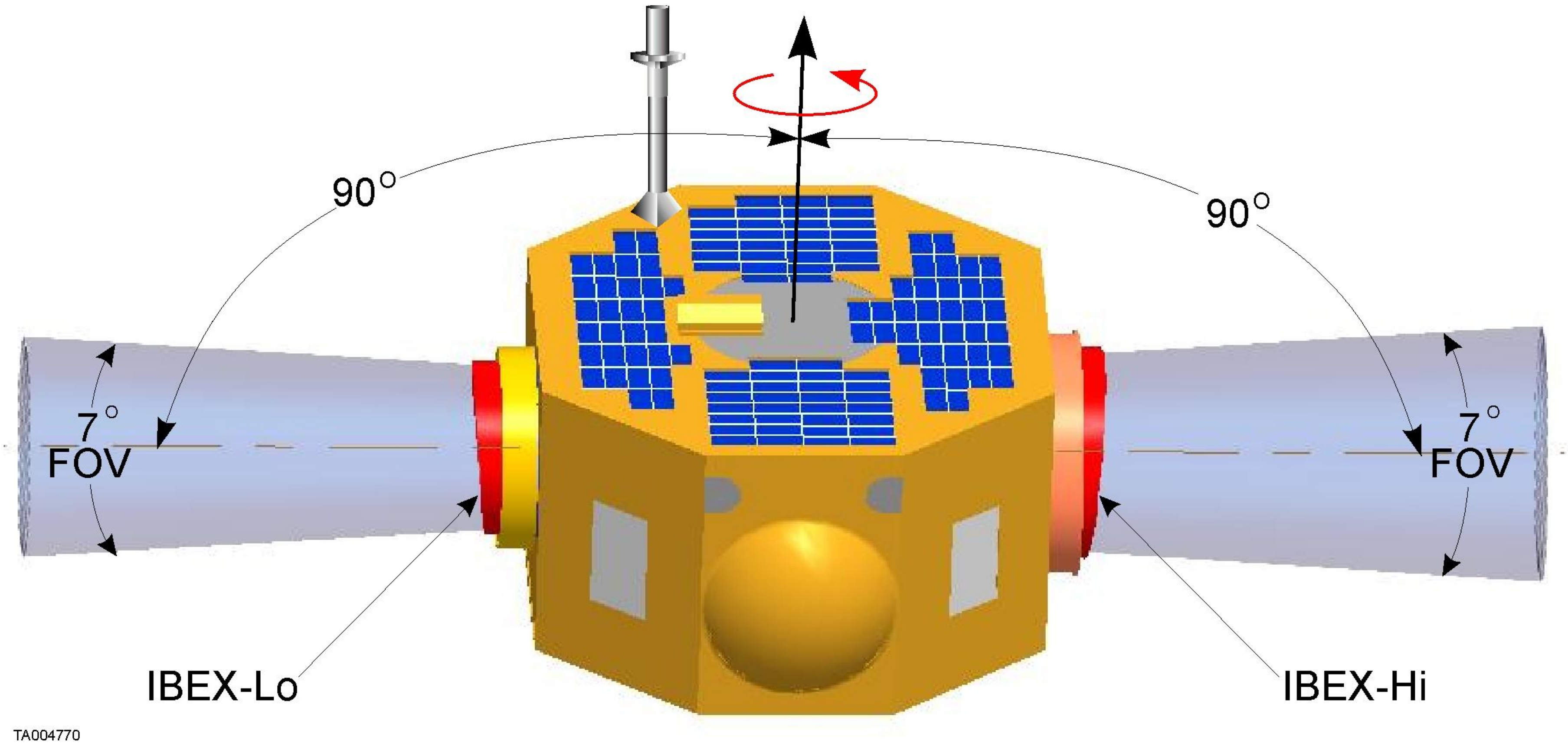


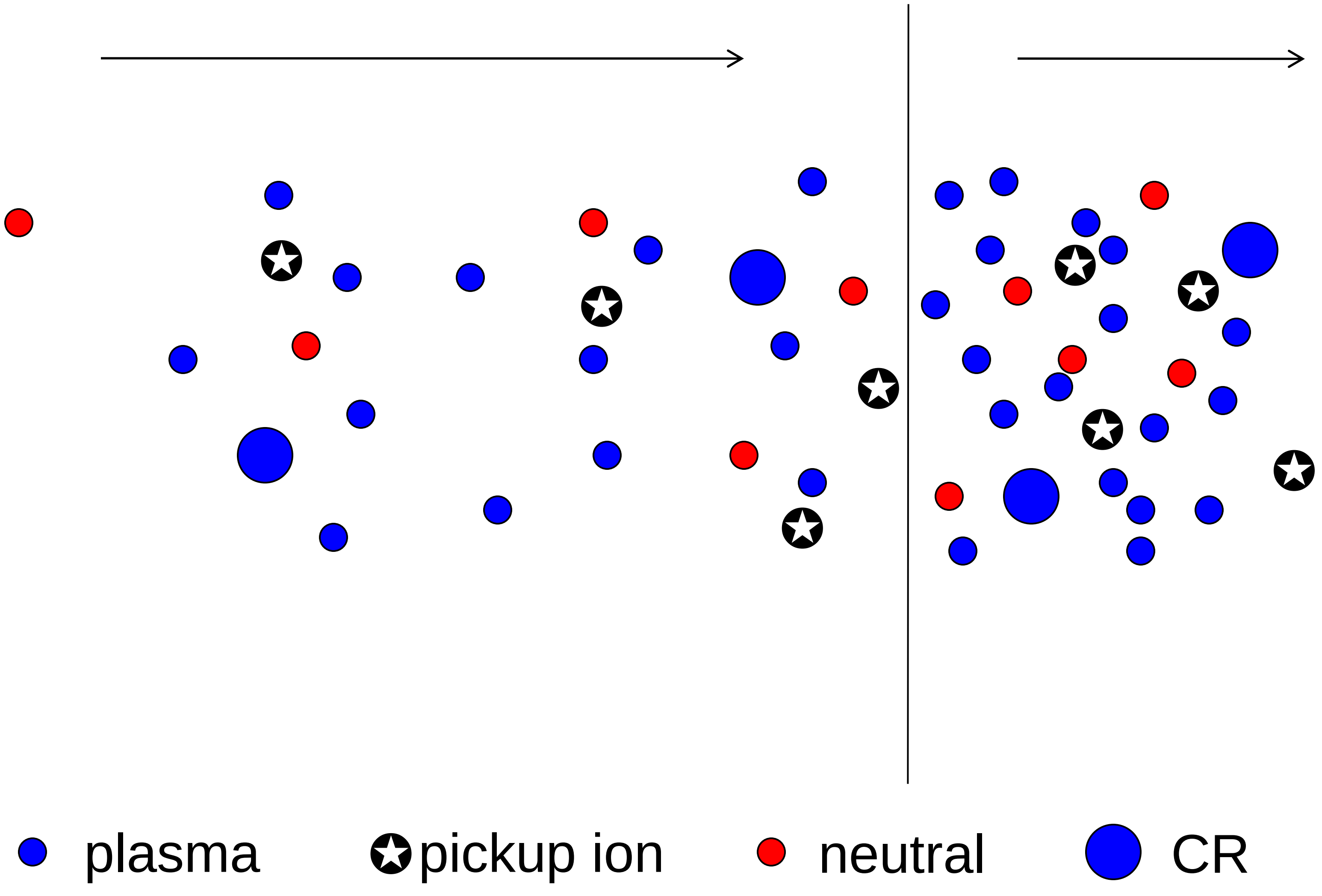
Fig. by J. Richardson

IBEX Spacecraft



- **Simple sun-pointed spinner (4 rpm)**
- **Two huge aperture single pixel ENA cameras:**
  - IBEX-Lo (~10 eV to 2 keV)
  - IBEX-Hi (~300 eV to 6 keV)

Termination Shock is Special



Adventures in the Outer Heliosphere

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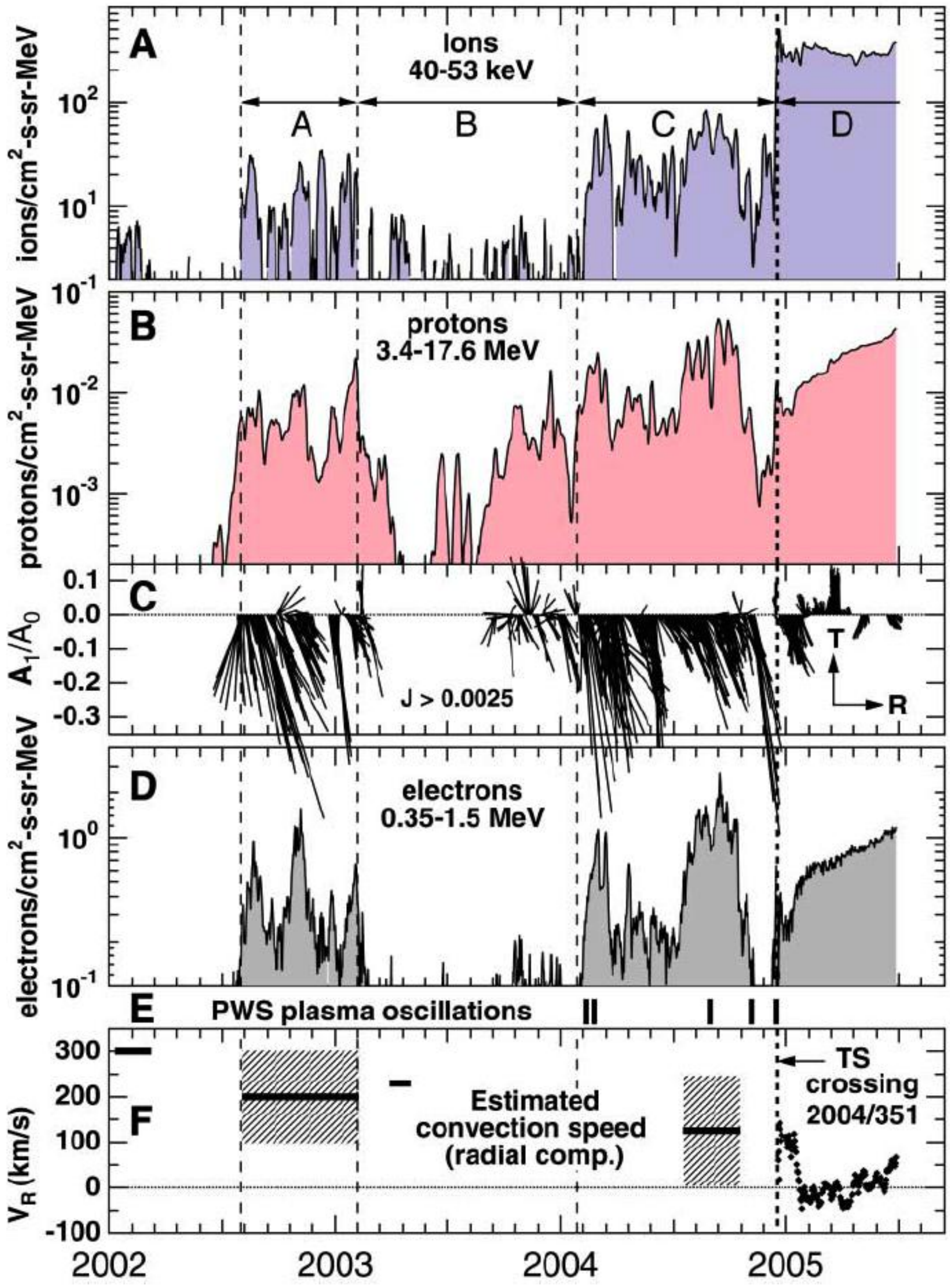
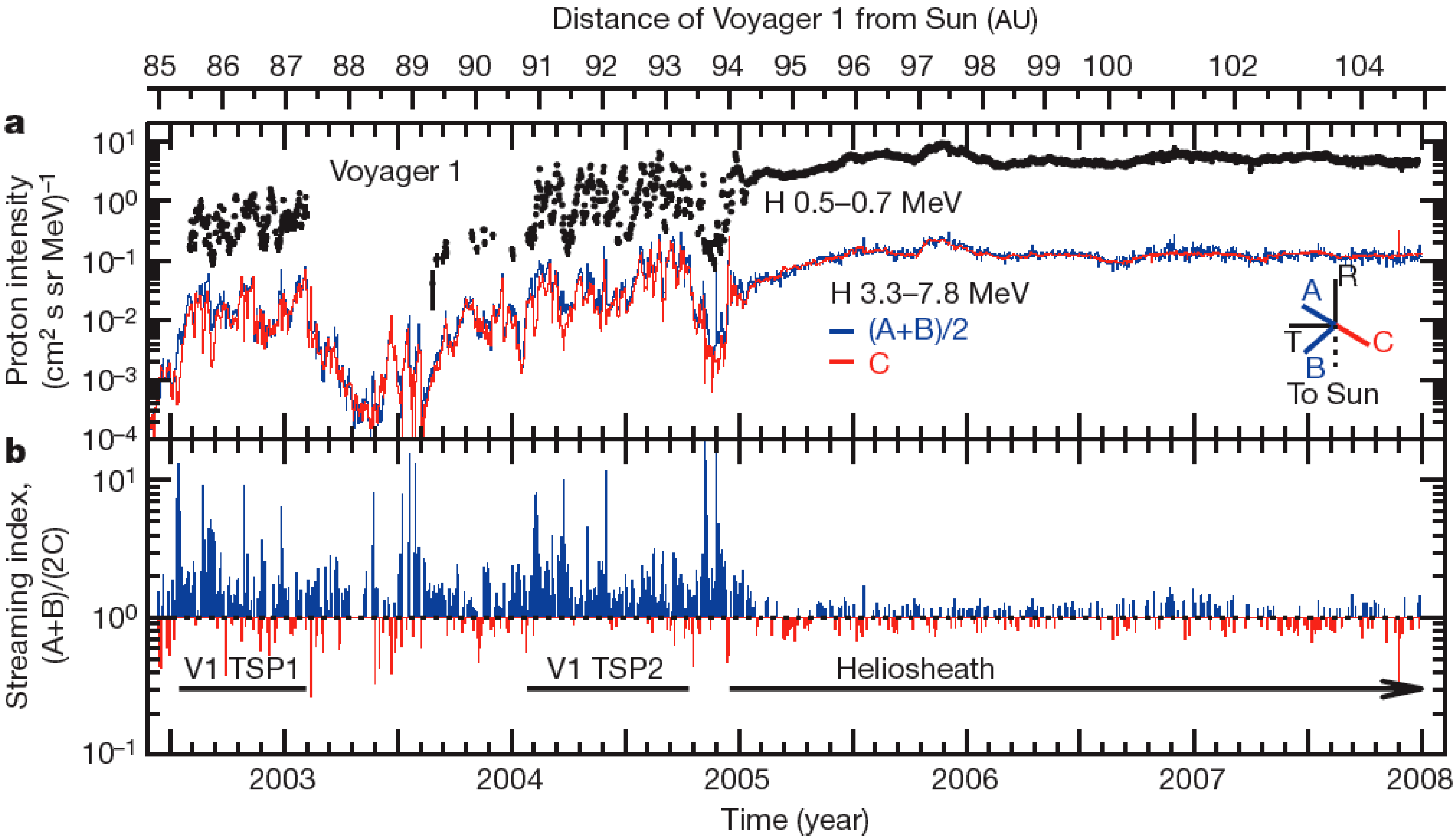
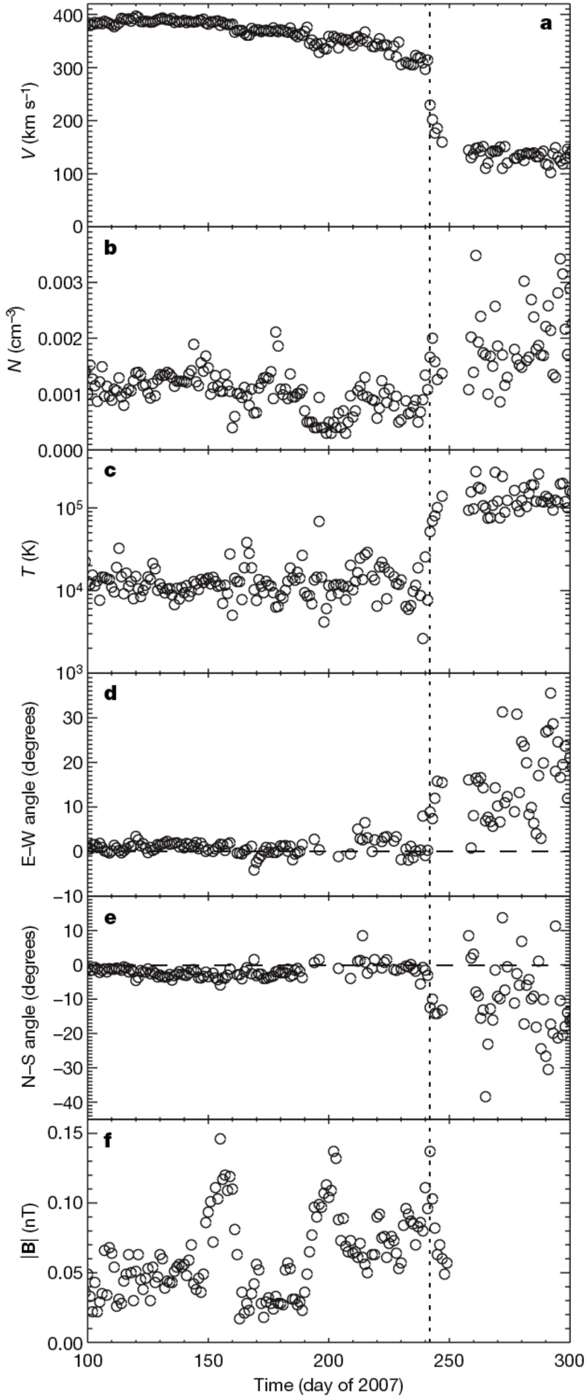


Voyager 1 Ions

Decker et al., 2005



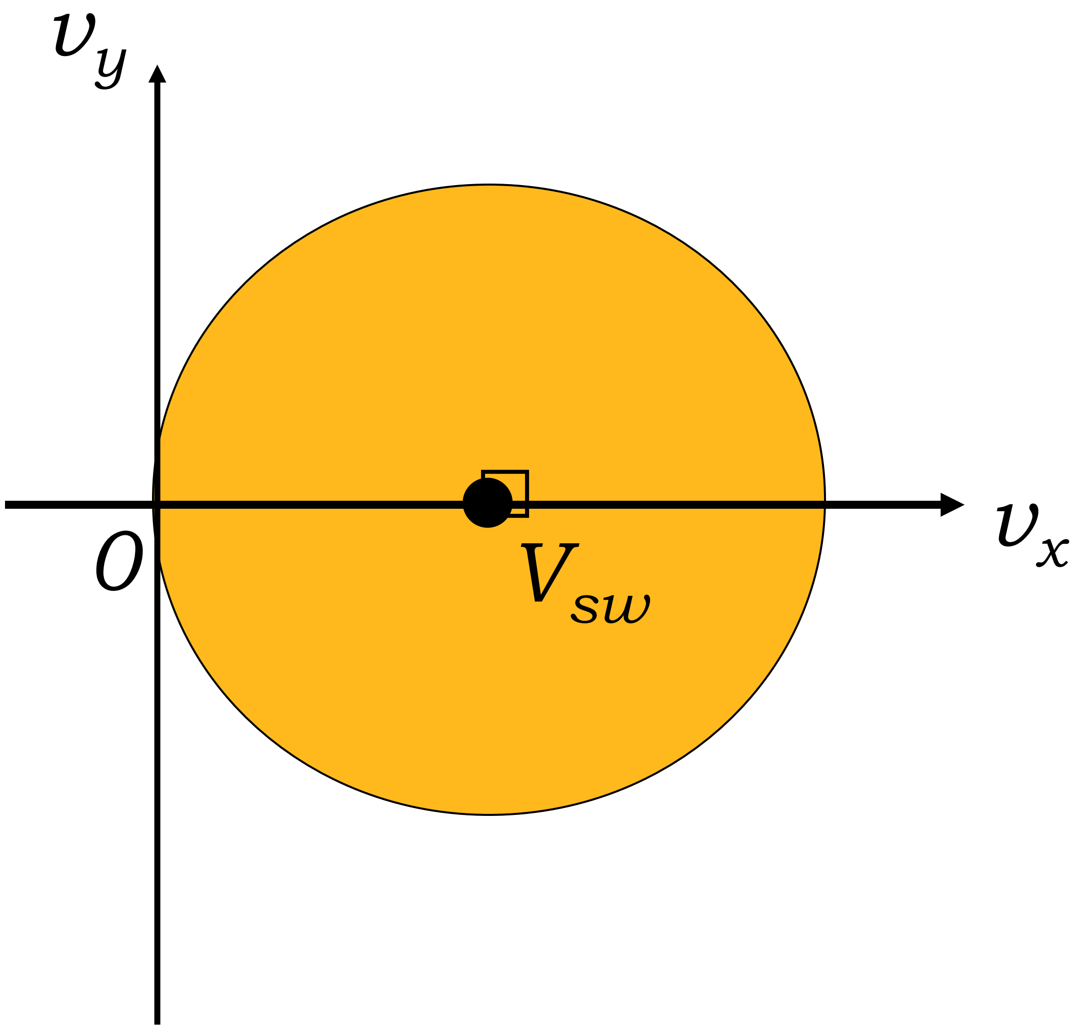
Stone et al., 2008



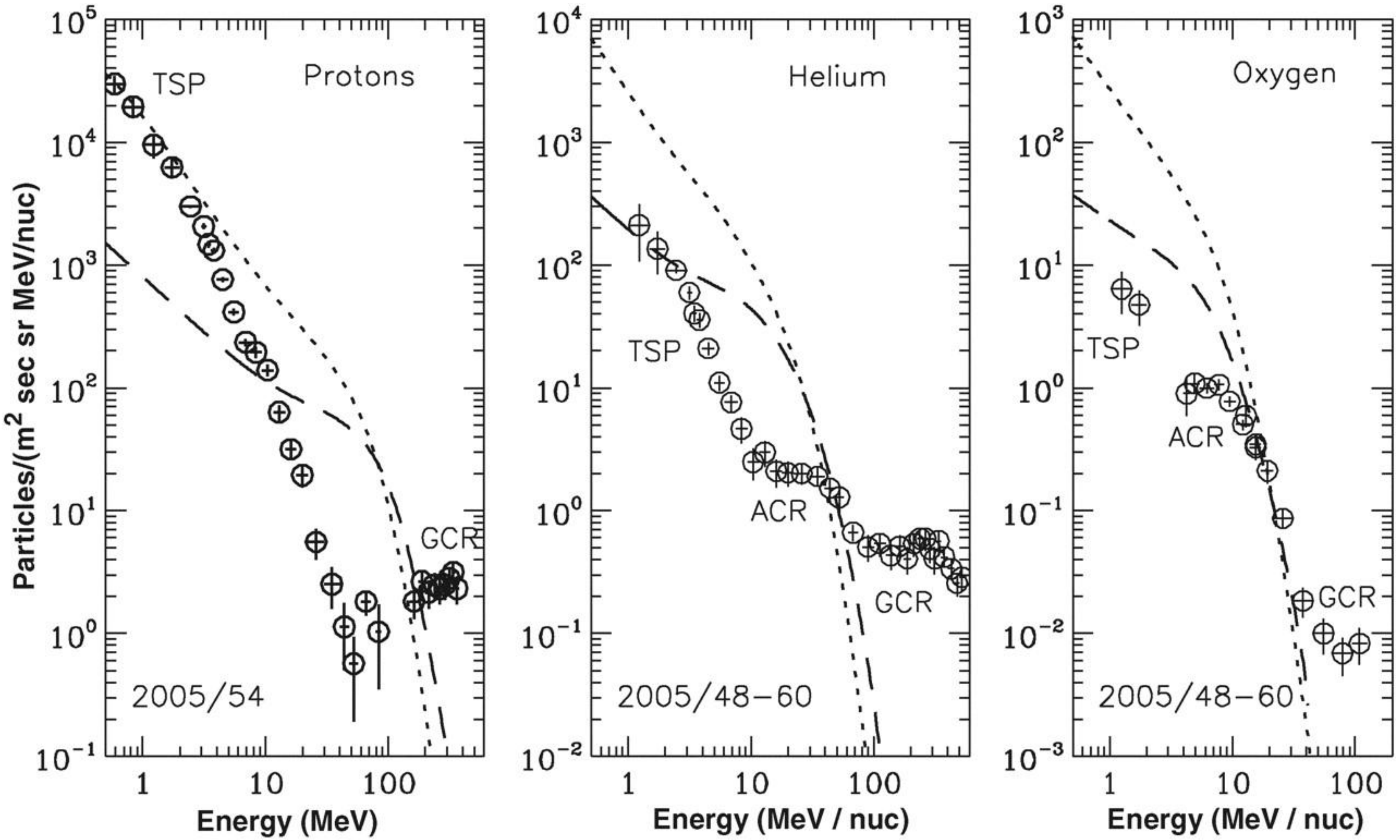
Termination Shock Plasma Data At Voyager 2

Richardson et al., 2008

Pickup Ion Distribution in SW



Voyager 1 Downstream Spectra



Stone et al., 2005

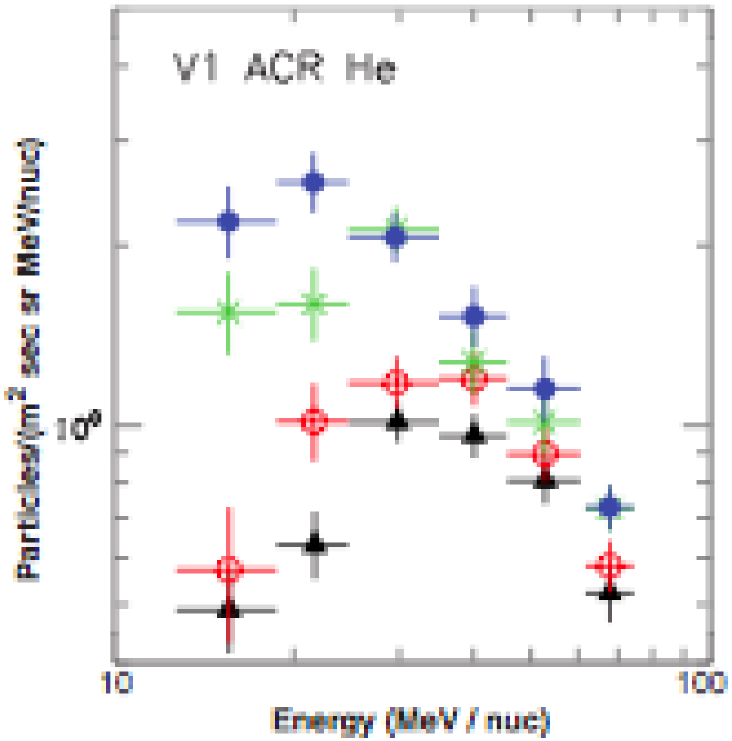
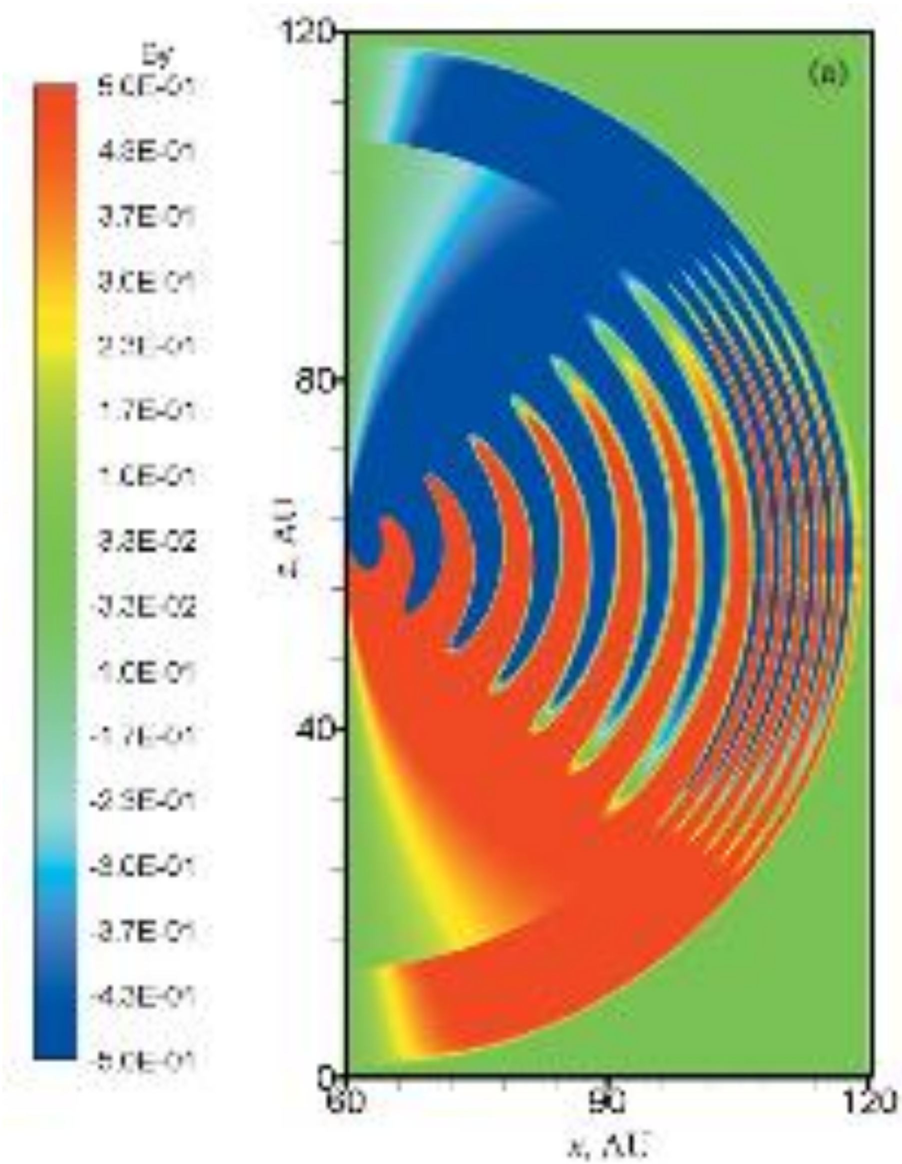


Fig. 3. ACR helium spectra just upstream of the shock (▲) (2004/313 to 350) and in the heliosheath [(○) 2004/352 to 2005/052, (×) 2005/053 to 104, (●) 2005/105 to 156]. The TSP, ACR, and GCR spectra overlap in the observed spectra in Fig. 2. Estimates of the TSP and GCR components have been subtracted in the regions of overlap to determine the ACR He spectra. The ACR He intensity did not reach a maximum at the shock, but continued to rapidly increase at lower energies in the heliosheath, indicating increasingly easy propagation from the ACR source to V1.

Stone et al., 2005

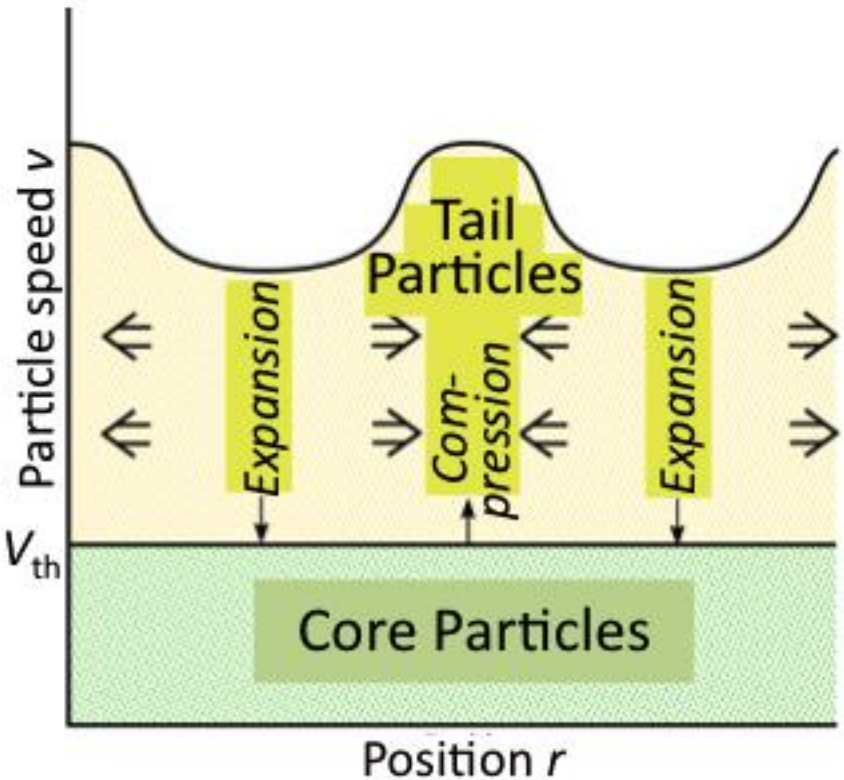
Current Sheets & Reconnection



Pogorelov et al., 2009

Particle acceleration

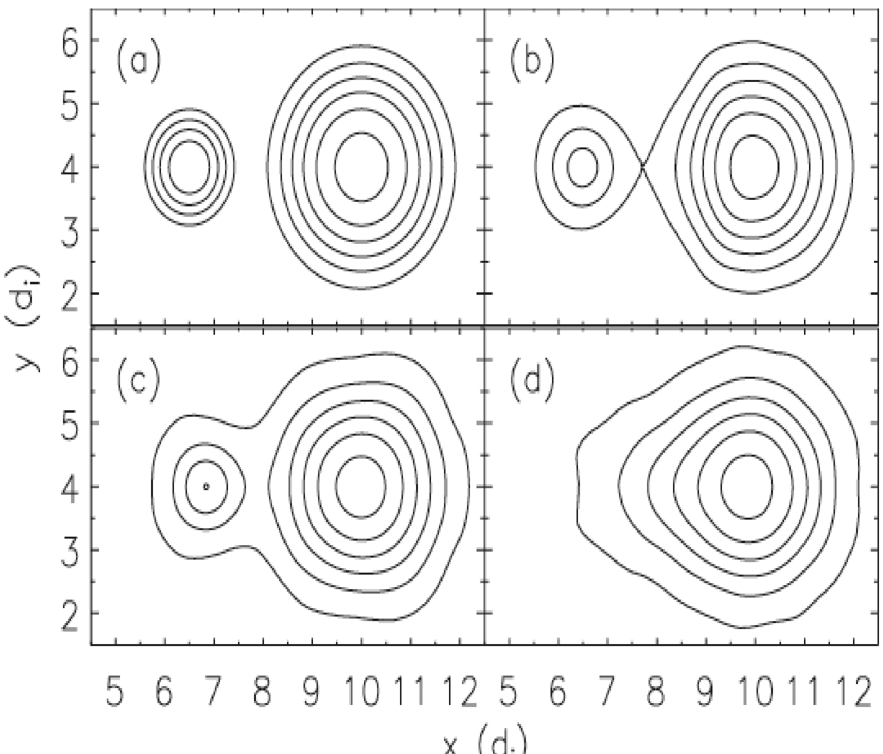
Pumping Mechanism



Fisk & Gloeckler 2010

Particles are accelerated by a series of adiabatic compressions and expansions, in which the particles can escape from a compression region.

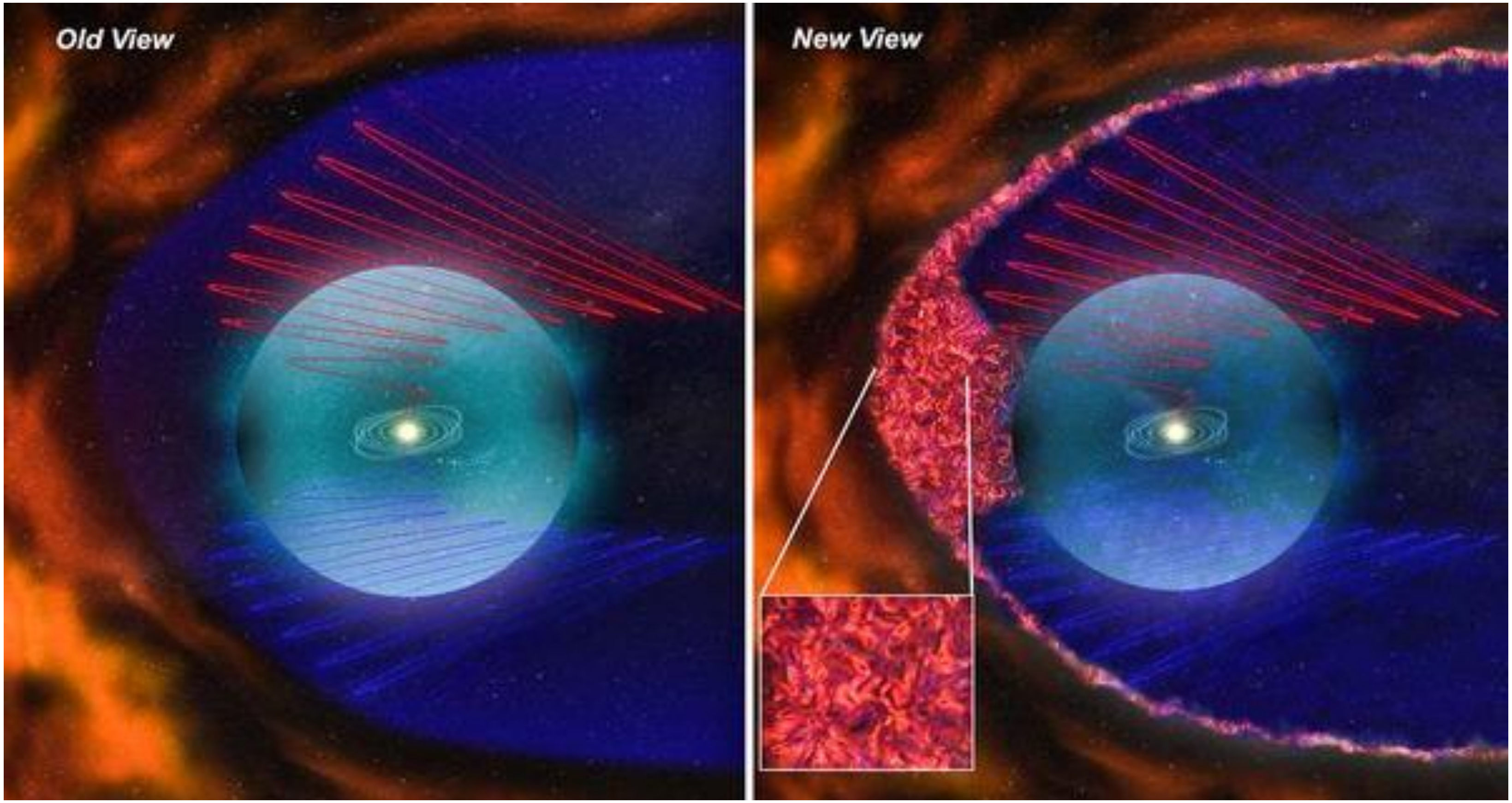
Island merging & contraction



Fermo, Drake, Swisdak, 2010

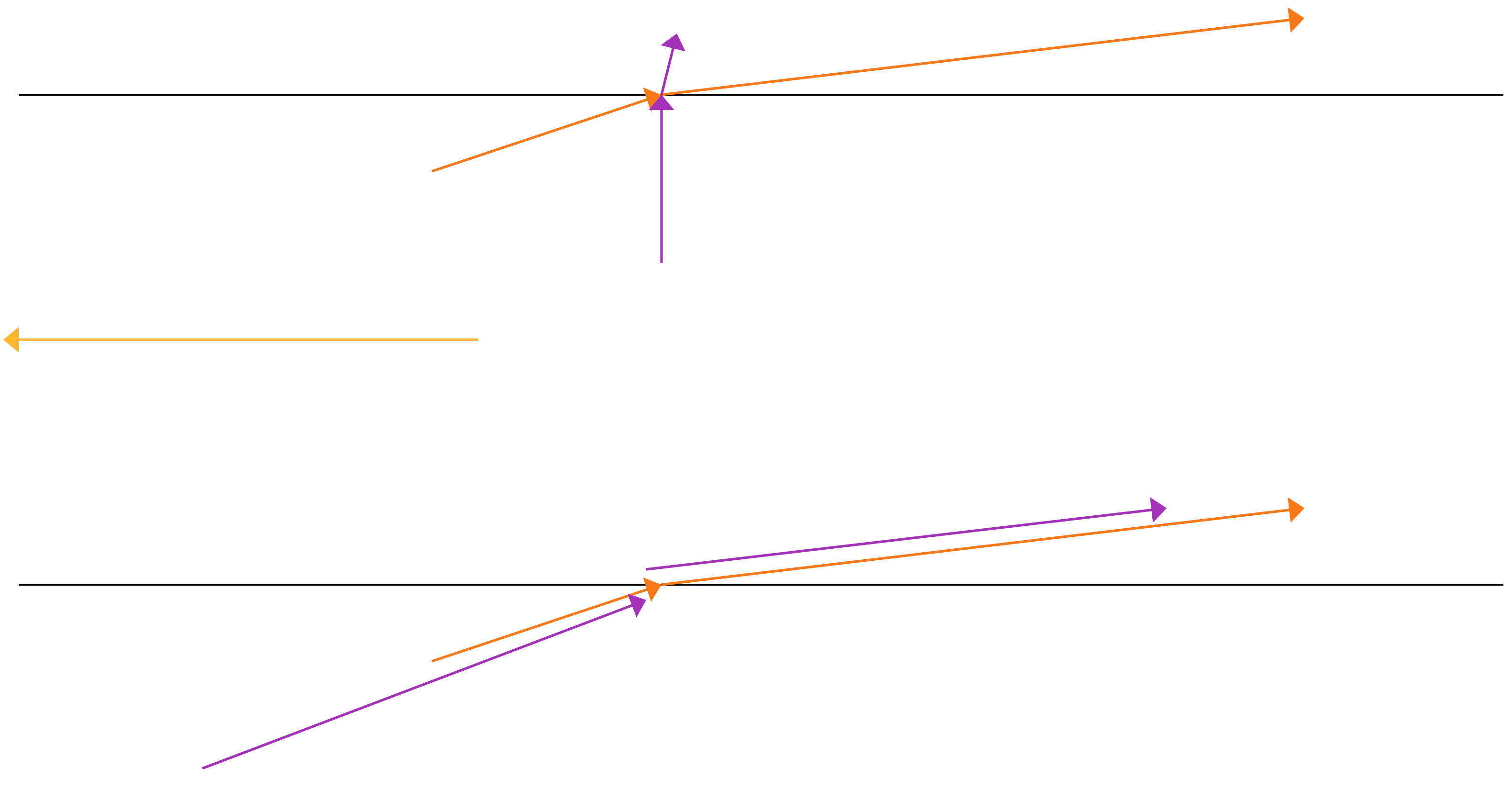
Particles are accelerated by merging and Contracting islands.

Ideas of Particle Acceleration (cont.)

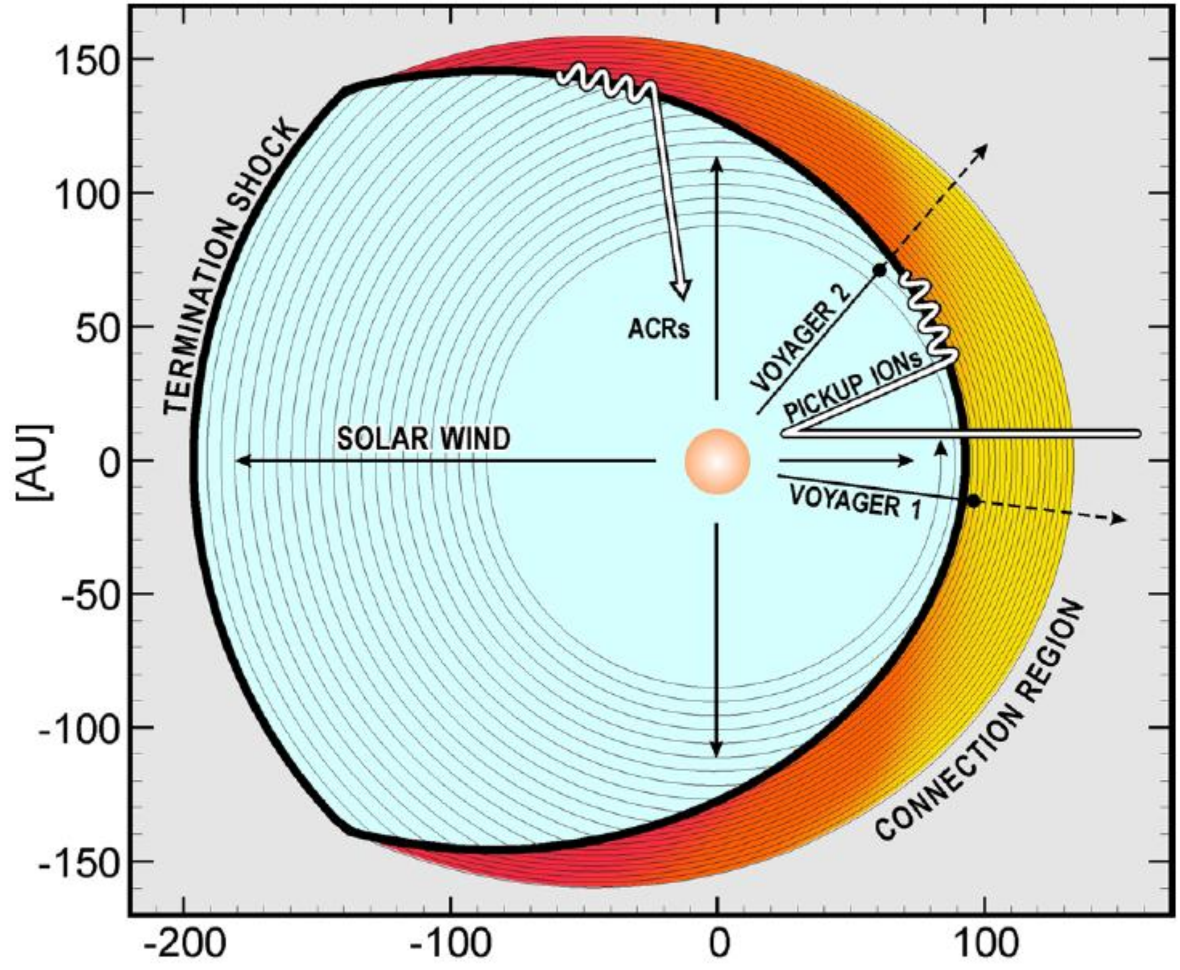


Credit: NASA

Diffusive Shock Acceleration



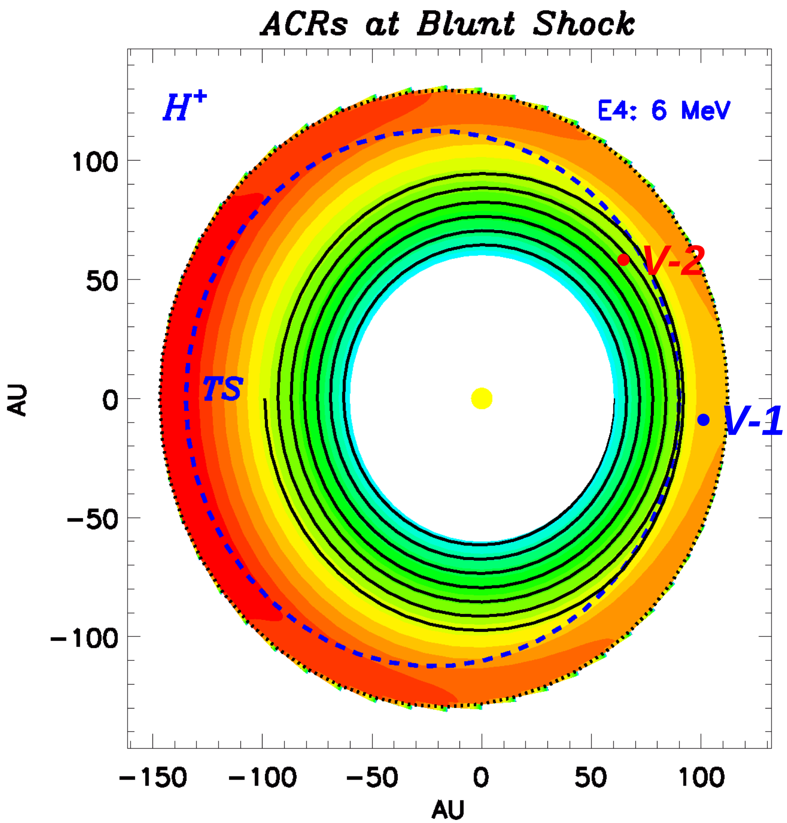
The Blunt Termination Shock

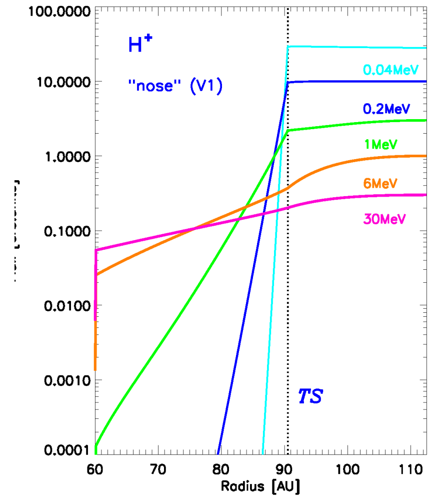


McComas and Schwadron, 2006

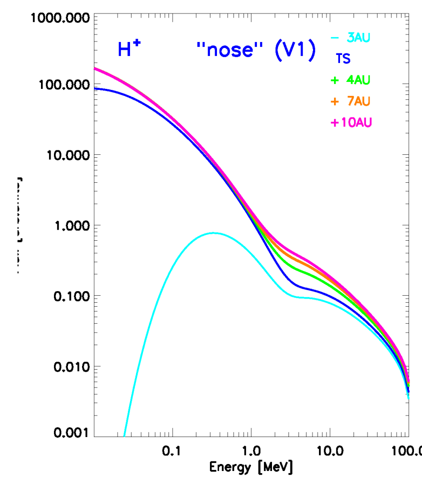
Blunt Shock:
2D Simulation for ACR energies

TS is offset circe,
small cross field diffusion:
η=0.02





ACR flux increases into the Heliosheath



Spectrum gradually unfolds

Kota, 2010

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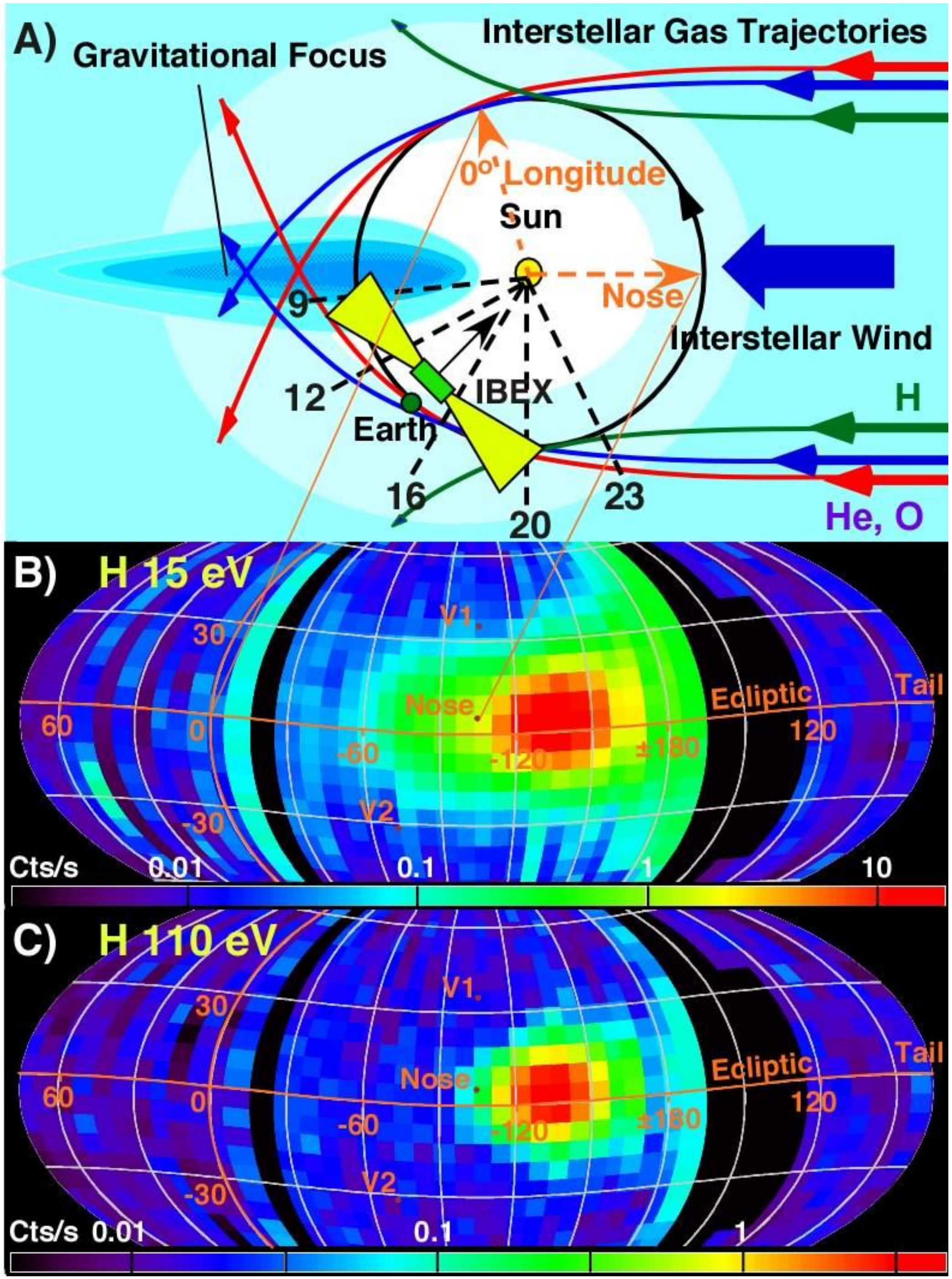
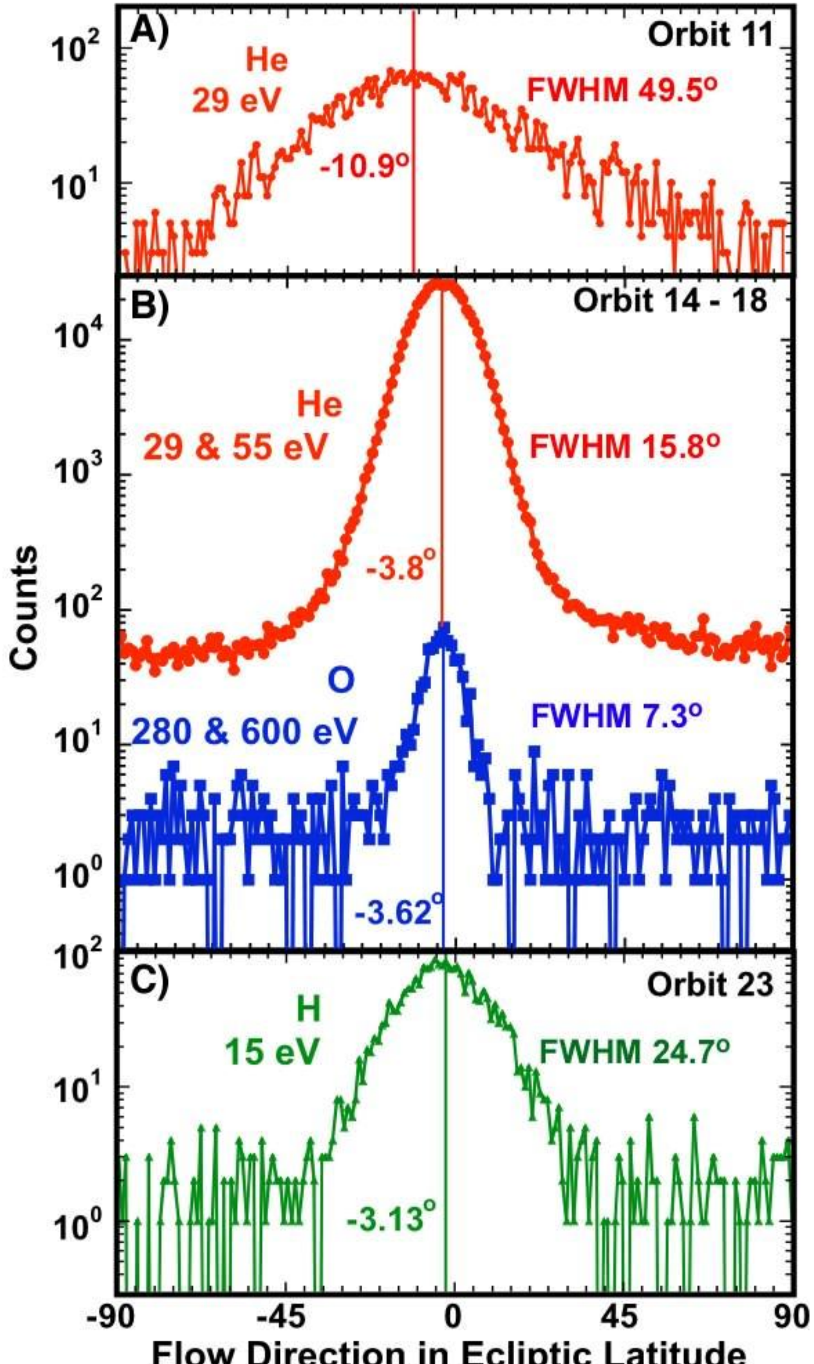
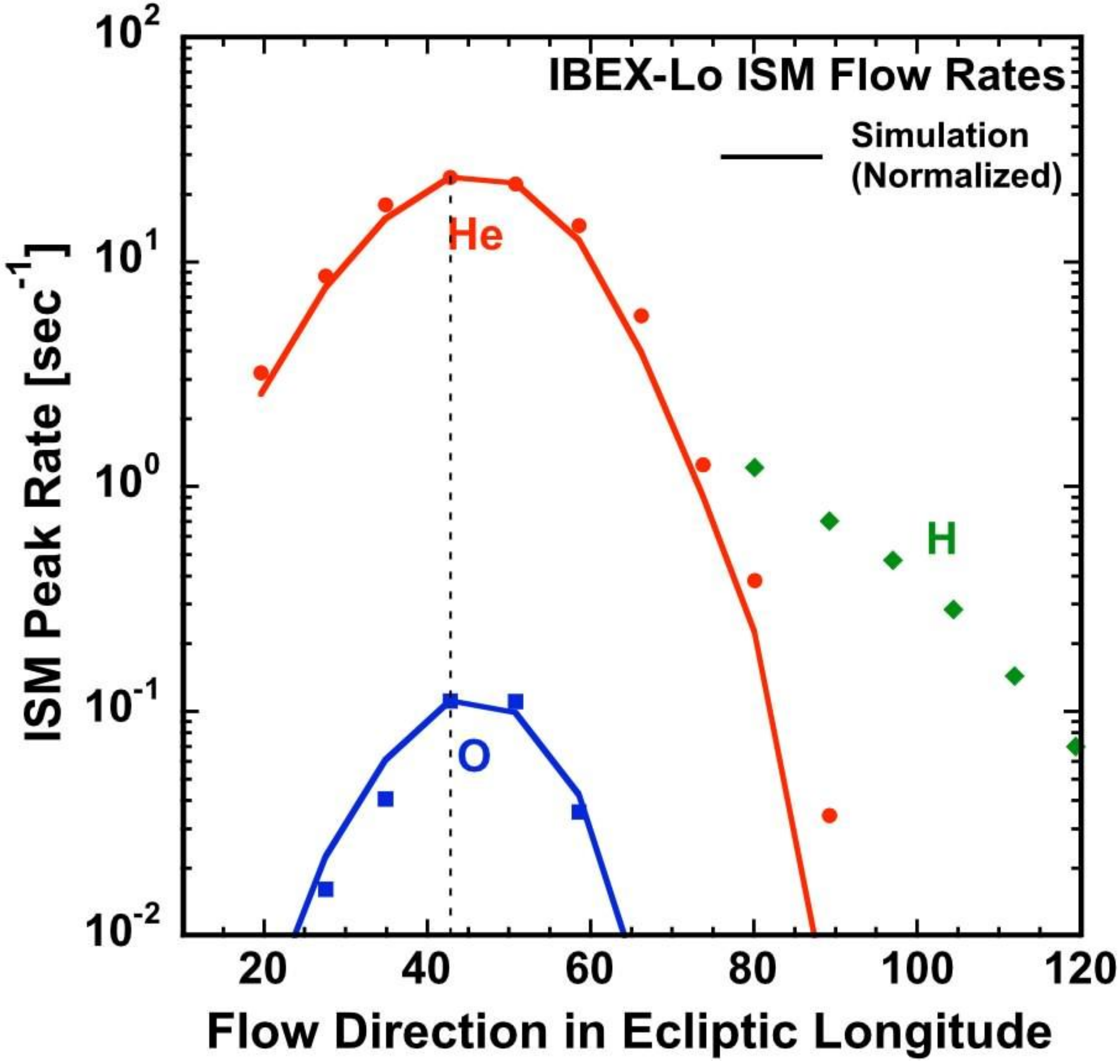


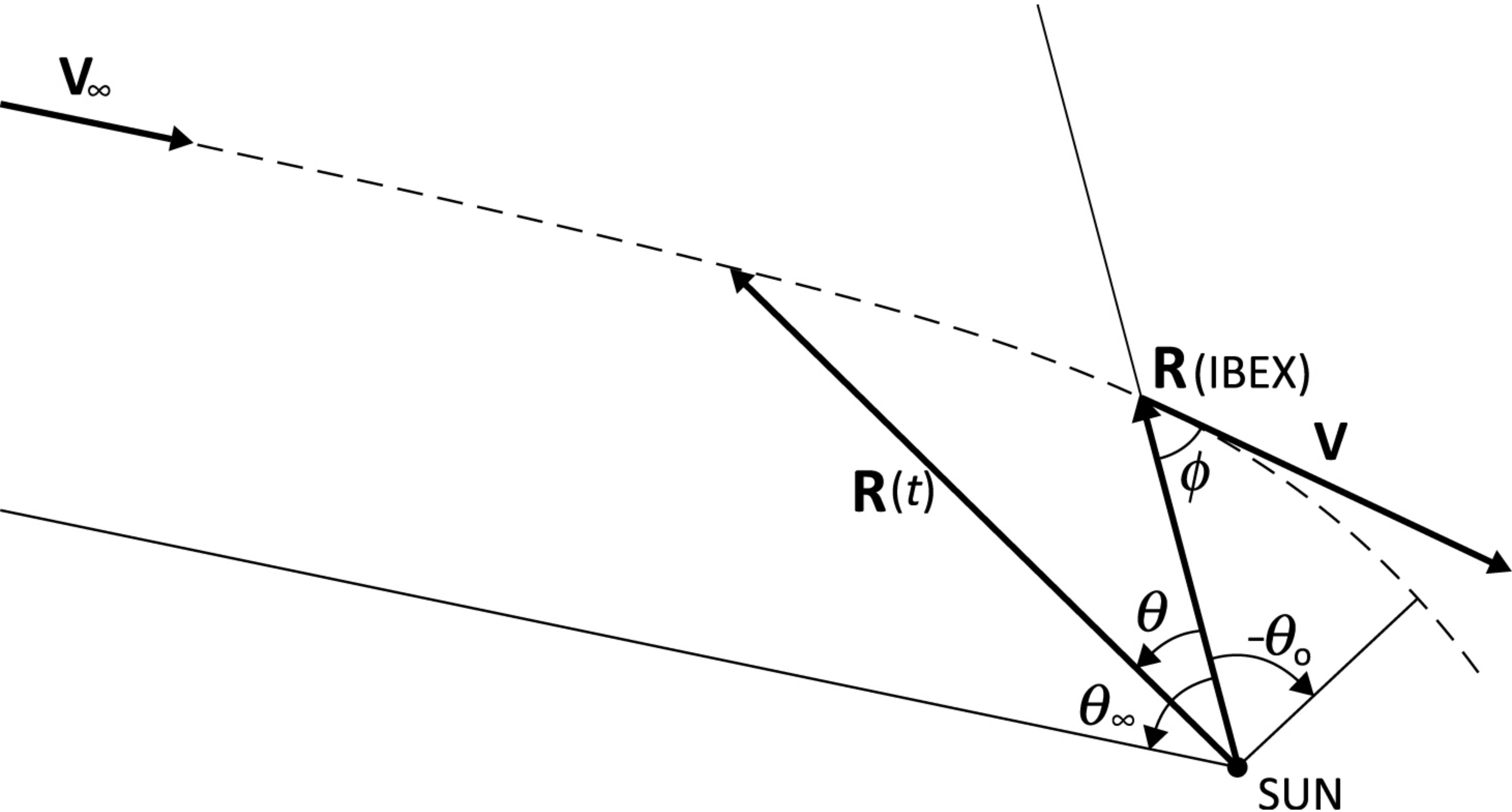
IBEX Observes He and H



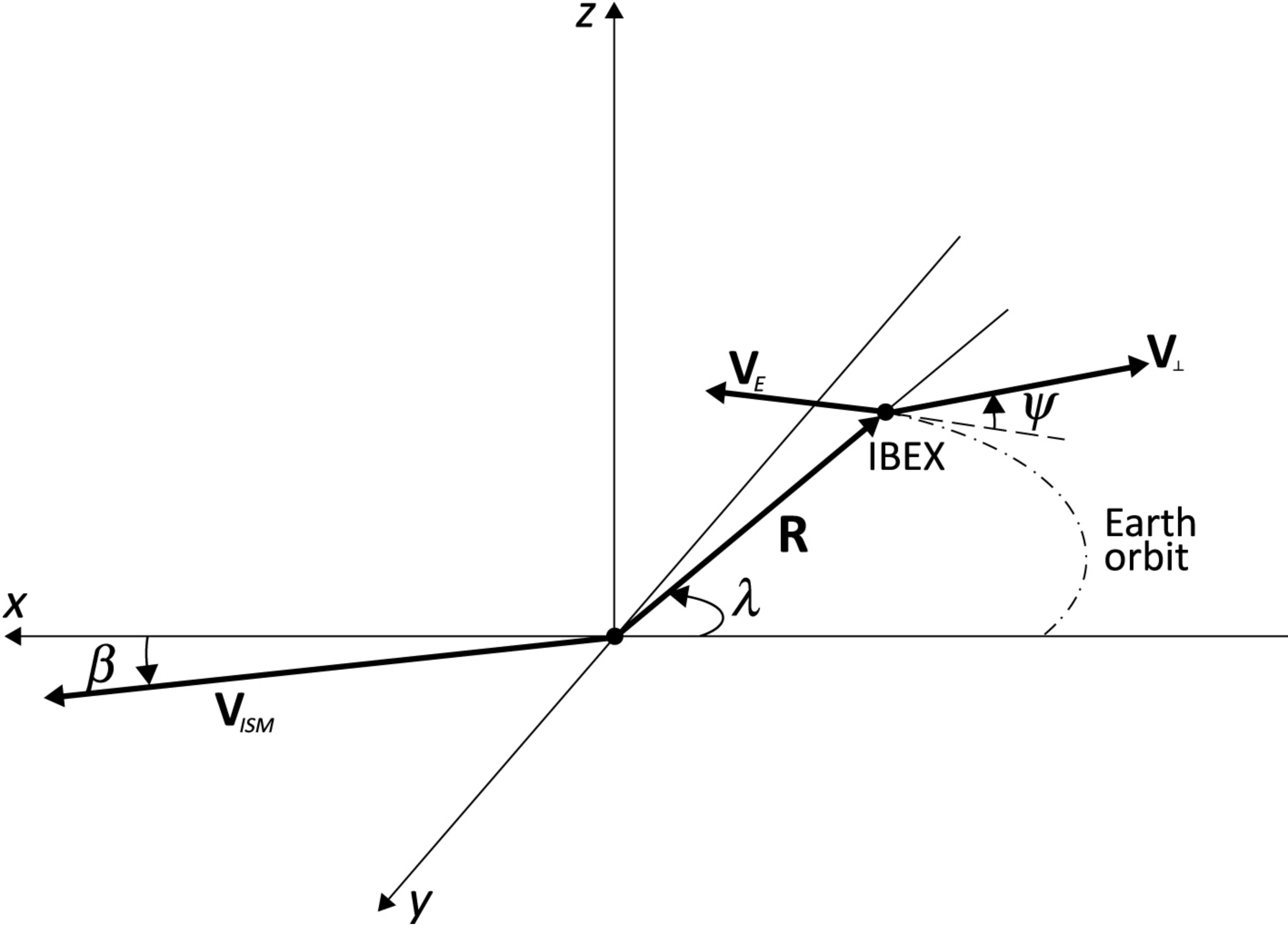
Flow Latitude Distribution

Flow Longitude Distribution





V∞
R(IBEX)
V
R(t)
ϕ
θ
-θo
θ∞
SUN



z
x
y
V_E
V_⊥
ψ
IBEX
R
Earth orbit
λ
β
V_ISM

Basic Equations (μ<1 and μ>1)

$$f(v,\phi,\psi)(\overline{V}_E^3/n)=(\pi t)^{-3/2}\exp\left\{-t^{-1}\left[v^2-2r^{-1}(1-\mu)+v_{ISM}^2-2v_{ISM}[v^2-2r^{-1}(1-\mu)]^{1/2}\times\right.\right.$$

$$\left.\left.\times\left(\cos\theta_\infty\cos\beta\cos\lambda-\sin\theta_\infty[\cos\beta\cos\psi\sin\lambda+\sin\beta\sin\psi]\right)\right]\right\}$$

$$\times\exp\left[-\eta r(v\sin\phi)^{-1}\cos^{-1}(\cos\theta_\infty)\right]$$

$$\cos\theta_\infty=\varepsilon^{-2}\left[1-rv^2(1-\mu)^{-1}\sin^2\phi+r^2v^3(1-\mu)^{-2}\left(v^2-2r^{-1}(1-\mu)\right)^{1/2}\sin^2\phi\cos\phi\right]$$

$$\sin\theta_\infty=\varepsilon^{-2}\left[\frac{rv^2}{(1-\mu)}\sin\phi\cos\phi+\left(\frac{rv^2}{1-\mu}\right)^{1/2}\left(\frac{rv^2}{1-\mu}-2\right)^{1/2}\left(\frac{rv^2}{1-\mu}\sin^2\phi-1\right)\sin\phi\right]$$

$$\varepsilon^2=[rv^2(1-\mu)^{-1}-1]^2\sin^2\phi+\cos^2\phi$$

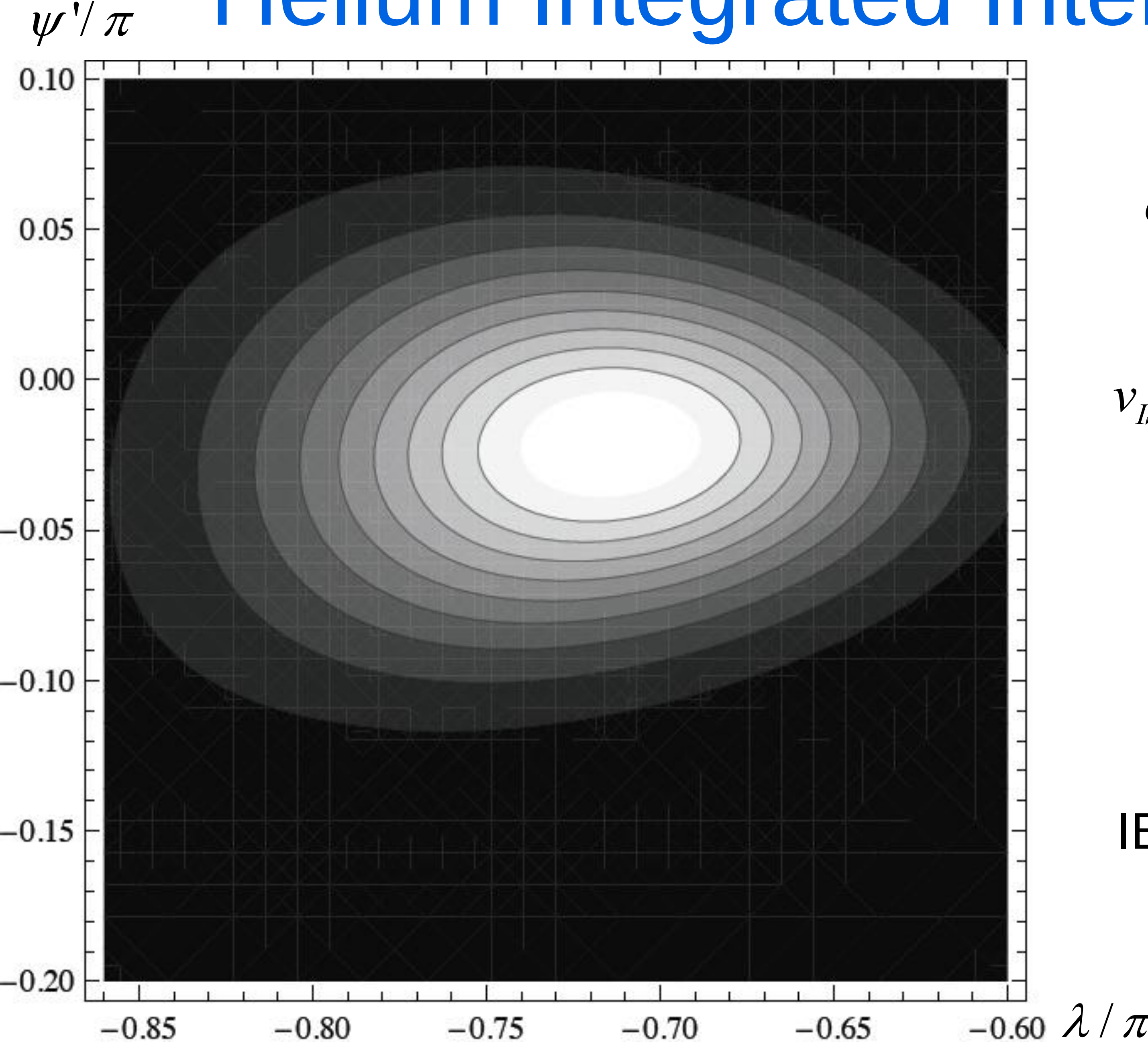
Sun to Earth Frame

$$V\cos\phi = V'\cos\phi'$$

$$V\sin\phi\sin\psi = V'\sin\phi'\sin\psi'$$

$$V\sin\phi\cos\psi = V'\sin\phi'\cos\psi' - V_E$$

Helium Integrated Intensity



$\phi' = \pi/2$

$t = 0.03$

$v_{ISM} = 0.75$

$\mu = 0$

$\eta = 0$

$\beta = 5°$

IBEX Frame

Peak in Latitude

$$f(v,\phi,\psi)(\overline{V}_E^3/n) = (\pi t)^{-3/2}\exp\left\{-t^{-1}\left[v^2 - 2 + v_{ISM}^2 - 2v_{ISM}(v^2-2)^{1/2}\times\right.\right.$$

$$\left.\left.\times\left(\cos\theta_\infty\cos\lambda - \sin\theta_\infty\sin\lambda\cos(\psi+\overline{\beta})\right)\right] + 2\ln v' - \eta v^{-1}\cos^{-1}\left(-(v^2-1)^{-1}\right)\right\}$$

$$\psi_{sc}^0 = -\frac{v_0}{(v_0+1)}\frac{\beta}{|\sin\lambda|} - \frac{v_0^2(\varepsilon_z\cos\psi_{sc}^0 + \varepsilon_E\sin\psi_{sc}^0)}{(v_0+1)(v_0^2-2)^{1/2}}\frac{\sin(\lambda+\theta_\infty^0)}{|\sin\lambda|}$$

1

Independent of Ionization Rate

Best ISM He Parameters

$$\lambda_{ISM\infty} = 79.0° \pm 0.47°$$

$$\beta_{ISM\infty} = -4.98° \pm 0.21°$$

$$V_{ISM\infty} = 23.2 \pm 0.3\,\mathrm{km\,s^{-1}}$$

$$T_{ISM\infty} = 6300 \pm 390\,°\mathrm{K}$$

McComas et al., 2012

$$\lambda_{ISM\infty} = 75.4 \pm 0.4°$$

Witte, 2004

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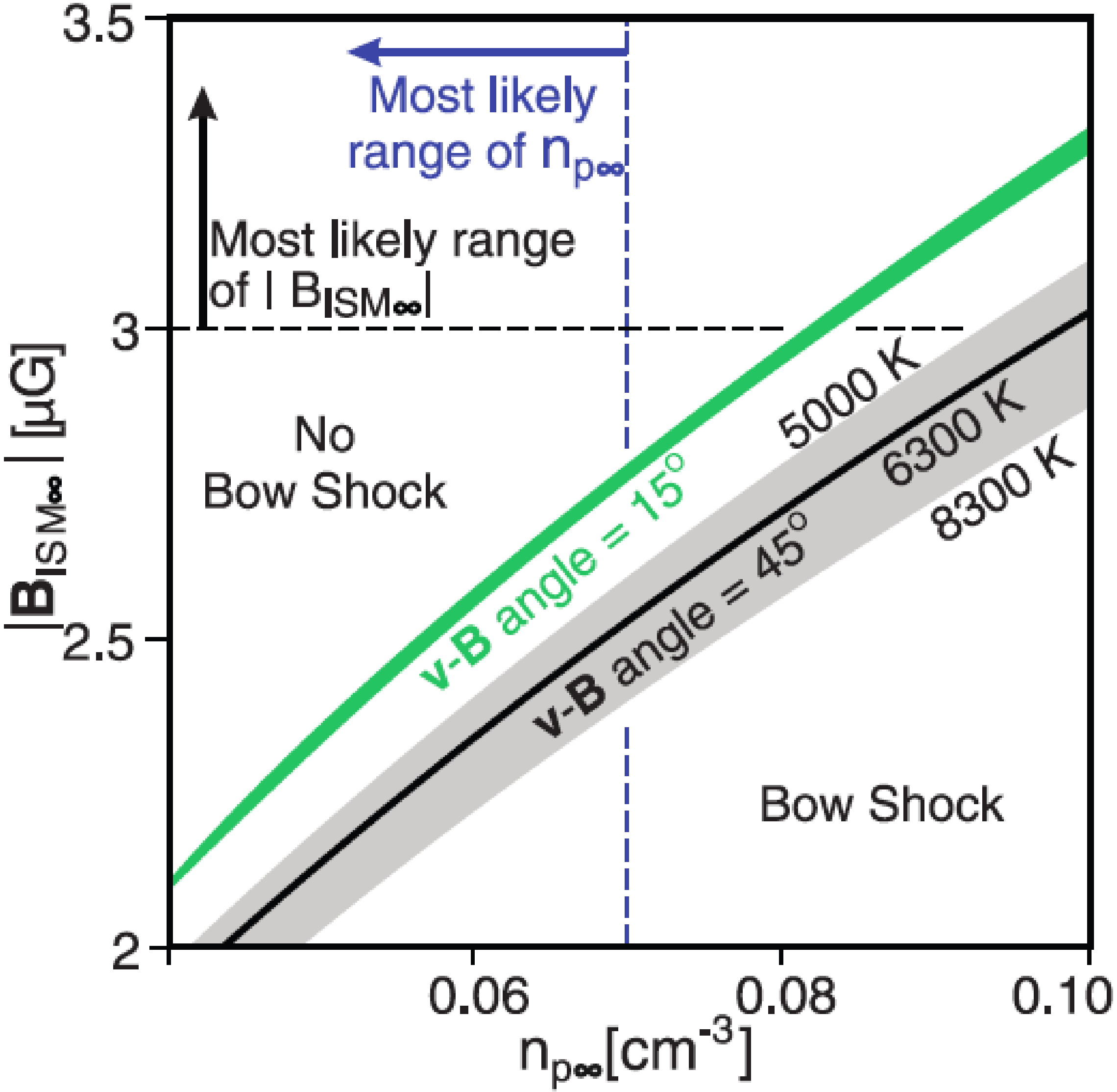
No Bow Shock!



McComas et al., 2012

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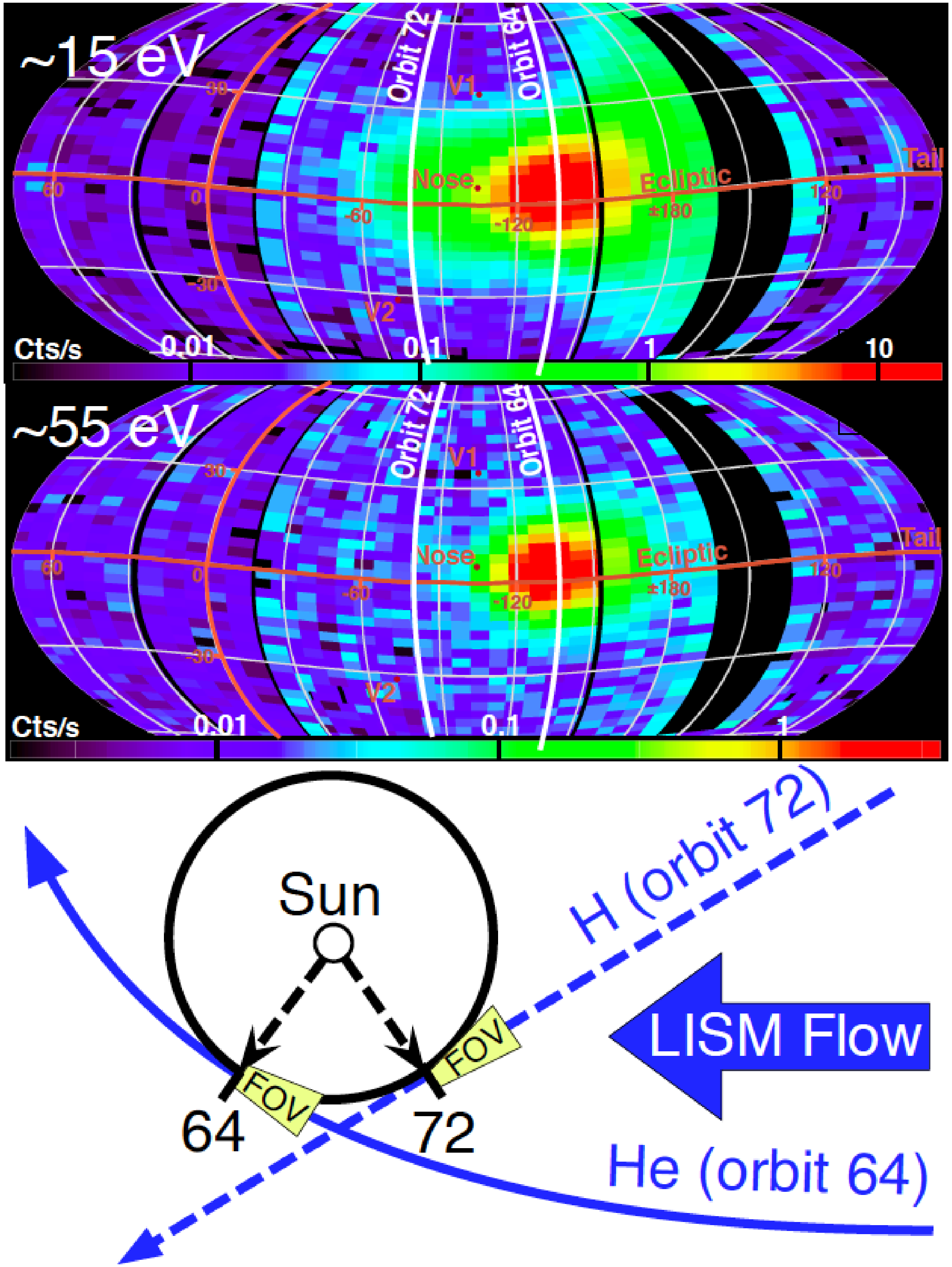
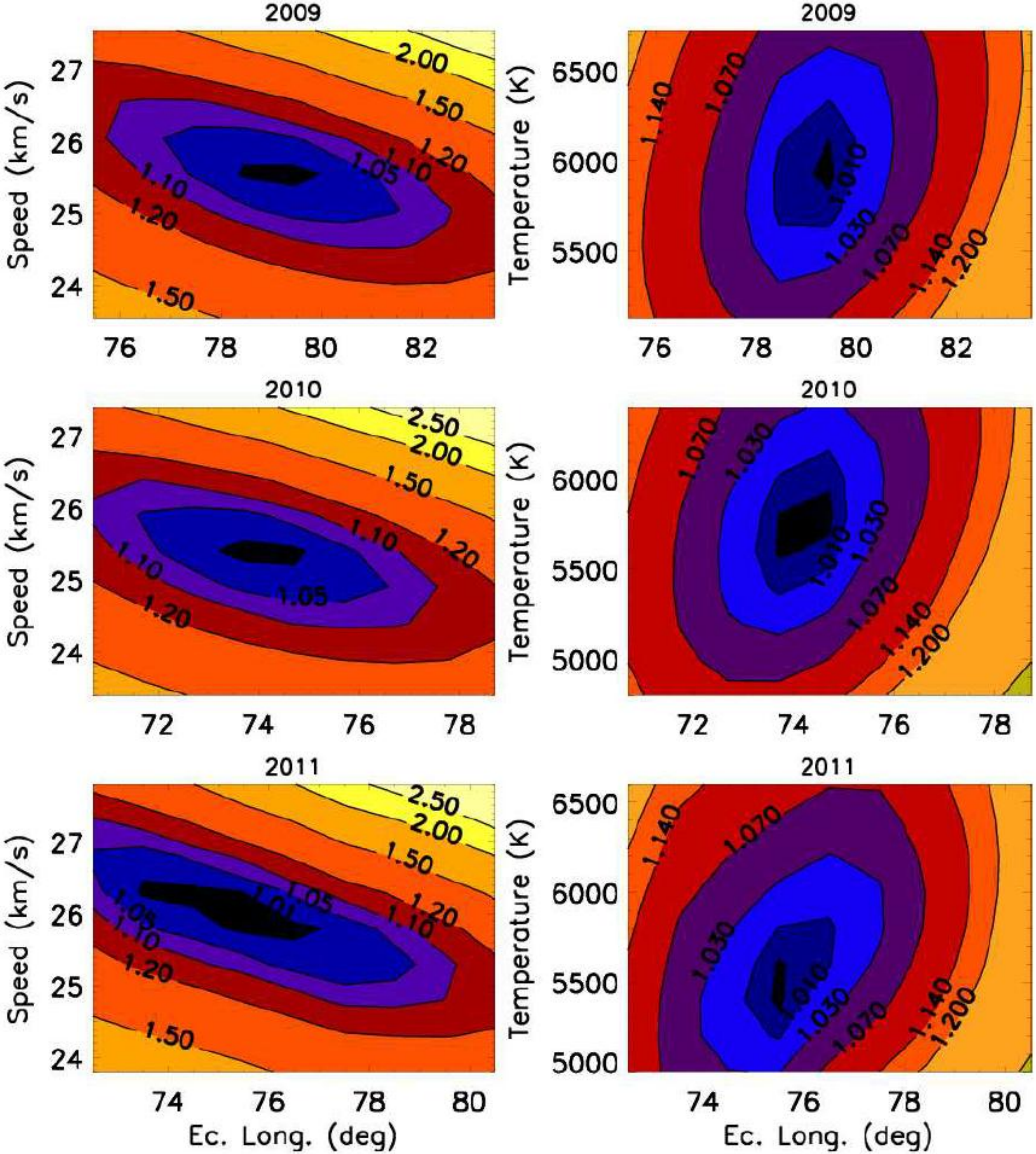
Interstellar Hydrogen



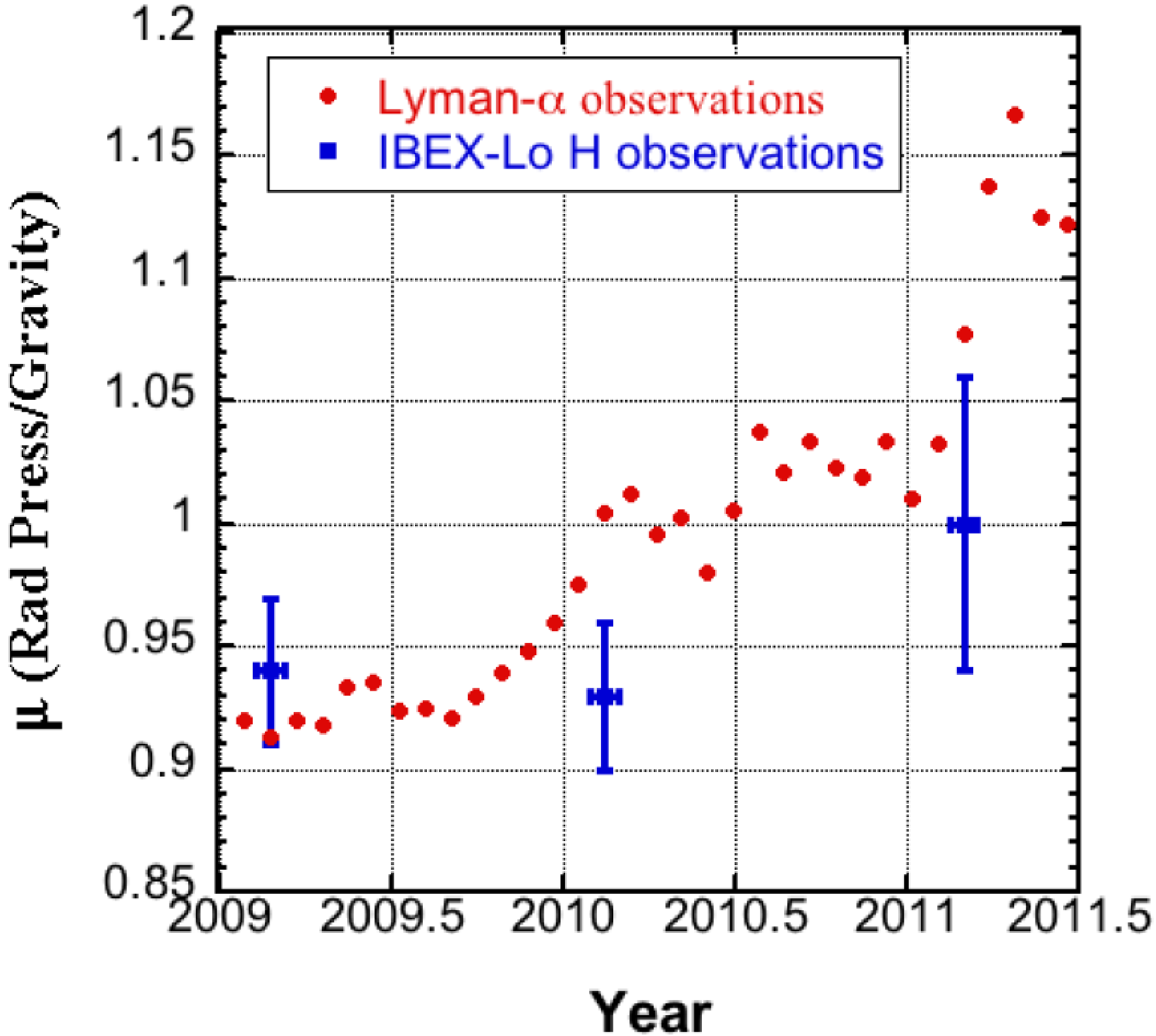
Schwadron et al., 2013

Hydrogen Speed, Temperat-ure and λ



Schwadron et al., 2013

Radiation Pressure on H



Schwadron et al., 2013

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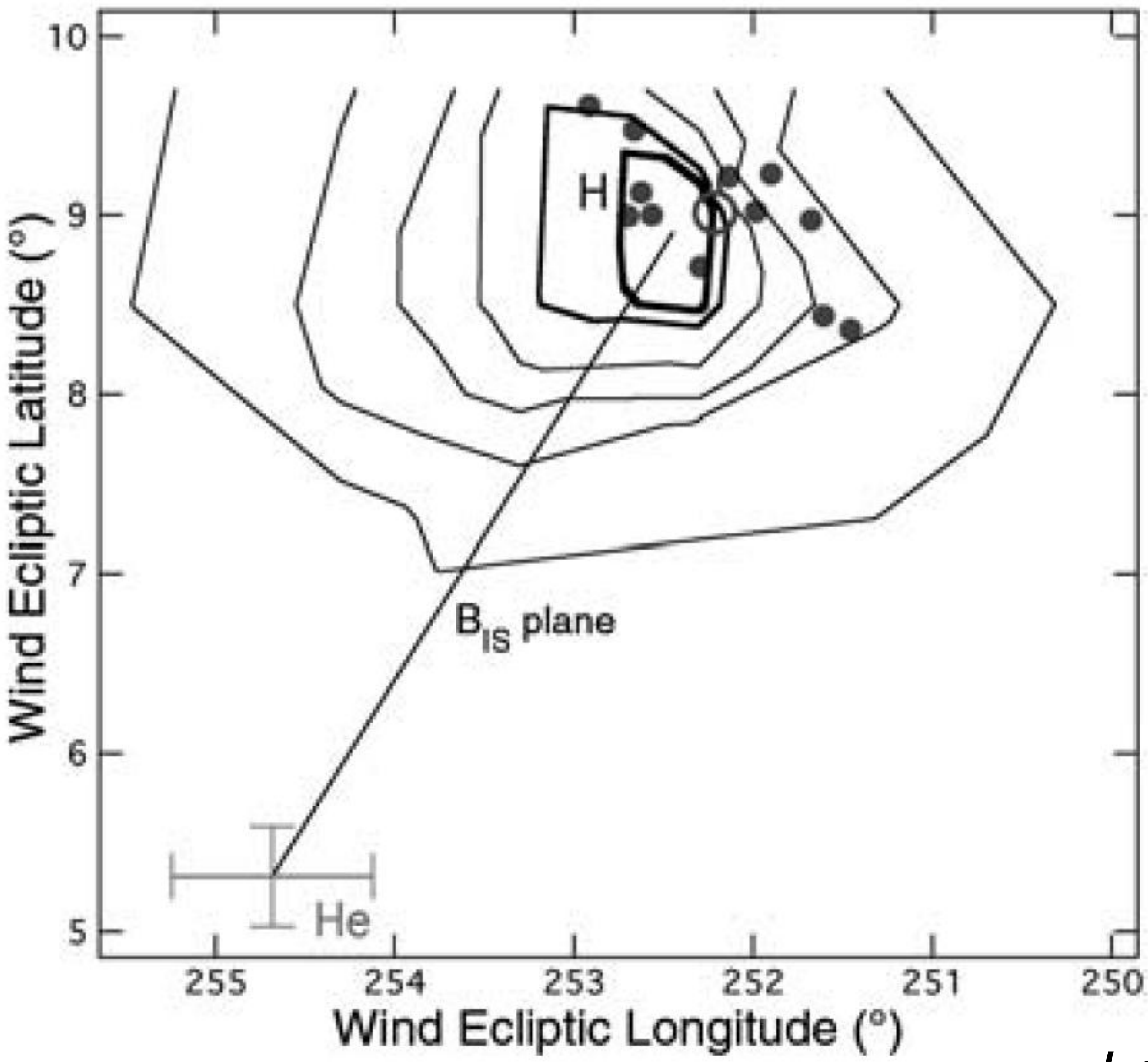
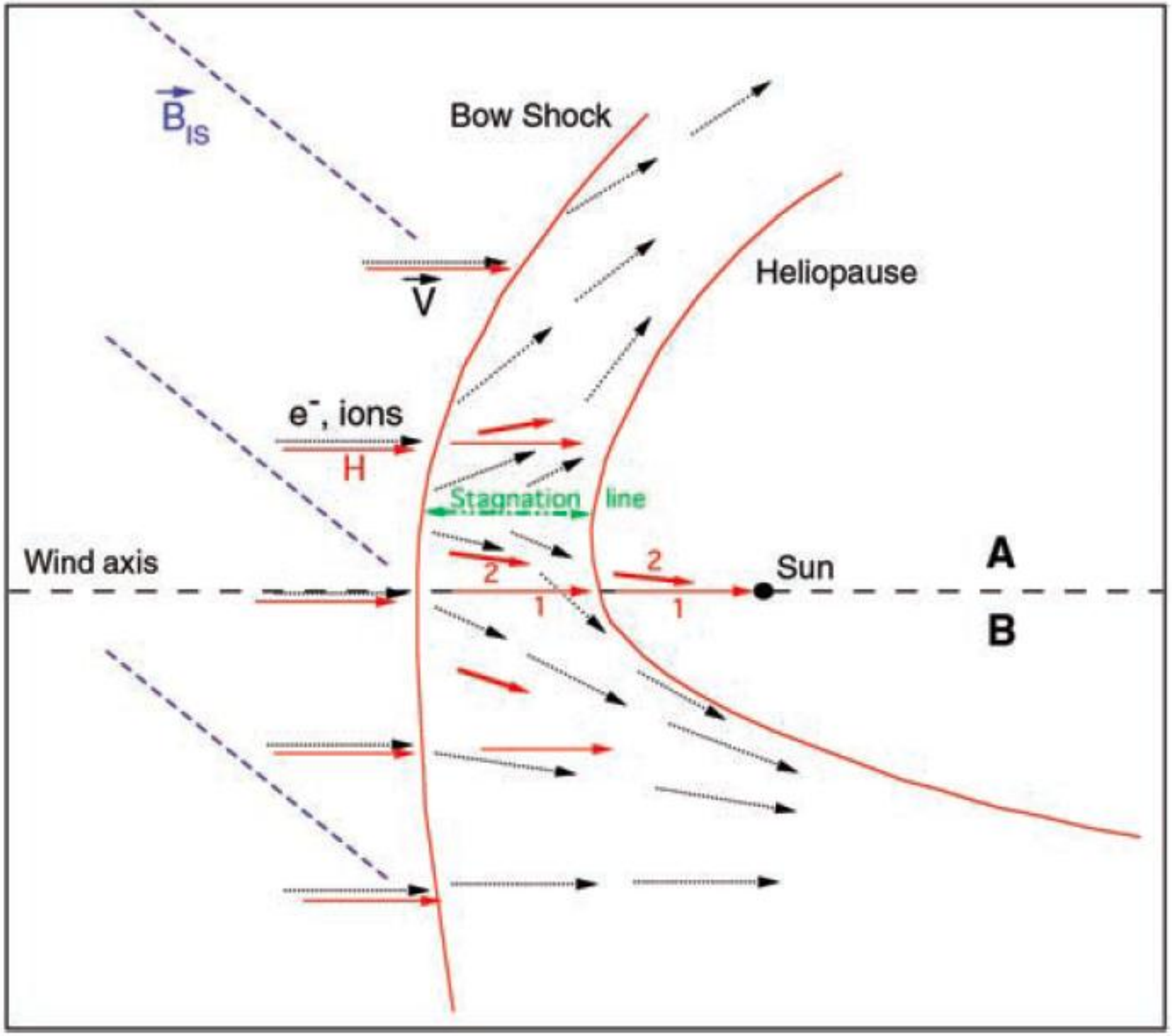


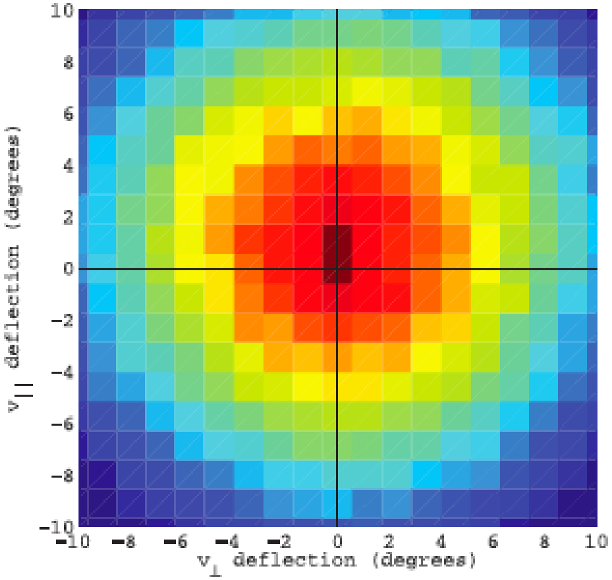
Lyman-α Backscatter

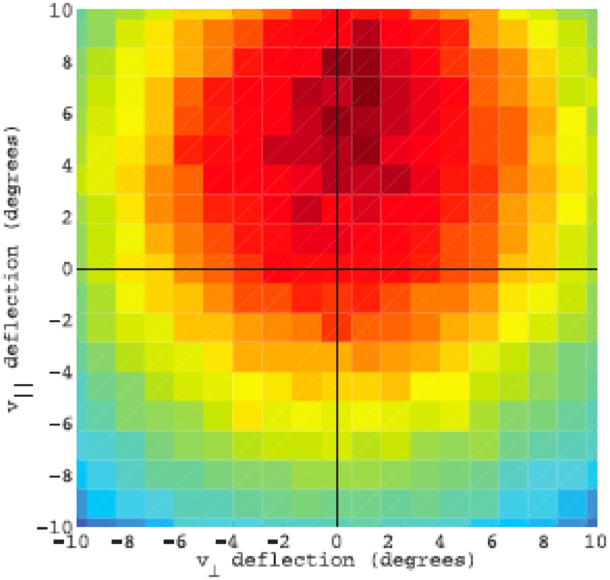
Lallement et al., 2005

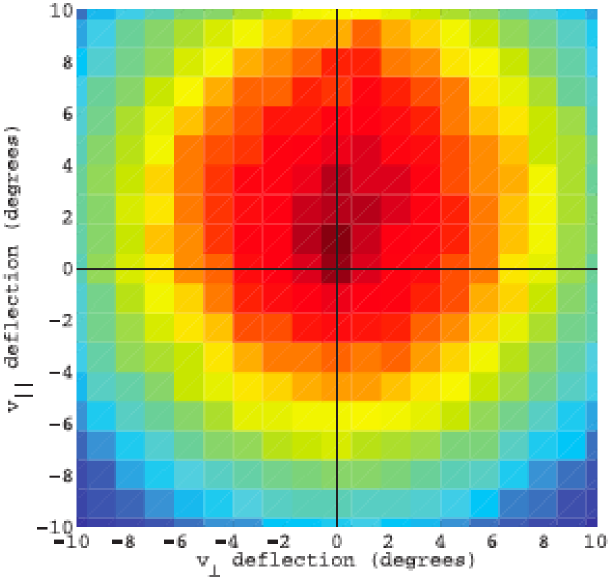
Origin of Secondaries



Primary and Secondary H







Pogorelov et al., 2008

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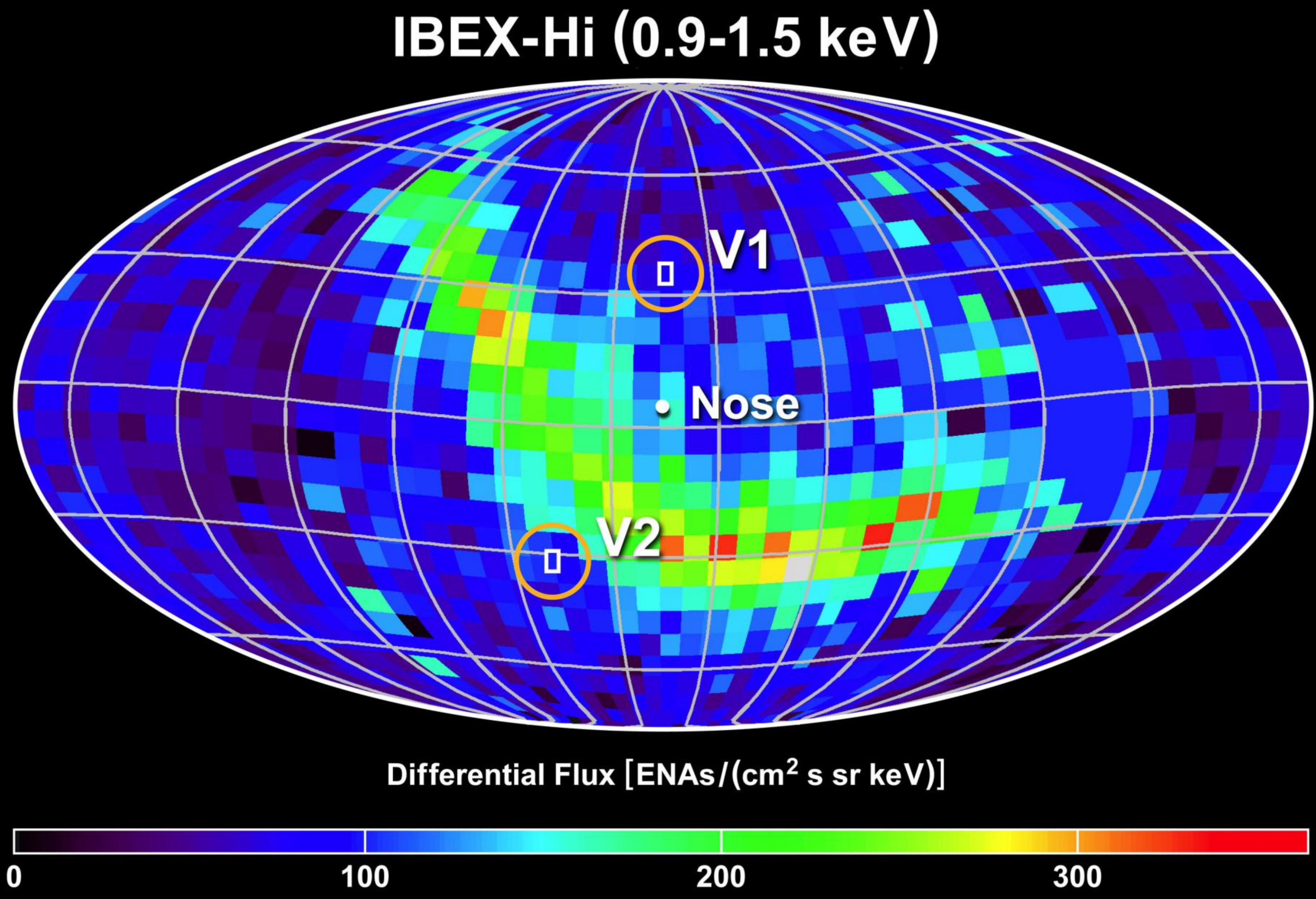
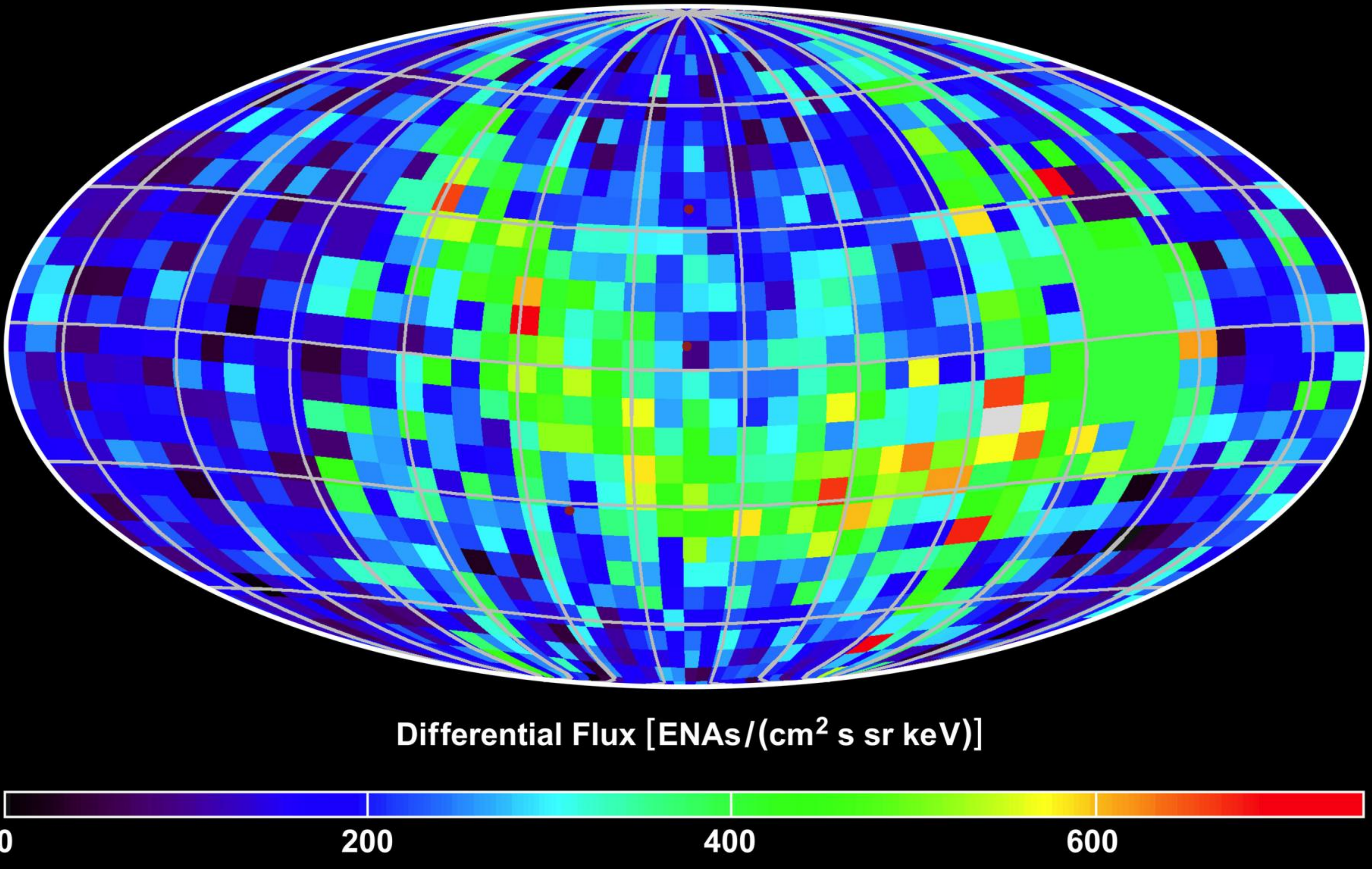
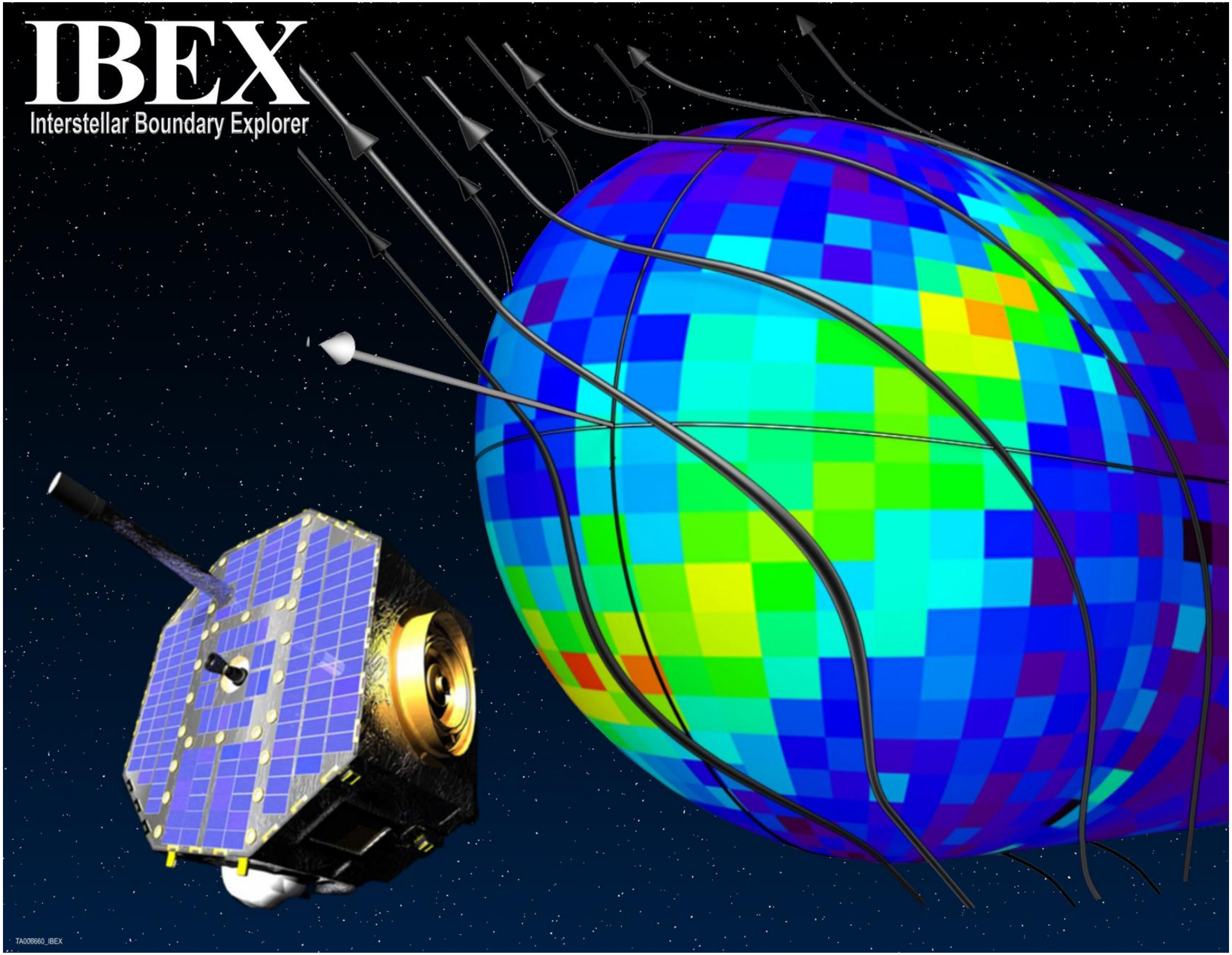
IBEX Reveals the "Ribbon"

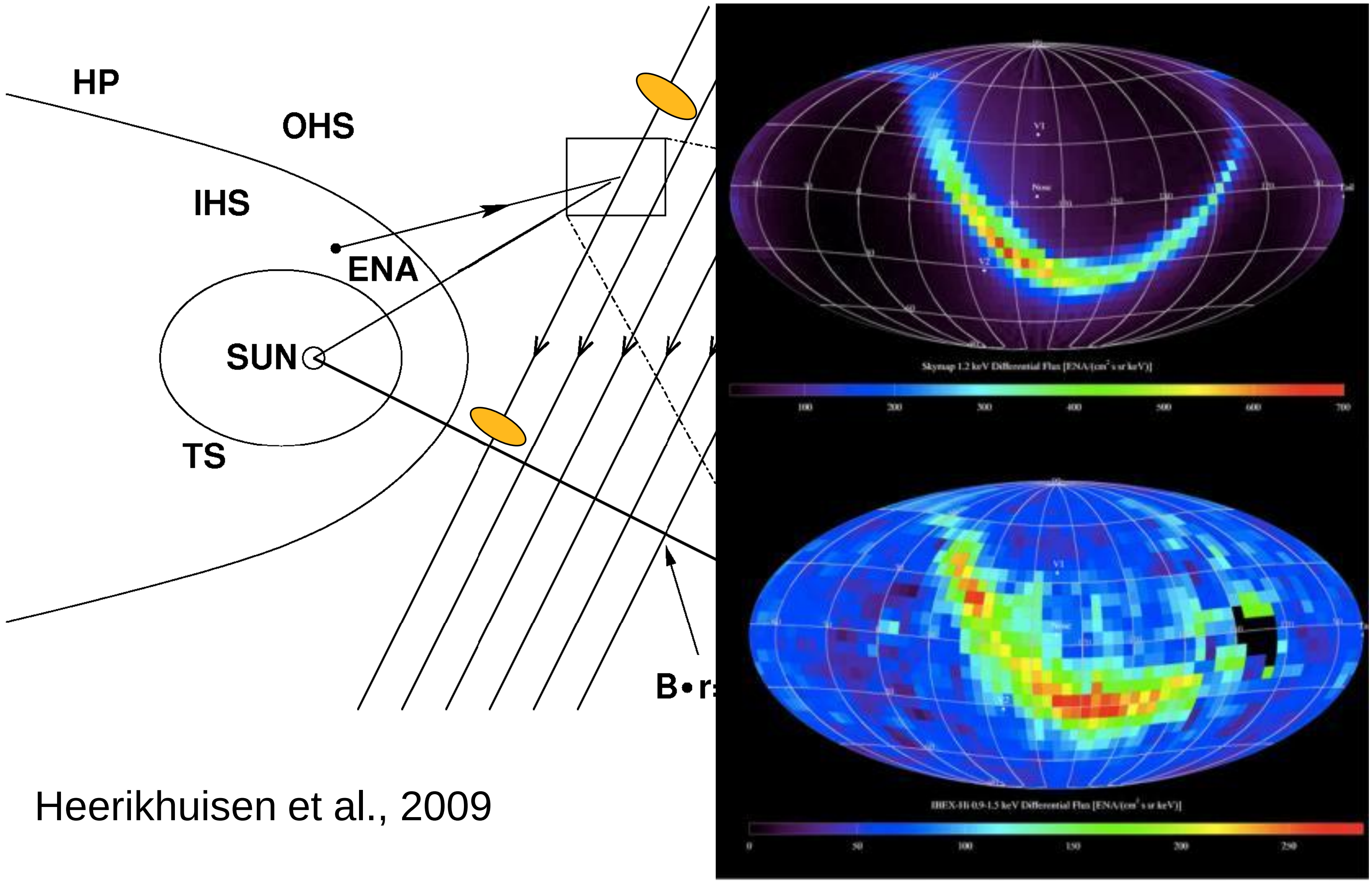


IBEX-Hi (0.6-1.0 keV)




IBEX
Interstellar Boundary Explorer

Secondary ENAs as Source for the IBEX Ribbon



Heerikhuisen et al., 2009

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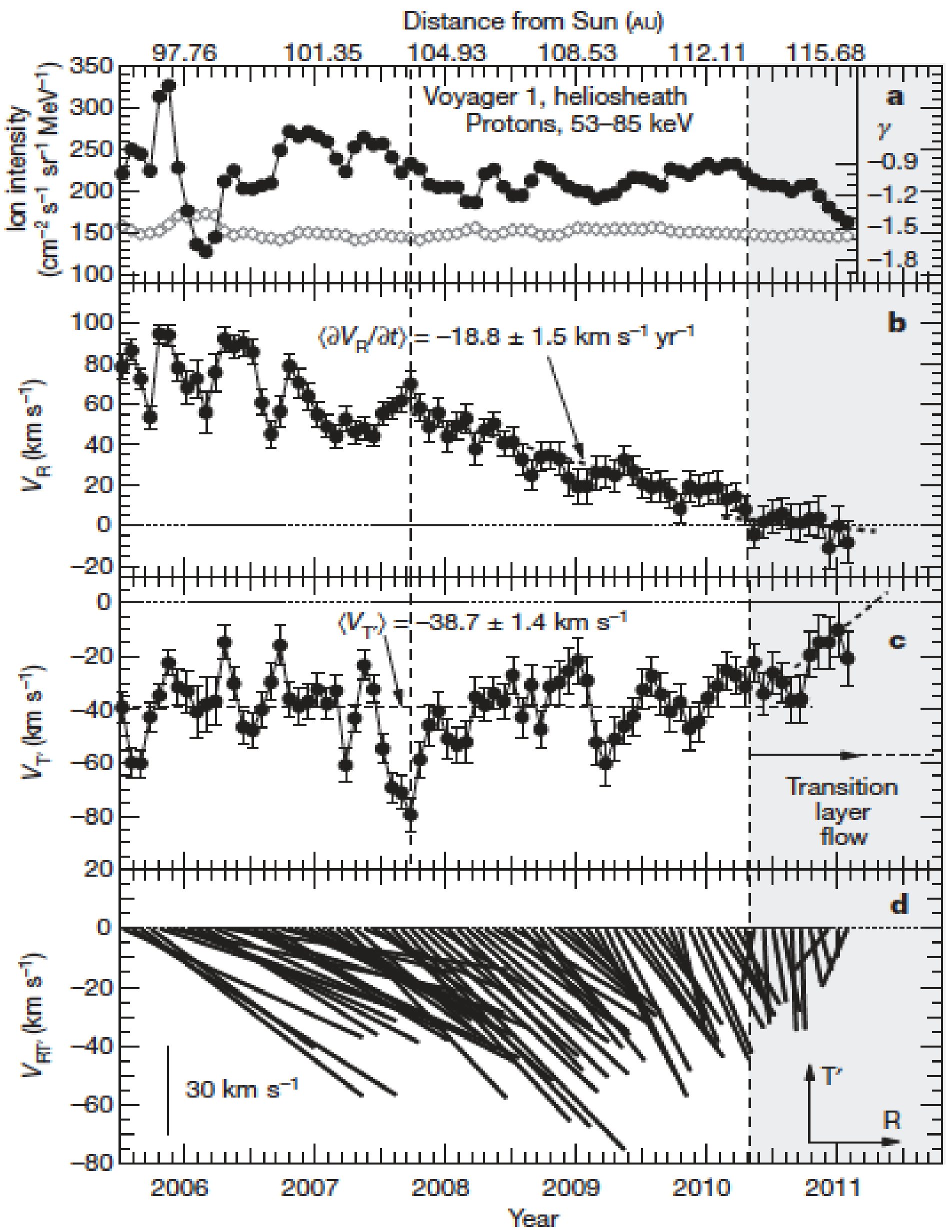
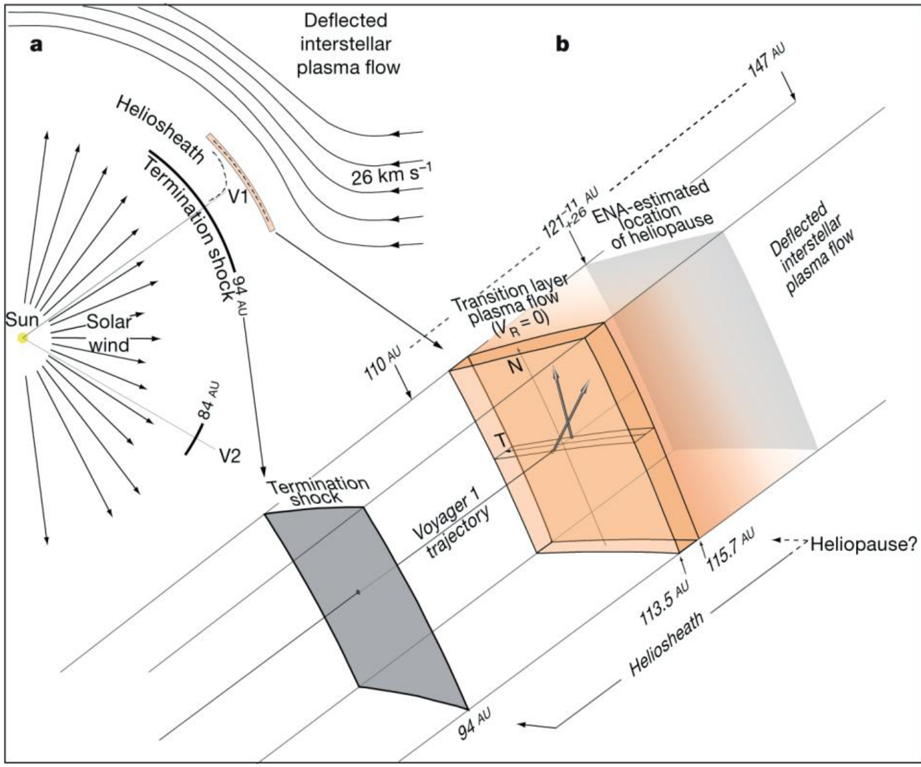
Voyager in the Transition Layer

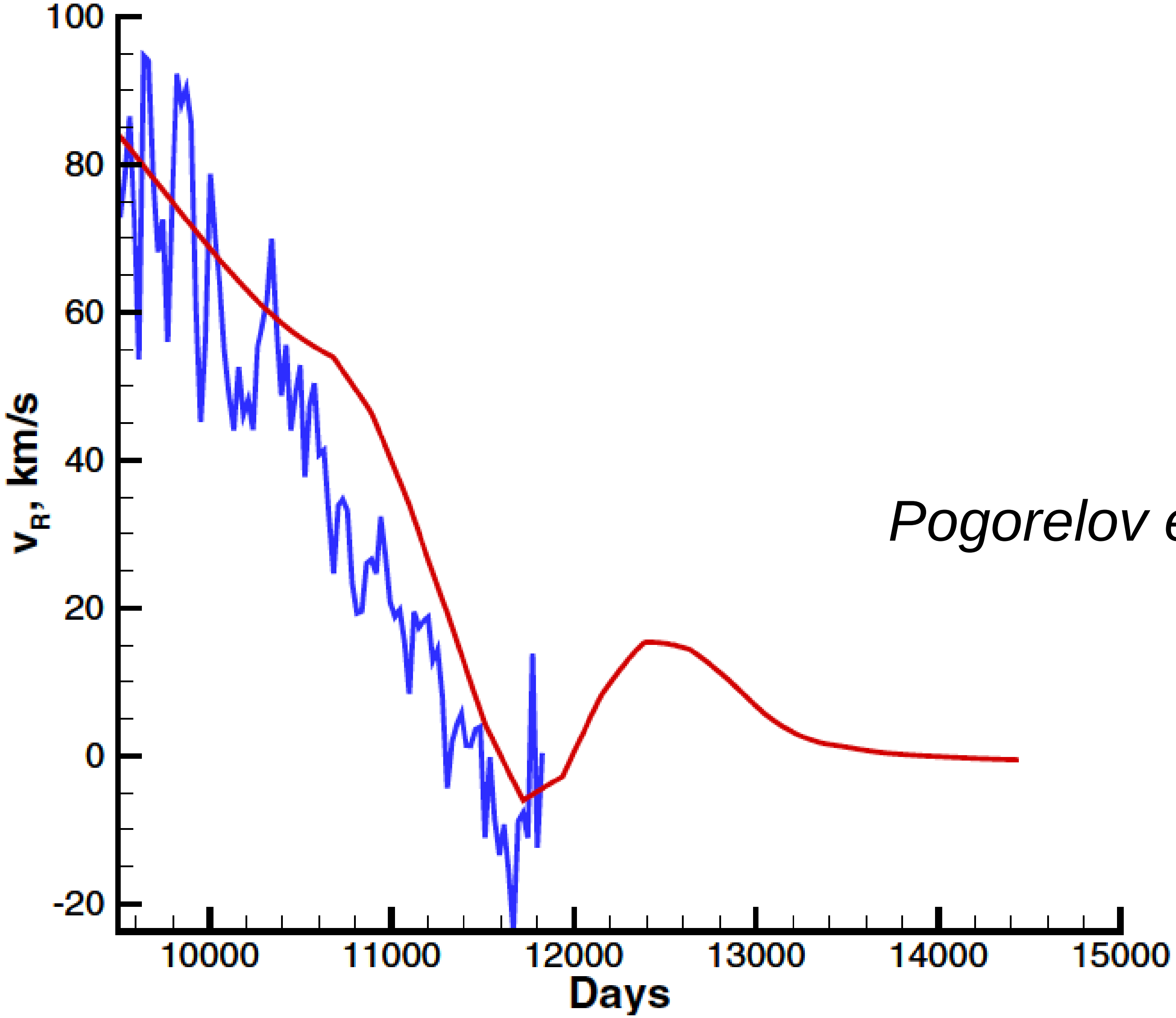




- Zero radial outflow !
- Increase of tangential speed

Krimigis et al., 2011

Time-Dependent Heliosheath



Pogorelov et al., 2012

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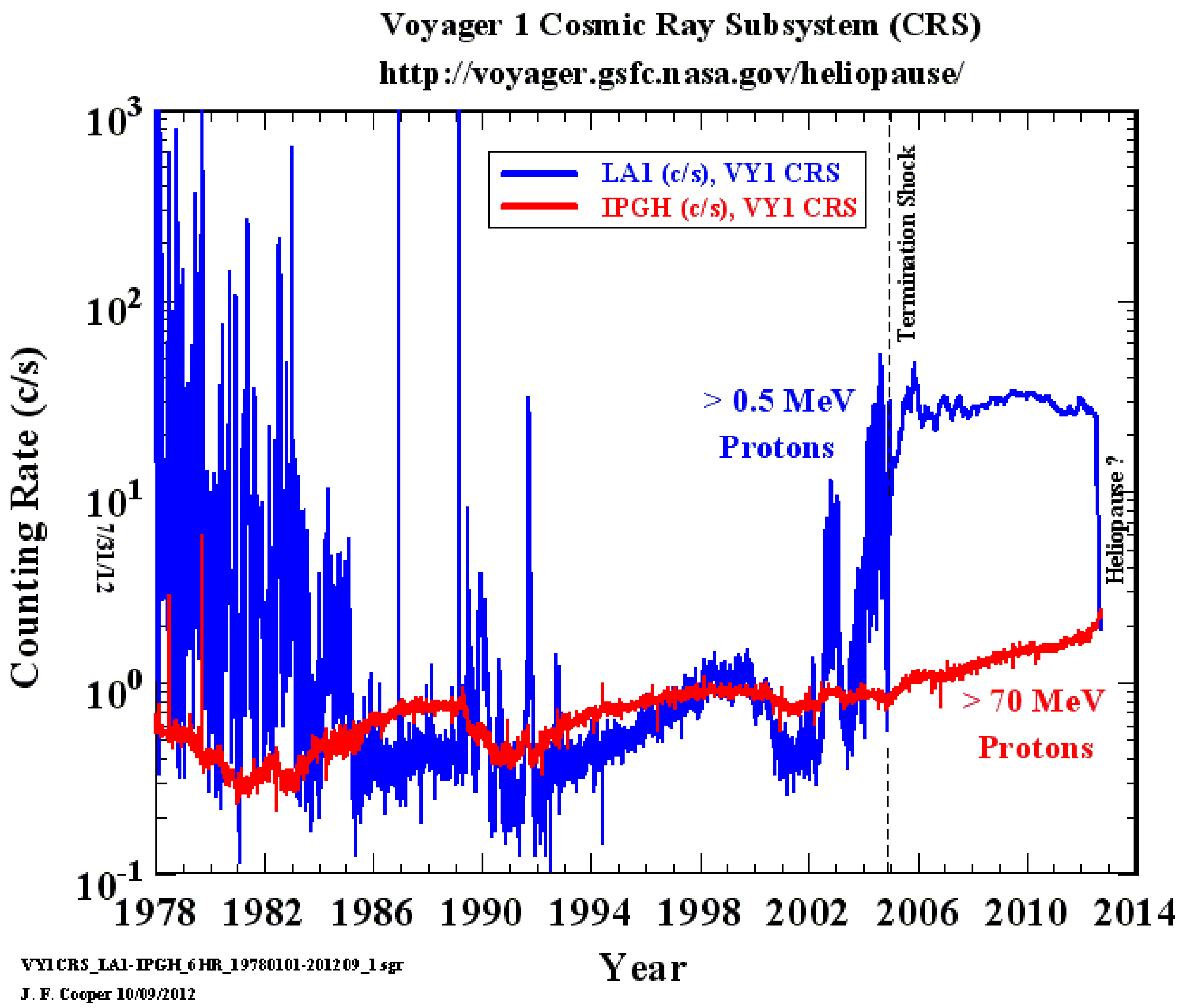
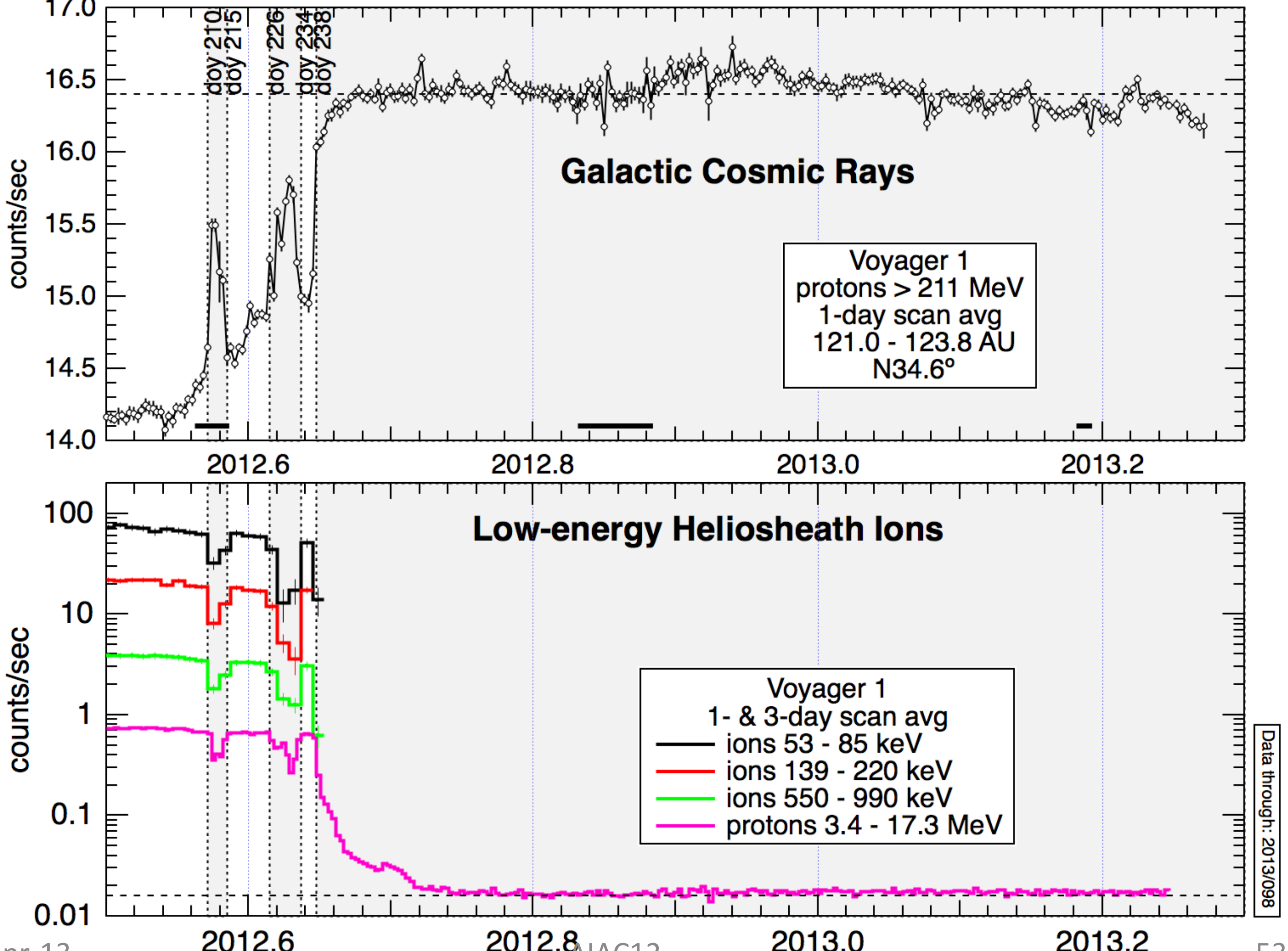
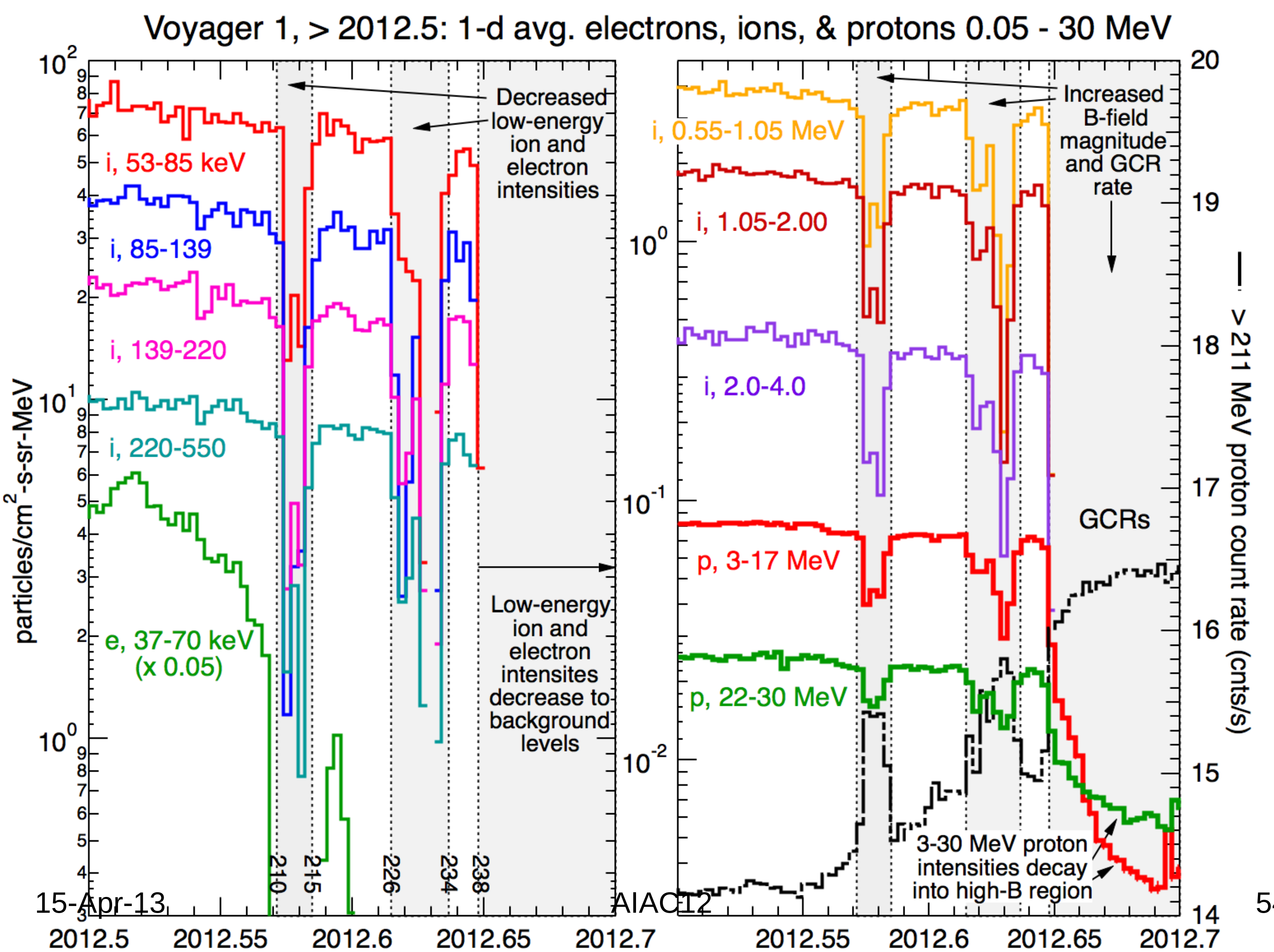
Voyager at the Heliopause?



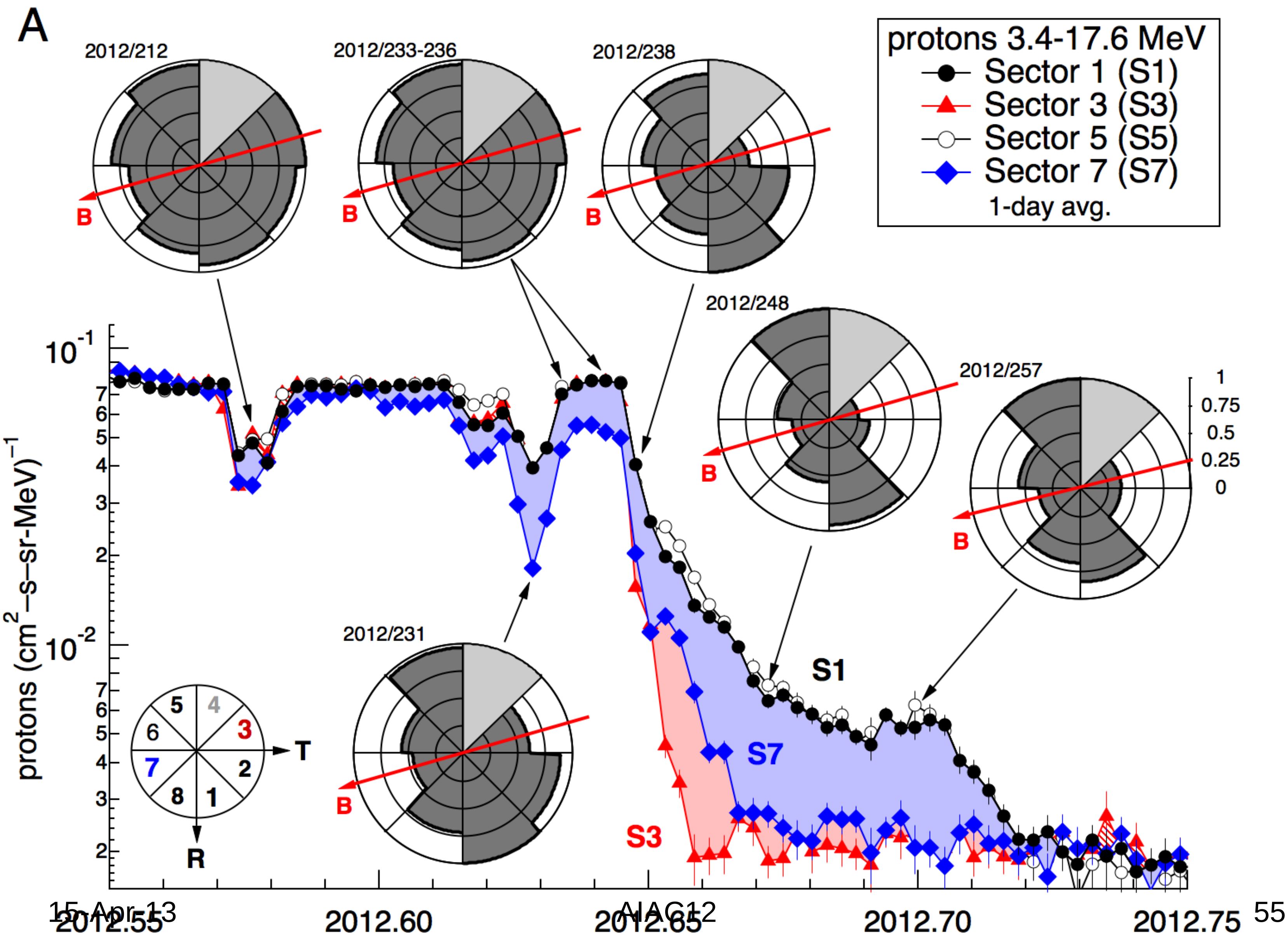
Voyager 1, 2012/183-2013/98: Galactic cosmic rays enter the high-B regions, while low-energy heliosheath particles leave via magnetic connection to LISM



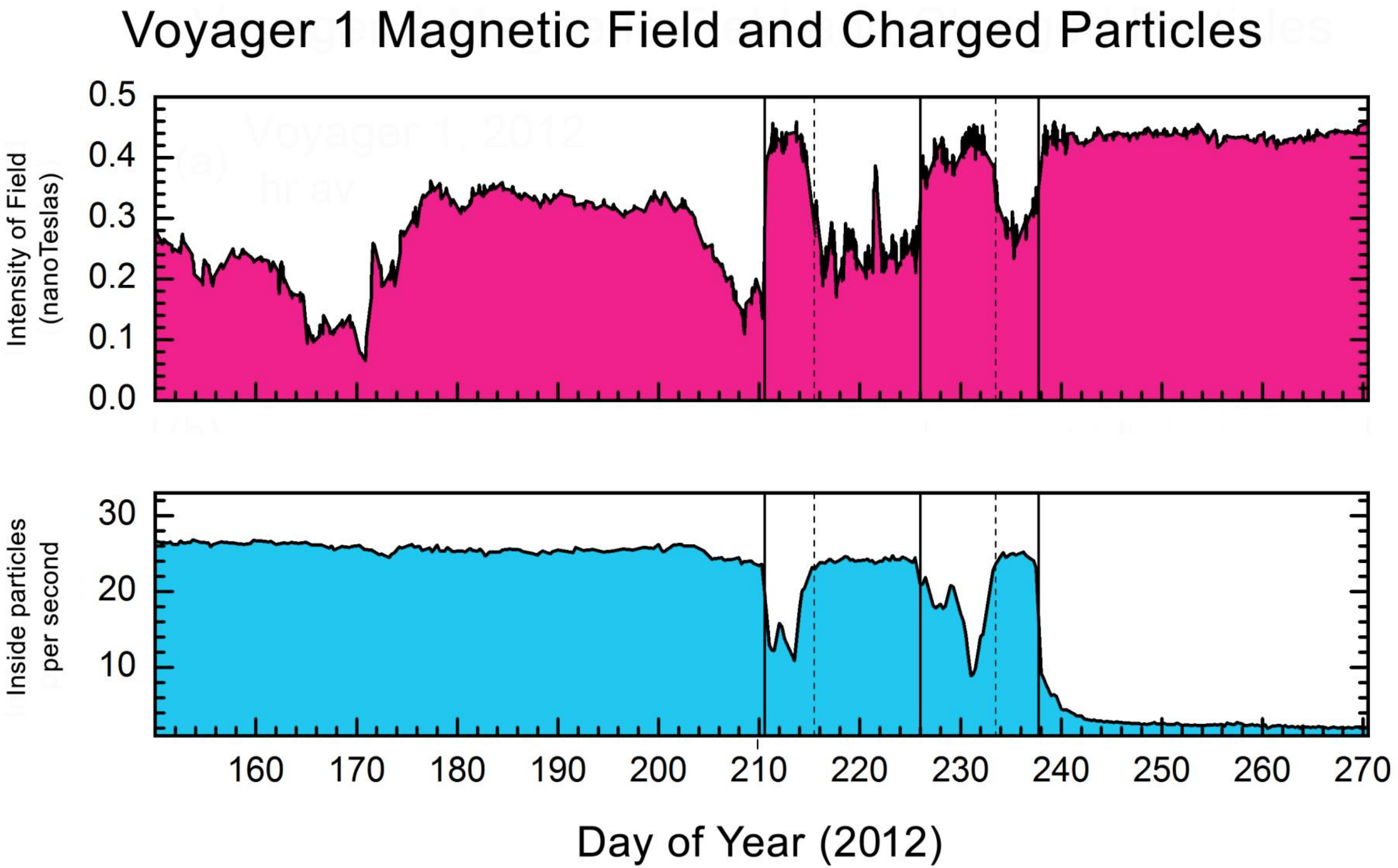
Voyager 1: Heliosheath particles escape, GCRs enter & B increases



Voyager 1: Angular distributions of protons 3.4-17.6 MeV (1-d avg.) 2012/183-330

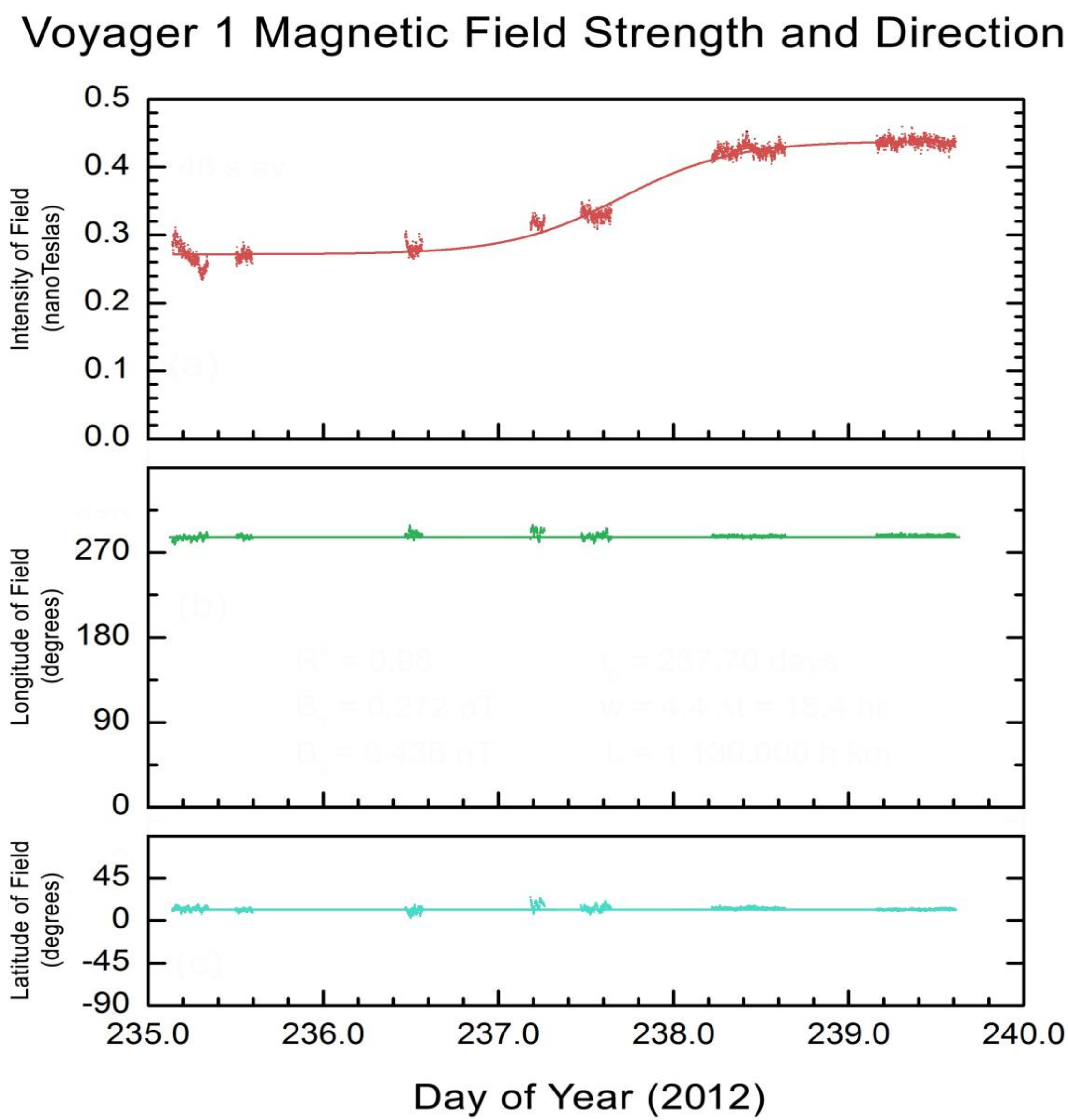


Voyager in the Heliosheath



Burlaga et al., 2013 Image credit: NASA/JPL-Caltech/GSFC/University of Delaware

Magnetic Field Observations



Conclusions:

- Increase of the magnetic field magnitude.
- NO change in the magnetic field orientation.

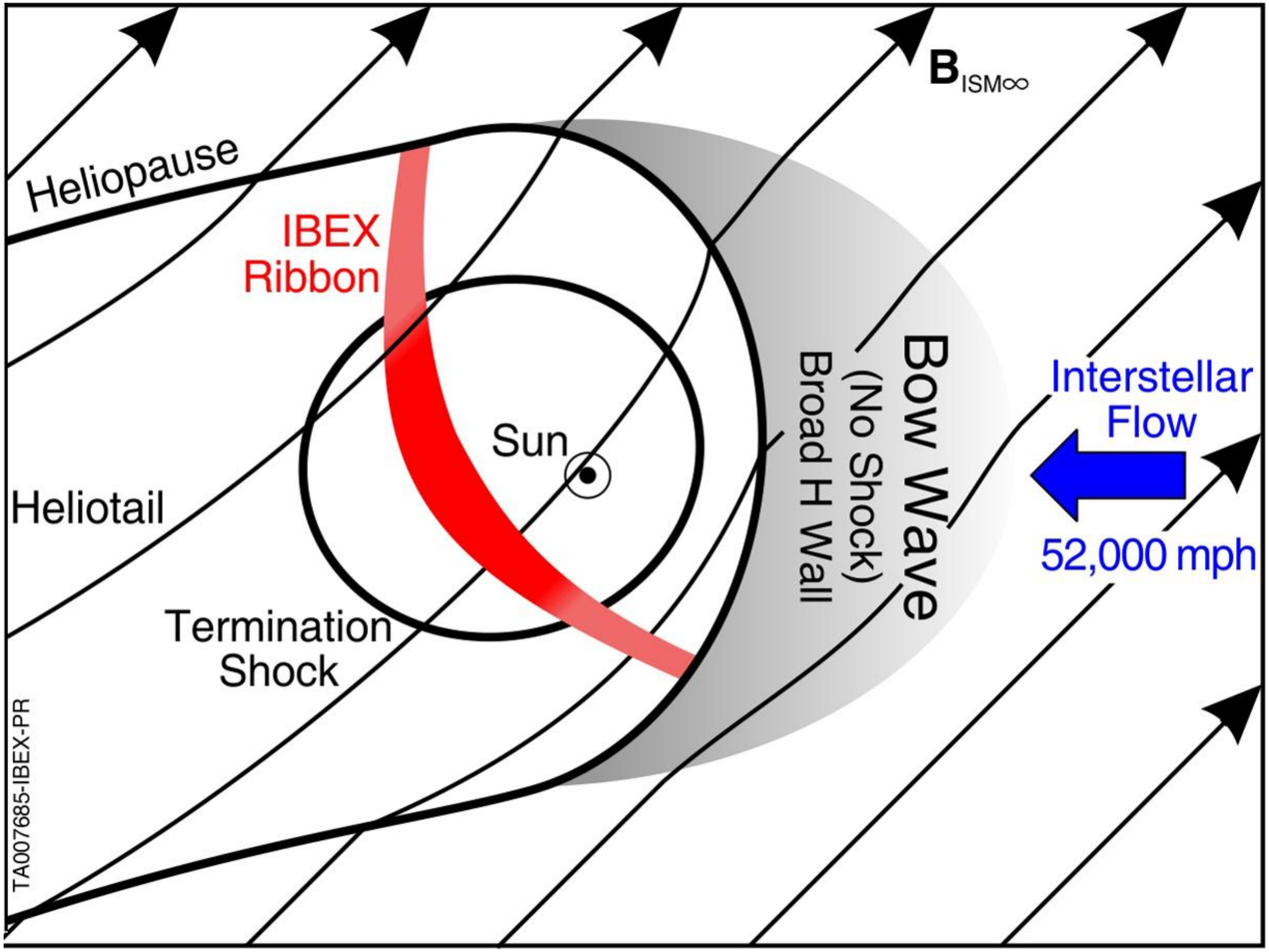
Parker Spiral magnetic field

Burlaga et al., 2013 Image credit: NASA/JPL-Caltech/GSFC/University of Delaware

(New) Puzzles and Controversies

- Where is the Shock and ACRs?
- ISM Gas Parameters
- No Heliospheric Bow Shock
- First Measurement of Primary ISM H
- "Hydrogen Deflection Plane" (Lallement)
- The IBEX "Ribbon"
- Heliosheath $V_r \sim 0$
- The "Heliocliff"
- First Measurement of Low-Energy GCRs

The Current Picture of the Heliosphere



McComas et al. 2012