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Max Planck Institute for
Solar System Research

The Source of Ubiquitous Suprathermal Ion Tails in the Inner Heliosphere

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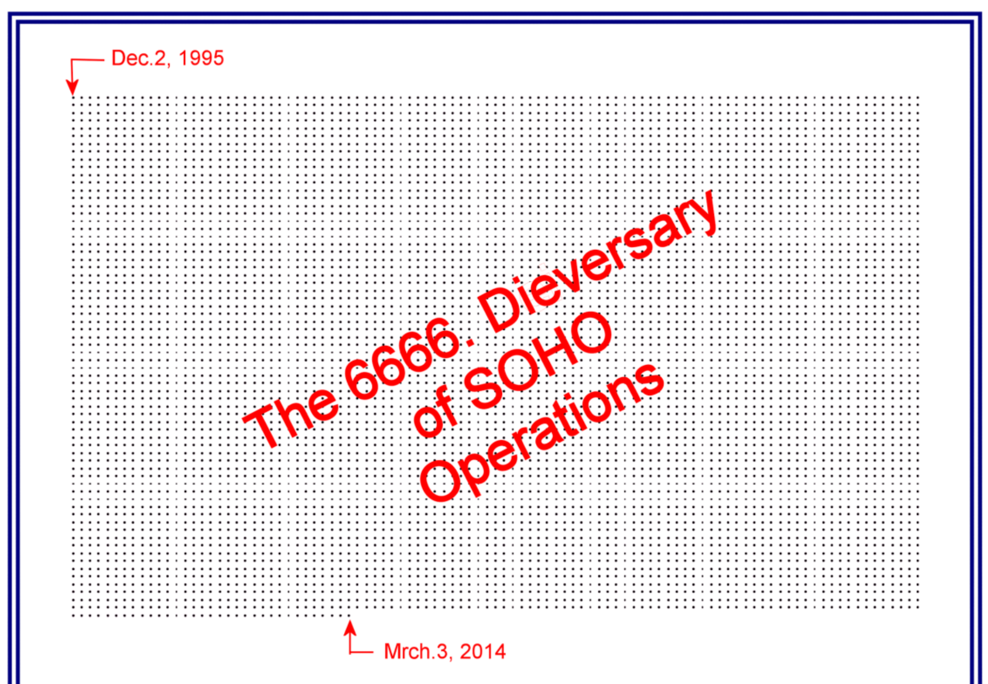
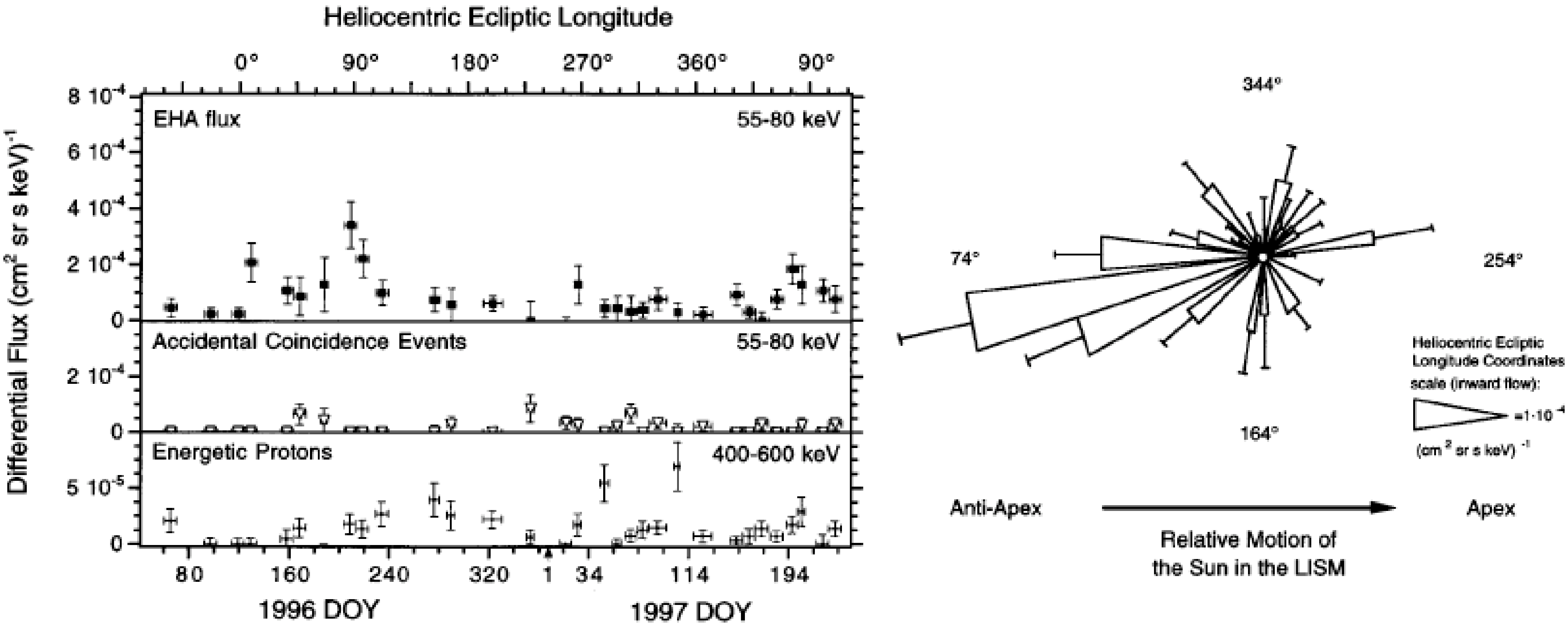


CELIAS Mini Workshop, Göttingen, Mission Day 6666 + 176 of SOHO

SOHO: First ENA Observations



Hilchenbach et al. 1998

Maximal ENA intensity from the heliotail direction but deviation in direction caused by the asymmetric shape of the heliosphere due to the interstellar magnetic field.
(«The Physics of the heliospheric boundaries», Scientific Report SR-005, ESA/ISSI, 2006)

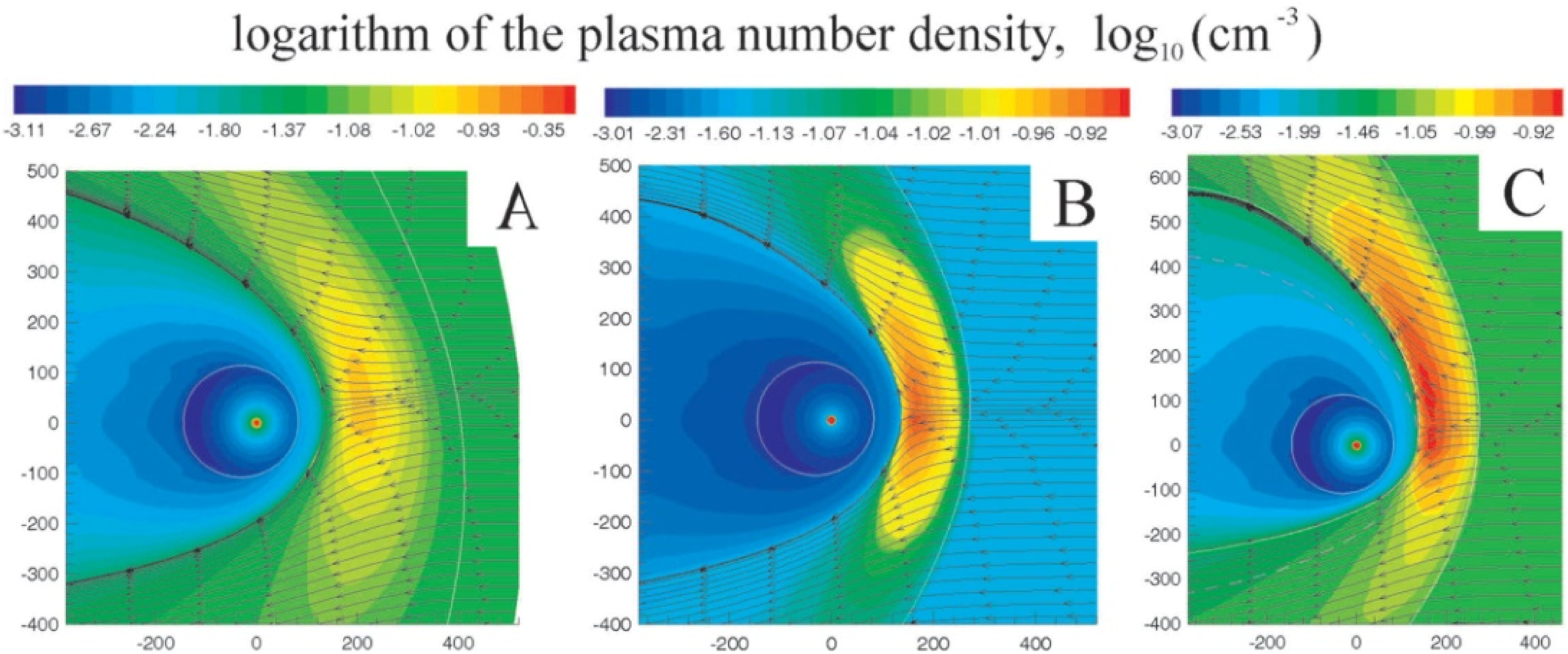
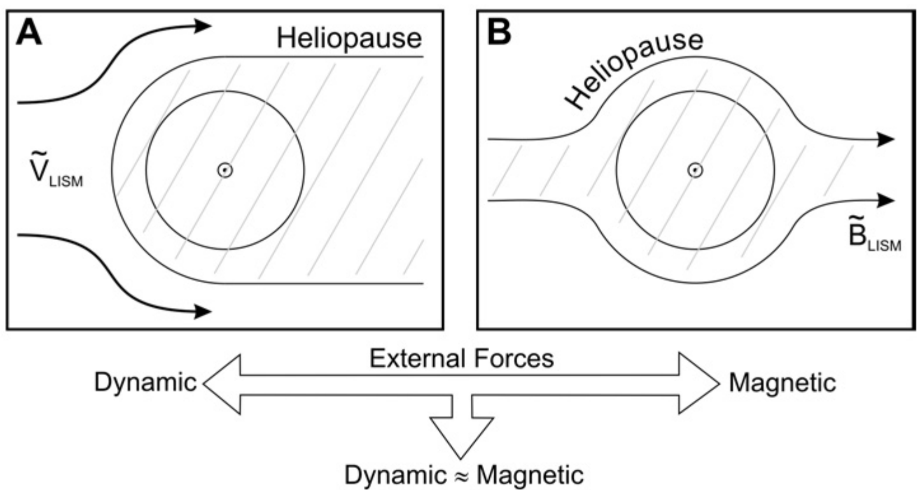
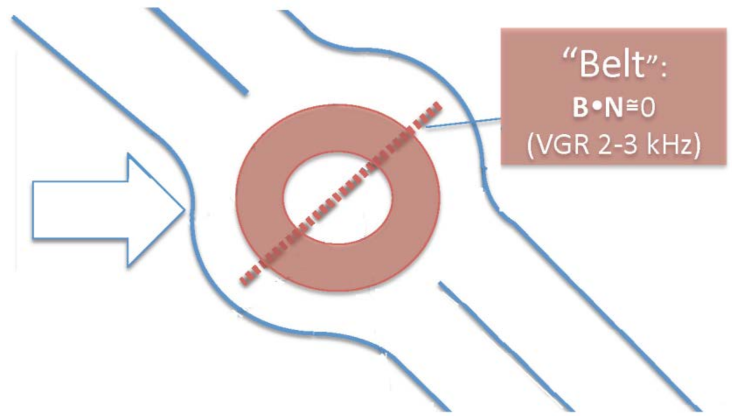
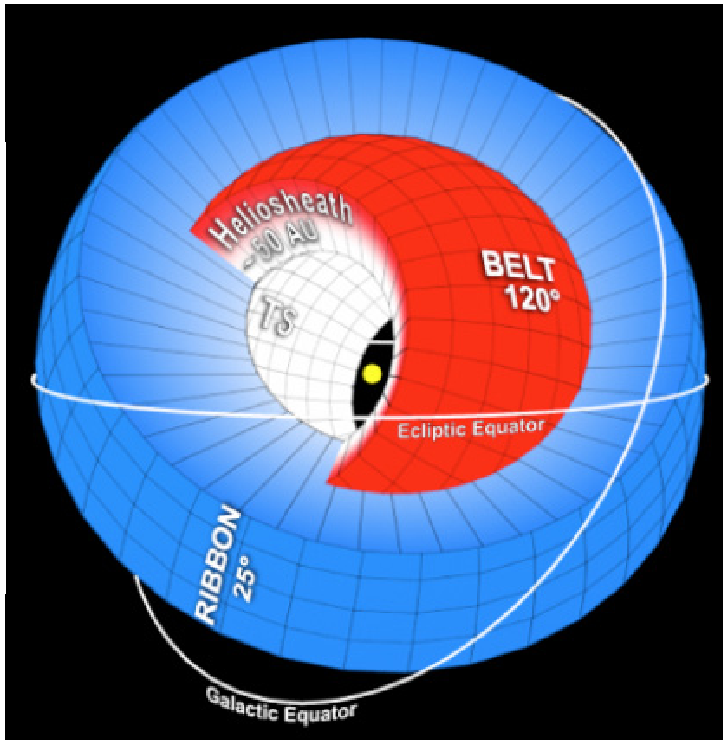


Figure 4.10: Isolines of the number density and streamlines of the plasma component. (From Izmodenov and Alexashov, 2006.)
A. 3D MHD-kinetic model with $B_{\rm LIC} = 2.5\mu$G, $\alpha = 45°$.
B. Test case of gas-dynamic flow around the fixed heliopause obtained in the case of $B_{\rm LIC} = 2.5\mu$G, $\alpha = 45°$.
C. Test case of gas-dynamic flow around the highly disturbed heliopause.

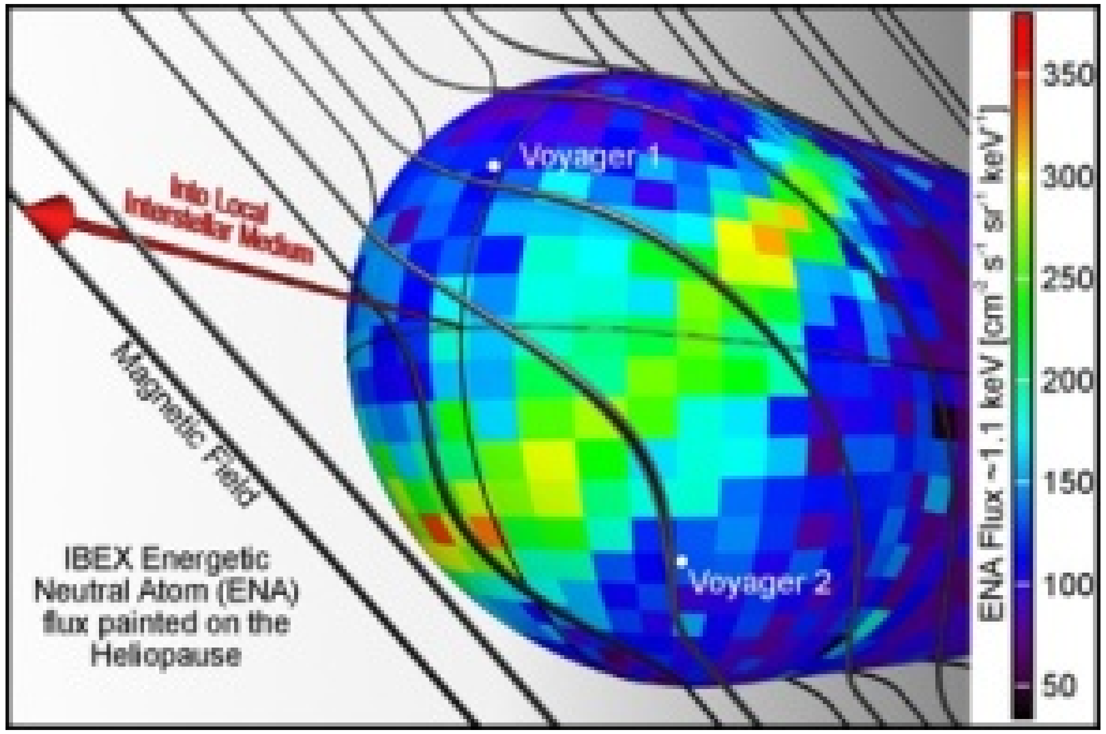
Parker, 1961



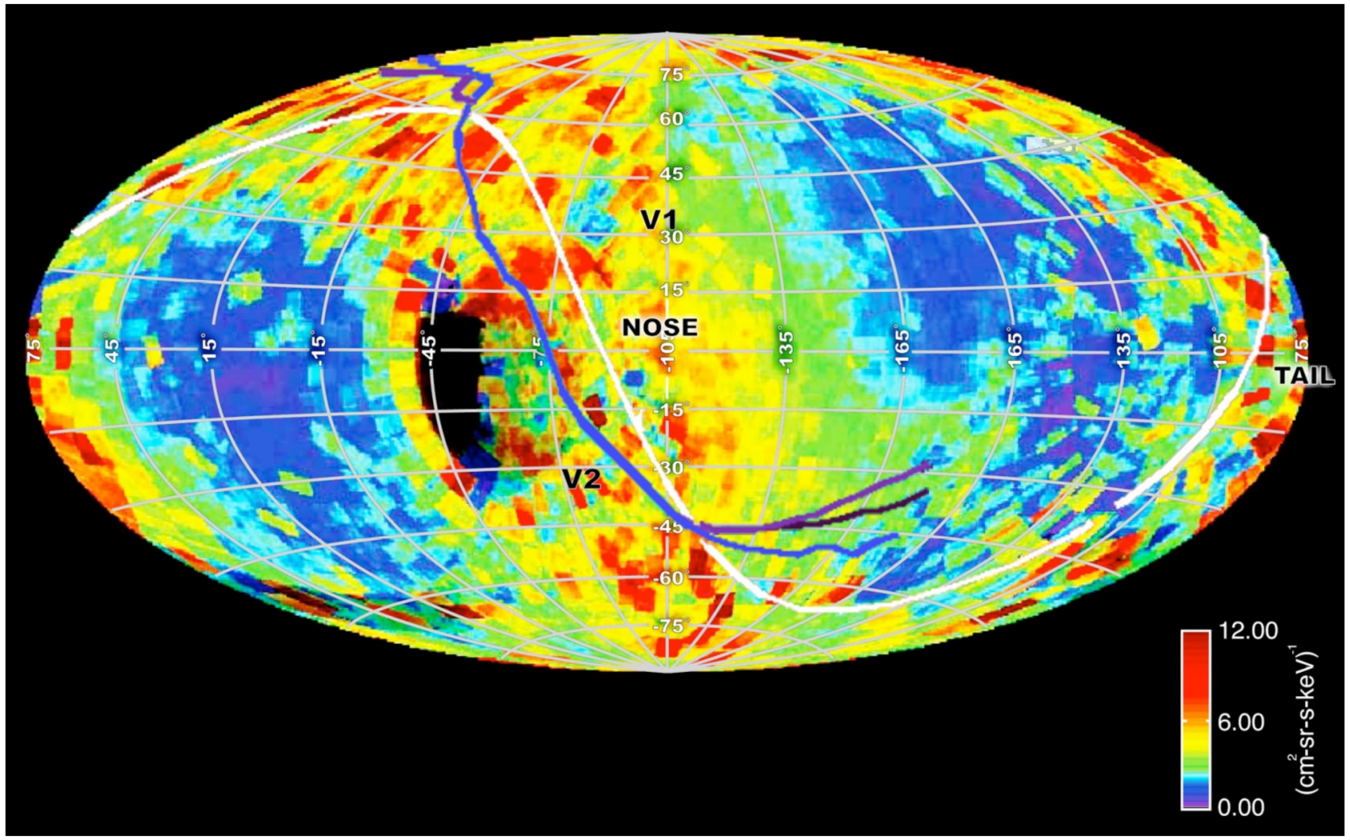




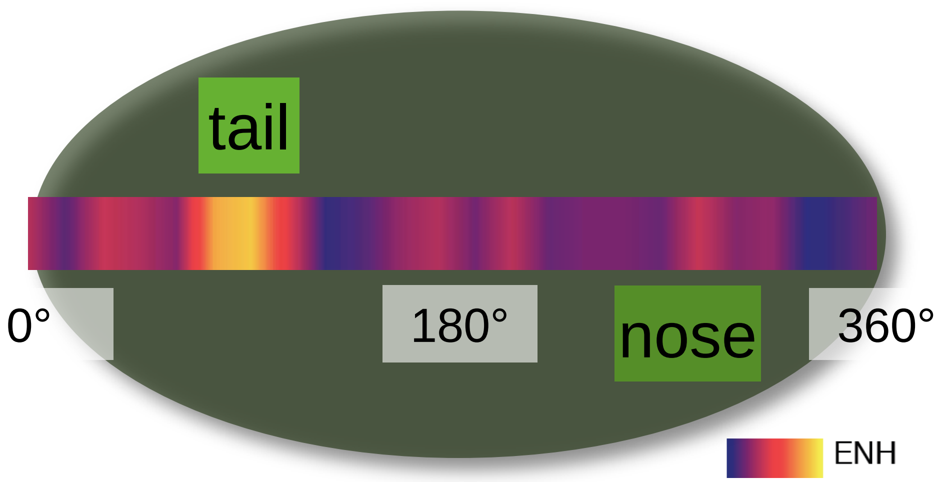
Krimigis et al. (2009, 2010)

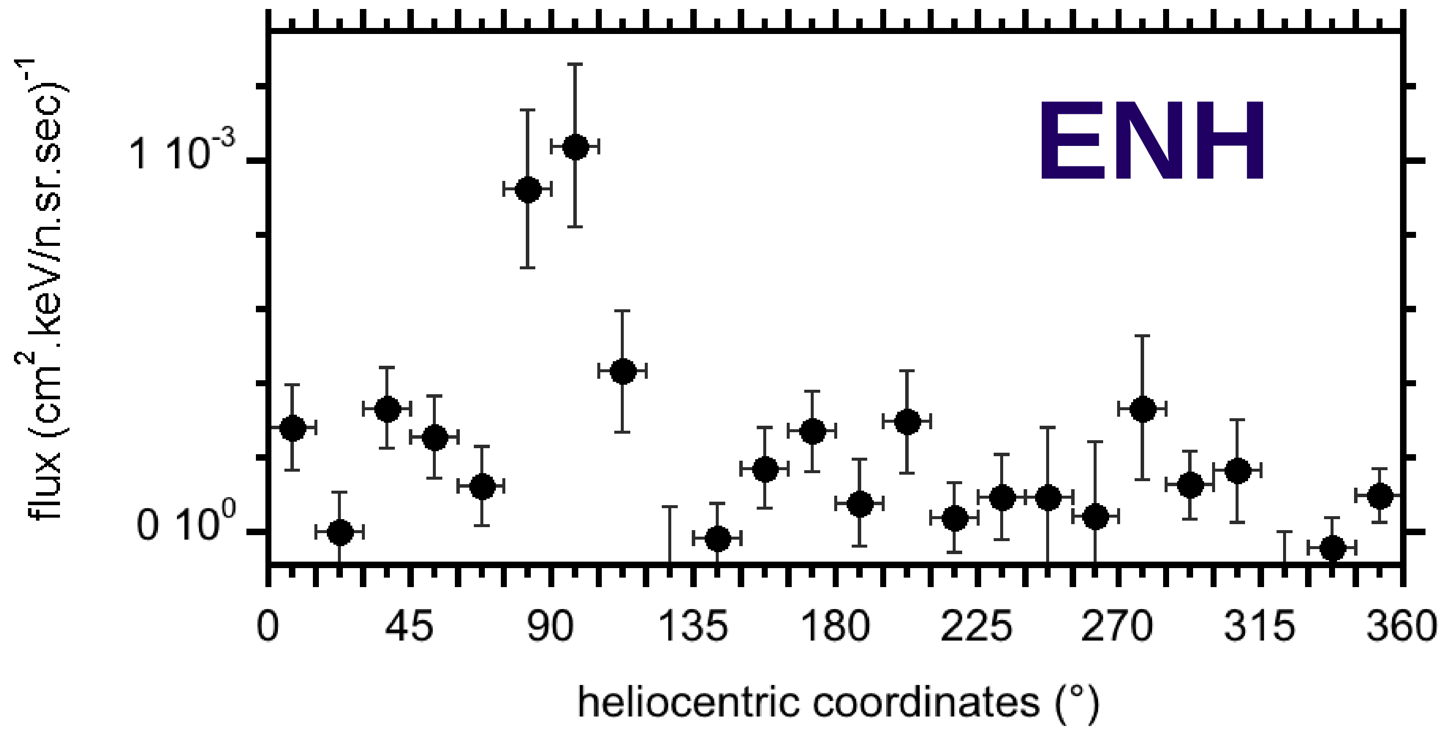


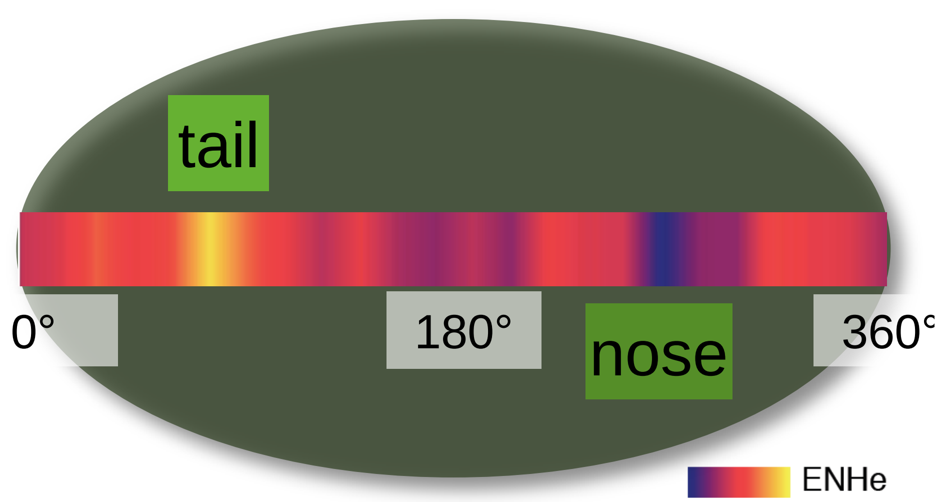
McComas et al. (2009)

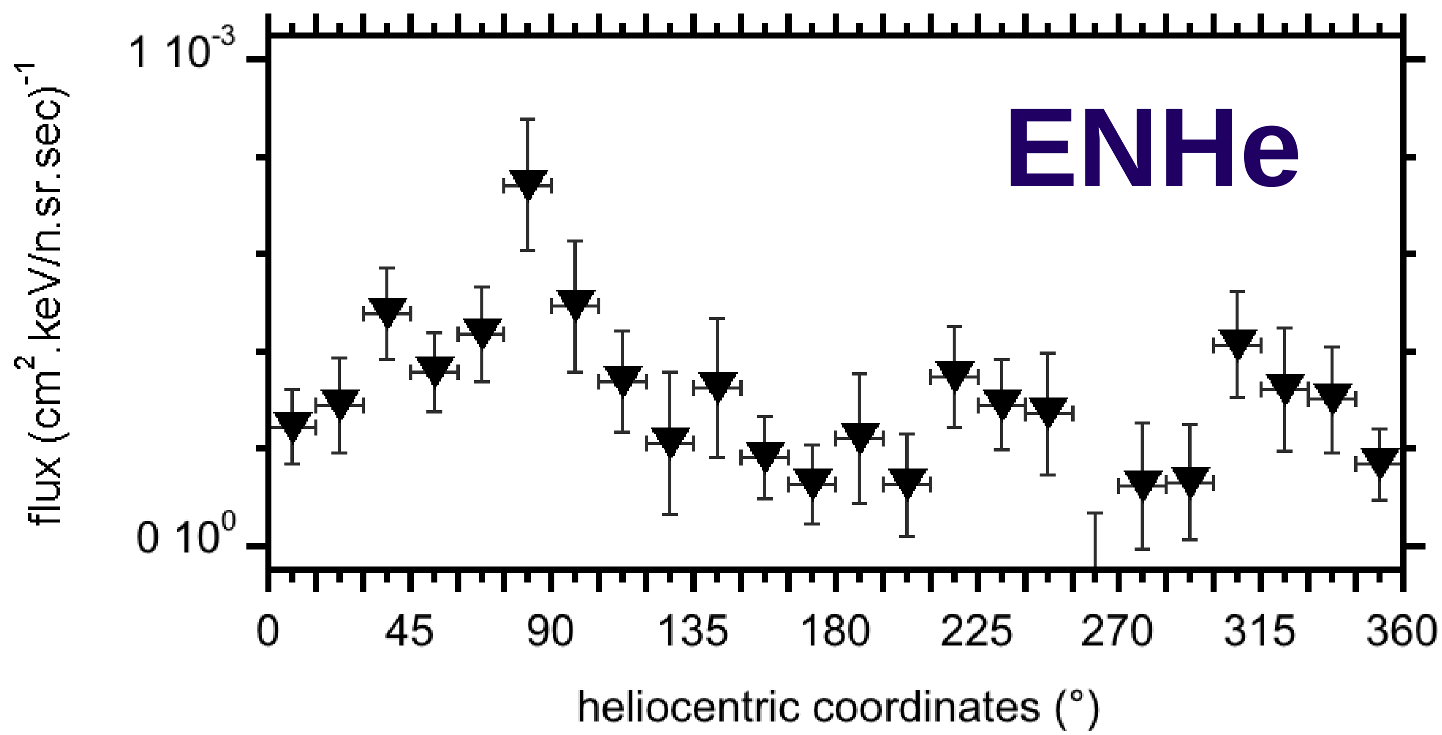


SOHO/CELIAS: Hydrogen and Helium

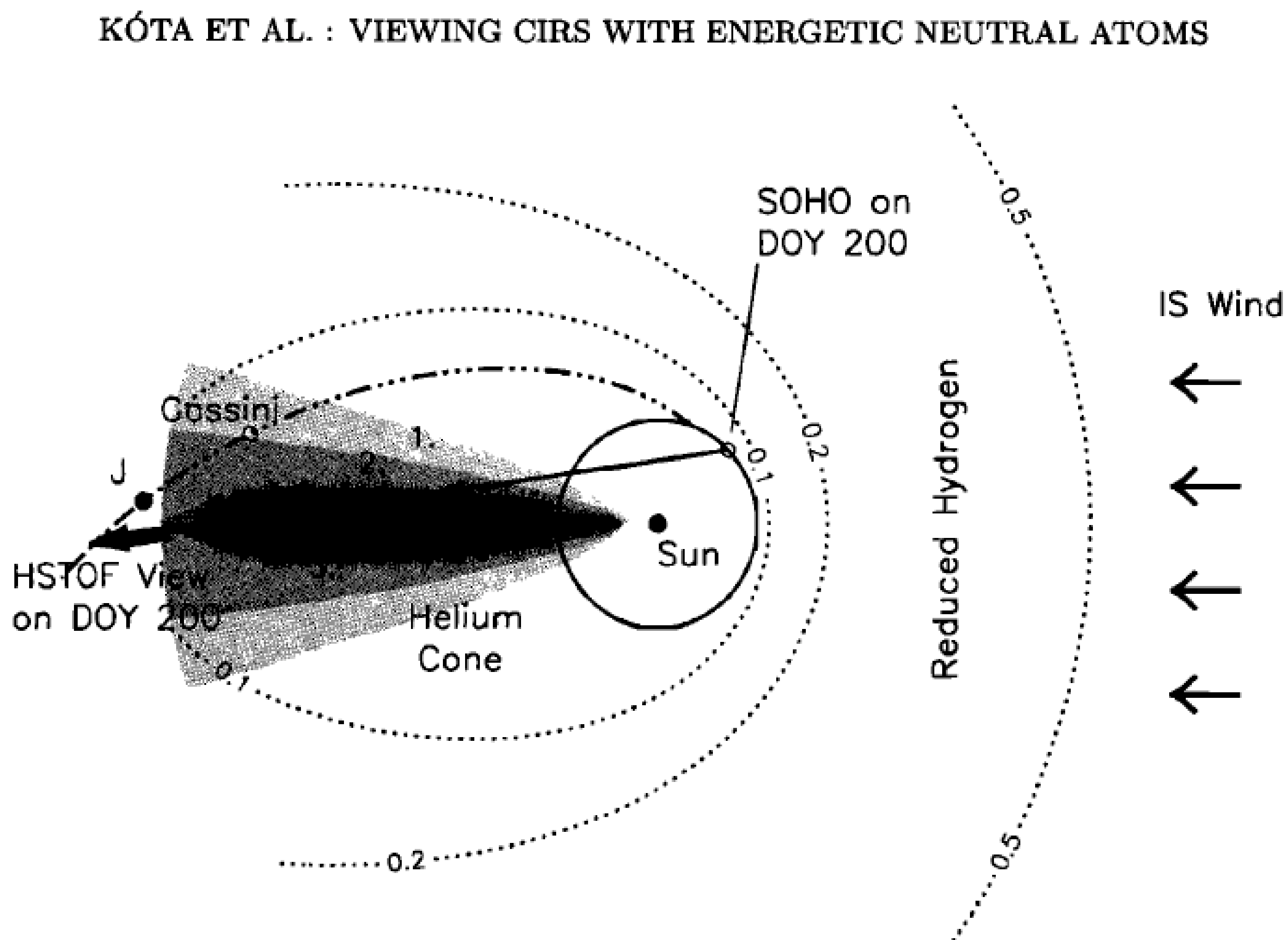




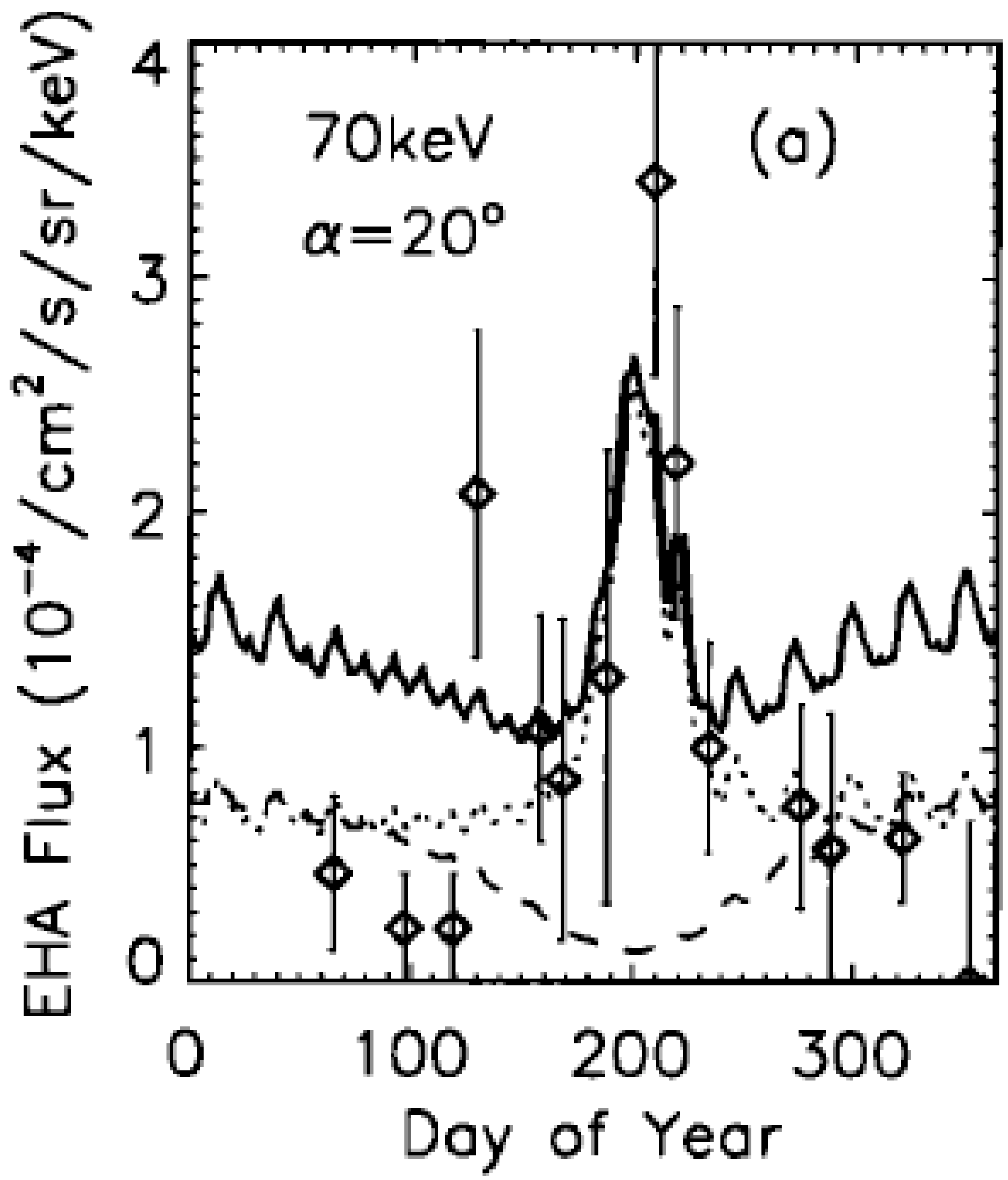




ENAs from Heliotail Direction - Another Potential Source?



Kota 2001



ENH Fluxes and a Time-Dependent Heliosphere

Assumption: No diffusion, only convection and no loss processes ...

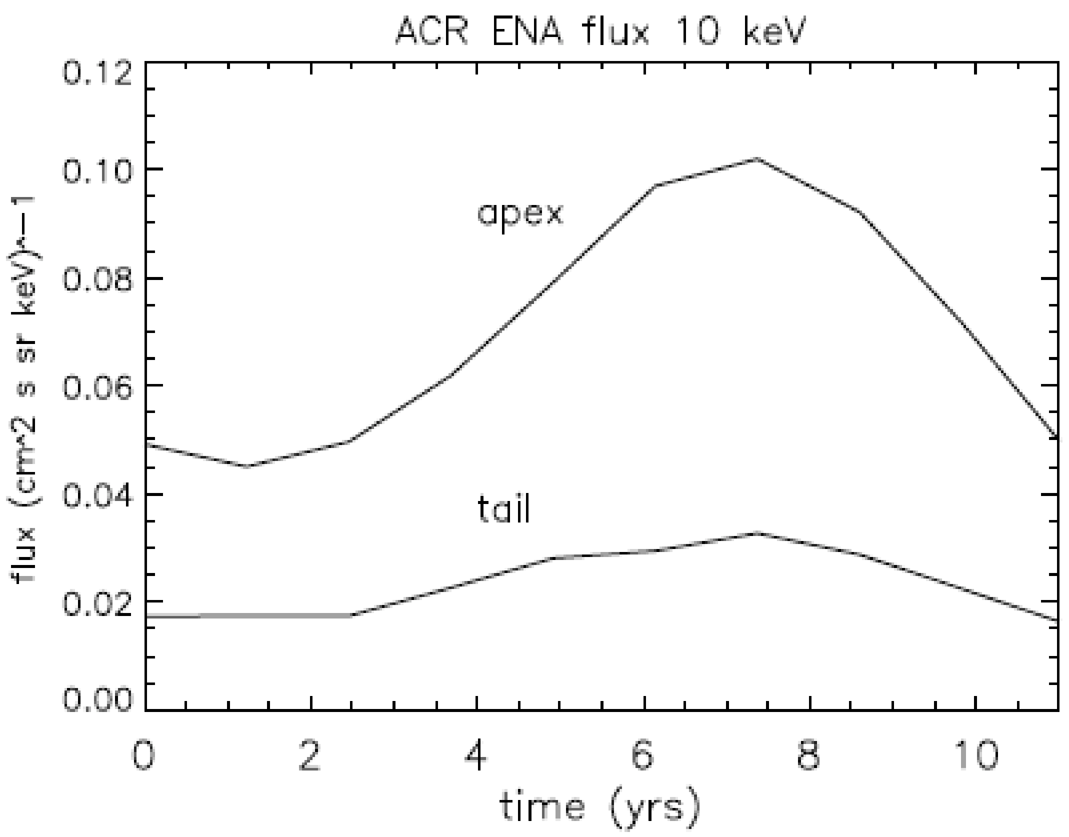


Figure 8. Energetic neutral hydrogen flux at 10 keV from the apex and the heliotail directions as a function of time. The peak of the flux occurs near "solar maximum".

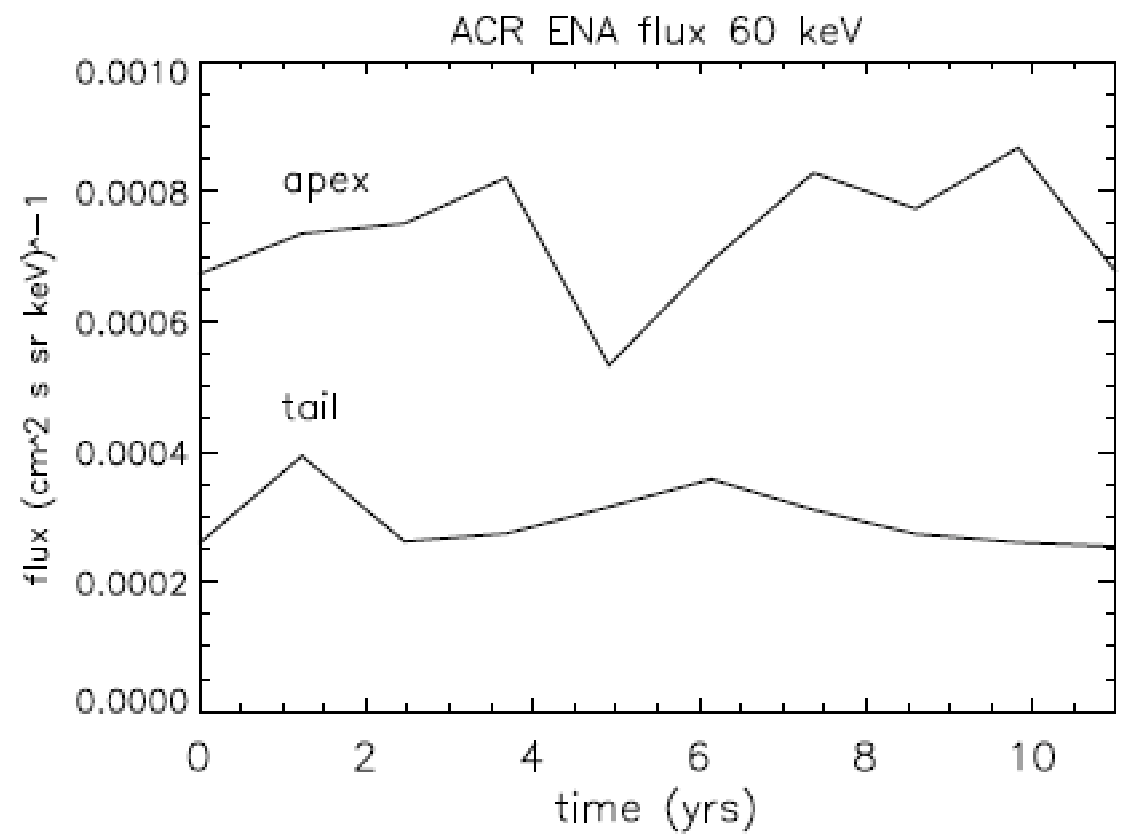
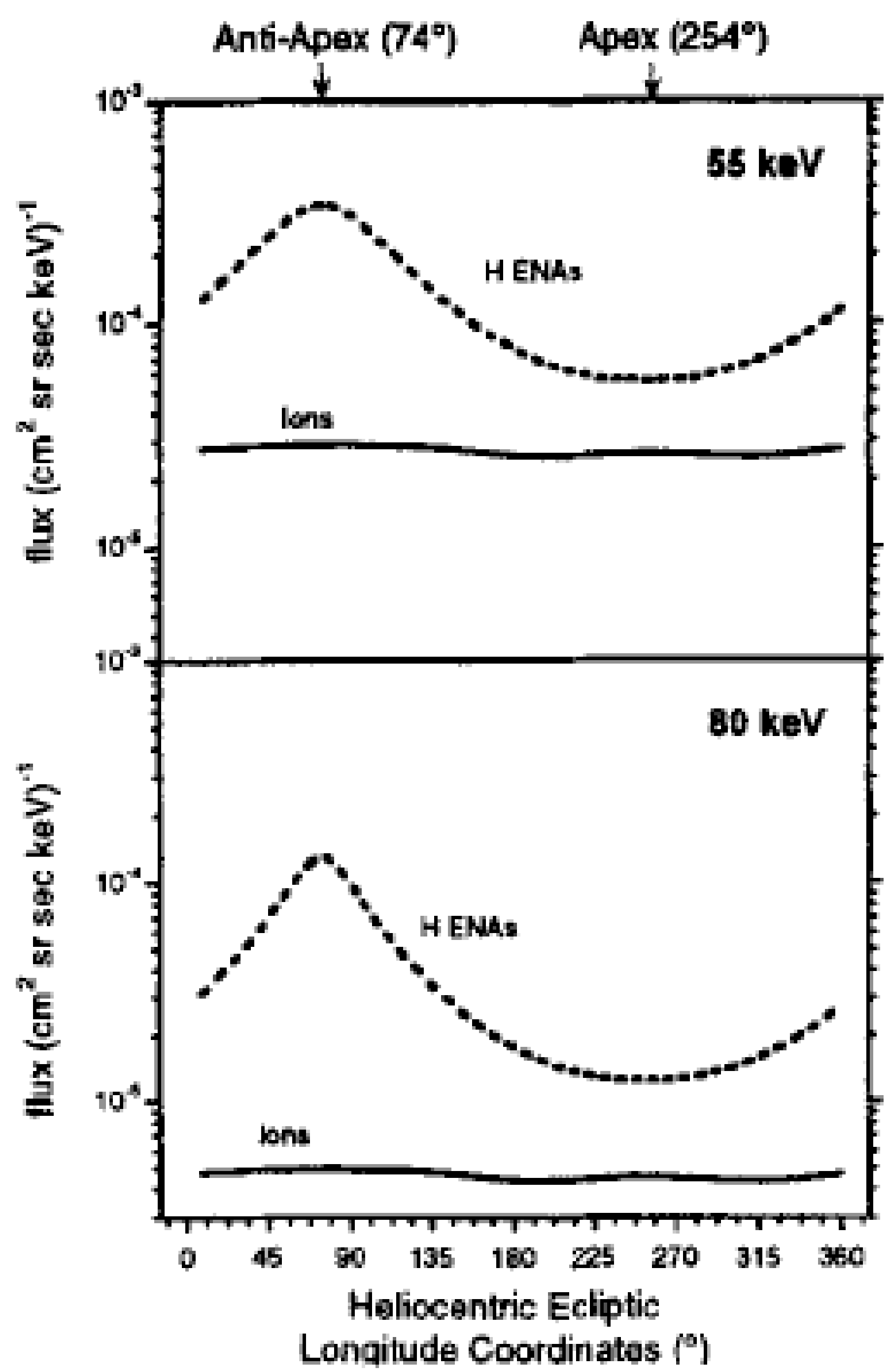


Figure 9. Energetic neutral hydrogen flux at 60 keV from the apex and the heliotail directions as a function of time. There is no peak at the "solar maximum".

Hilchenbach 2005

ENA as a Source of the "Quiet-Time" Ion Populations



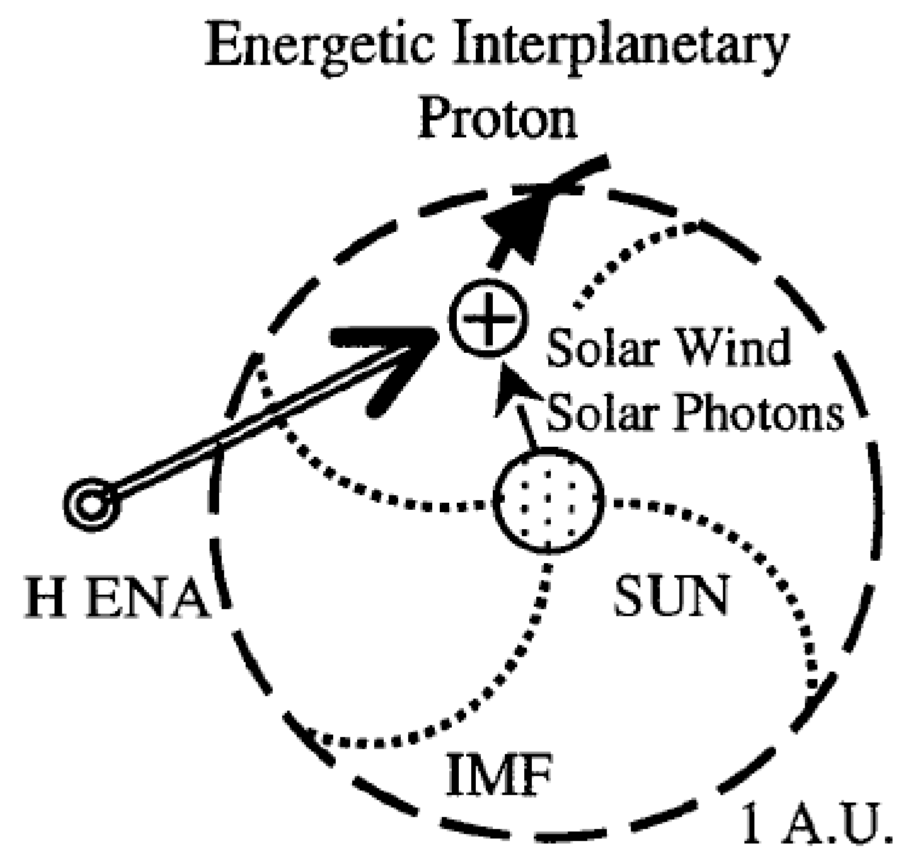
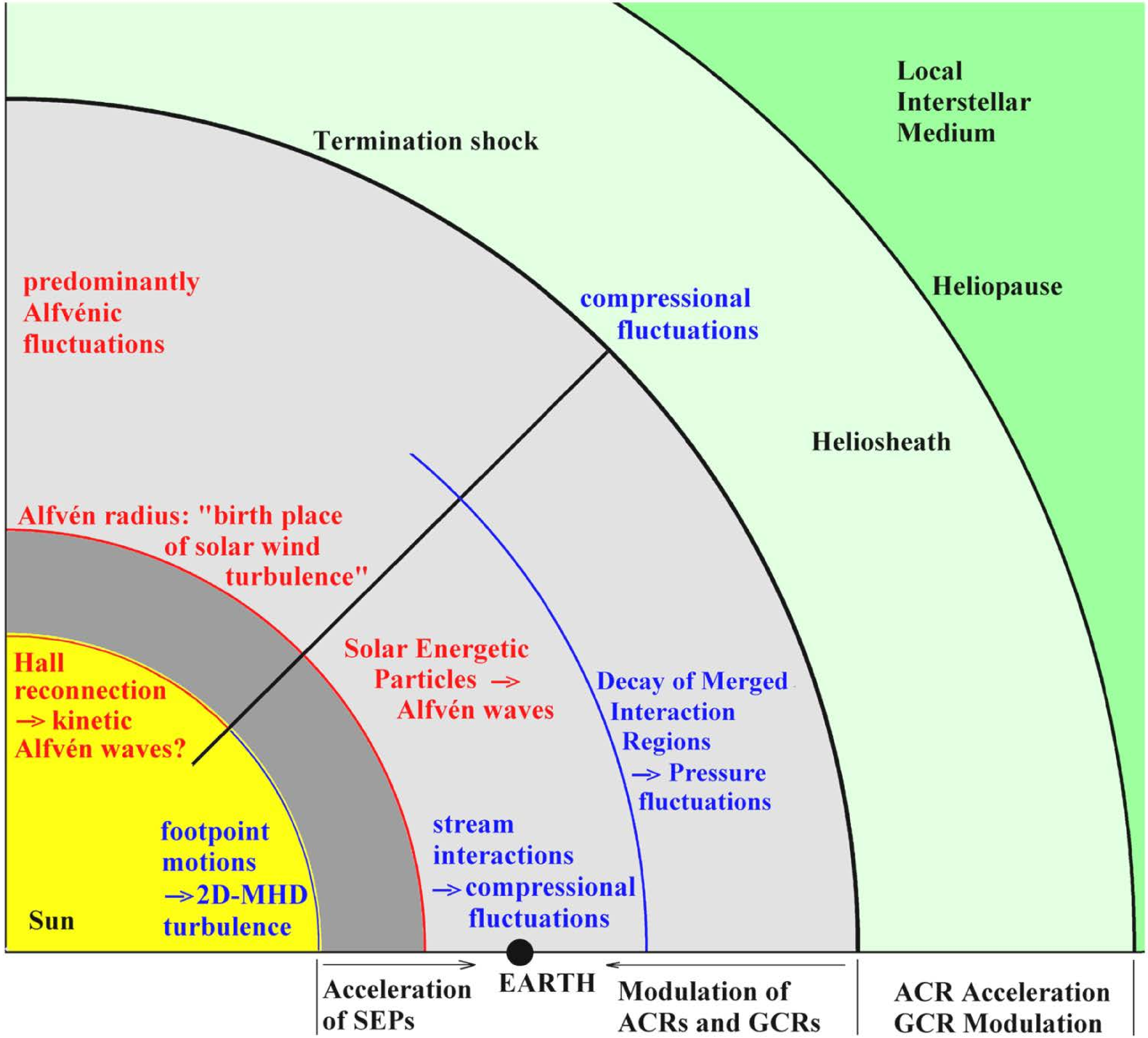
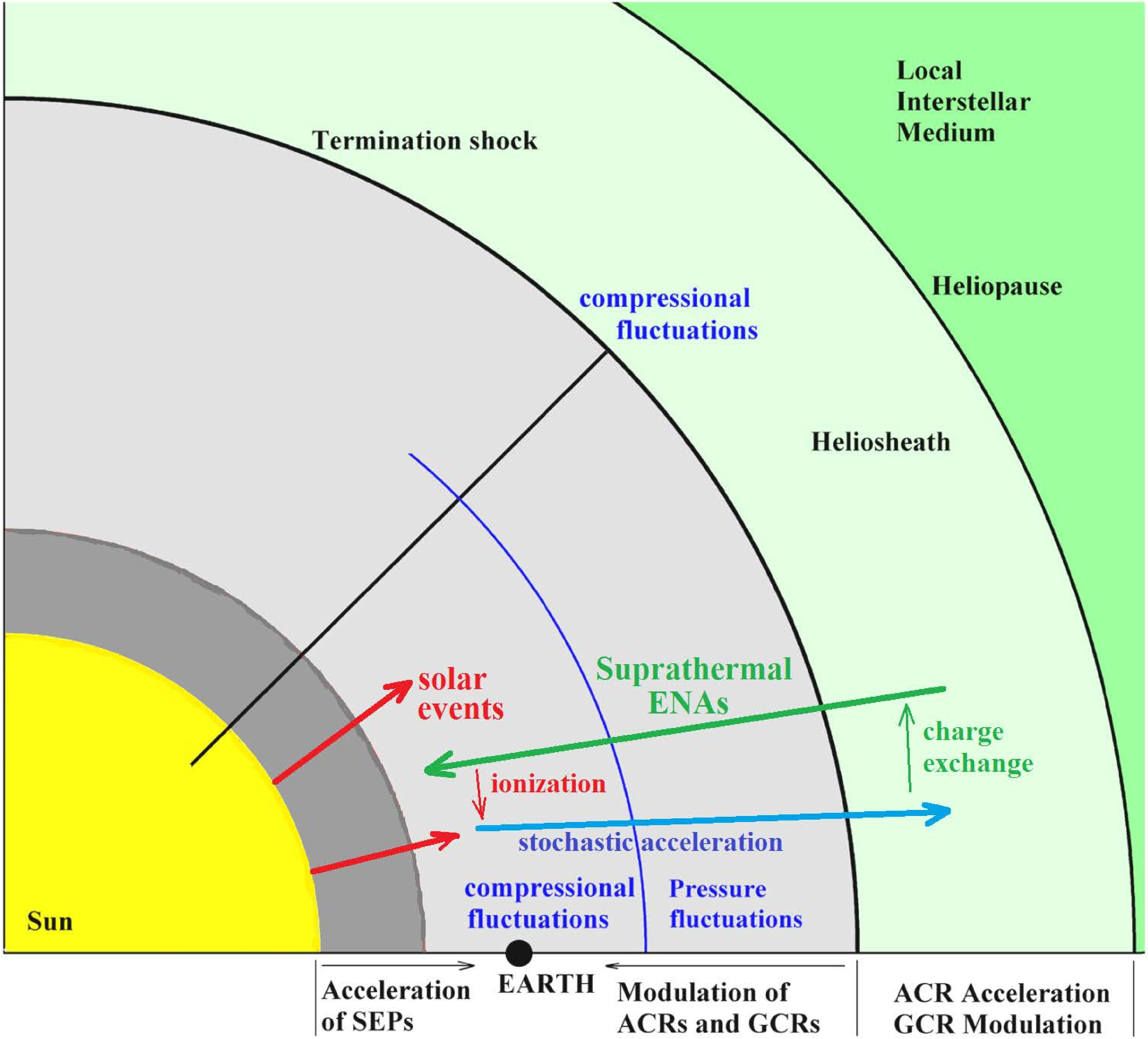
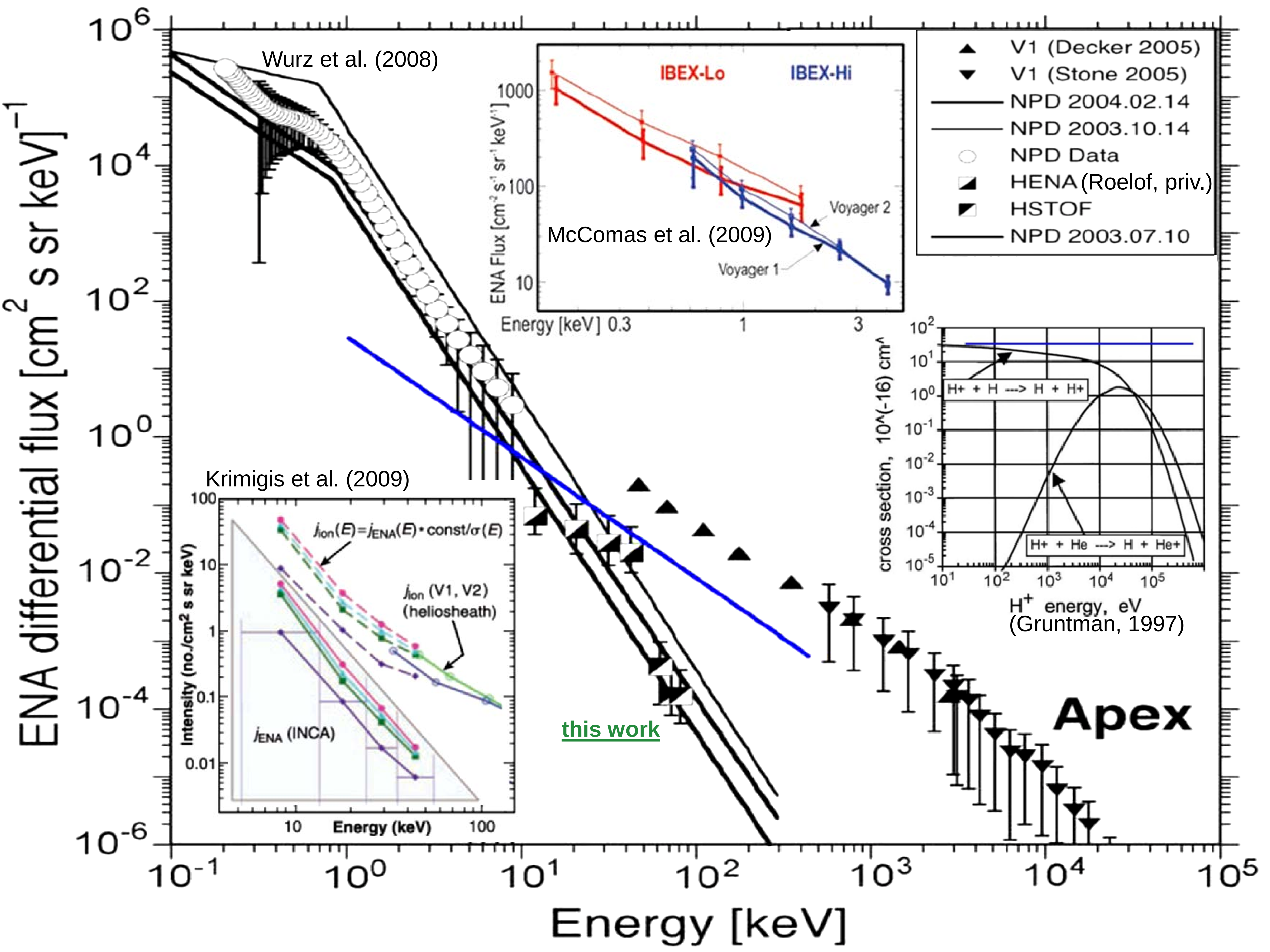


FIGURE 1. Energetic interplanetary protons of outer heliospheric origin (Schematic view, drawing not to scale). The energetic neutrals are ionised in the vicinity of the sun due to solar wind charge exchange, electron impact or by photoionisation due to solar UV radiation. The new born energetic ion then travels more or less along the interplantary magentic field lines (IMF).

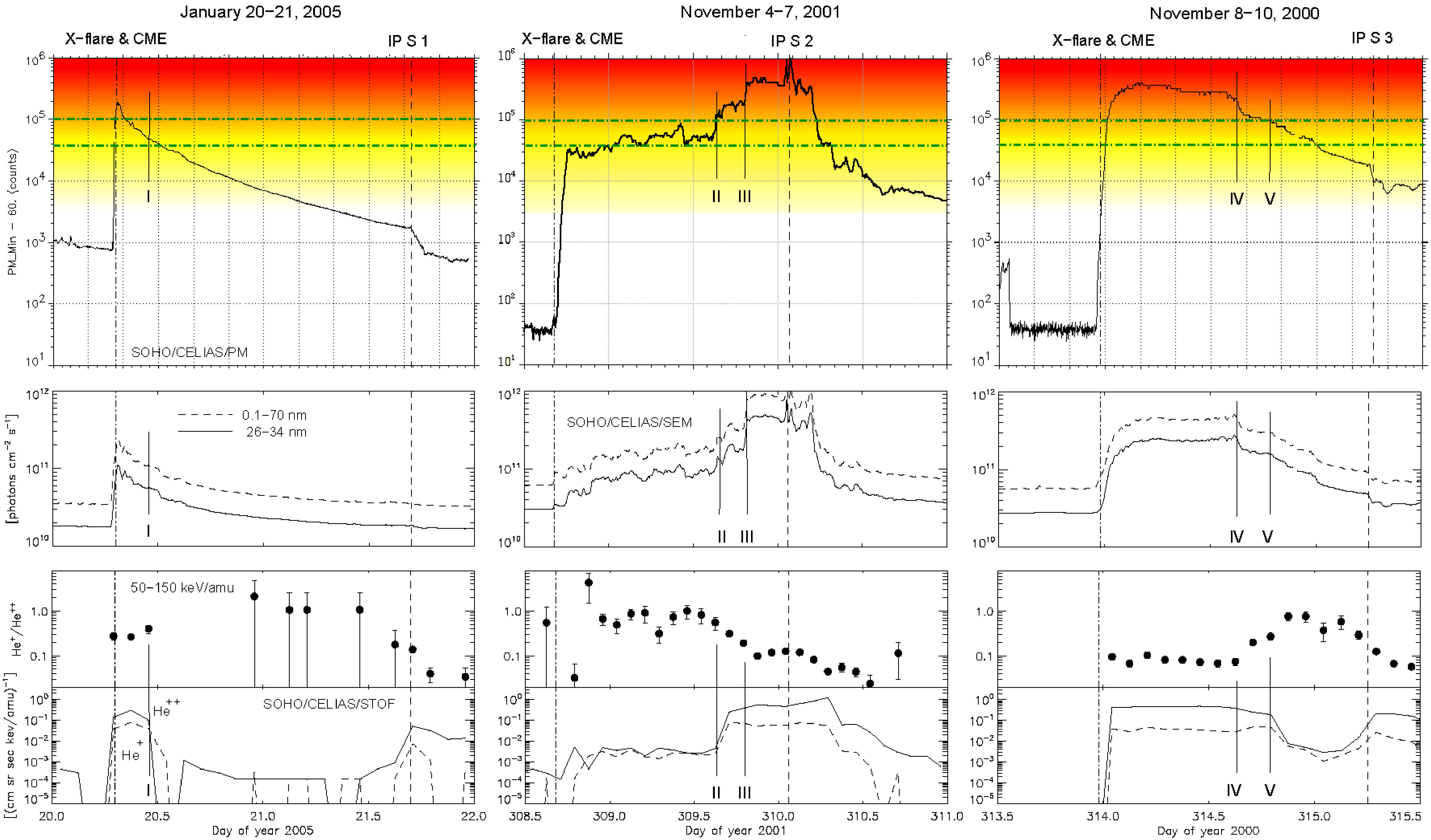
Hilchenbach 1999


Local
Interstellar
Medium
Termination shock
Heliopause
predominantly
Alfvénic
fluctuations
compressional
fluctuations
Heliosheath
Alfvén radius: "birth place
of solar wind
turbulence"
Hall
reconnection
-> kinetic
Alfvén waves?
Solar Energetic
Particles ->
Alfvén waves
Decay of Merged
Interaction
Regions
-> Pressure
fluctuations
footpoint
motions
->2D-MHD
turbulence
Sun
stream
interactions
->compressional
fluctuations
EARTH
Acceleration
of SEPs
Modulation of
ACRs and GCRs
ACR Acceleration
GCR Modulation


Local
Interstellar
Medium
Termination shock
Heliopause
compressional
fluctuations
Heliosheath
Suprathermal
ENAs
solar
events
charge
exchange
ionization
stochastic acceleration
compressional
fluctuations
Pressure
fluctuations
Sun
EARTH
Acceleration
of SEPs
Modulation of
ACRs and GCRs
ACR Acceleration
GCR Modulation



ENA differential flux [cm^2 s sr keV]$^{-1}$
Energy [keV]
Wurz et al. (2008)
McComas et al. (2009)
IBEX-Lo
IBEX-Hi
Voyager 2
Voyager 1
ENA Flux [cm^{-2} s^{-1} sr^{-1} keV^{-1}]
Energy [keV]
V1 (Decker 2005)
V1 (Stone 2005)
NPD 2004.02.14
NPD 2003.10.14
NPD Data
HENA (Roelof, priv.)
HSTOF
NPD 2003.07.10
Krimigis et al. (2009)
$j_{ion}(E)=j_{ENA}(E)\cdot const/\sigma(E)$
j_{ion} (V1, V2) (heliosheath)
j_{ENA} (INCA)
Intensity (no./cm^2 s sr keV)
Energy (keV)
this work
H+ + H ---> H + H+
H+ + He ---> H + He+
cross section, 10^(-16) cm^
H^+ energy, eV
(Gruntman, 1997)
Apex



January 20−21, 2005
November 4−7, 2001
November 8−10, 2000
X−flare & CME
IP S 1
IP S 2
IP S 3
PM_Min − 60. (counts)
SOHO/CELIAS/PM
I
II
III
IV
V
[photons cm^{-2} s^{-1}]
0.1−70 nm
26−34 nm
SOHO/CELIAS/SEM
He^{+}/He^{++}
50−150 keV/amu
[(cm sr sec kev/amu)$^{-1}$]
SOHO/CELIAS/STOF
He^{++}
He^{+}
Day of year 2005
Day of year 2001
Day of year 2000

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J. Phys. B: At. Mol. Opt. Phys. **21** (1988) 2751-2761.

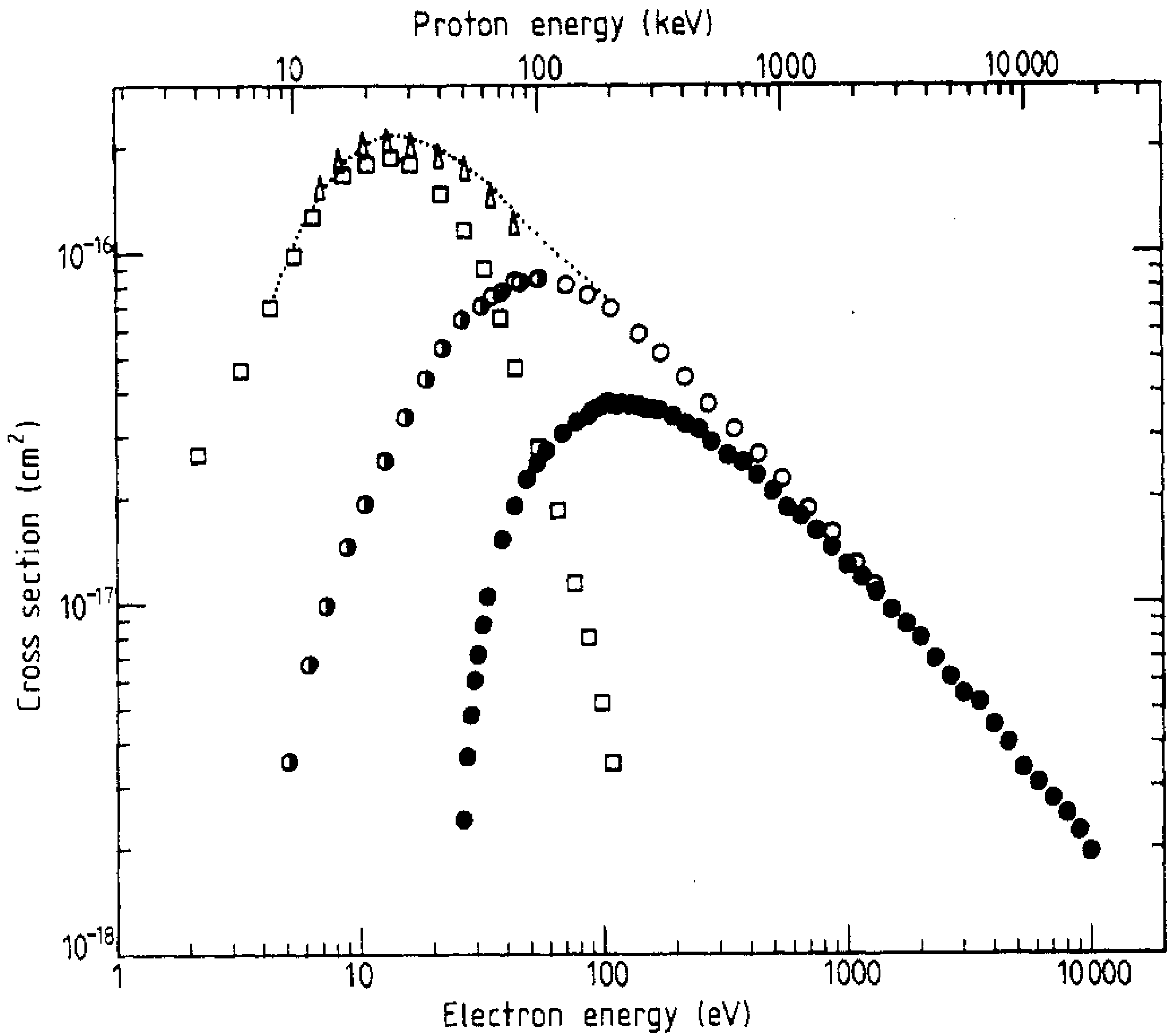
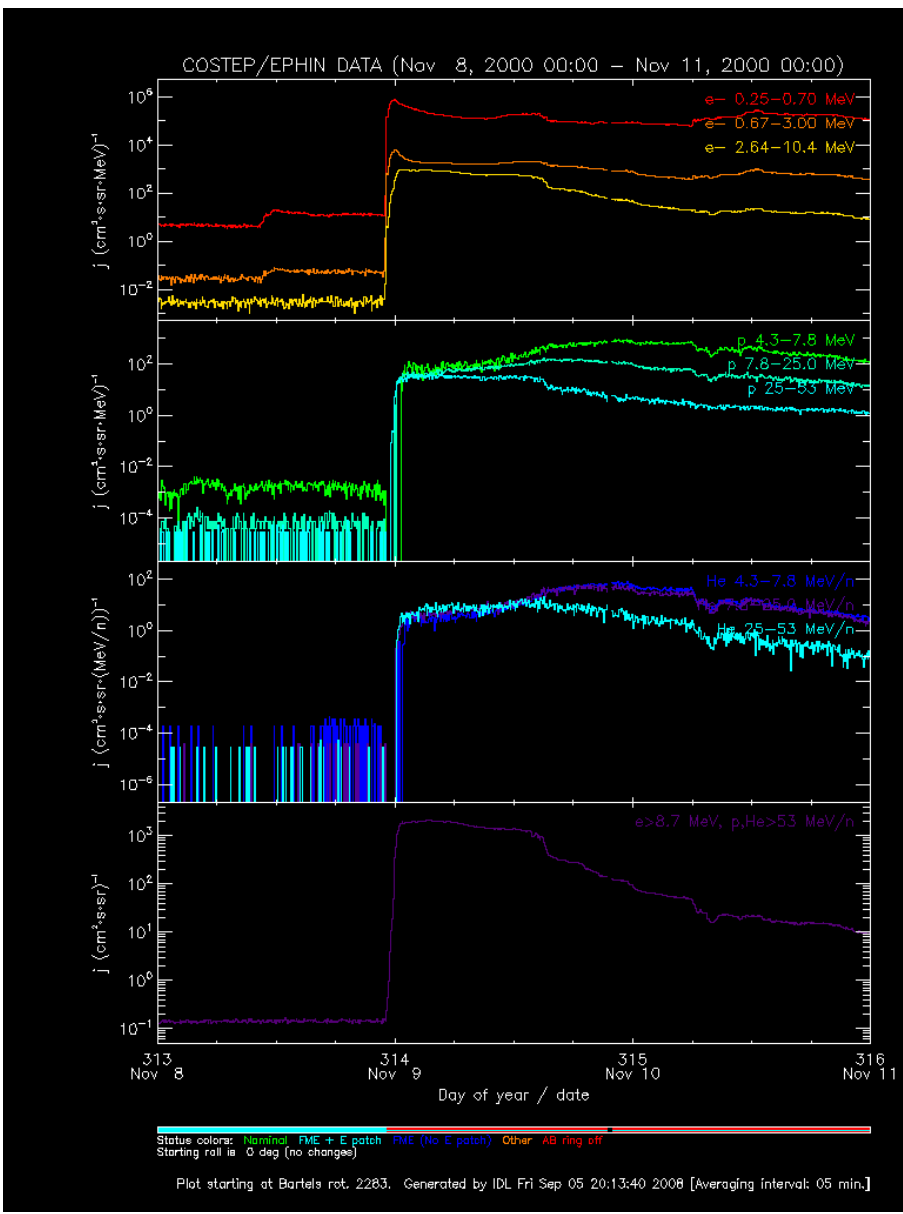
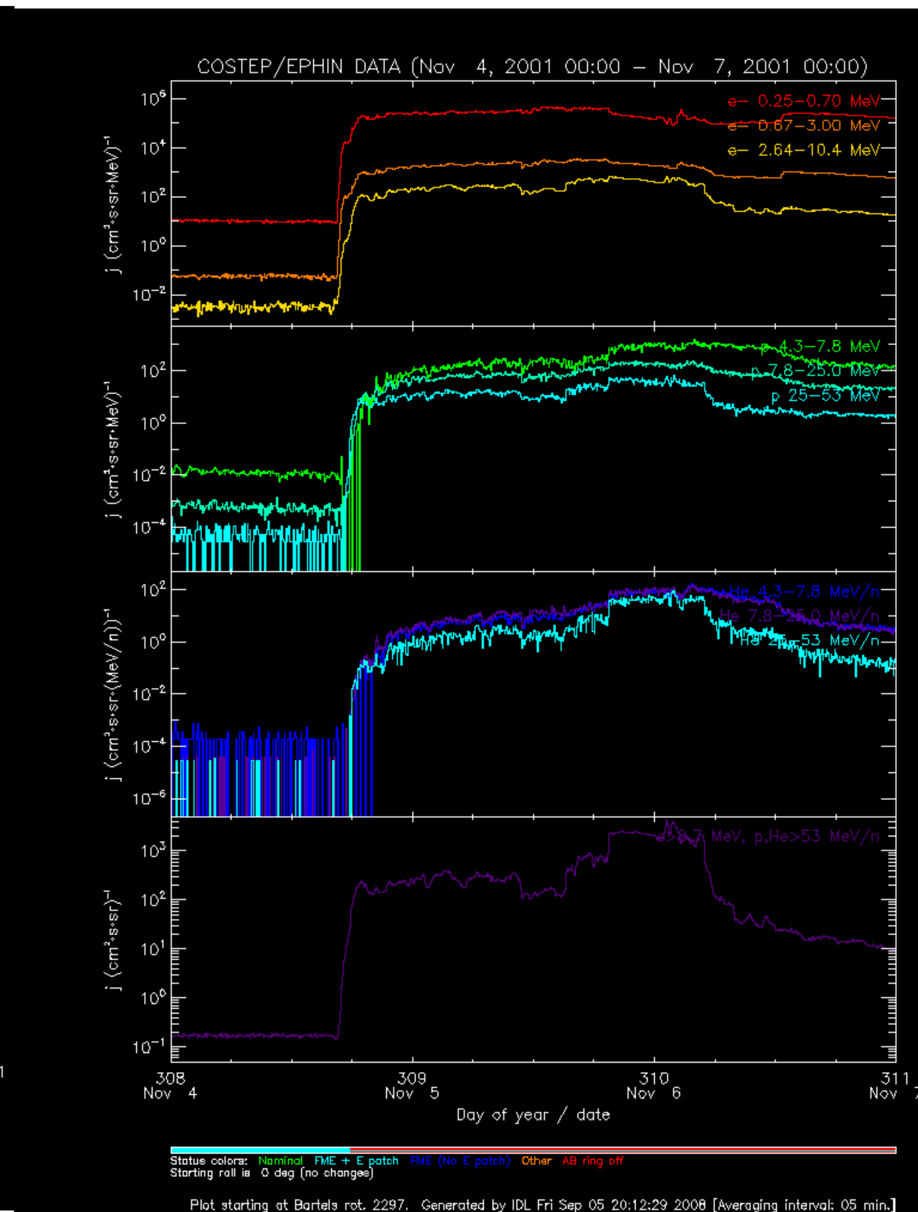
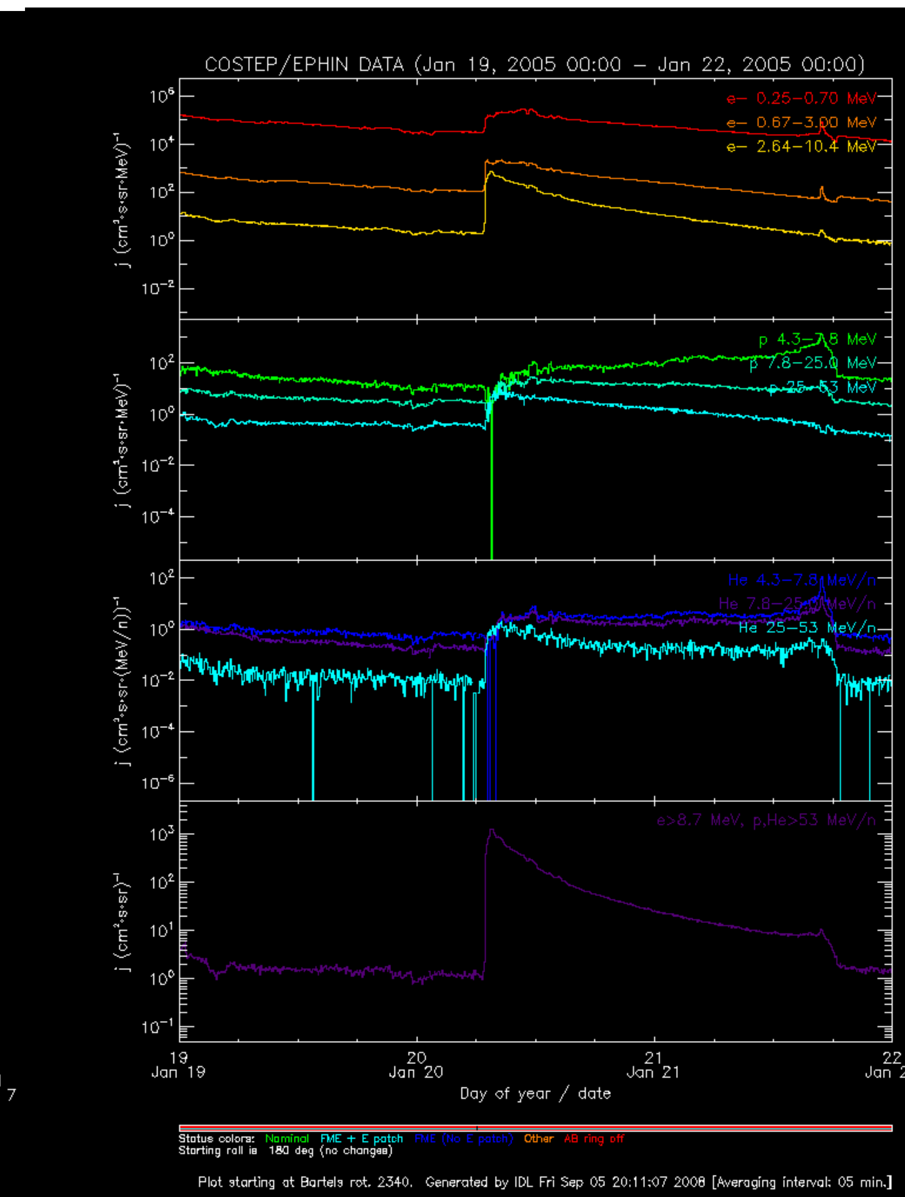


Figure 2. Equivelocity cross sections for He^+ production in collisions of protons and electrons with hydrogen atoms. ●, cross sections σ_1 for single ionisation of He by electron impact (present work); ○, ◑, cross sections σ_i for single ionisation of He by proton impact (Shah and Gilbody 1985 and unpublished data); □, cross sections σ_c for charge transfer in collisions of protons with He (Stier and Barnett 1956); △, cross section sum $\sigma_i + \sigma_c$ for proton impact (present work); . . . , cross section sum $\sigma_i + \sigma_c$ with σ_i taken from ○ above and σ_c taken from □.

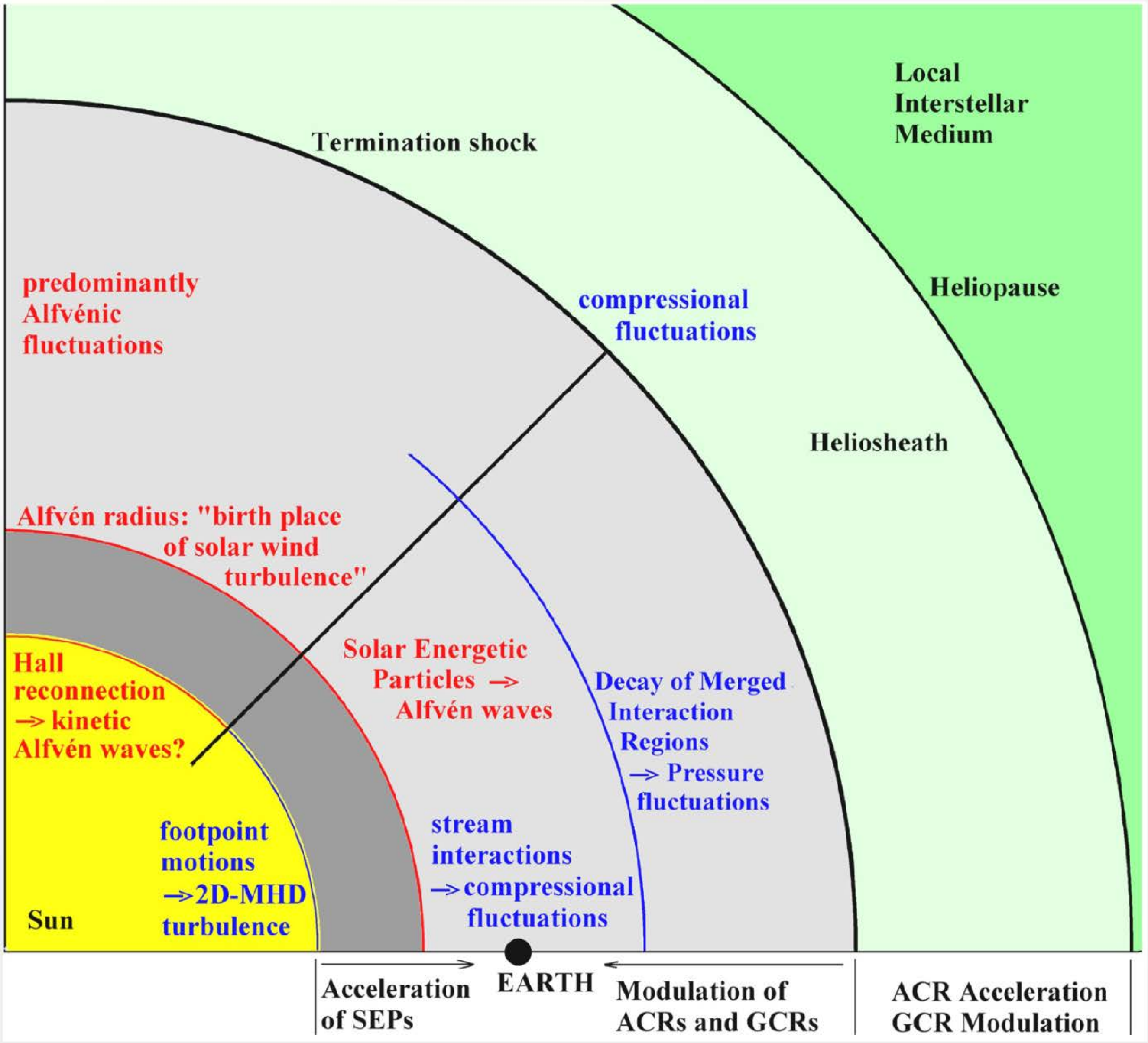
Proton impact ionization and solar UV ionization are not sufficient to explain He+/He++ ratios -> electron impact ionization EPHIN data







Stochastic Acceleration vs. First-order Fermi Acceleration in the Heliosphere



THE ASTROPHYSICAL JOURNAL, 601:L99–L102, 2004 January 20

Observations

MPS

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HYDROMAGNETIC WAVE EXCITATION UPSTREAM OF AN INTERPLANETARY TRAVELING SHOCK

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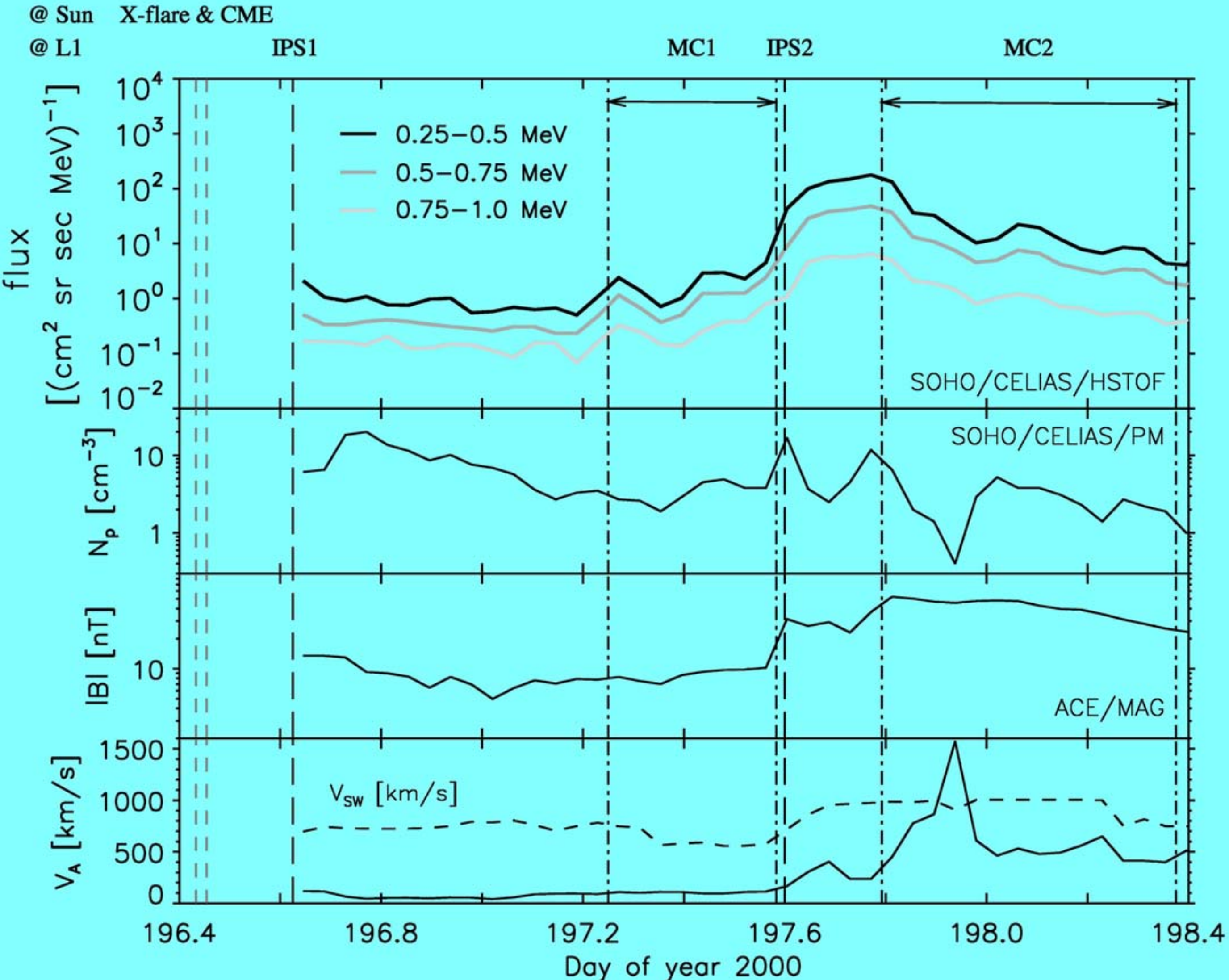
The Bastille Day Event (July 14-16, 2000)



Stochastic acceleration in the region downstream of the shock

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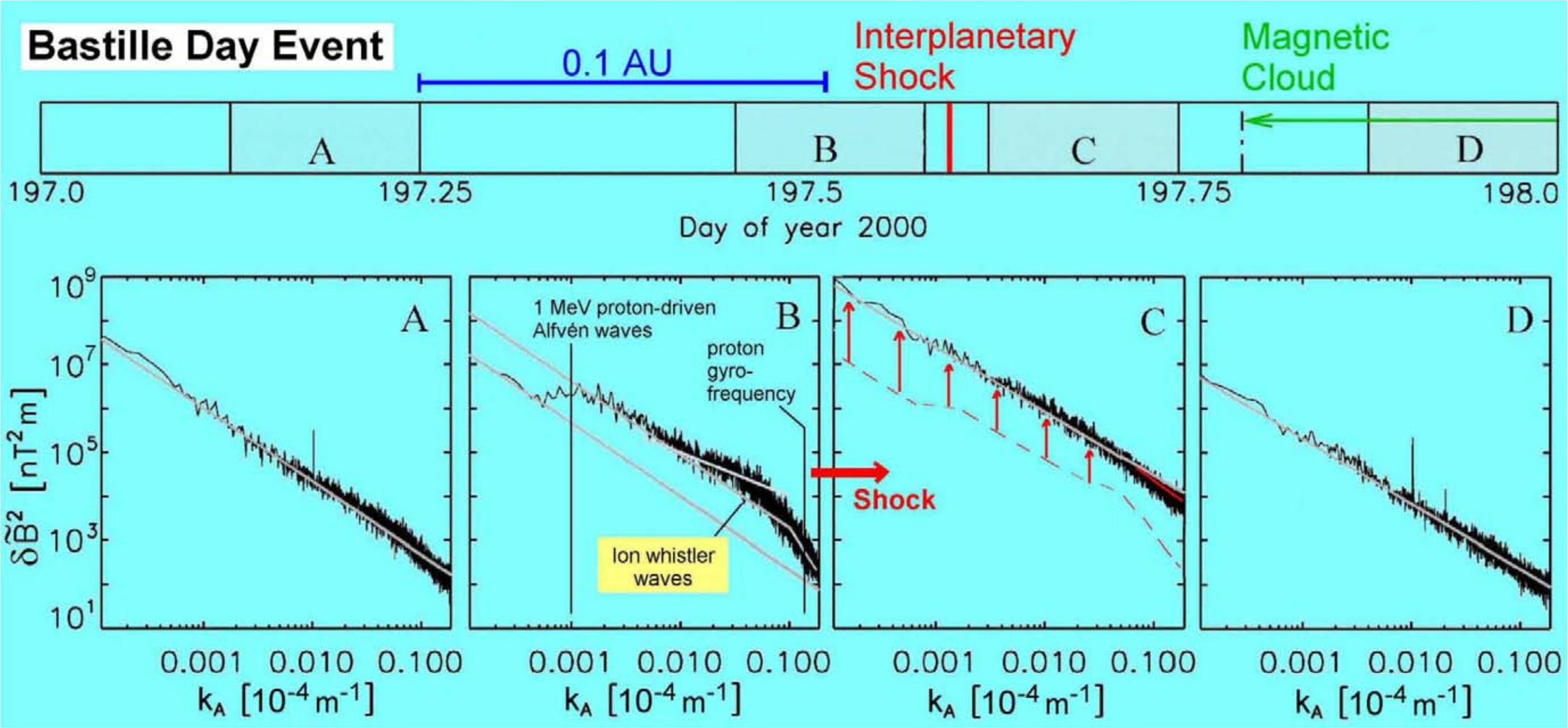


Wave Activity near Interplanetary Traveling Shocks: Excitation of Alfven and Ion Whistler Waves

ACE News #91 - Aug 30

Energetic particles on top of bulk:

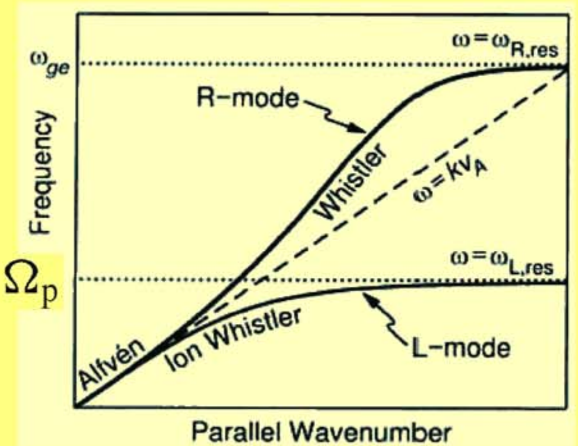
Theory

growth (damping) rate $\gamma_L \approx \pi \frac{\Omega_p^2}{|k|} \frac{1}{1 + k^2c^2/\omega_{pp}^2} \left[F_p \left(\frac{\Omega_p - \omega}{|k|} \right) - F_p \left(- \frac{\Omega_p - \omega}{|k|} \right) \right]$

$$F_p(v_\parallel) = 2\pi \int_0^\infty v_\perp \mathrm{d}v_\perp f_p(v_\parallel, v_\perp)$$

$k \ll 2\omega_{pp}/c$ quasi-linear theory by Lee (1982, 1983)
Alfvén waves

$k \gg 2\omega_{pp}/c$ $\omega \approx \Omega_p$ ion whistler waves



$$\omega \approx v_A k \left(\sqrt{1 + \frac{k^2c^2}{4\omega_{pp}^2}} - \frac{kc}{2\omega_{pp}} \right)$$

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Cascading time scale of solar wind turbulence

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EVIDENCE FOR IROSHNIKOV-KRAICHNAN-TYPE TURBULENCE IN THE SOLAR WIND UPSTREAM OF INTERPLANETARY TRAVELING SHOCKS

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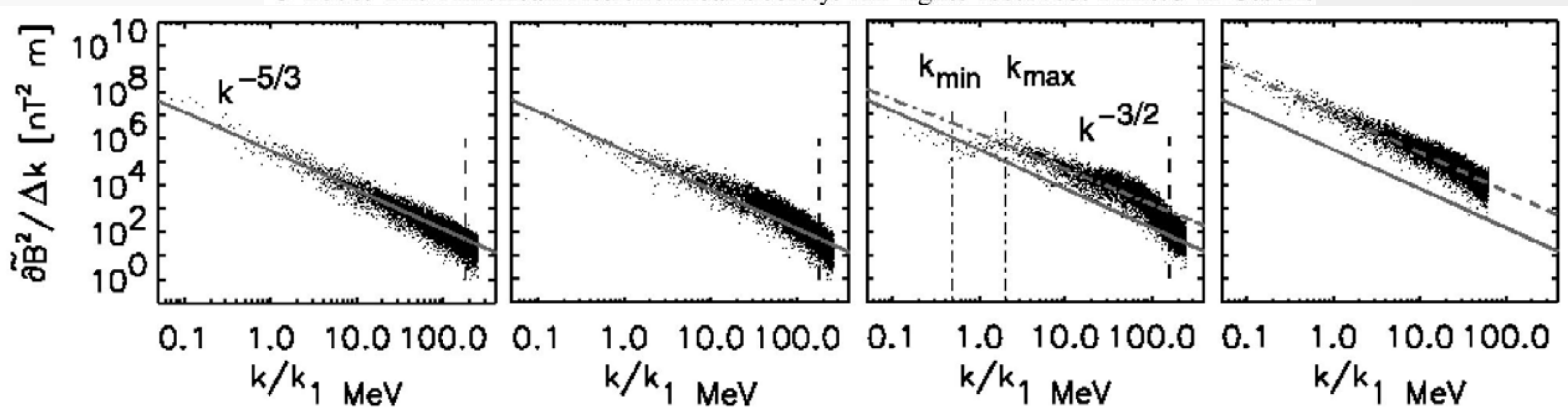

$$\frac{\partial}{\partial k}\left[D_{kk}^{\pm}\frac{\partial P(k,\ z)}{\partial k}\right]$$

Diffusion term in wave kin. eq.

$$D_{kk}^{\pm}=\frac{1}{\tau_A}\sqrt{P(k,\ z)}k^{5/2}$$

Kolmogorov-type (Zhou & Matthaeus, 1990)

$$D_{kk}^{\pm}=\frac{1}{\tau_A}k^3P(k,\ z)$$

Iroshnikov-Kraichnan-type

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Alfven wave transmission through shocks

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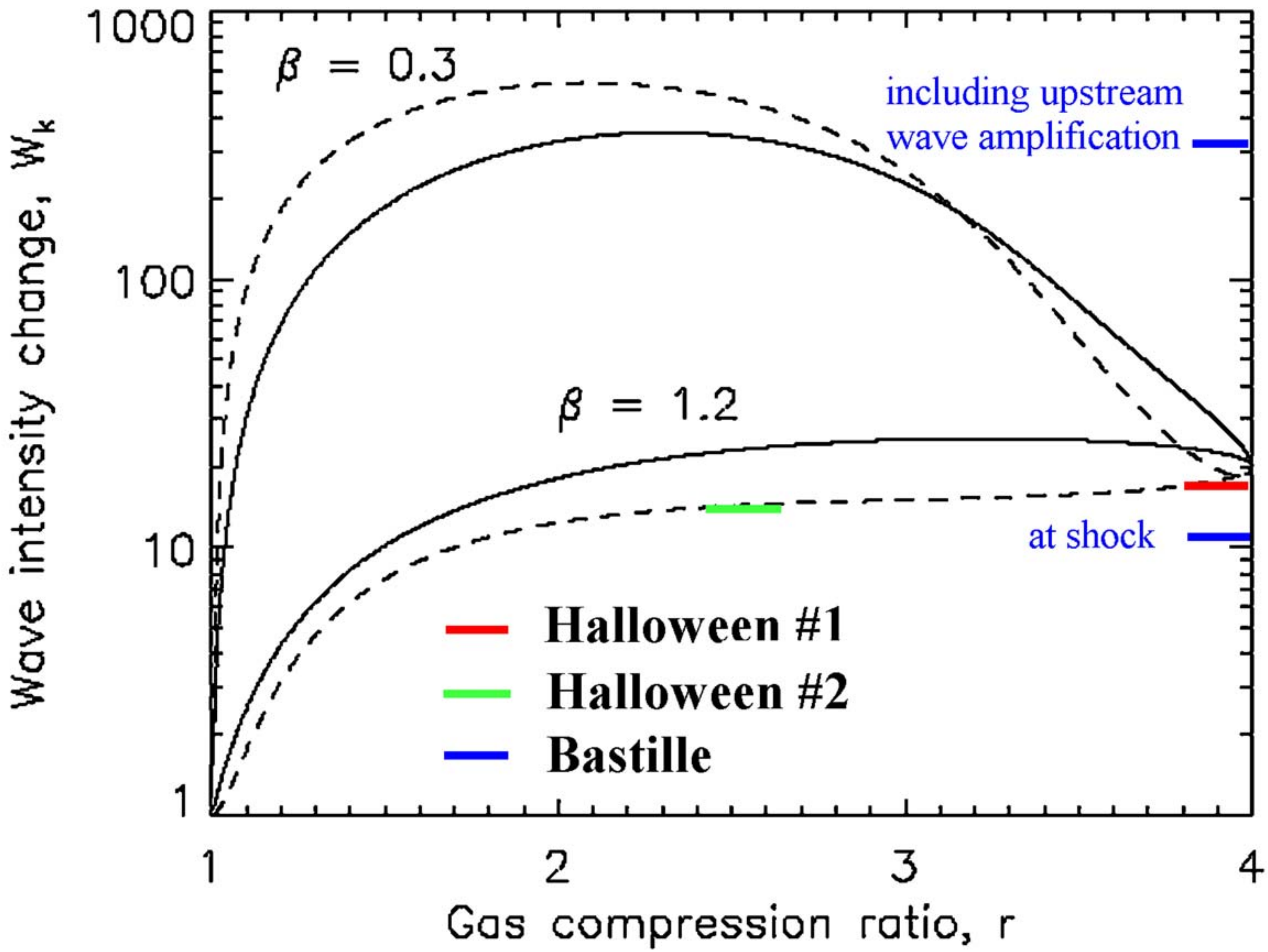
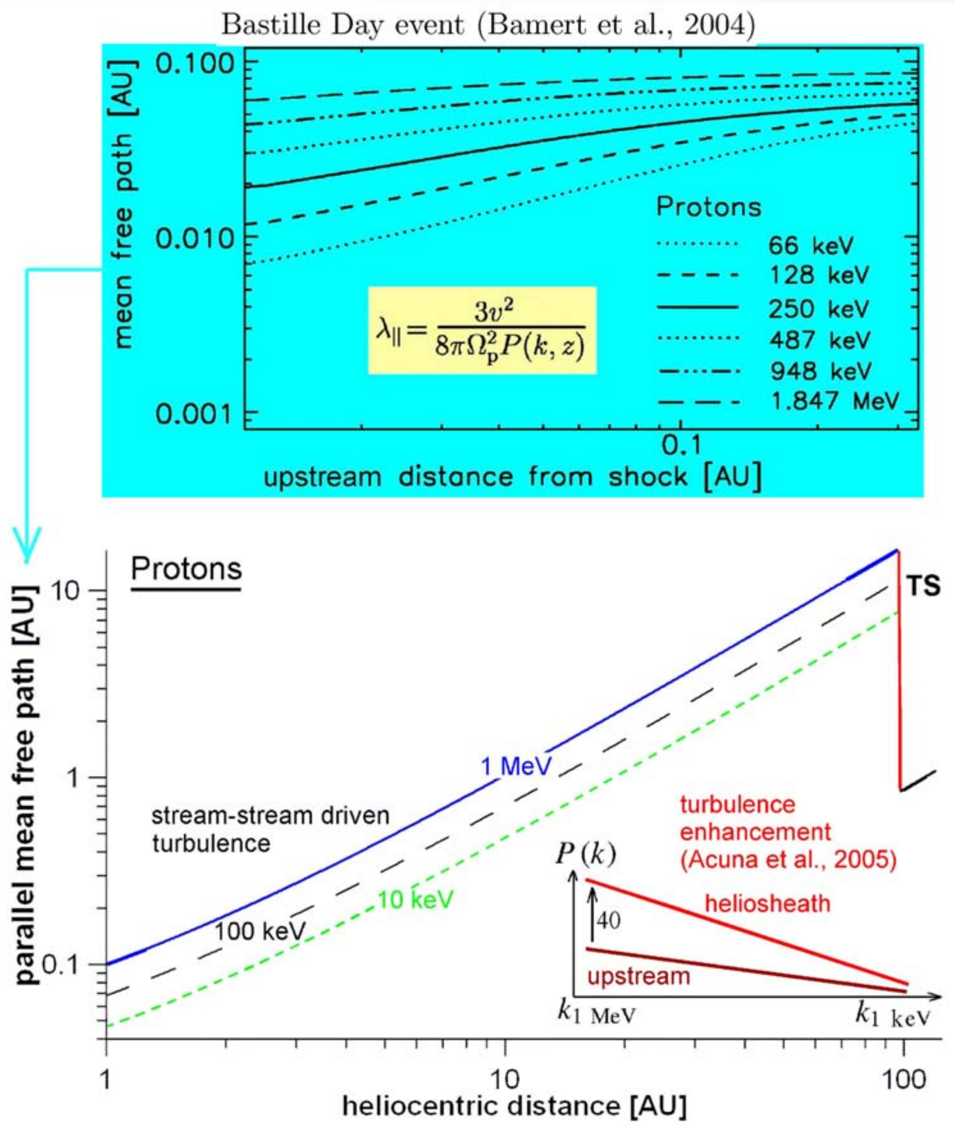
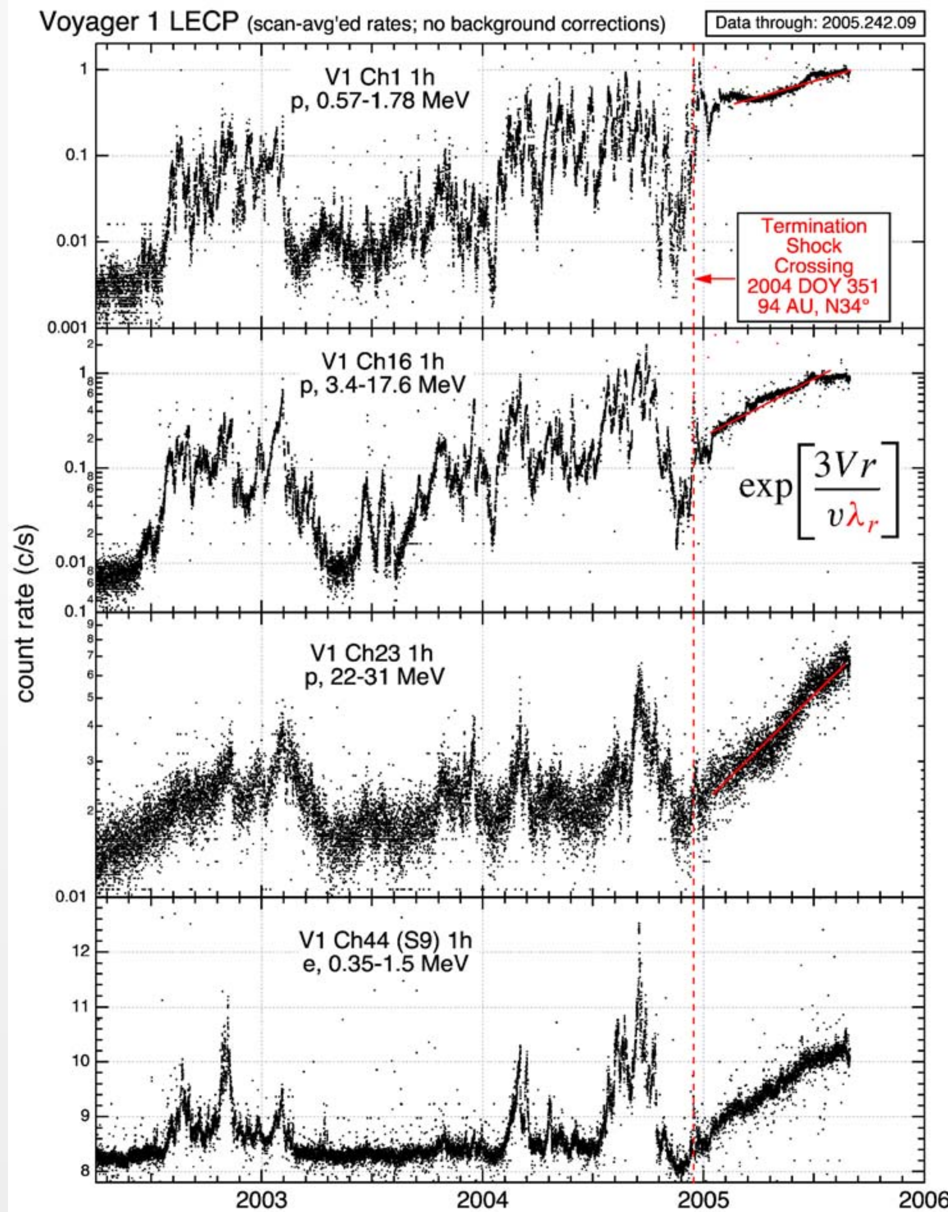
McKenzie & Westphal (1969)

Vainio & Schlickeiser (1999)



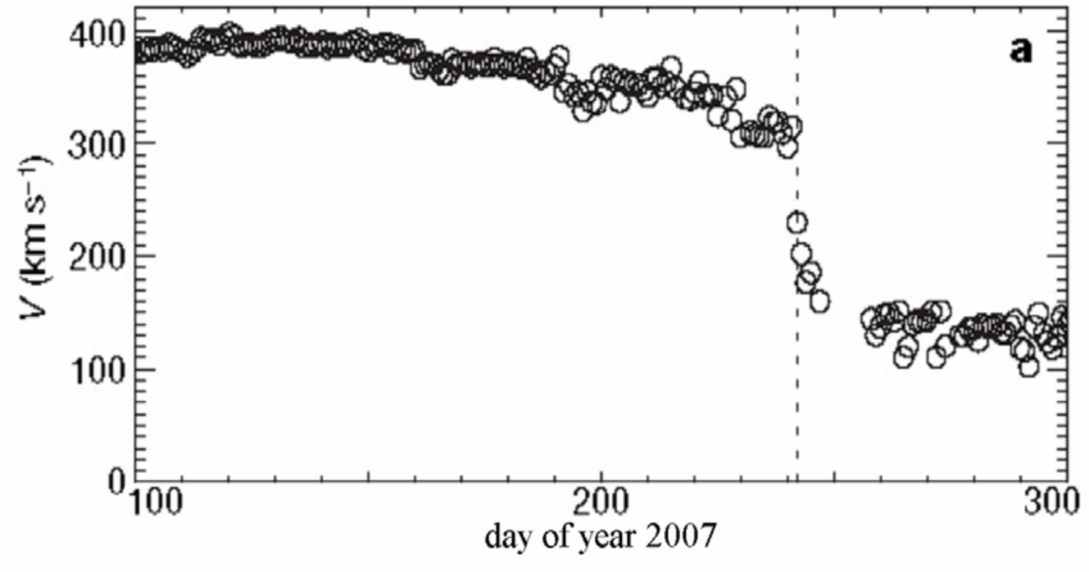
Evolution of mean free path with heliocentric distance



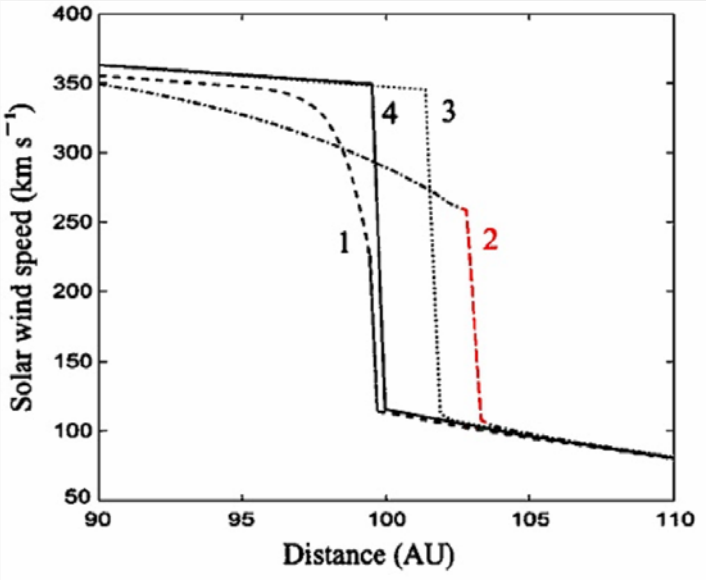


Data from Stone et al. (2005)

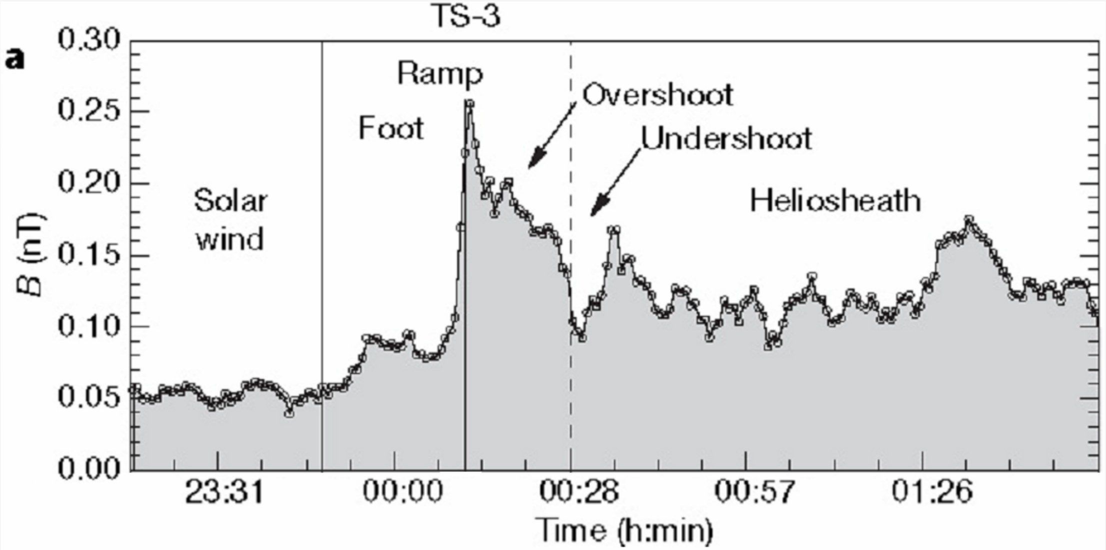
Voyager 2 observations and interpretations



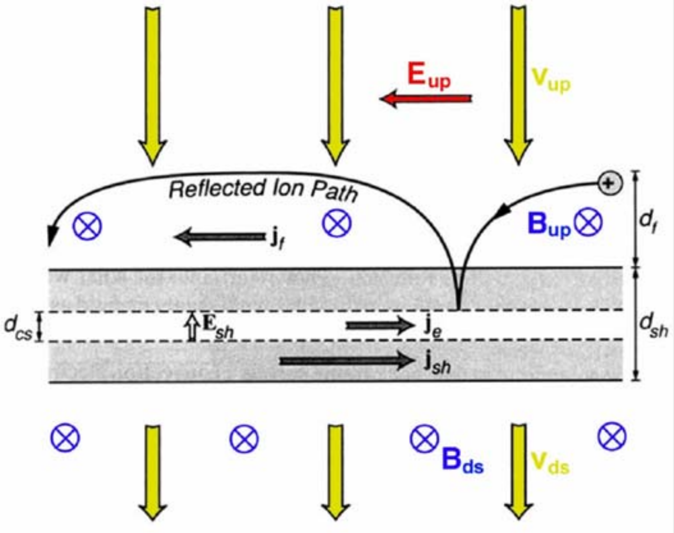
Richardson et al. (2008):
Shock mediation by non-thermal ions



Alexsashov et al. (2004)

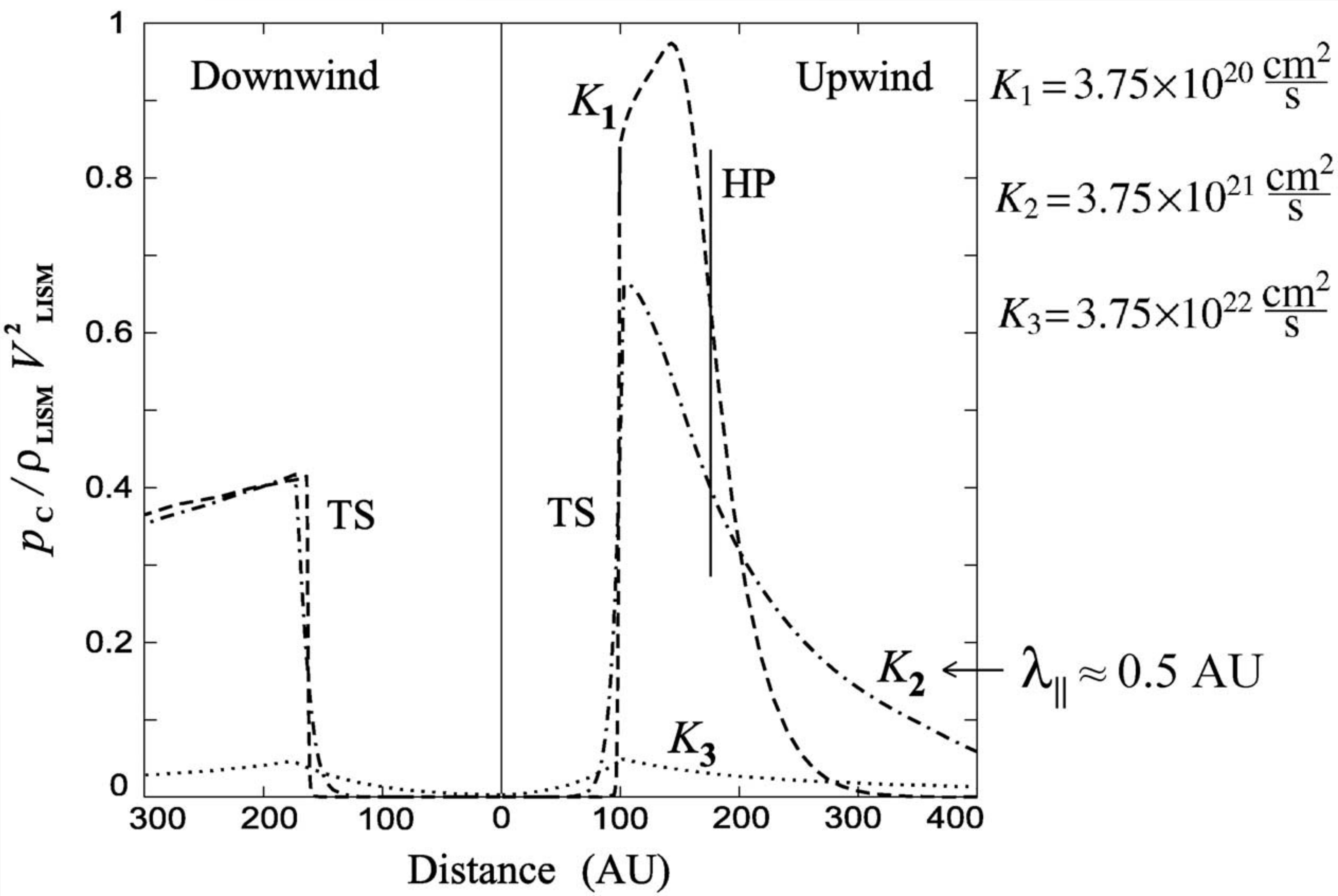


Burlaga et al. (2008)



Baumjohann & Treumann (2008)

Slow down of upstream SW due to ACR pressure



Alexsashov et al. (2004)

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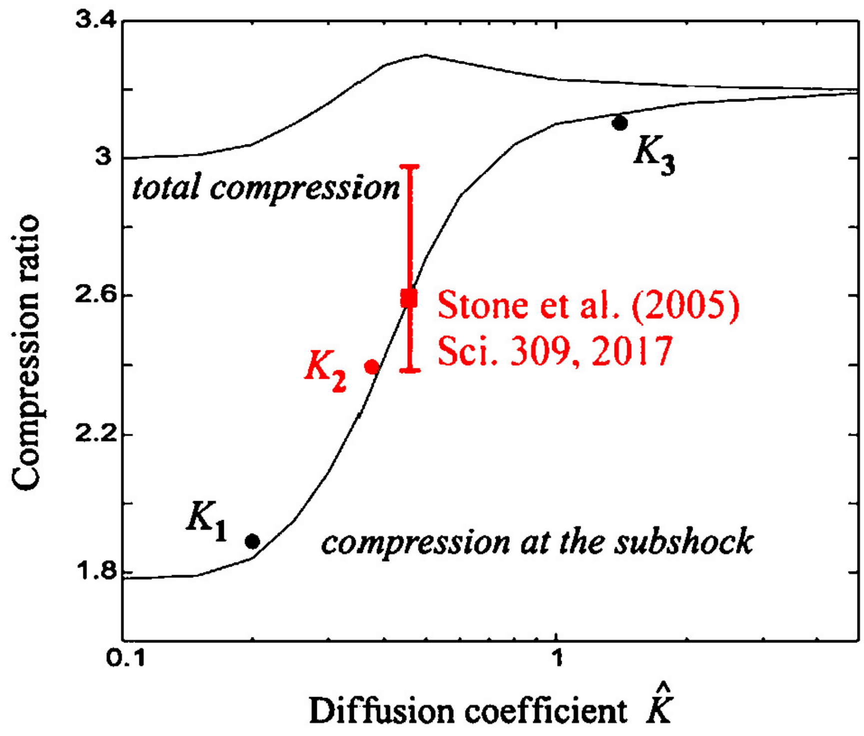


Table 1 | Termination shock parameters

Parameter	Termination shock motion	
	TS-2: outwards	TS-3: inwards
East–west shock normal	188.0° ± 4.0°	5.8° ± 10.3°
Shock speed	94.0±3.4 km s^{-1}	67.9±17.3 km s^{-1}
North–south shock normal	2.0° ± 6.2°	−4.6° ± 19.2°
∢ shock normal, magnetic field	82.8° ± 3.9°	74.3° ± 11.2°
Compression ratio	2.38 ± 0.14	1.58 ± 0.71
Solar wind fast-mode Mach	4.9 ± 0.1	8.8 ± 1.2
Heliosheath fast-mode Mach	1.1 ± 0.1	2.8 ± 0.4

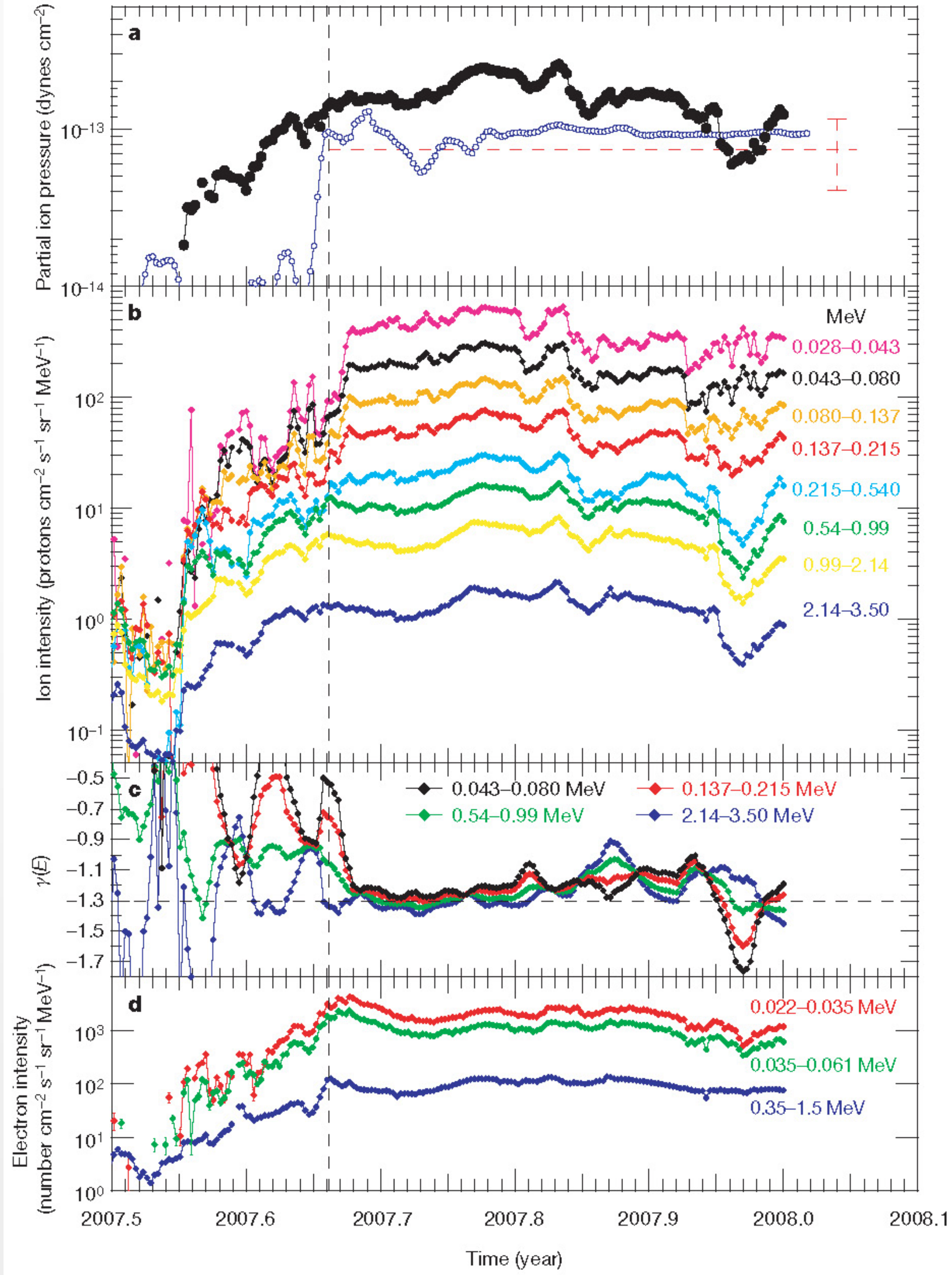
Burlaga et al. (2008)

Voyager 2 LECP observations

- Spectral index ≈ -1.25 would correspond to shock compression ratio of about 3;
  observed in plasma:
  ≈ 1,5 – 2.5

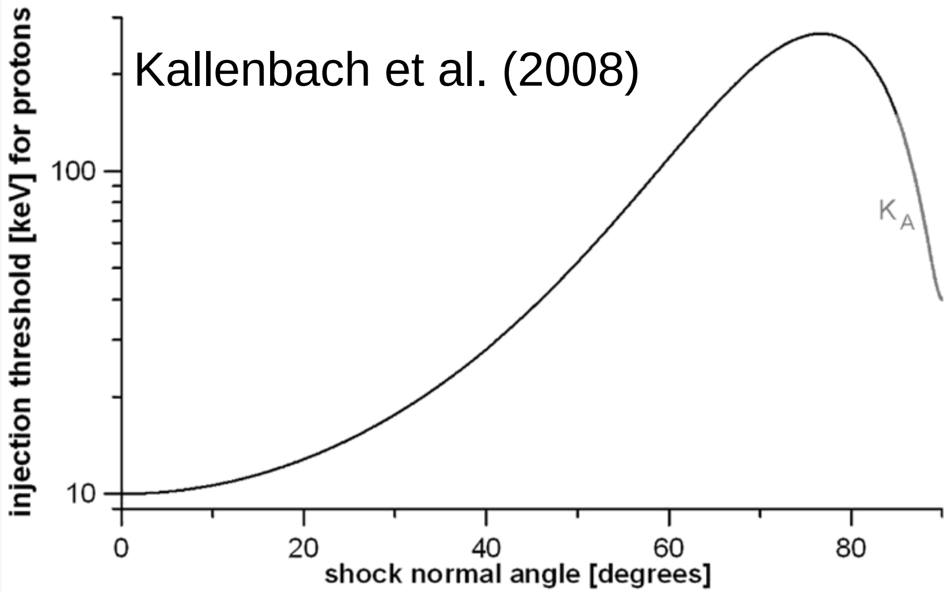
  Ubiquitous suprathermal tails ≈ -1.5
  (Gloecker, Fisk et al.)

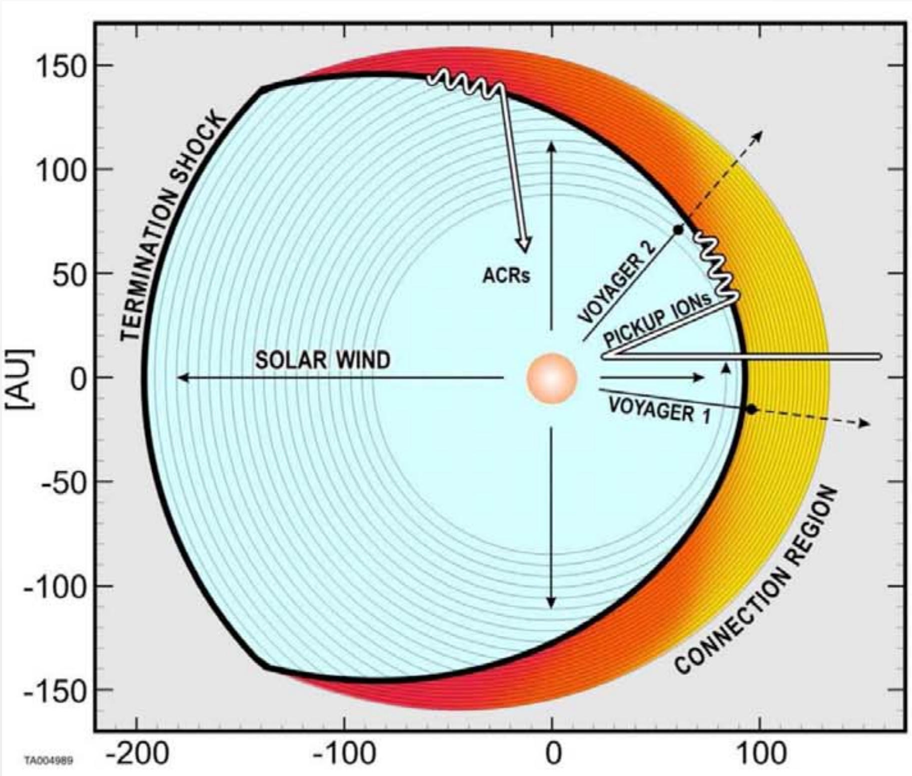
- Flux comparable to V1



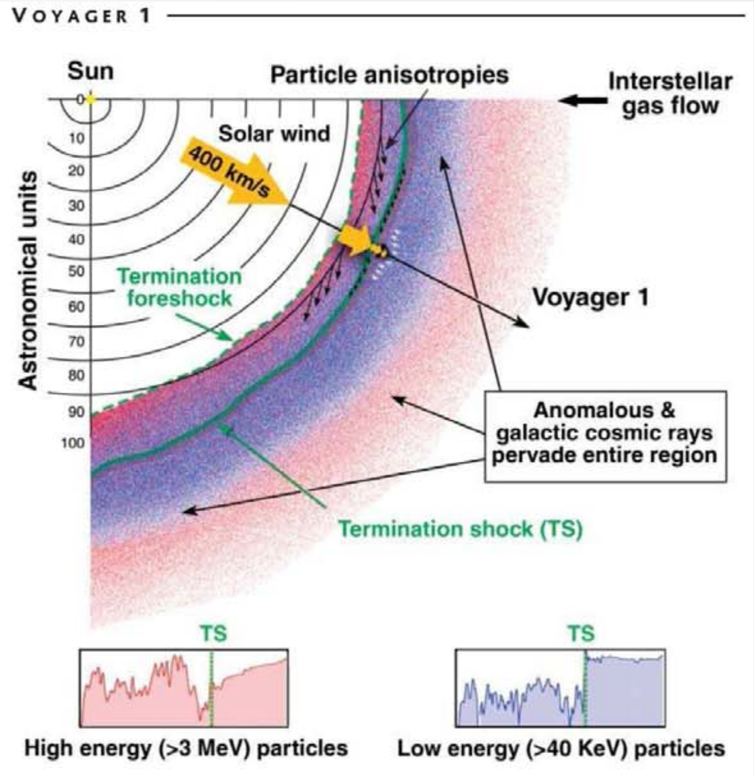
Decker et al. (2008)

Source of ACRS: Locations of more parallel TS?



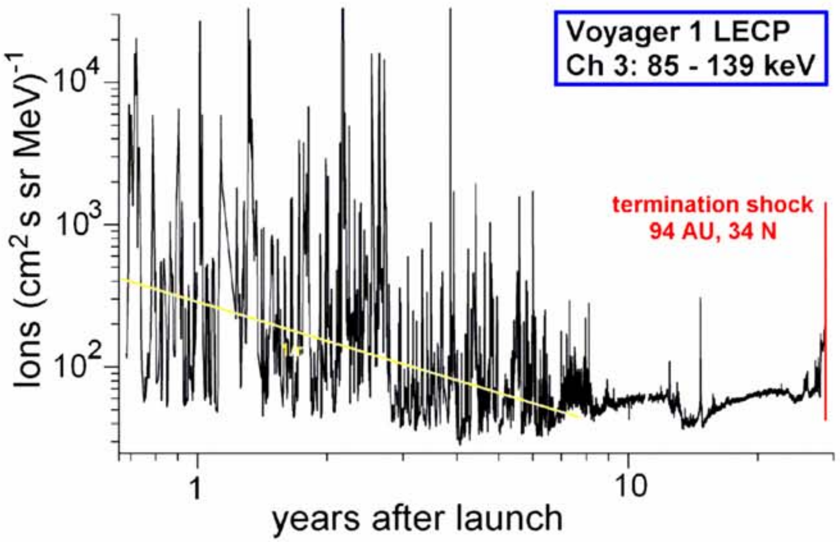


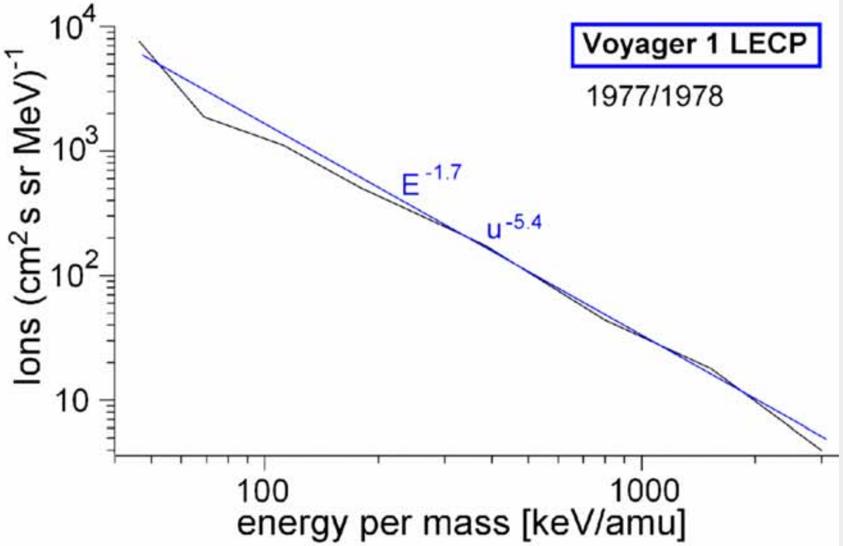
McComas & Schwadron (2005)



Decker et al. (2004)

Stochastic acceleration in the outer heliosphere





$$-\frac{\partial f}{\partial \rho} + \frac{1}{\rho}\frac{2u}{3}\frac{\partial f}{\partial u} + \frac{D_2}{\rho}\frac{1}{u^2}\frac{\partial}{\partial u}\left[u^4 \frac{\partial f}{\partial u}\right] = 0 \quad \Rightarrow \quad f_{\text{hom}}(u,\rho) = f_0 \rho^{-\beta} u^{-\alpha}$$

$$\text{with} \quad \beta = \frac{2}{3}\alpha - \alpha(\alpha - 3) D_2 \quad \text{or} \quad \alpha \approx 1.8\left(\frac{3}{2} + \frac{1}{3D_2}\right)$$

ACR acceleration time scale

$$\tau_{\mathrm{acc;\,\underline{Fermi\,1}}} = \left(\frac{E}{1\ \mathrm{MeV/amu}}\right)^{2/3} \cos^2\Psi \left(\frac{A}{Q}\right)^{1/3} \ \mathrm{years}$$

$$\eta = \frac{\lambda_{\parallel}}{r_{\mathrm{g}}} = 1000 \left(\frac{E}{1\ \mathrm{MeV/amu}}\right)^{-2/3} \left(\frac{A}{Q}\right)^{-2/3}$$

$$-\frac{\partial f}{\partial \rho} + \frac{1}{\rho}\frac{2u}{3}\frac{\partial f}{\partial u} + \frac{D_2}{\rho}\frac{1}{u^2}\frac{\partial}{\partial u}\left[u^4 \frac{\partial f}{\partial u}\right] = 0$$

$$\tau_{\mathrm{acc;\,\underline{Fermi\,2}}} \approx 0.1\ \ \mathrm{years}$$

Conclusions

Clear indications for:

- Shock mediation by non-thermal ions (TSPs/ACRs)
- Major fraction of heliosheath pressure by TSPs/ACRs
- Shock reformation
- TSPs/ACRs are the source of ENAs at 1 AU

Unresolved issues (?):

- Relative importance of shock vs. stochastic acceleration