Comparative plasma interactions

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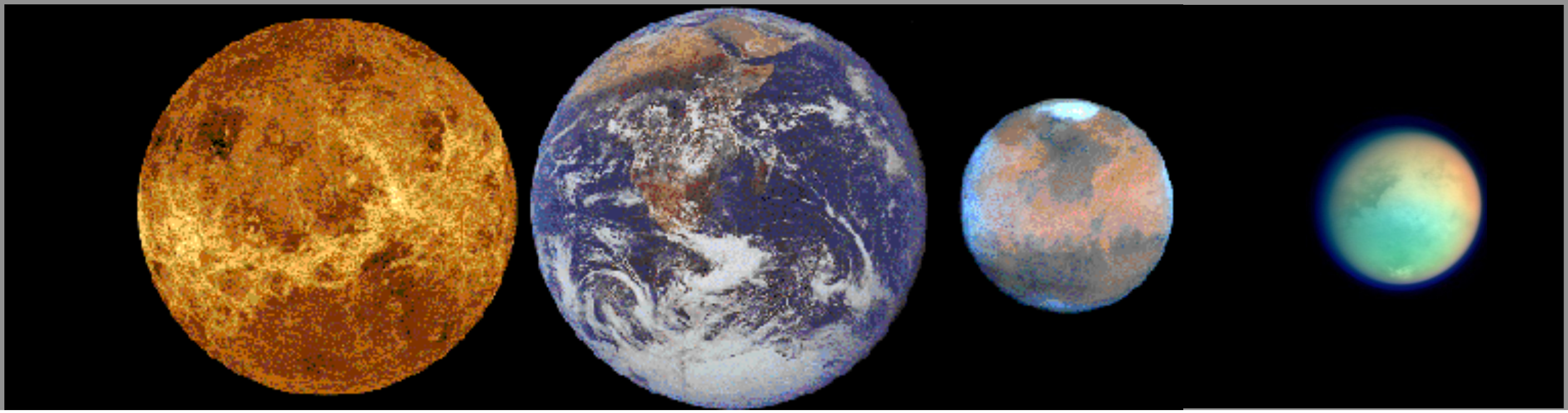
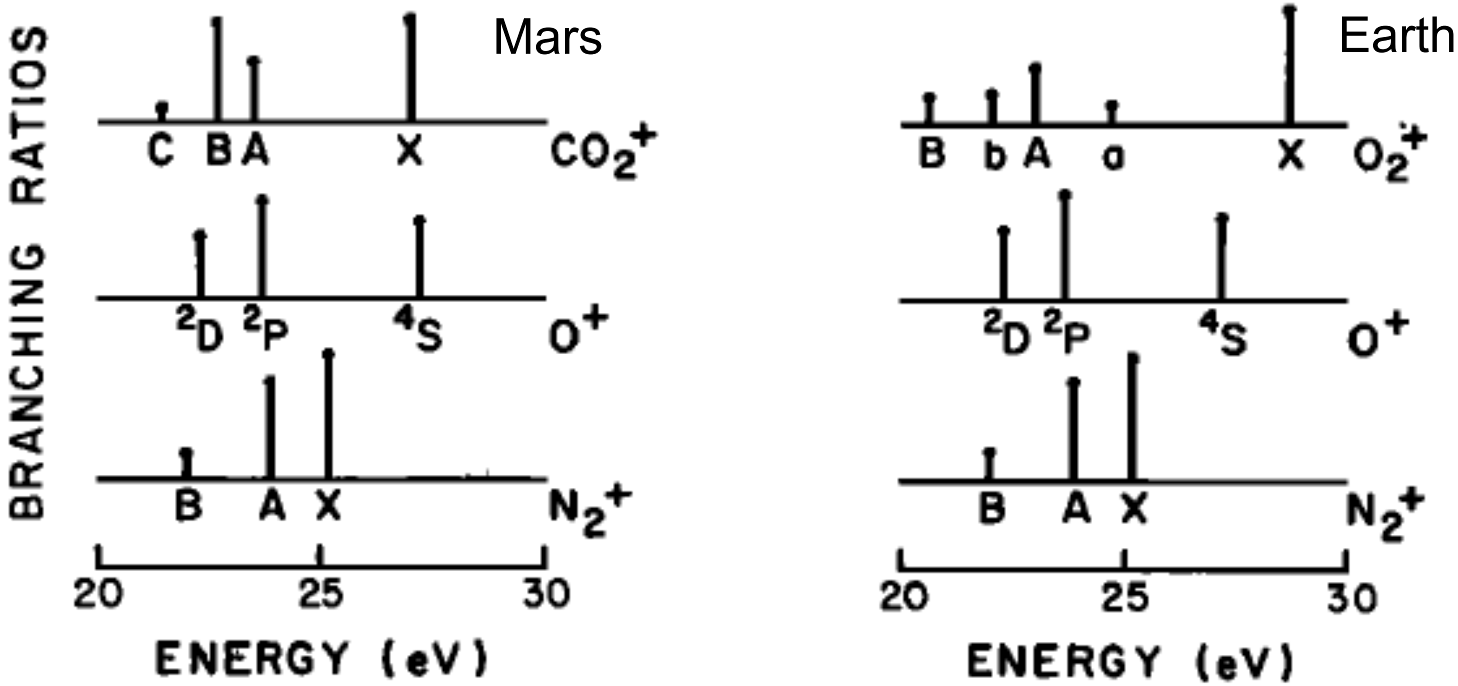


Comparative plasma interactions

- Processes in unmagnetized body interactions
  - Ionospheric photoelectron production and transport
  - Ion pickup and mass loading
- Recent results from other unmagnetized objects: Venus, Moon, icy satellites (Titan, Enceladus, Rhea) – Venus Express, Cassini-Huygens
- Recent and anticipated results from comets, Jupiter moons (Ganymede, Europa) – Giotto, DS1, Rosetta, JUICE

Ionospheric photoelectron production and transport



Mantas and Hansen, 1979; see also Fox & Dalgarno, 1979

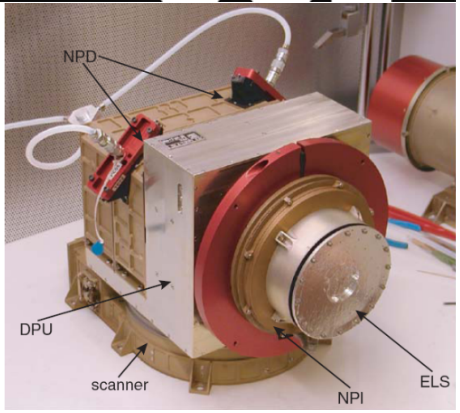
- Photoionisation in ionospheres – produces ions and photoelectrons
- Solar EUV gives peaks: HeII 30.4nm gives ~21-24, 27 eV photoe$^-$ at M, E; ~24eV Titan, e.g. Haider 86, Gan et al., 92, Galand et al., 06
- Additionally, shoulder at ~50-60eV due to solar decrease <~16nm
- Measurements in Earth ionosphere give detailed spectra (e.g. Lee et al., 80, Doering et al, 76), also models e.g. Nagy & Banks 70
- Peaks and shoulder are ‘fingerprints’ for day side ionosphere

Earth		Mars		Venus		Titan	
Transition	Energy (eV)	Transition	Energy (eV)	Transition	Energy (eV)	Transition	Energy (eV)
$N_2\ X^2\Sigma_g$	25.2	$CO_2\ X^2\Pi_g$	27.02	O ^2P	22.29	$N_2\ A^2\Pi_u$	24.09
O ^2P	22.29	$CO_2\ B^2\Sigma_u$	22.69	O ^4S	27.17		
$N_2\ A^2\Pi_u$	24.09	O ^2P	22.29	O ^2D	23.69		

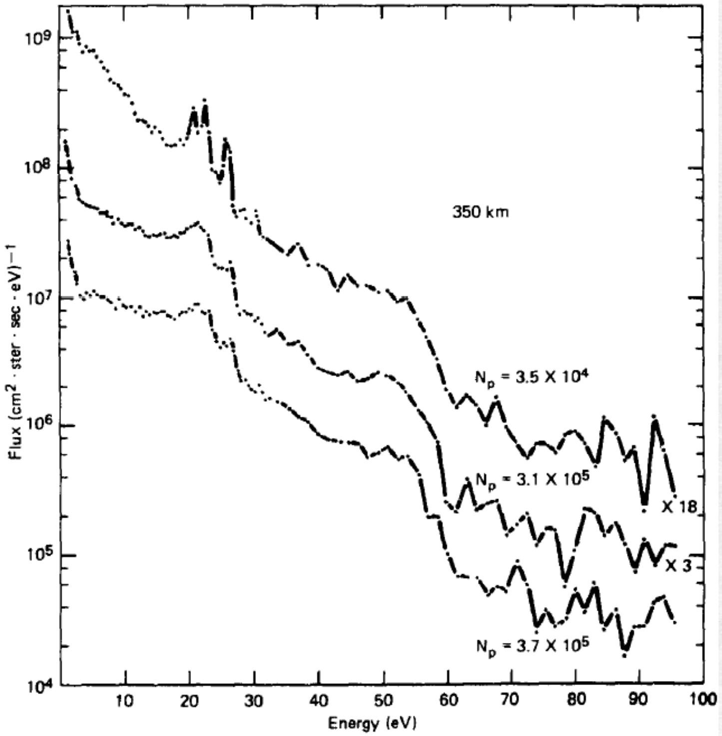
Some dominant photoelectron energies from 30.4 nm solar UV illumination (40.79 eV)
Ionisation potentials associated with ground and excited states of O, N_2, CO_2 are similar – table shows dominant peaks expected in 20-30eV range

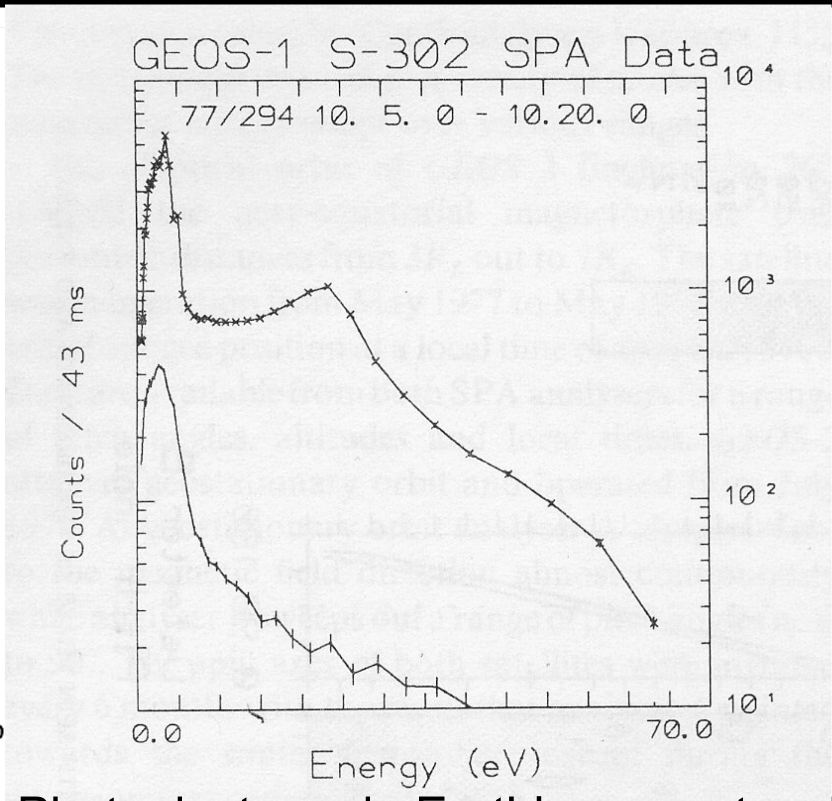
From Coates et al., PSS, 2011

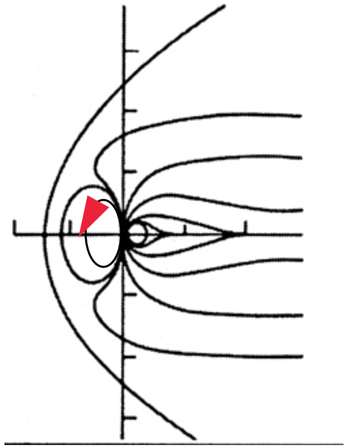
CAPS, ASPERA-ELS can measure ionospheric photoelectron spectrum at Titan, Mars, Venus



Sensor	Reference	Measures	Energy range (eV/ q)	Energy resolution (ΔE/E, %)	Angle range (°)	Angle bin (°)
GEOS-1, 2 S-302 Suprathermal Plasma Analyser	Wrenn et al., 1981	Energy, direction	0.5-500	11	0, 80	18x18, 8x32
Cassini CAPS Electron spectrometer (ELS)	Young et al, 04, Linder et al., 98	Energy, direction	0.6-28,000	16.7	160x5	20x5
Mars Express ASPERA-3 ELS	Barabash et al., 2007a	Energy, direction	10-20,000	8	360x4	22.5x4
Venus Express ASPERA-4 ELS	Barabash et al., 2007b	Energy, direction	1-30,000	8	360x4	22.5x4





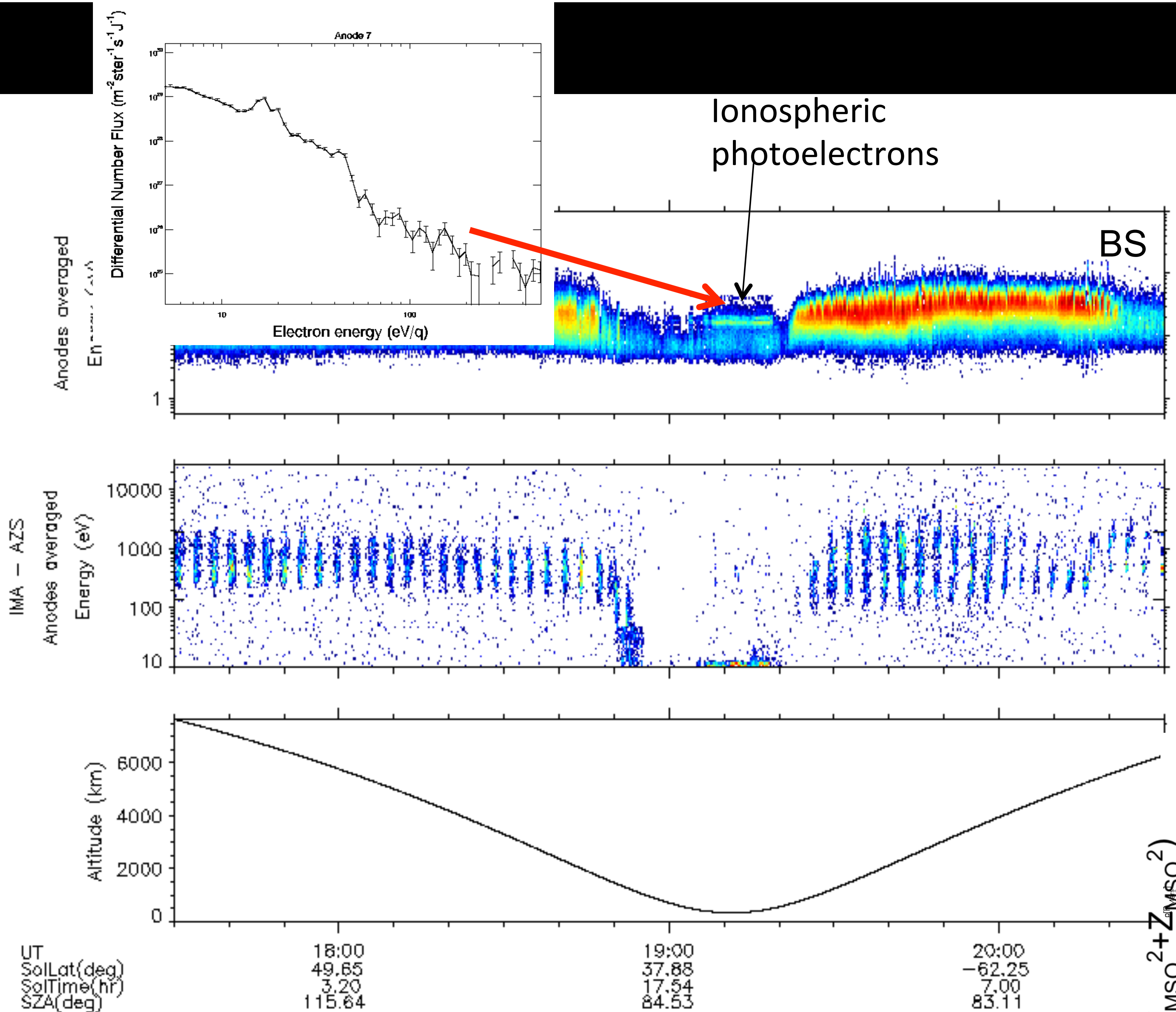


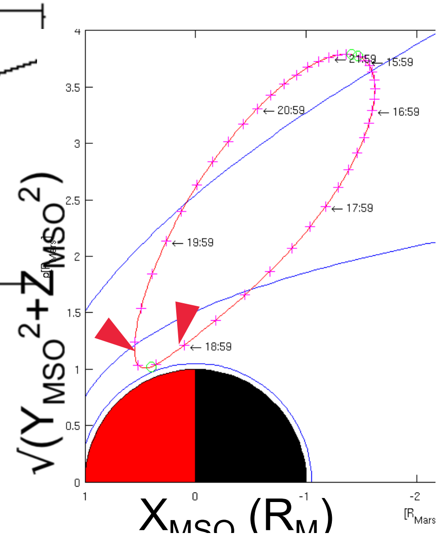
Photoelectrons in Earth's ionosphere (from Lee et al., 80)

Photoelectrons in Earth's magnetosphere up to 6.6 R_e (Coates et al, 1985)

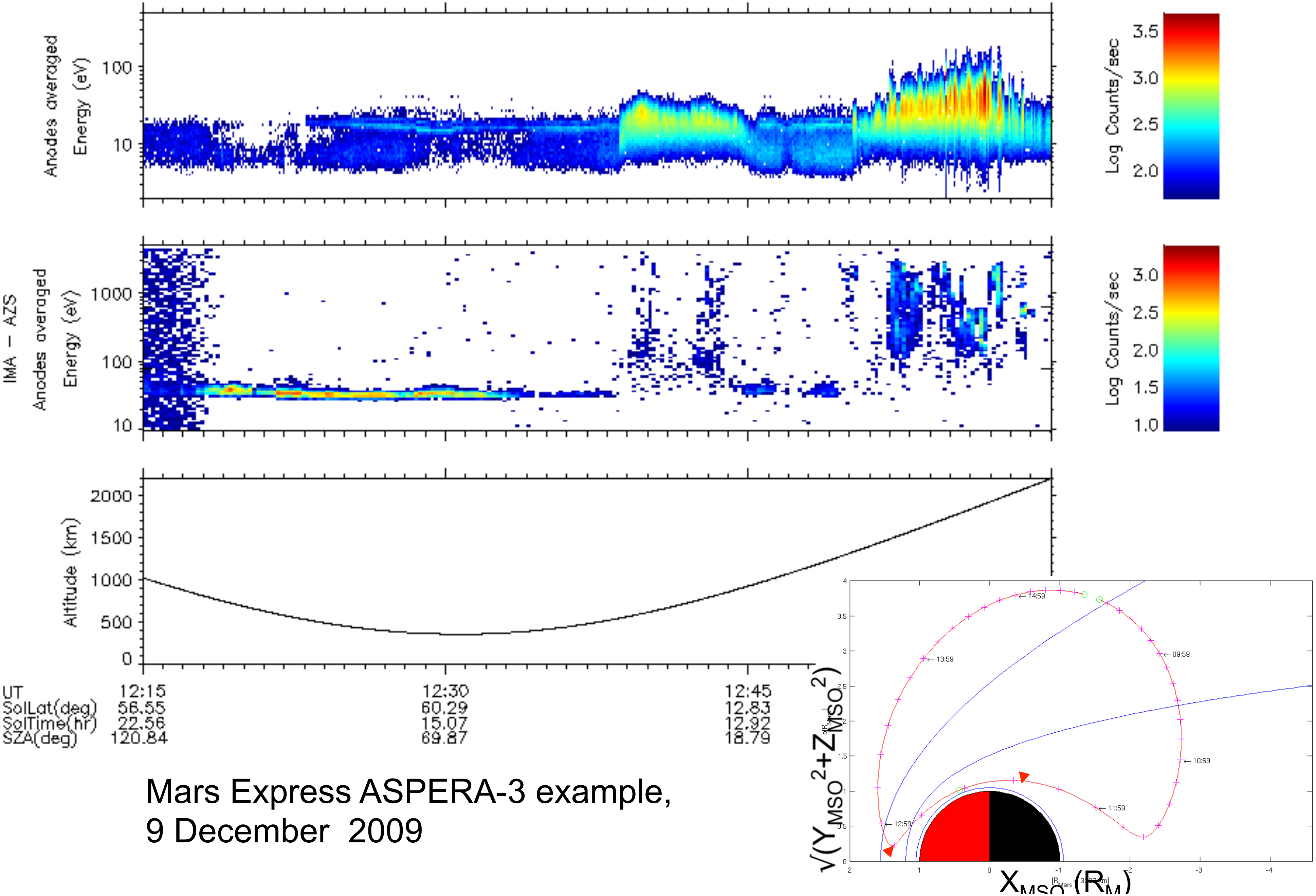
•Magnetic connection from sunlit ionosphere to spacecraft

•Provides non-thermal escape mechanism – electric field set up (polar wind)



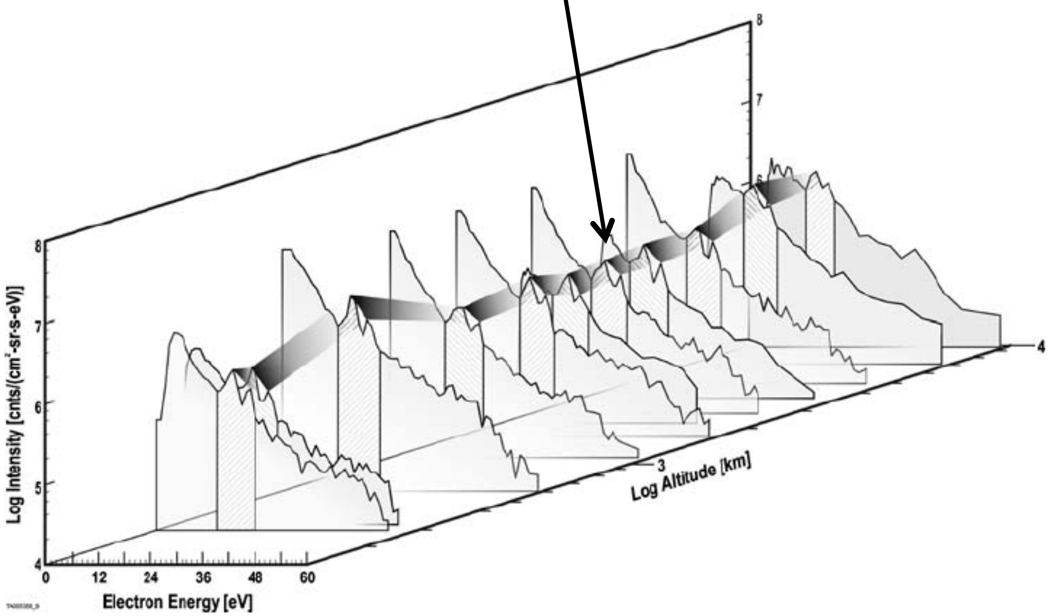


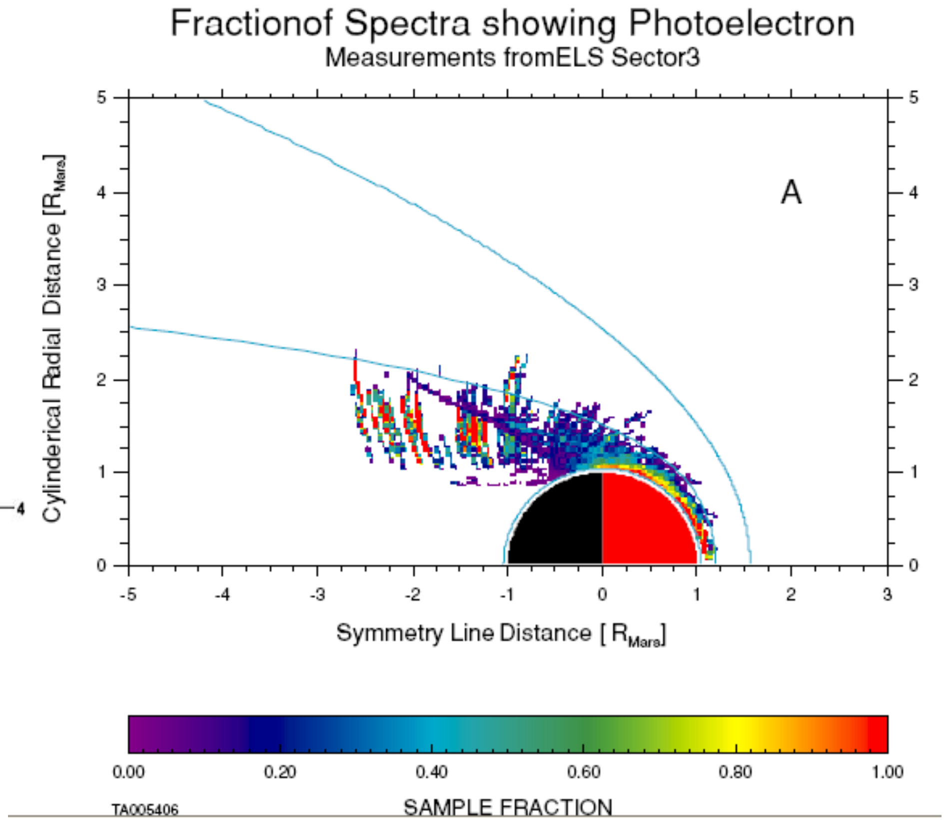
Mars Express ASPERA-3 example, 27 August 2009
Coates et al., (PSS, 2011)



Mars Express ASPERA-3 example,
9 December 2009

Ionospheric photoelectrons

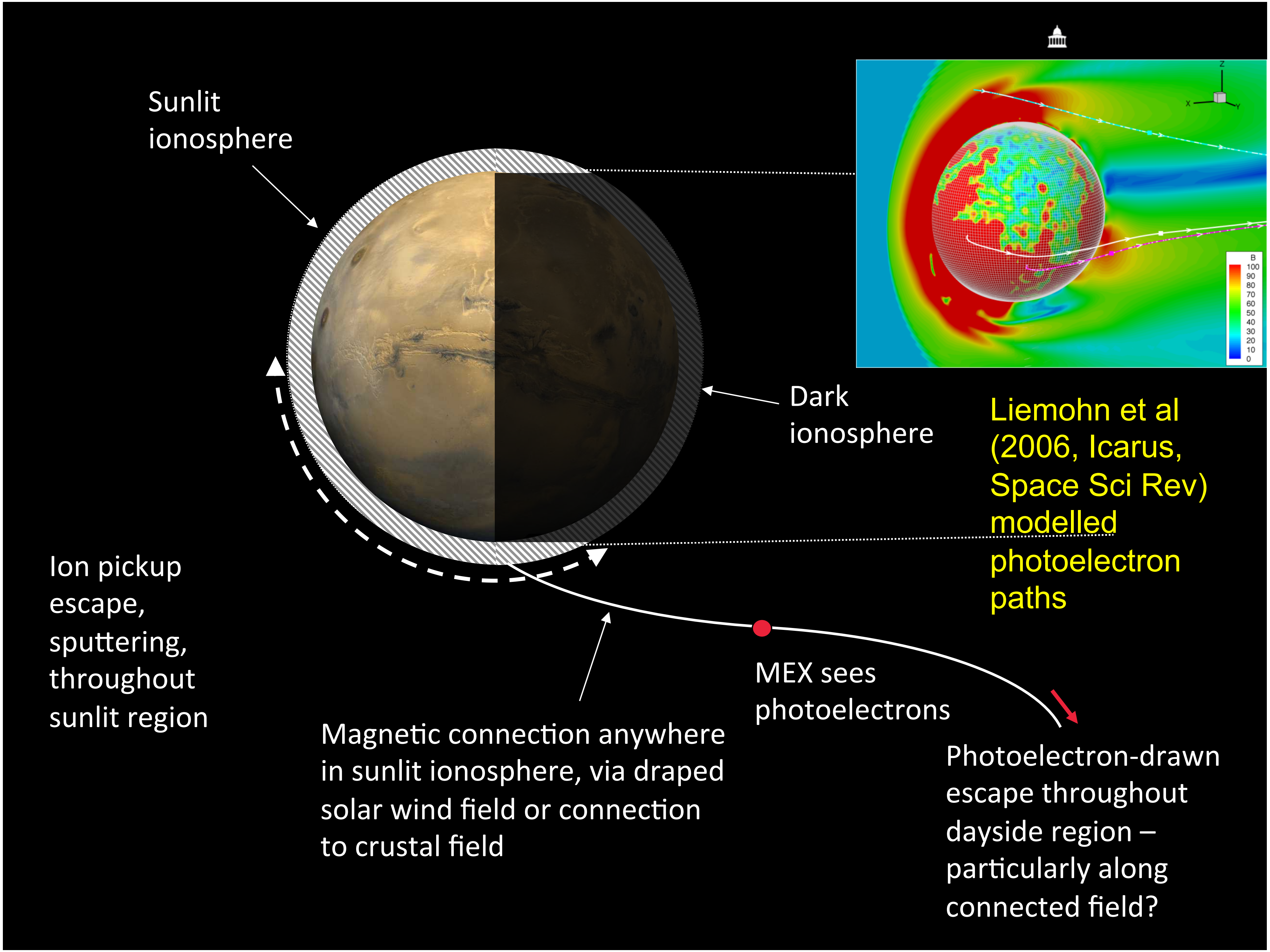




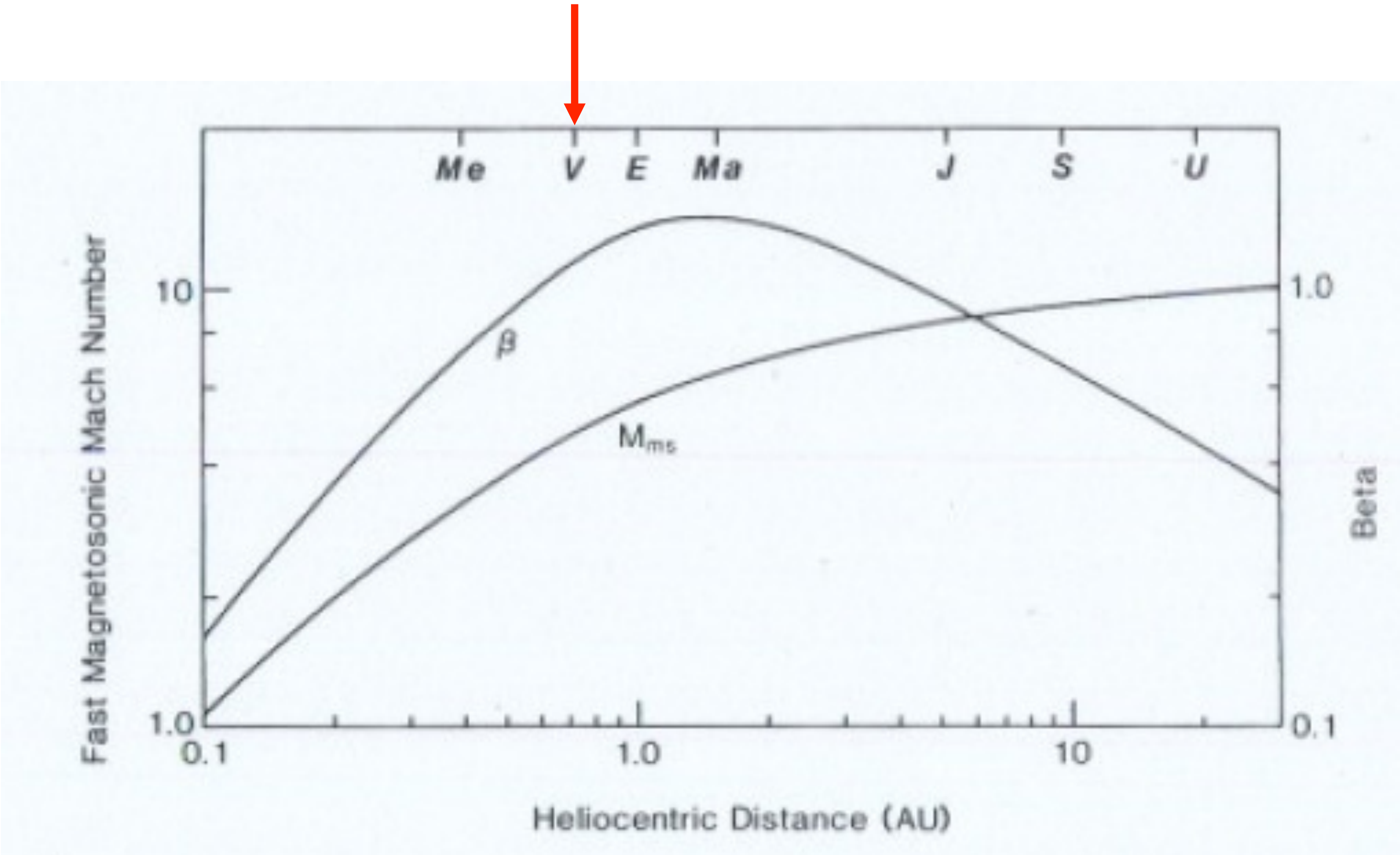
***Mars** Express – photoelectrons in tail*

Frahm et al, Icarus 06, Space Science Reviews 2007

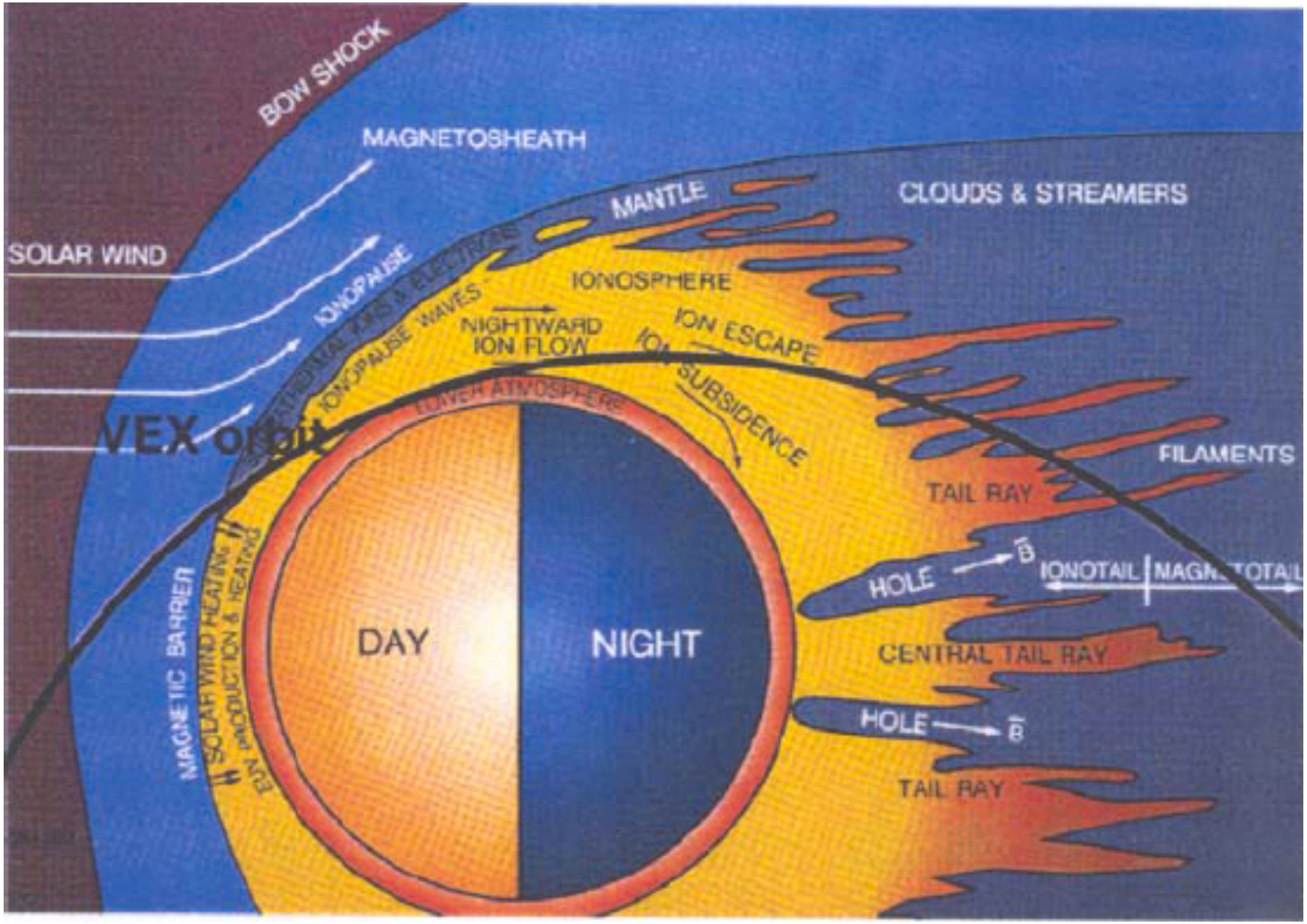
Estimate for Mars photoelectron escape 3.14x10^{23} s^{-1} (Frahm et al Icarus 2010) – preliminary - photoelectron drawn escape contributes?


Sunlit
ionosphere
Dark
ionosphere
Liemohn et al
(2006, Icarus,
Space Sci Rev)
modelled
photoelectron
paths
Ion pickup
escape,
sputtering,
throughout
sunlit region
Magnetic connection anywhere
in sunlit ionosphere, via draped
solar wind field or connection
to crustal field
MEX sees
photoelectrons
Photoelectron-drawn
escape throughout
dayside region –
particularly along
connected field?

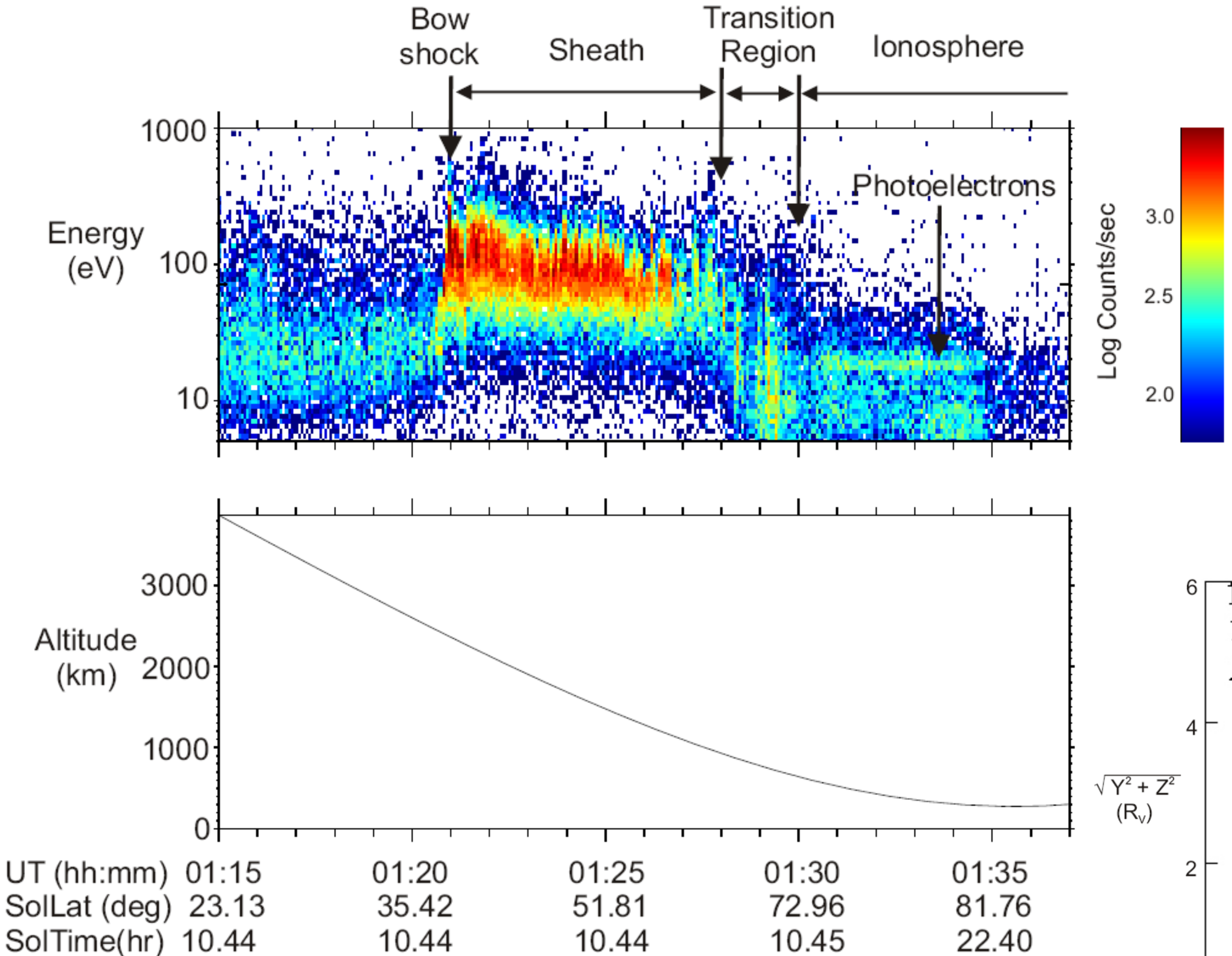
Venus plasma environment



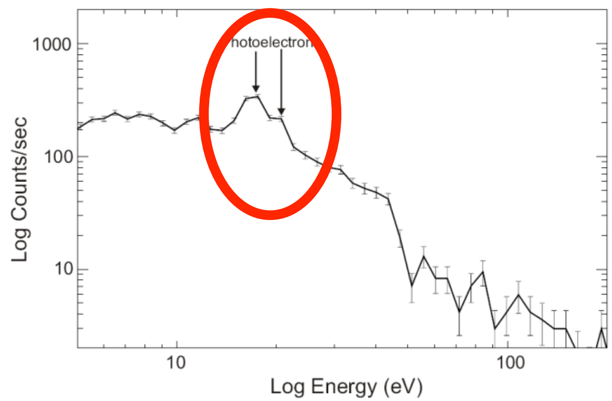
Venus interaction with solar wind

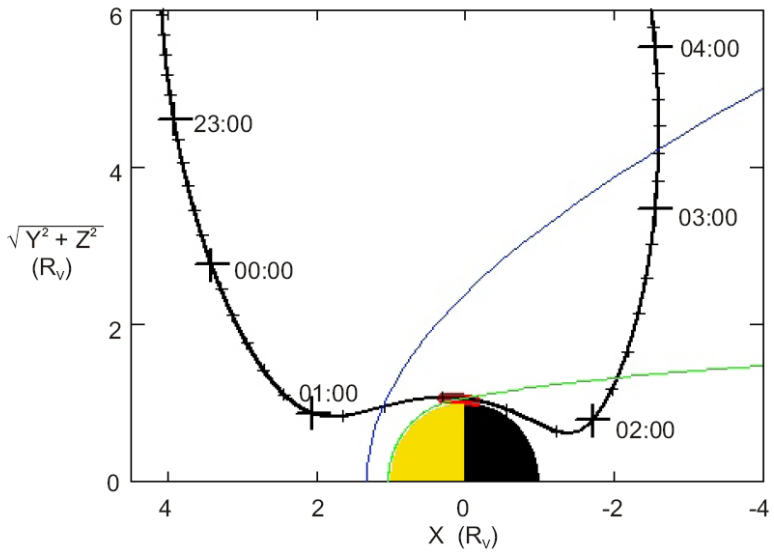


Venus: solar wind interaction – 18 May 06



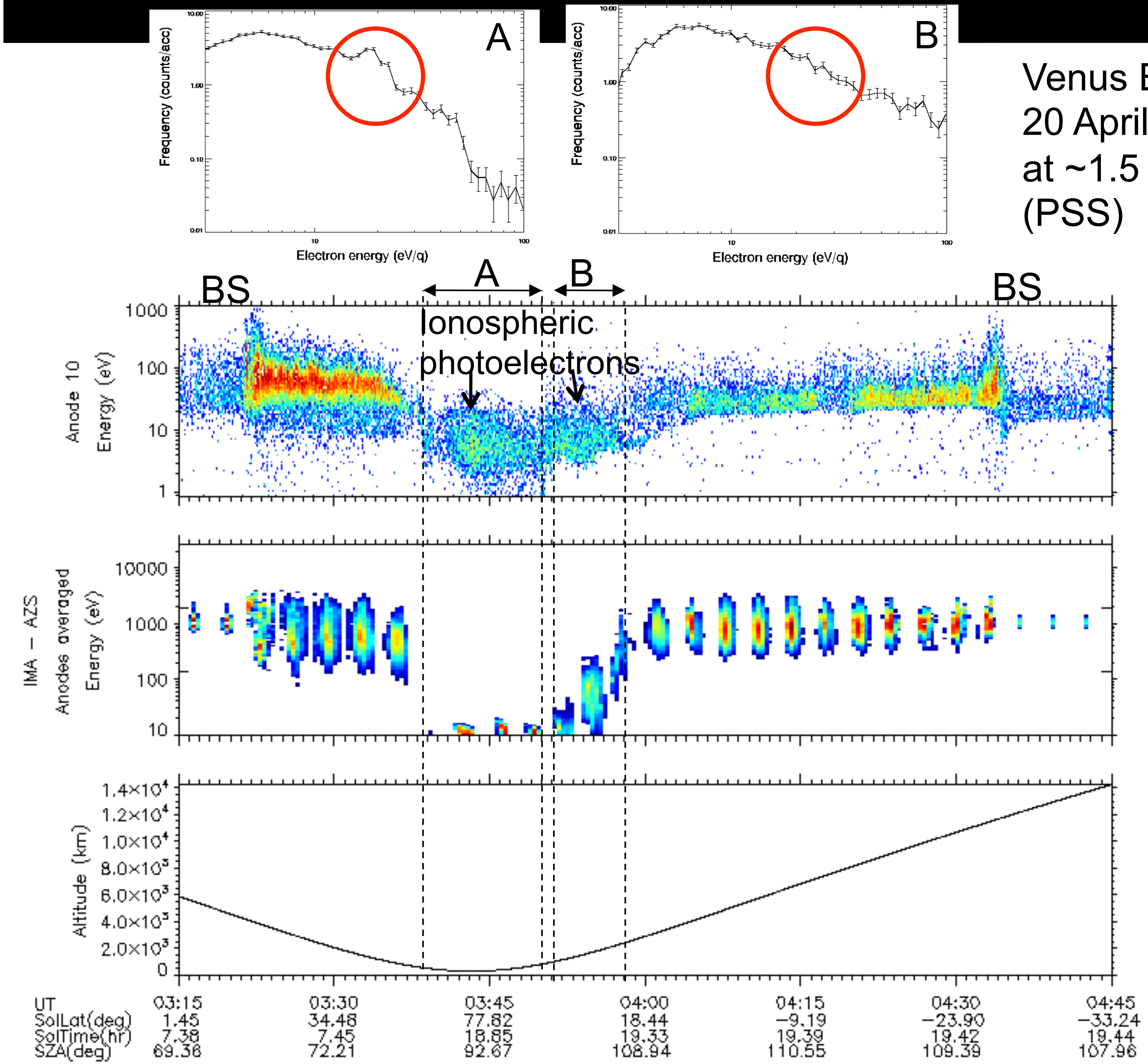
- First observation in Venus ionosphere by VEX ASPERA-4 ELS
- From O rather than CO_2

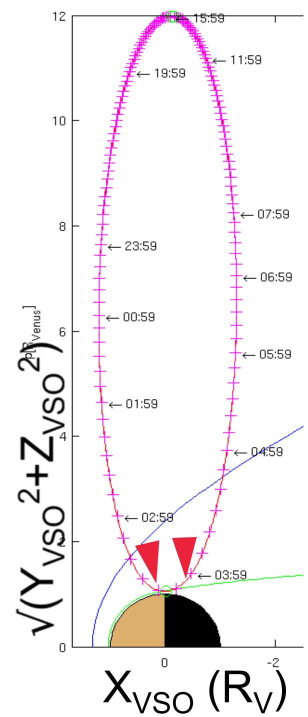




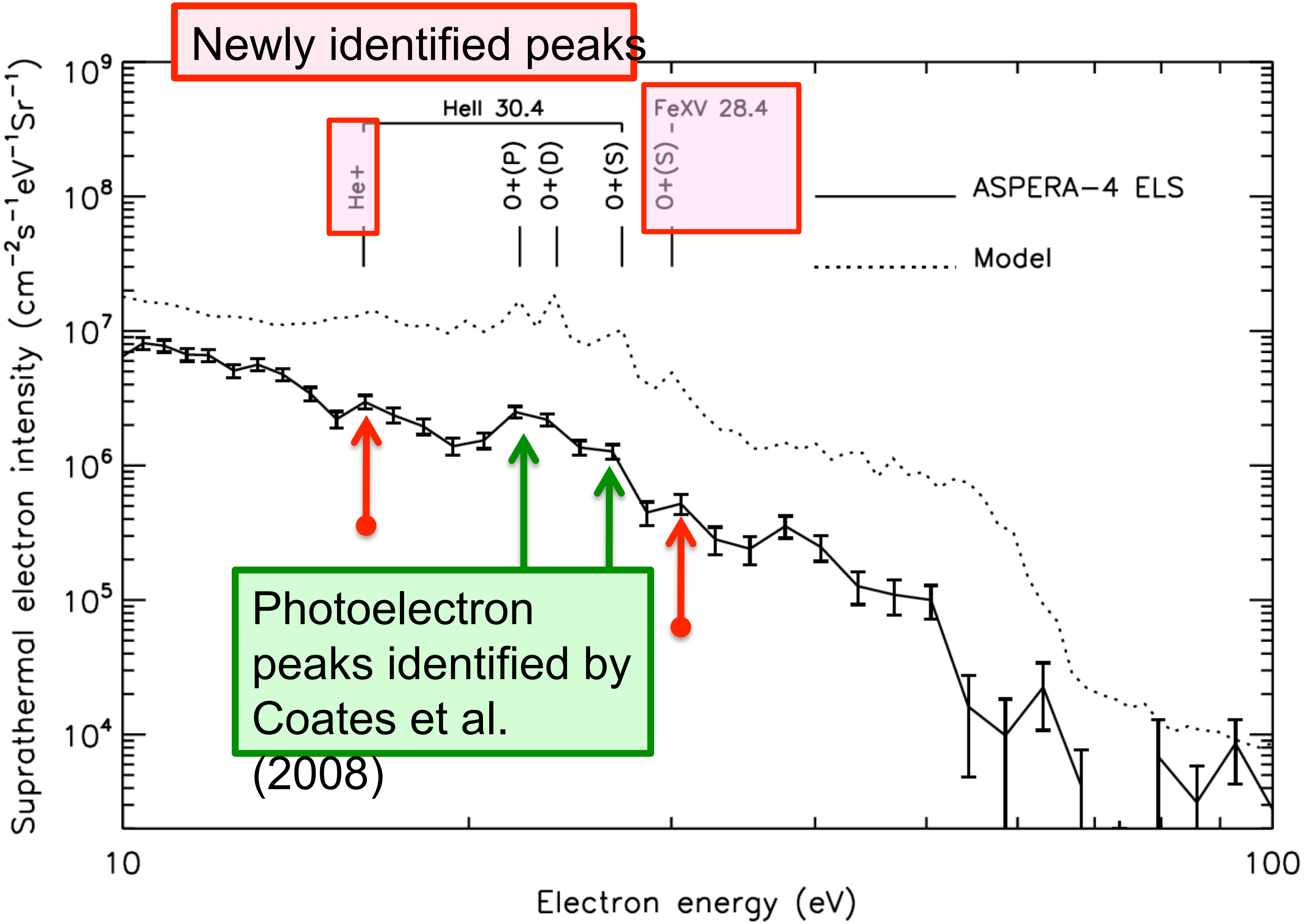
From Coates et al, PSS 2008

Venus Express example 20 April 2008, interval B ends at ~1.5 R_v Coates et al., 2011 (PSS)





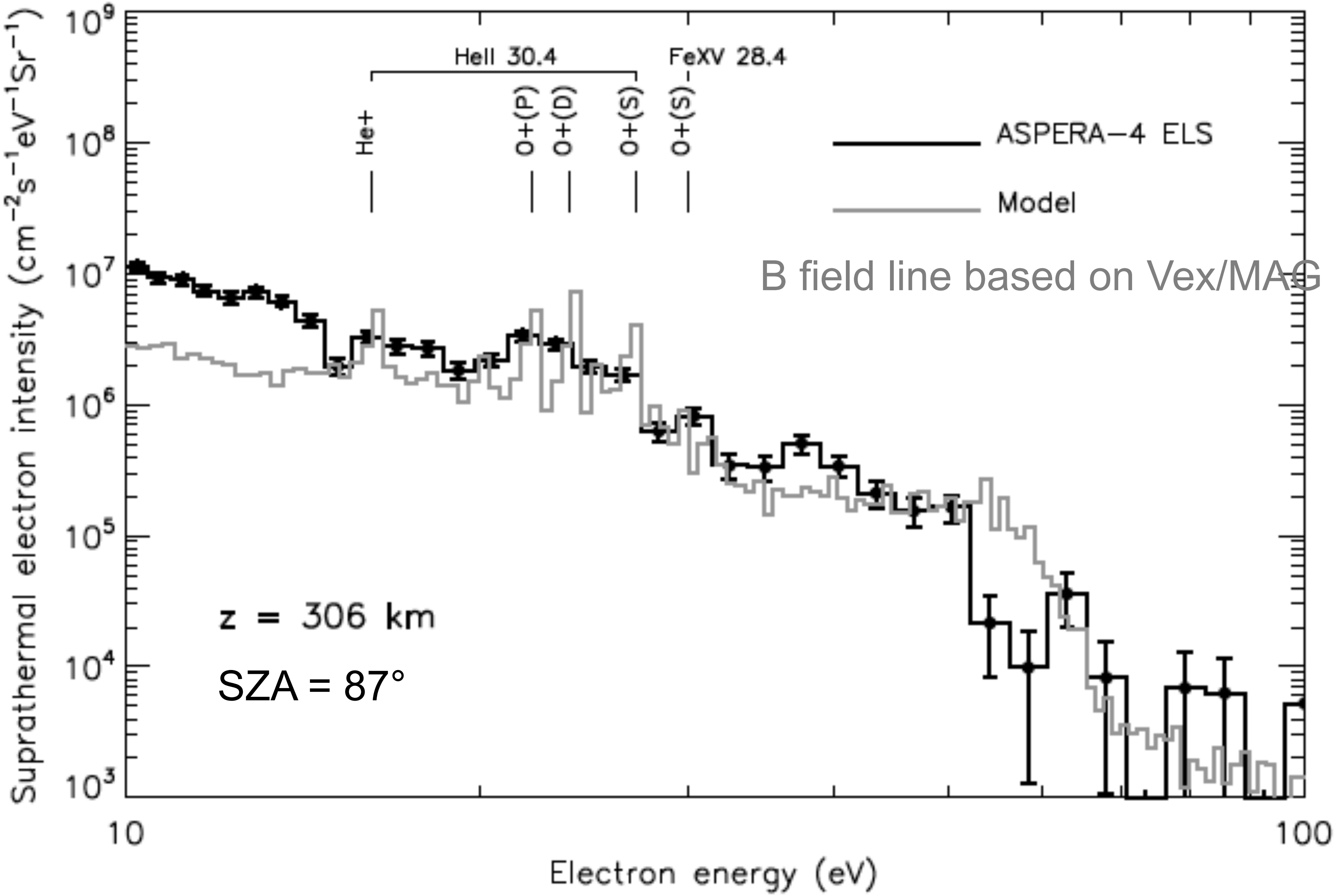
Comparison of shapes: Model - VEx/ASPERA4/ELS



✓O^+- & He^+-related photoelectrons → S/C potential (-4.9 eV)

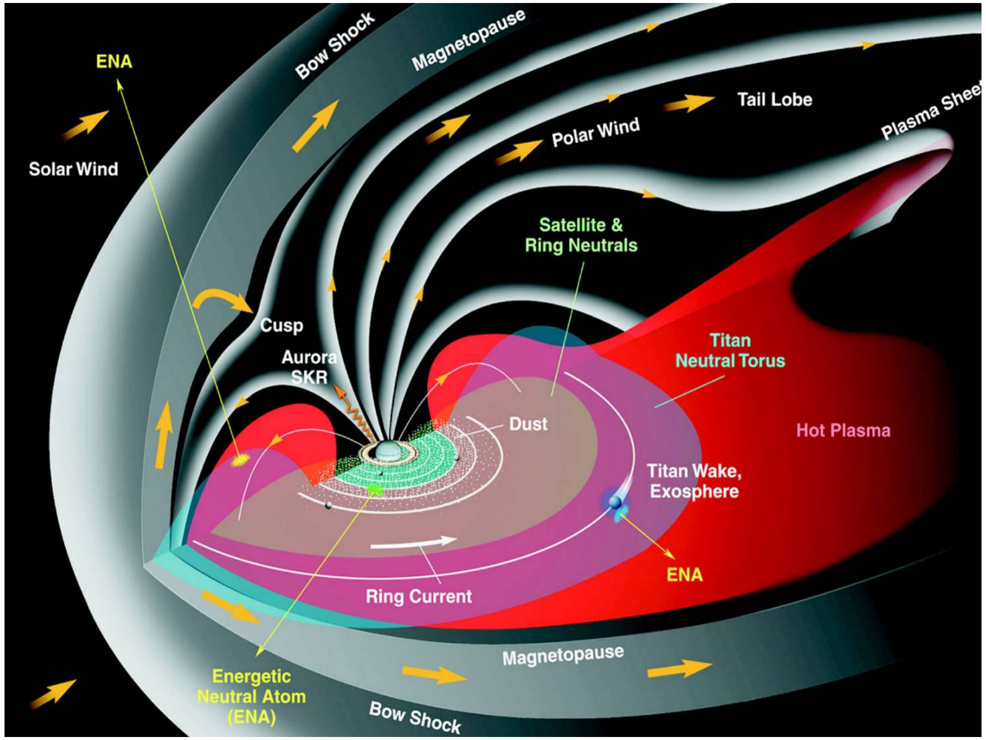
Cui et al., 2011 (JGR)

Comparison: Model - VEx/ASPERA4/ELS

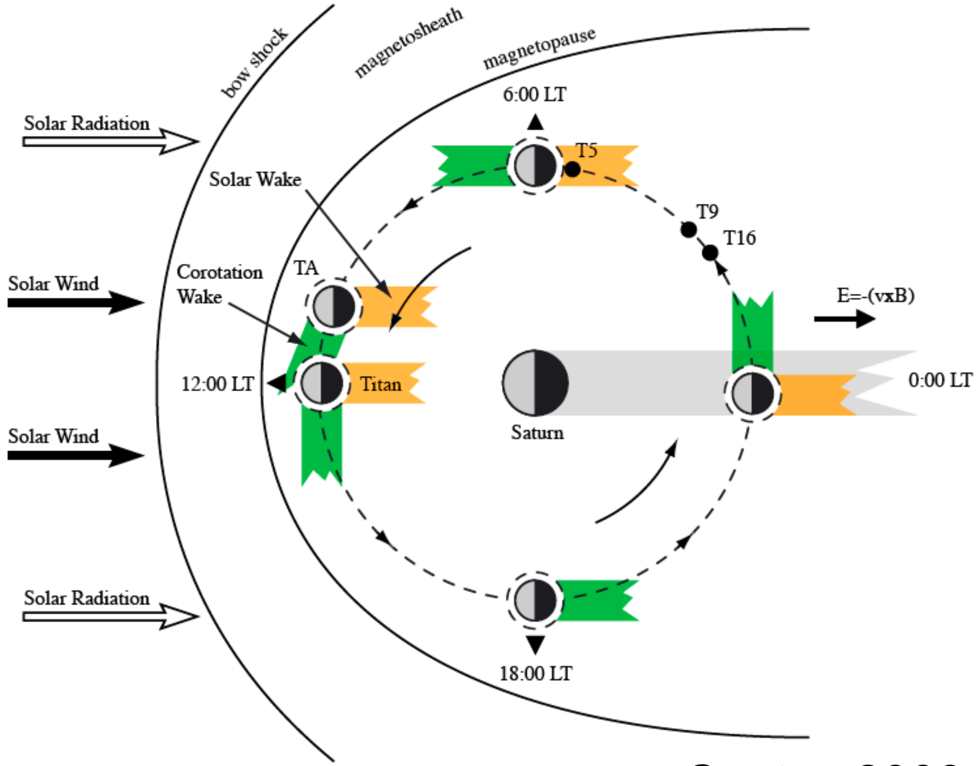


Magnetic field orientation improves quantitative comparison
Cui et al., 2010 (JGR)

Titan plasma environment:
Rotating (period ~10.75 h), hot magnetosphere of Saturn

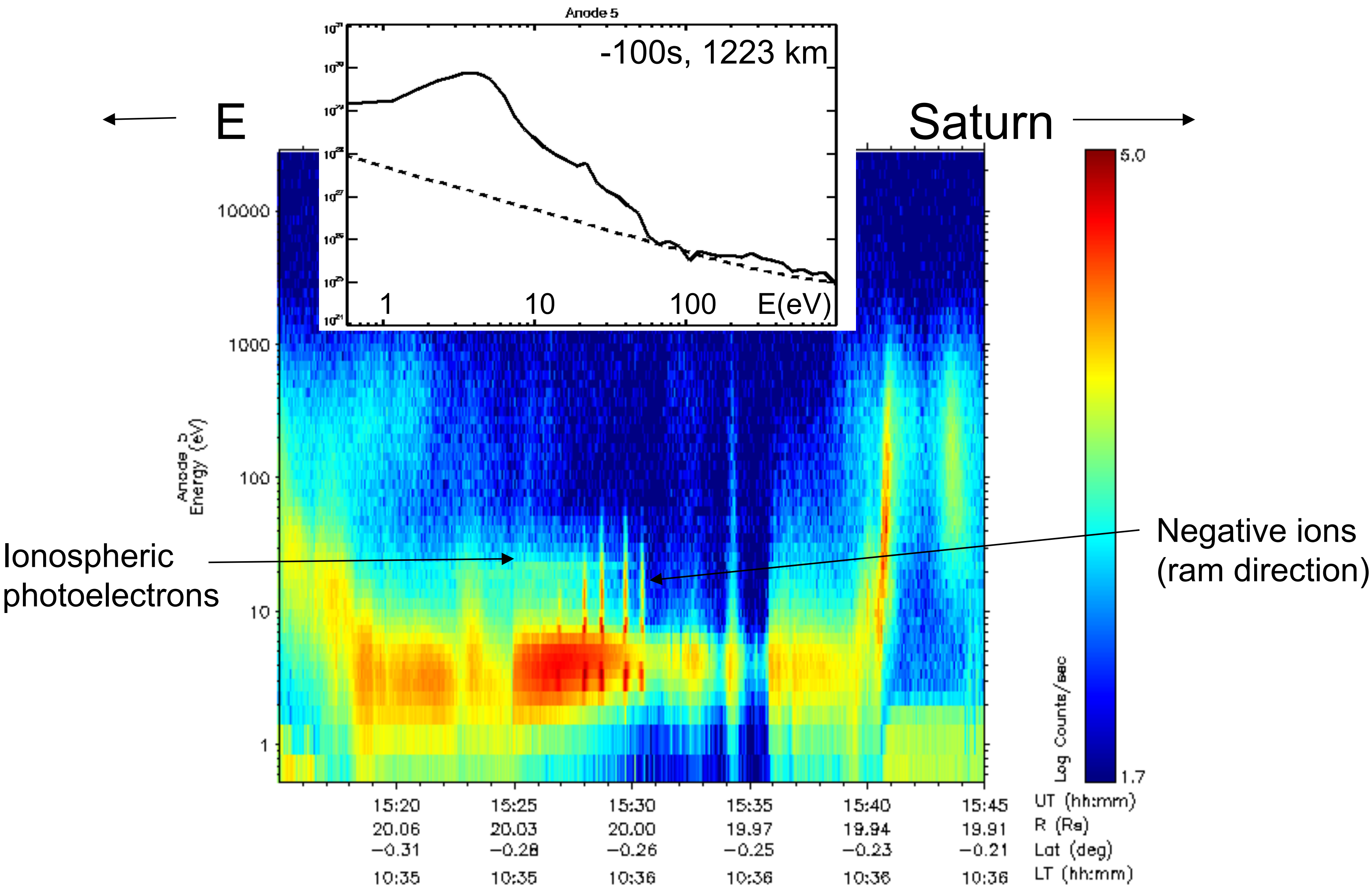


MIMI team

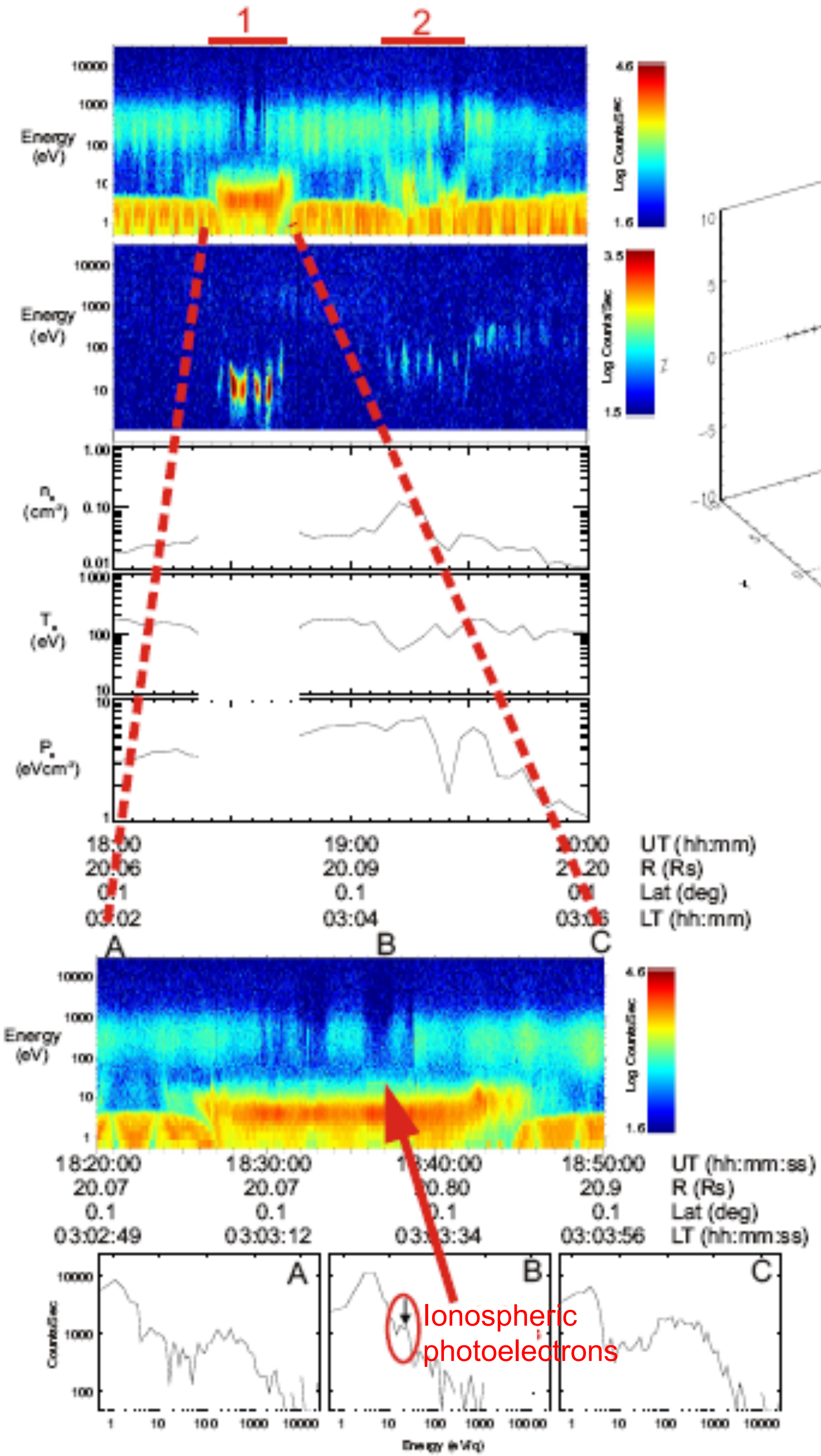


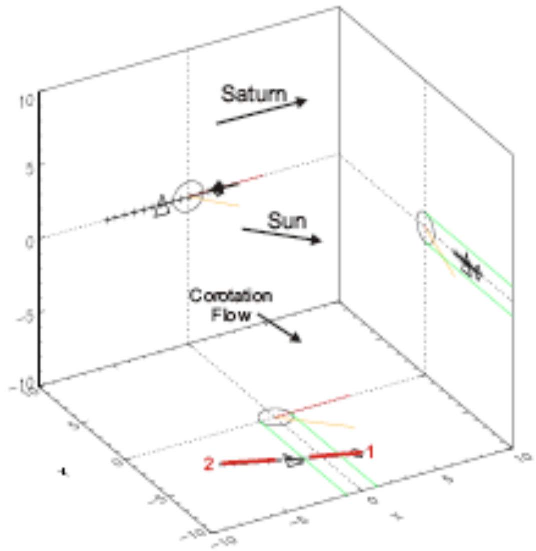
Coates 2009

	Density (cm-3)	Temperature (eV)
Magnetosphere	0.1-1	100-1000
Solar wind (few %)	<0.1	few



Titan dayside ionosphere





Titan - Ionospheric electrons in the tail: T9 encounter

•Interval 1 – evidence of ionospheric plasma escape & connection to sunlit ionosphere; heavy ions, at 6.8-5.4 R_T,

•Interval 2 – mixed ionospheric and magnetospheric plasma; light ions

•Role of ambipolar electric field in escape – similar to Earth's polar wind – and lower mass from higher altitude

•Coates et al, 2007b, Coates 2009, Coates et al 2010

Conclusions on ionospheric photoelectrons (IPE)

- IPE are seen clearly in the dayside ionospheres with suitable instrumentation
- The energy spectrum of IPE is distinctive, acting as a 'fingerprint' for ionisation processes
- IPE can, at times, be seen at large distances from the dayside ionospheres, e.g. in Earth's magnetosphere, and in the tails of Mars, Venus and Titan
- IPE are a sensitive diagnostic 'tracer' of a magnetic connection to the production location, namely the dayside ionospheres
- IPE may play a role in setting up an ambipolar electric field at the top of the ionosphere which would enhance ionospheric escape in a mechanism analogous to the Earth's polar wind (e.g. Ganguli, 1996 and refs), enhancing pressure-driven plasma escape. A similar mechanism was suggested at Venus (Hartle and Grebowsky, 1995), and a polar wind-related electric field escape mechanism at Titan was modelled by Keller and Cravens (1994).

See Coates et al., PSS, 2011 for further details

Conclusions

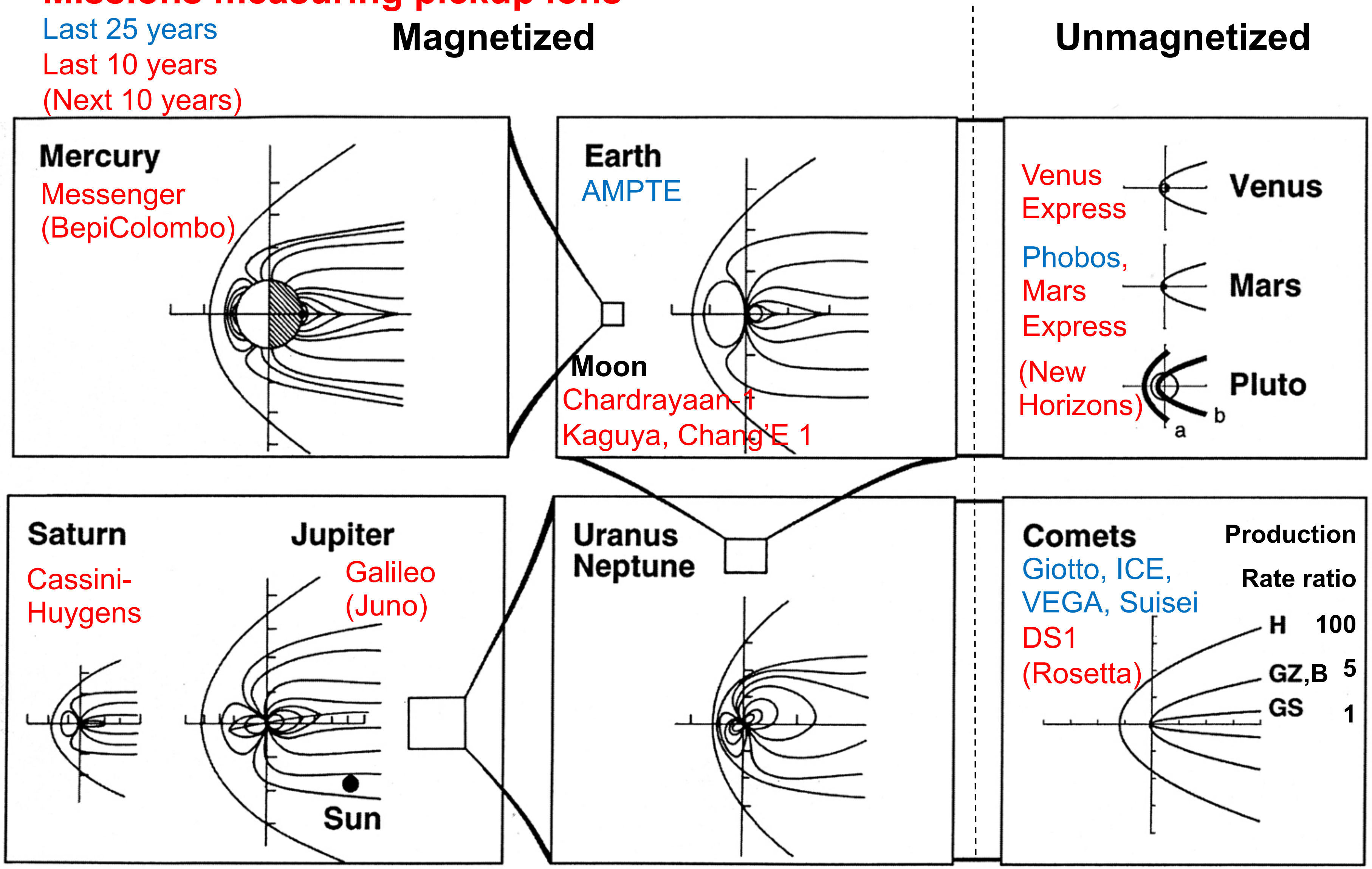
(Coates et al., PSS, 2011)

	Venus	Earth	Mars	Titan
Interaction	Solar wind	Solar wind	Solar wind	Saturn magneto-sphere
Intrinsic magnetic field	No	Yes - dipole	Localised crustal magnetization associated with heavily-cratered S. highlands	No
Species associated with dominant photoelectron peaks (dayside, high altitude)	O	N_2, O	CO_2, O	N_2, (CH_4)
Location of ionospheric photoelectrons seen remotely from dayside ionosphere	Tail	Magneto-sphere	Tail	Tail
Related ion escape?	Yes (VEx)	Polar wind	Yes (MEx)	Yes (T9, T15, T40)

Ion pickup and mass loading

Missions measuring pickup ions

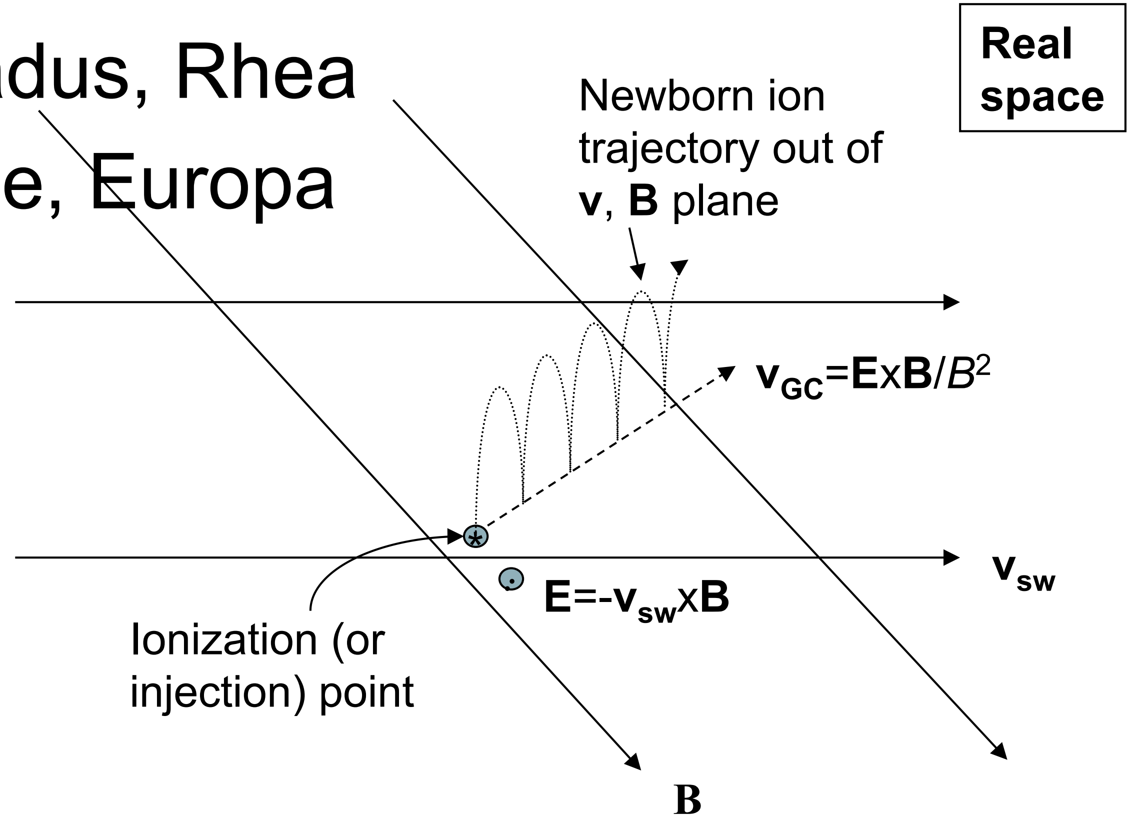
Last 25 years
Last 10 years
(Next 10 years)



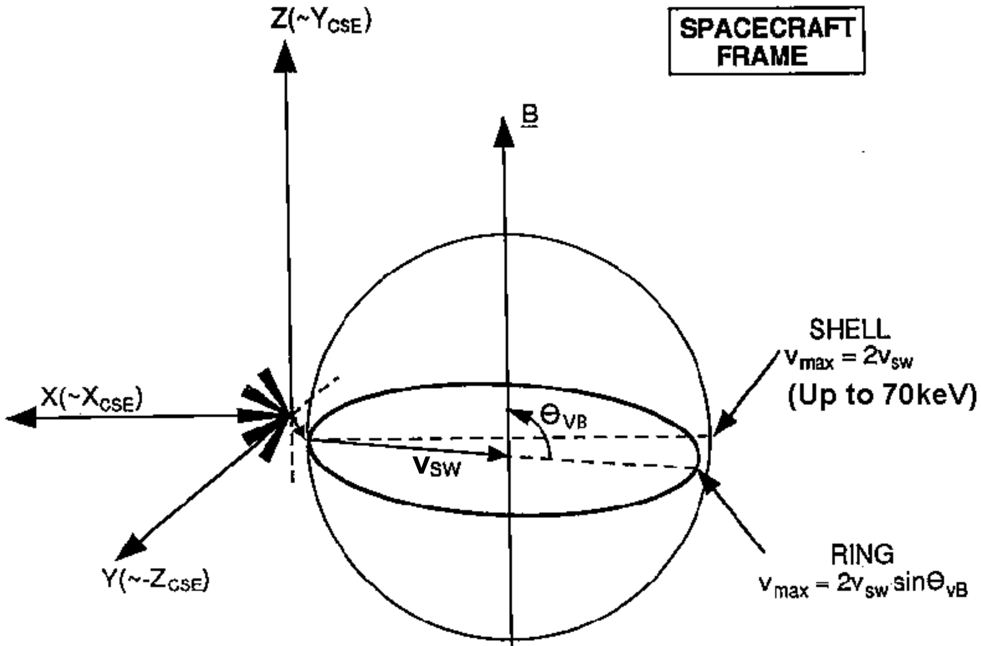
Adapted from Coates 2011, Russell and Walker 1995

Outline

- Pickup process
  - Ring, shell, bispherical shell
  - Wave excitation, particle acceleration
- Comets
- Saturn: Titan, Enceladus, Rhea
- Jupiter: Io, Ganymede, Europa
- Pluto
- Mars, Venus
- Mercury, the Moon
- Summary



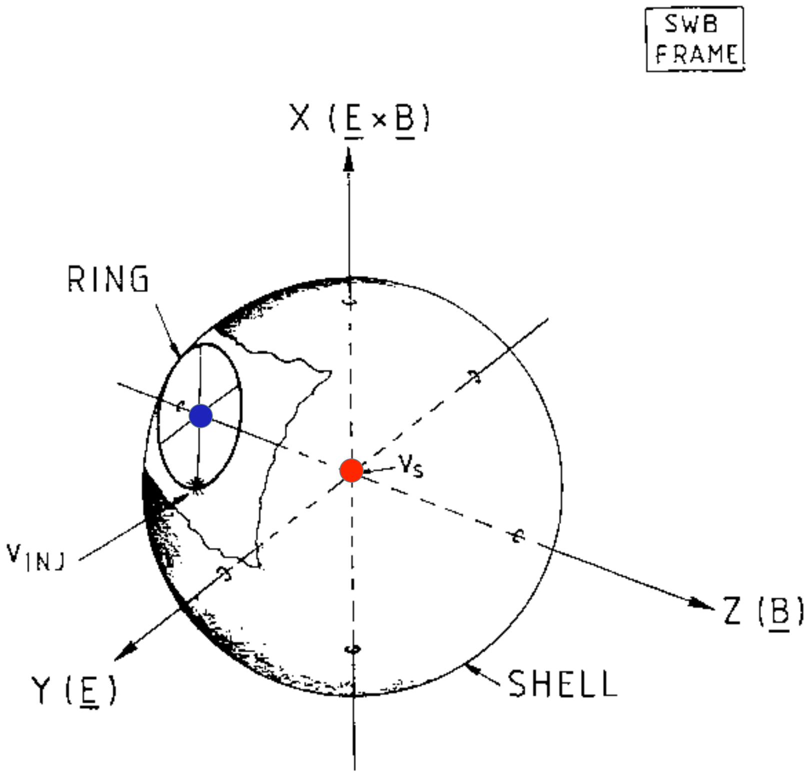
Coates, 1991; Coates & Jones, PSS, 2009



$$E_{max,\ ring} = 2mv_{sw}^2 \sin^2 \theta_{vB}$$
$$= 4m_{amu} E_{sw} \sin^2 \theta_{vB}$$
$$E_{max,\ shell} = 4m_{amu}E_{sw}$$

(e.g. Up to ~70keV for a water group ion in the solar wind)

Velocity space picture of ion pickup (Coates et al 1993)



Solar wind, field aligned (SWB) frame:

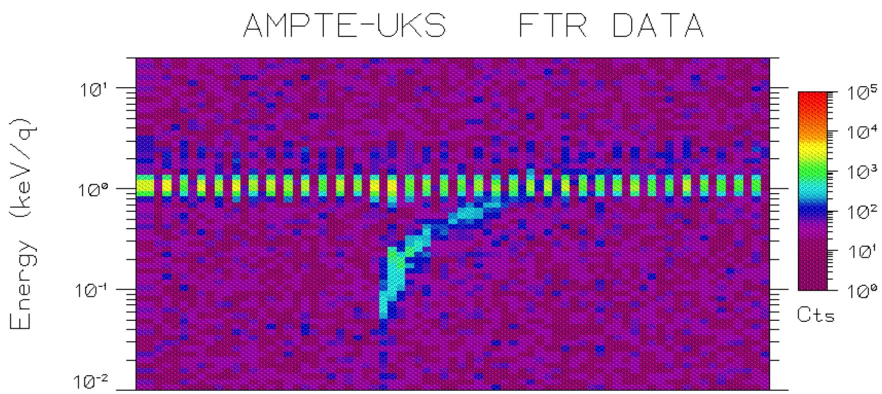
$\mathbf{v}_{\mathbf{ring}}=(0,0,v_{||}),\ v_{||} = \mathbf{v.B}/B$

$\mathbf{v}_{\mathbf{shell}}=(0,0,0)$

(Coates et al 1990)

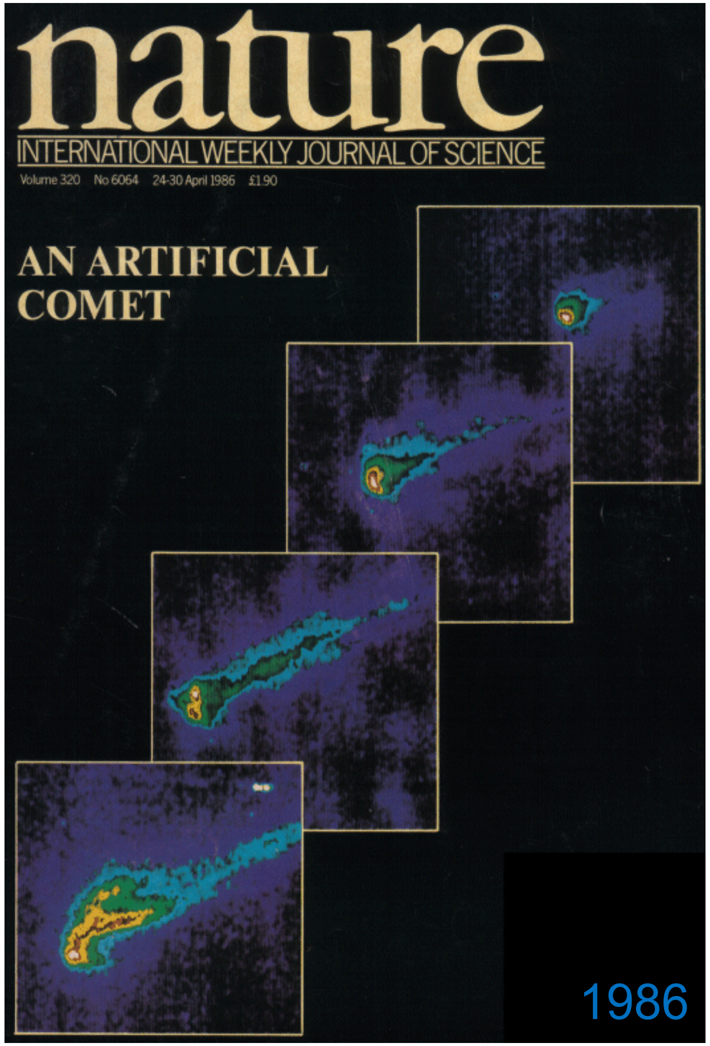
Ion pick-up process

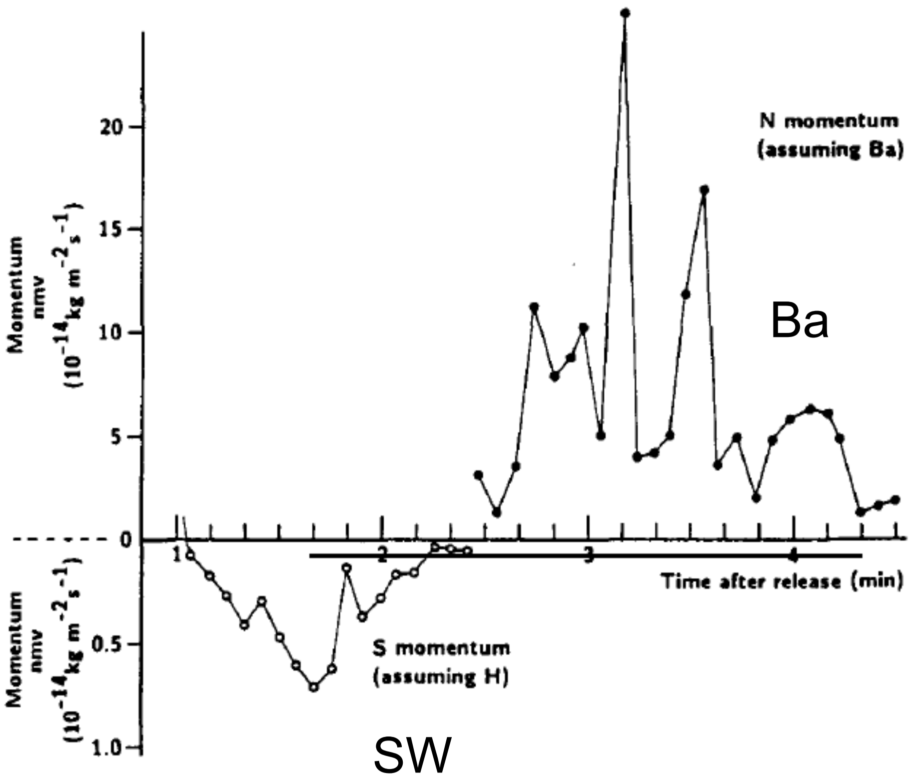
- In velocity space, cycloid translates to a ring
- Ring distribution unstable, plasma waves are produced
- Waves scatter particles in pitch angle to a shell and in energy (thick shell)
- Given long enough shell fills and distribution tends to Maxwellian (e.g. comet inner coma measurements by Schwenn et al, 1987, Goldstein et al 1992)
- Energy from solar wind given to newborn ions and to waves. Solar wind slows – **mass loading**
- Accommodation of ions into the solar wind flow
- Works at artificial & real comets



Coates et al. 1986
Also Mobius et al

AMPTE barium release in the solar wind: momentum balance between SW and Ba





Coates et al., Adv Space Res., 1988

Cometary plasma environment

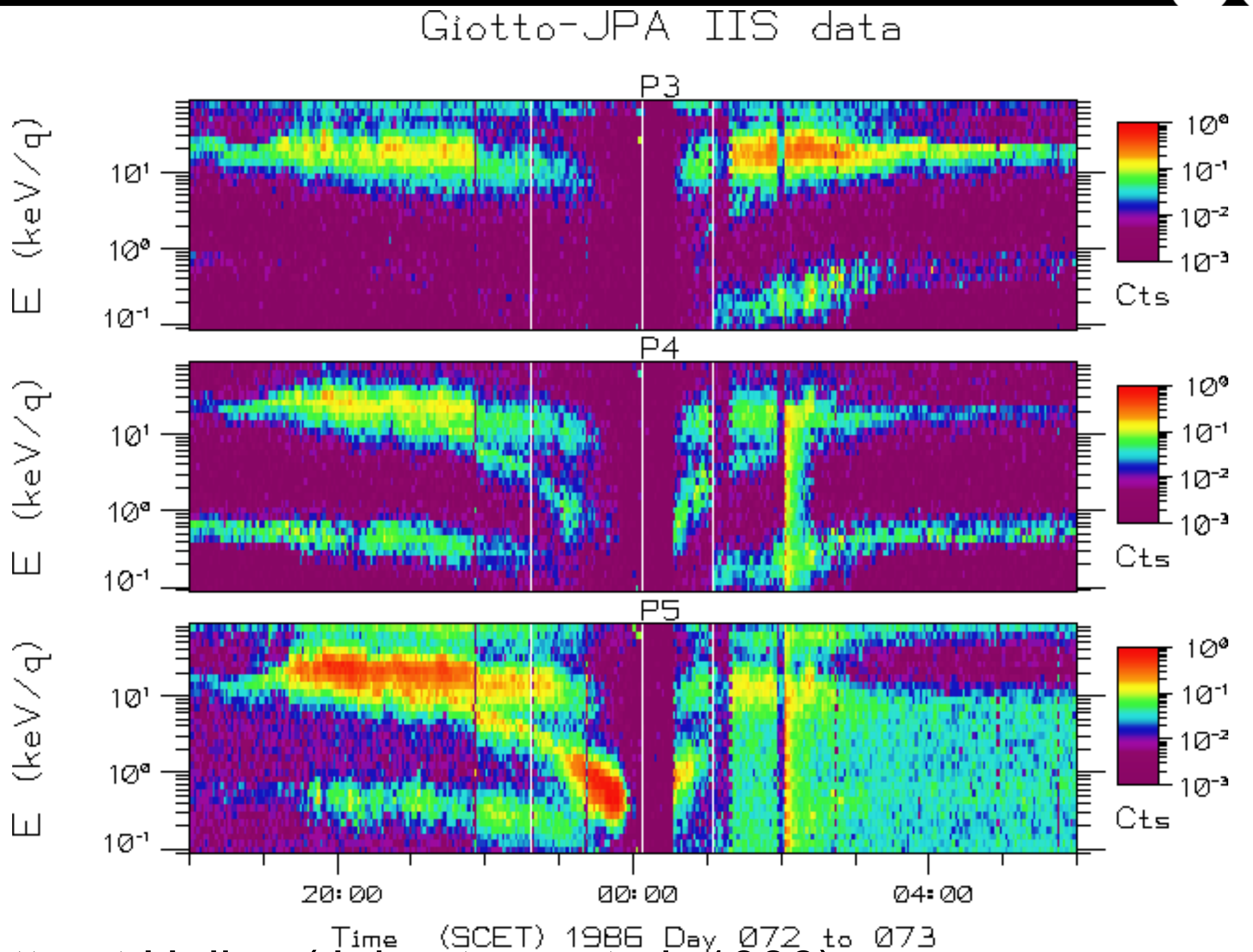
- As nucleus (dirty snowball) approaches the Sun, volatiles sublime into space
- Gas pulls dust away also
- Neutrals drift from nucleus (v_{escape} ~m/s) at ~1km/s
- Production rate Q (s^{-1}) varies with distance from Sun
- Neutrals ionize in sunlight or by charge exchange
- Source term of form $$Q = \frac{Q_0}{r^2} \exp\left(\frac{-r}{v_e t} \right)$$

where v_e is expansion velocity and t ionization time. Describes spherical expansion of gas, depletion due to ionization.

Comet encounters – gas production rates

Comet	Spacecraft	Production rate (s^{-1})	Ratio (Halley=100)	Reference
Giacobini-Zinner	ICE	$4x10^{28}$	5.8	Mendis et al, 96
Halley	Giotto, Vega, Suisei, Sakigake	$6.9x10^{29}$	100	Krankowsky et al, 86
Grigg-Skjellerup	Giotto (GEM)	$7.5x10^{27}$	1.1	Johnstone et al, 93
Borrelly	DS1	$3.5x10^{28}$	5.1	Young et al, 2004
Churyumov-Gerasimenko	Rosetta	$3x10^{24}$-$5x10^{27}$	$4.3x10^{-4}$-0.7	Hansen et al., 07, Motschmann & Kuehrt, 06

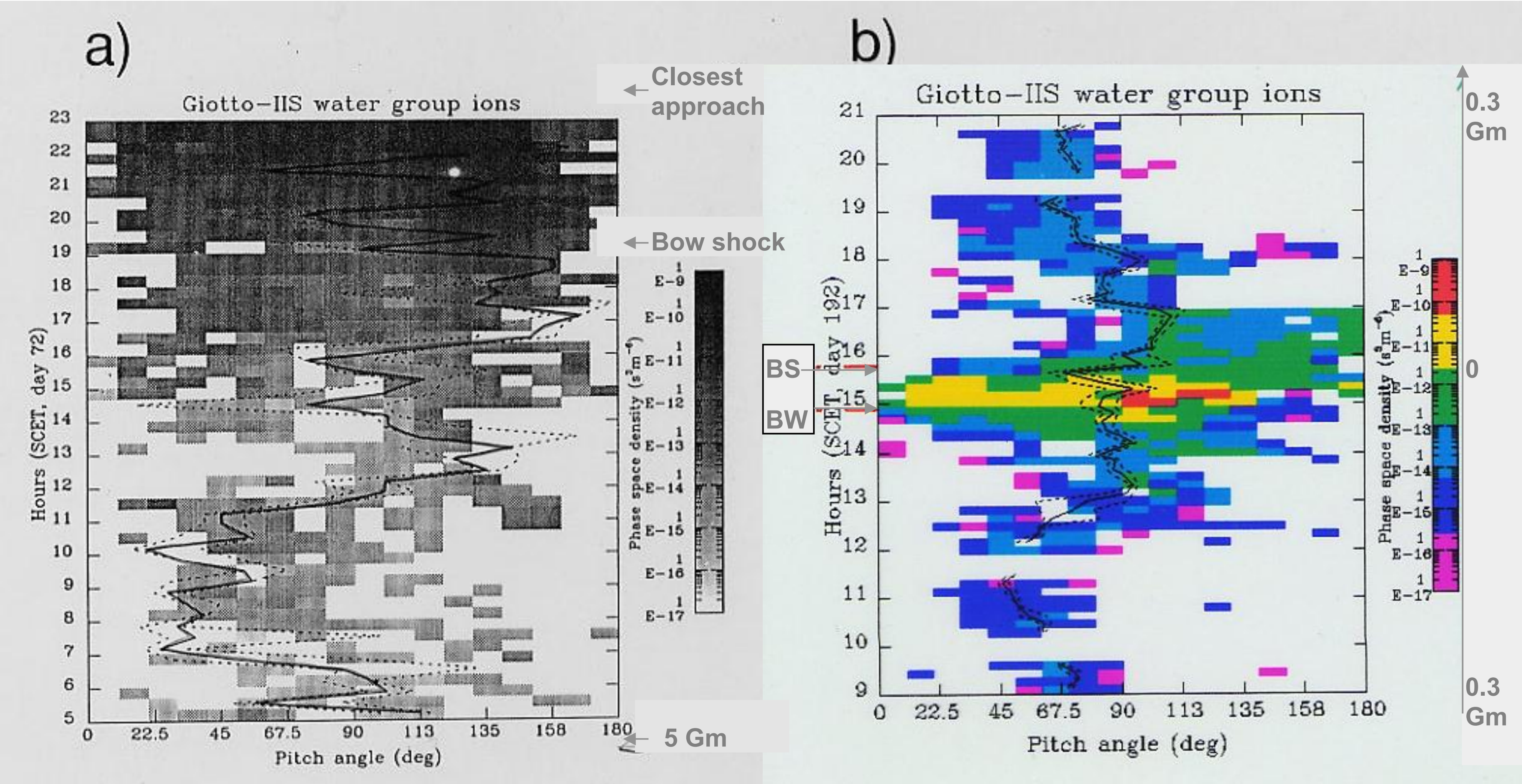
From Coates, 2011, Ion Pickup and Acceleration: Measurements From Planetary Missions, AIP proceedings volume 'Physics of the heliosphere: a 10-year retrospective', 10th Annual Astrophysics Conference, in press, Sep 2011



Giotto at Halley (Johnstone et al, 1986)

Bifurcation due to slowing of flow (Thomsen et al 1987)

Cometary water group ion pitch angle distributions: SWB frame



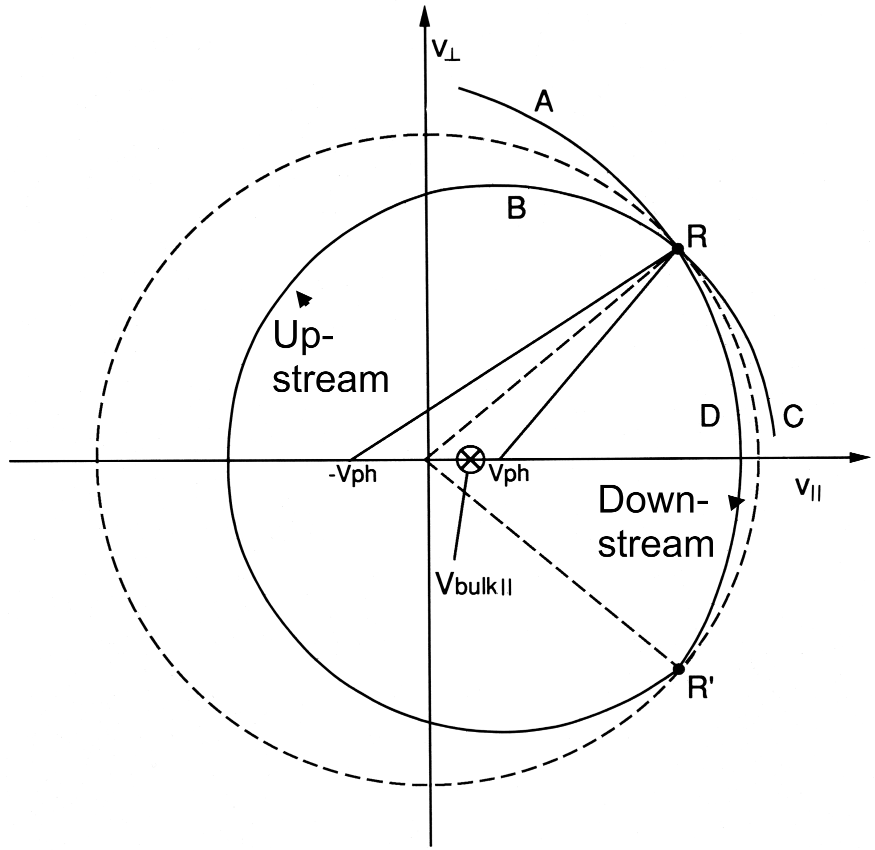
Halley inbound (Coates et al 1990)

GS (Coates et al 1993)

Rings far from comet, PA scattering closer at Halley; non-gyrotropic ions close to GS

Pitch angle scattering

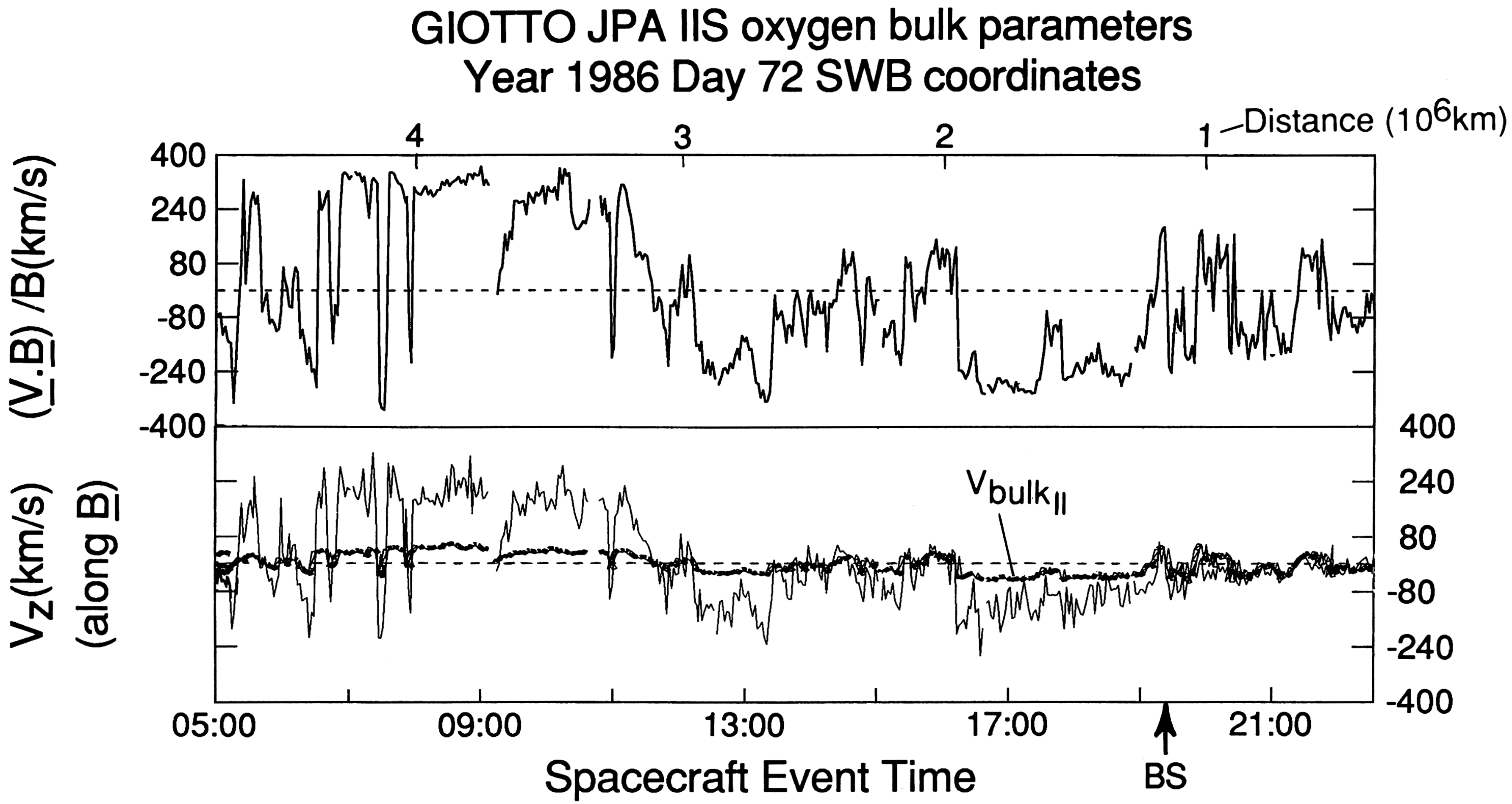
- Pitch angle scattering from ring to shell (predicted by Wallis 1970, Wu and Davidson 1972, etc)
- Maximum velocity of particles in simple shell $2v_{sw}$
- More realistic distribution is a bispherical shell
- Two shells centred on upstream, downstream propagating waves, at $\pm v_{wave}$
- Pitch angle scattering follows these in velocity space



Following Galeev & Sagdeev, 1988

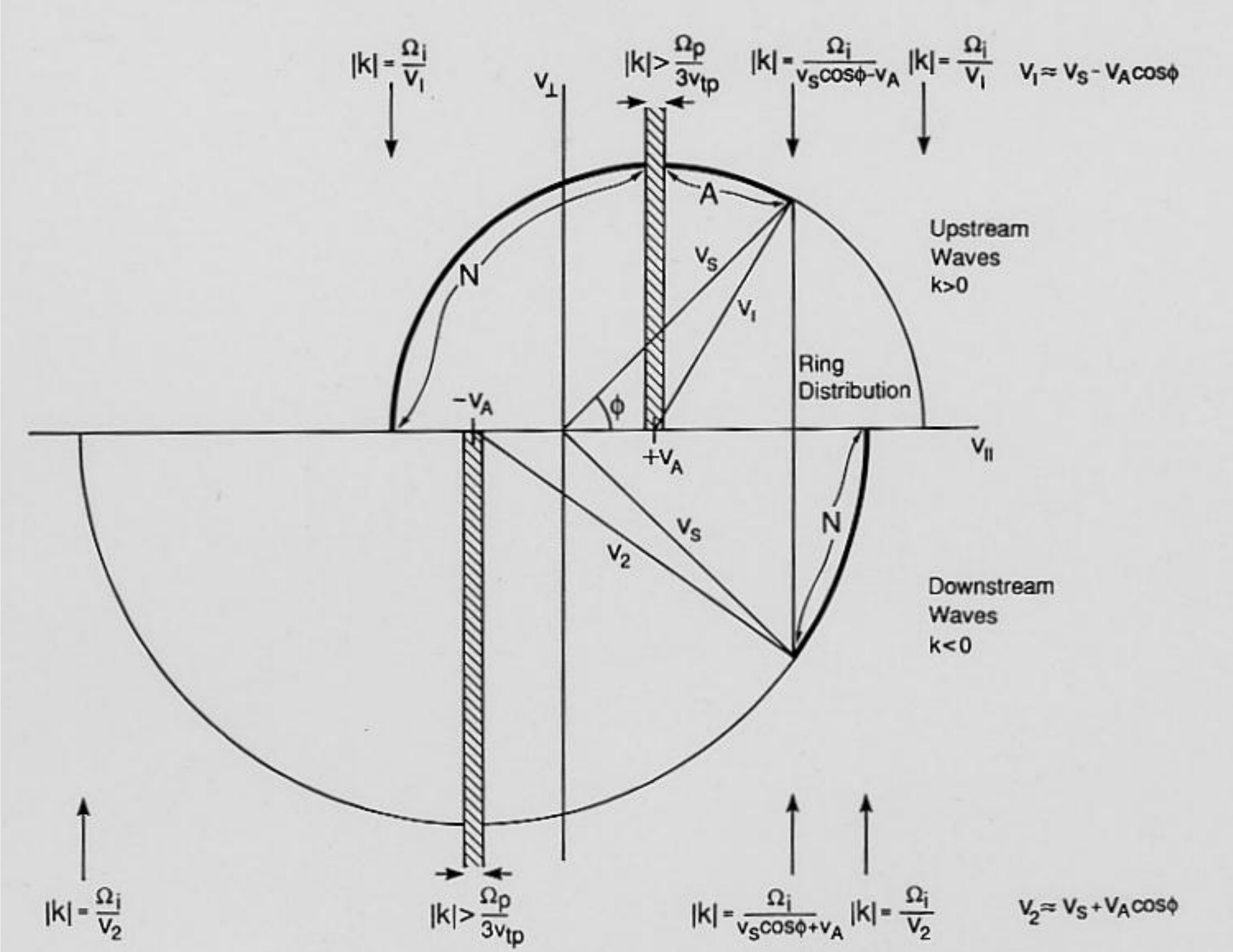
Bulk velocity now $(0,0,v_{bulk||})$

Coates et al 1990

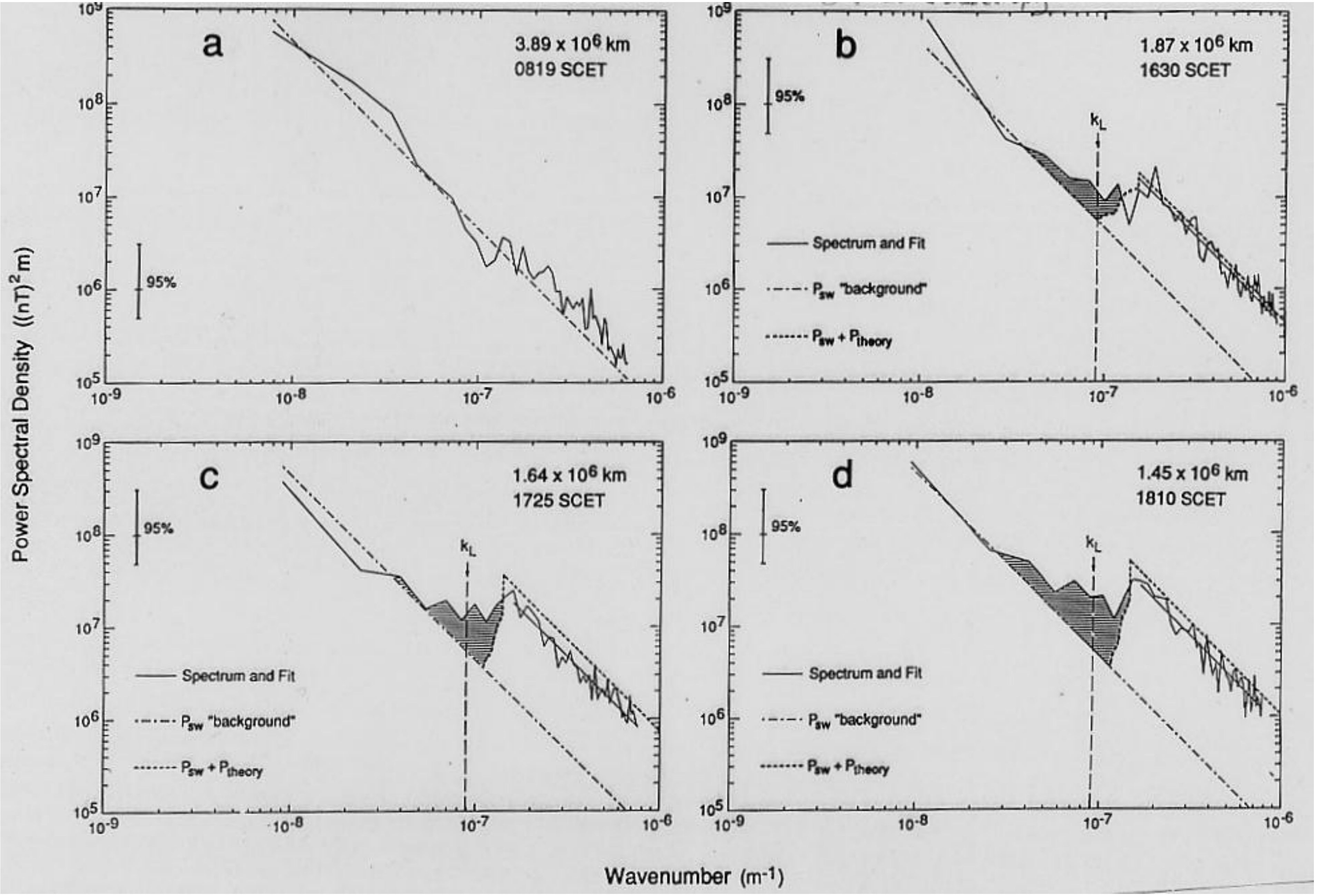


Water group bulk speed at Halley follows ring prediction upstream, bispherical bulk speed near bow shock

Coates et al 1990

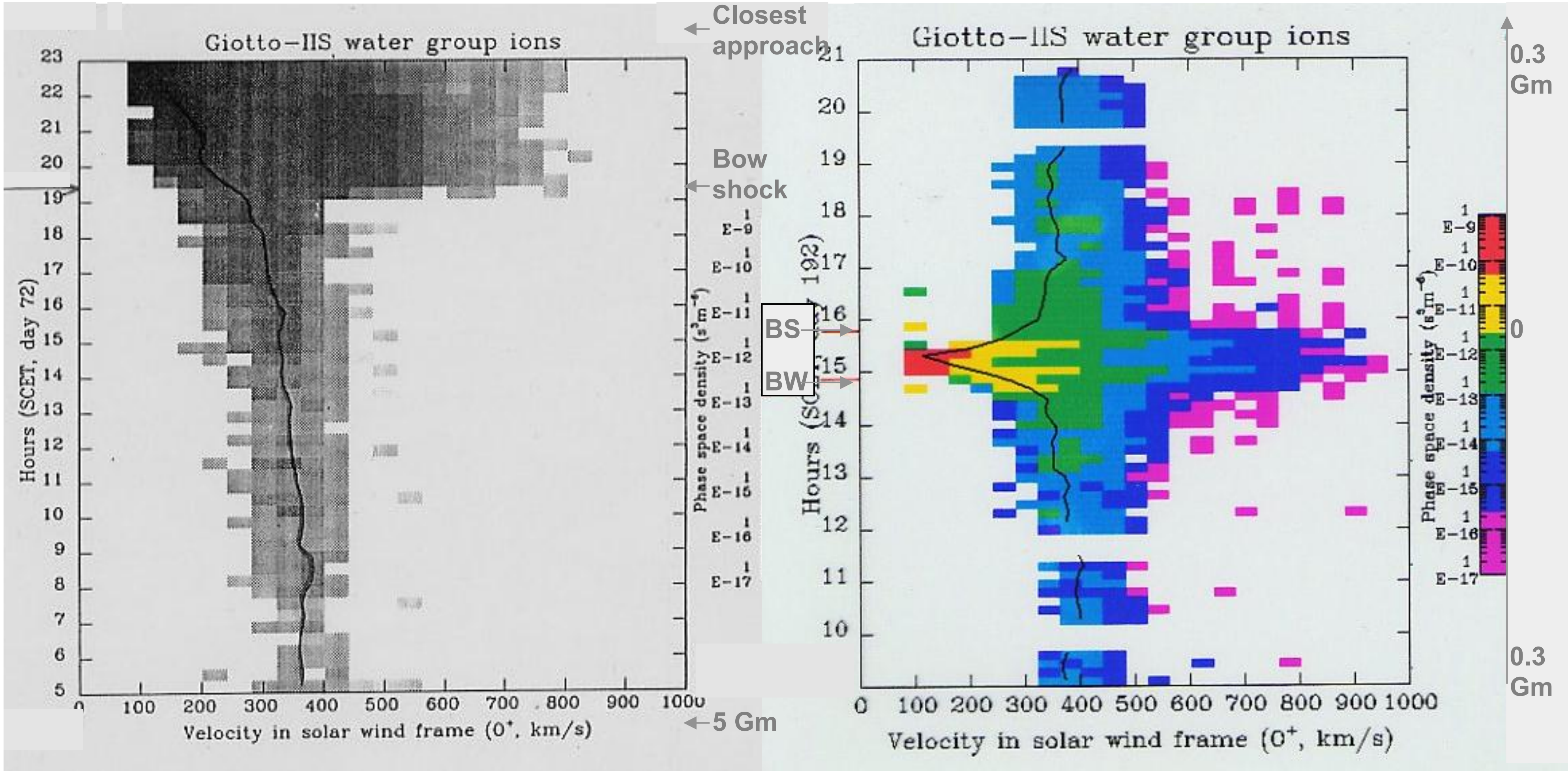


Resonant wave-particle interactions show that different parts of shell interact with particular waves (Johnstone et al, 1990)



Huddleston and Johnstone 1992

Cometary water group velocity distributions



Halley inbound (Coates et al 1990)

GS (Coates et al 1993)

Most acceleration seen downstream of bow shock

Acceleration beyond pickup seen by EPA (S. McKenna-Lawlor talk)

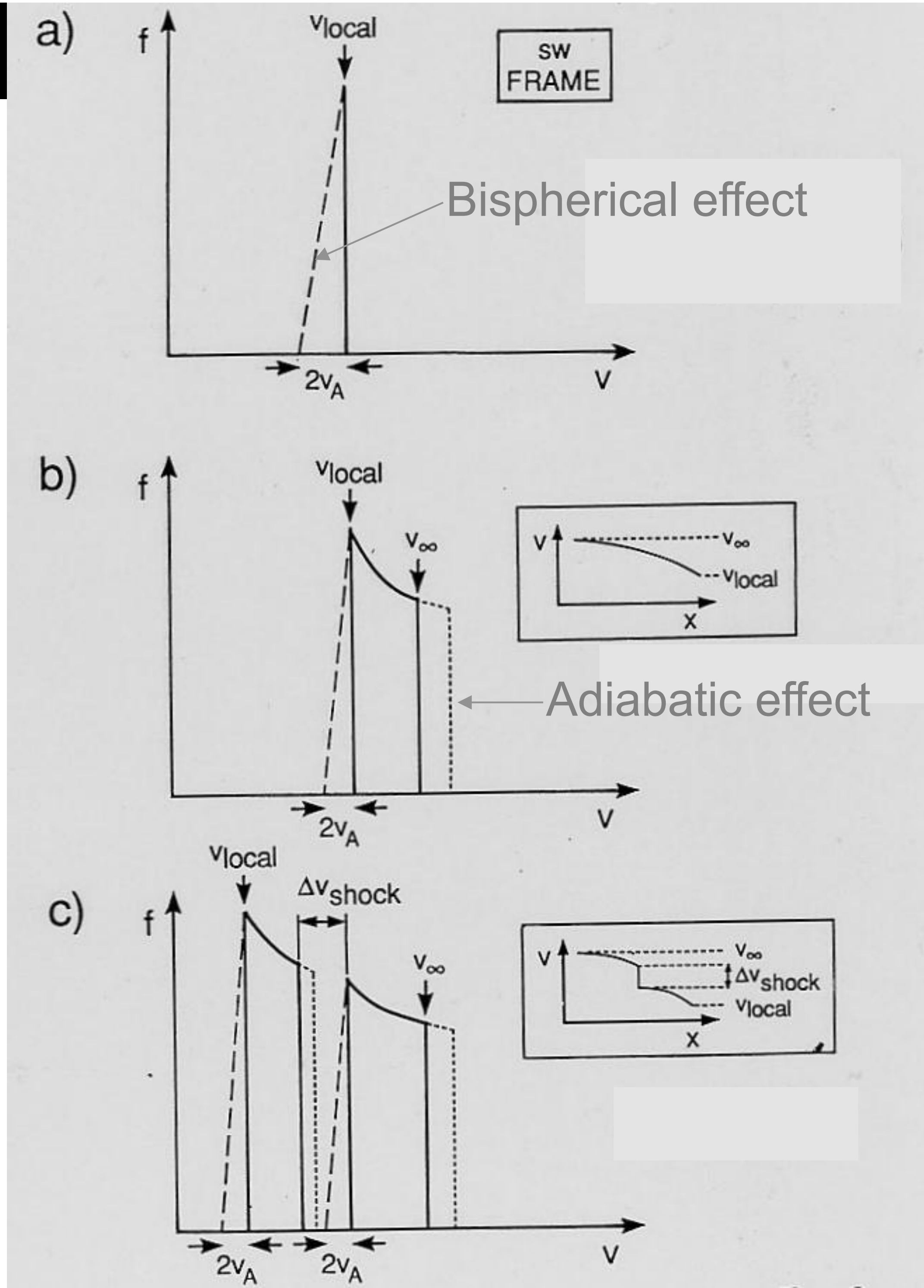
[redacted]

Well upstream

(no mass loading)

Upstream of bow shock

Downstream of bow shock



Coates 1991, adapted from Galeev, Cravens and Gombosi 1986

[redacted]

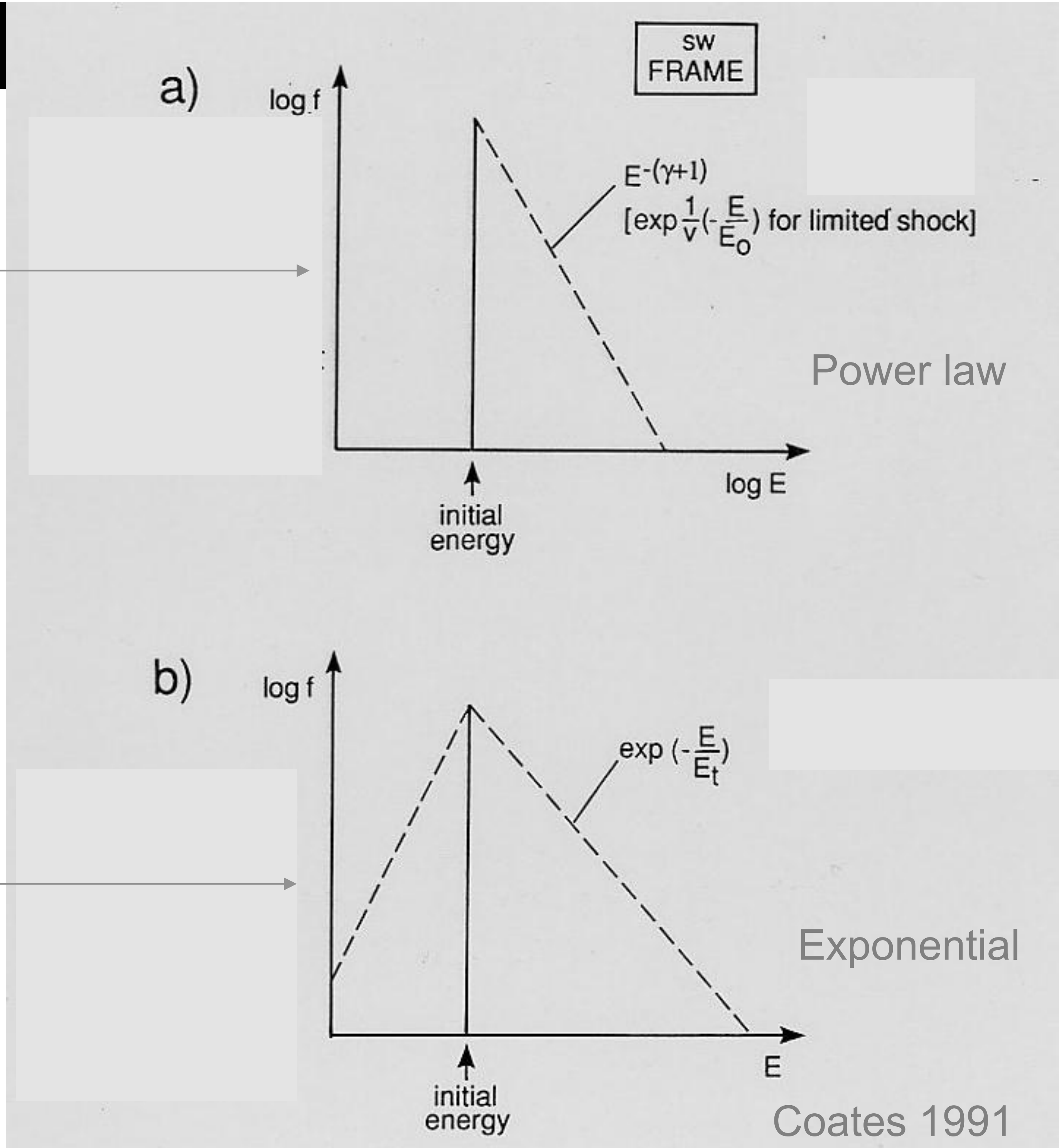
Fermi I

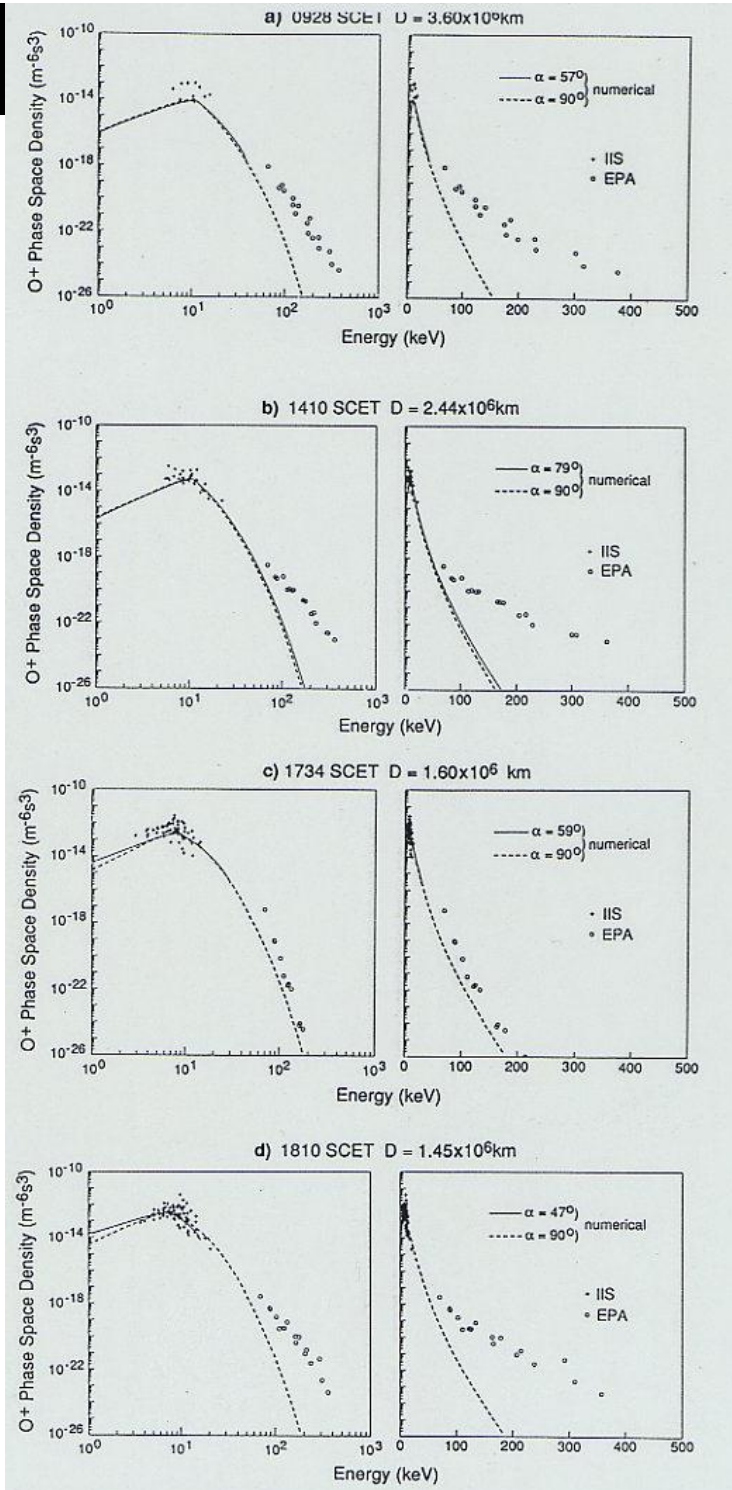
Scattering centres move at different speeds upstream and downstream of shock

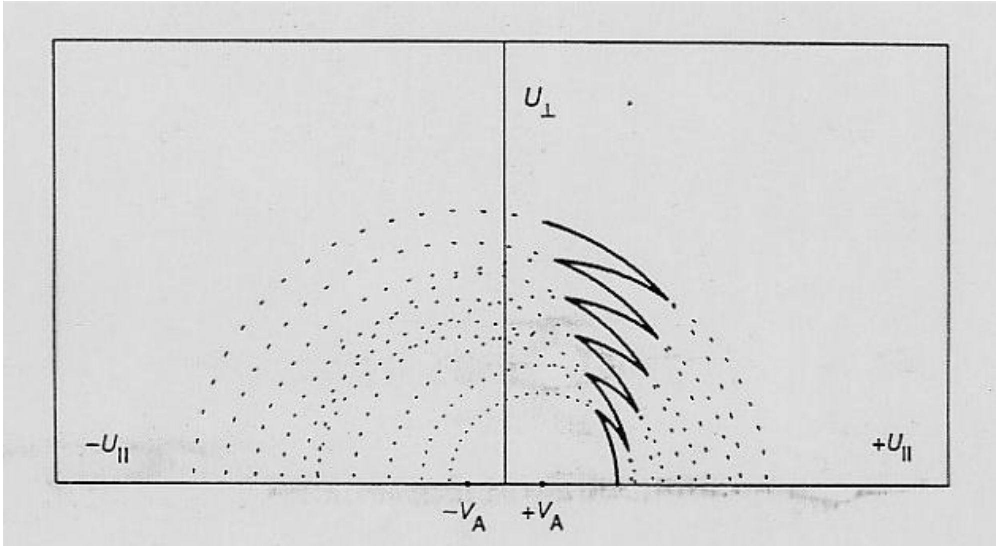
Fermi II

Scattering centres sunward and antisunward Alfven waves

c.f. Ip & Axford, 1986





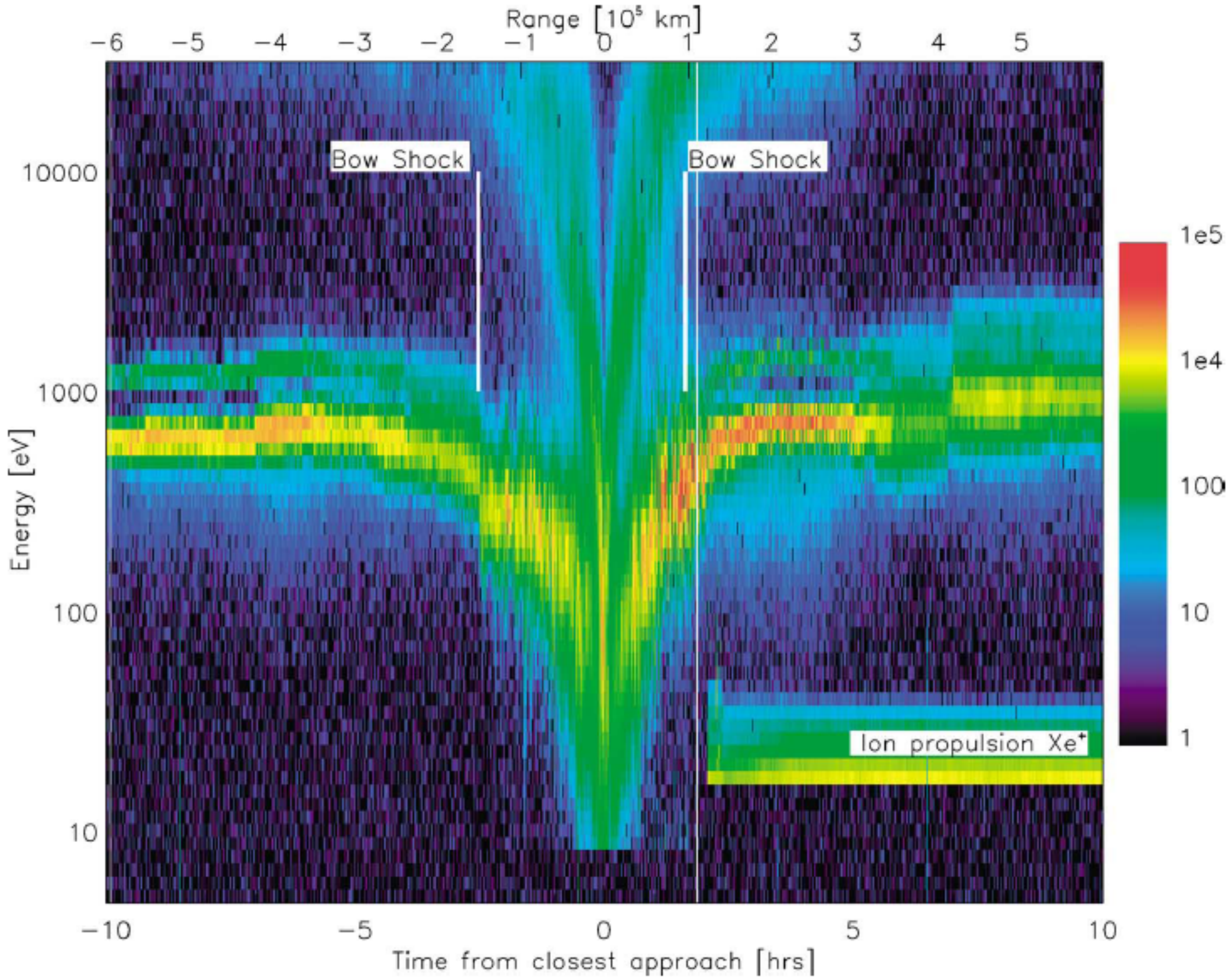


Velocity space diffusion by Fermi II e.g. Terasawa and Scholer, 1989

Quasilinear model works (Huddleston et al, 1992, also e.g. Lee et al) but acceleration underestimated

Maybe nonlinear effects are important (more diffusion, e.g. Terasawa and Scholer, 1989)?

DS1 PEPE Energy-Time Spectrograph--Borrelly Encounter

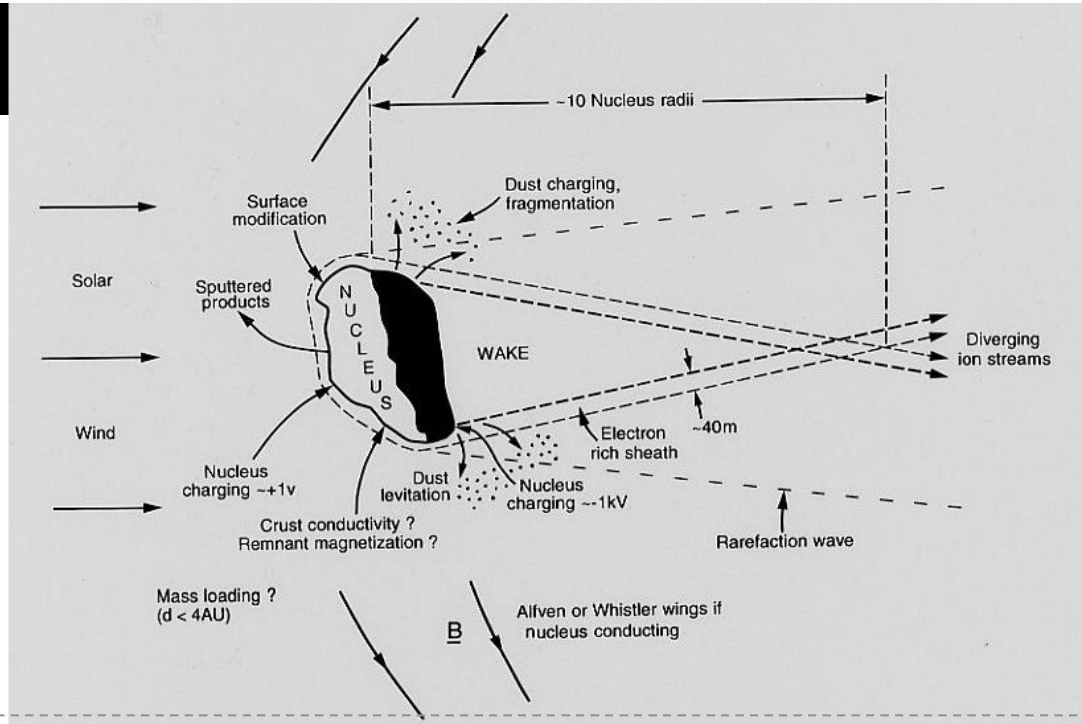


Pickup water group ions asymmetric – gas/dust emission (Young et al 2004)

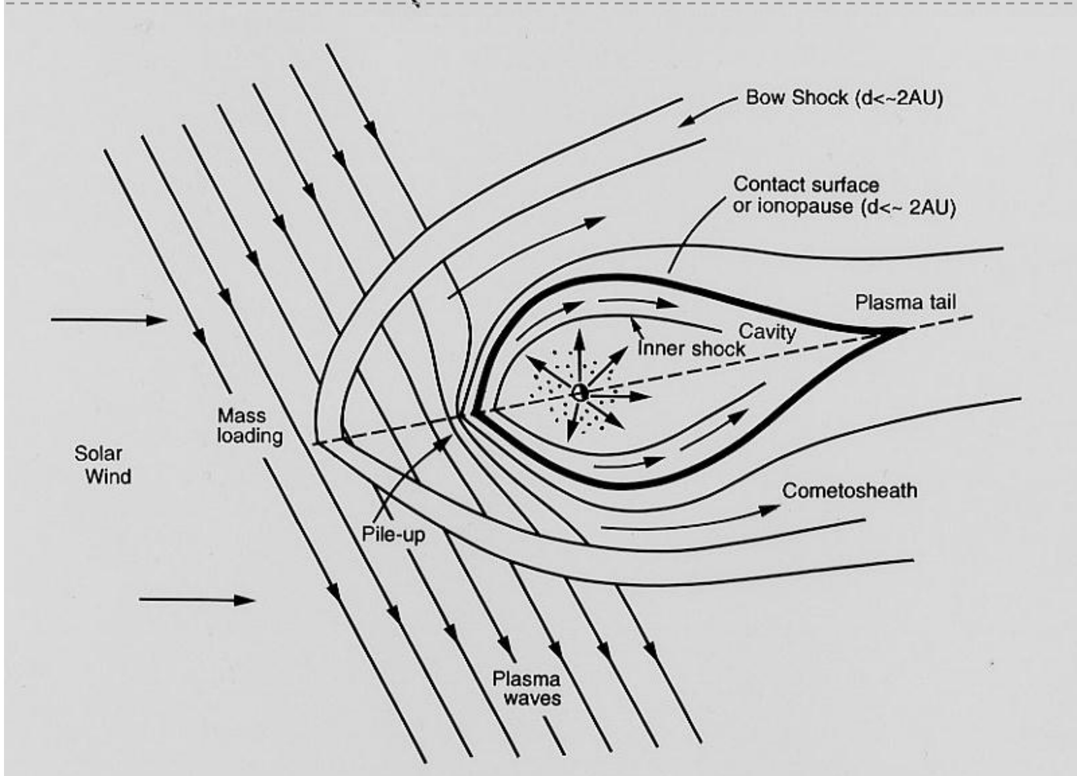
Distant comet observations by Ulysses – field draping (Jones et al, 2000) and composition Gloeckler et al., 2000, 2004, Neugebauer et al., 2007)

[redacted]

Far from Sun



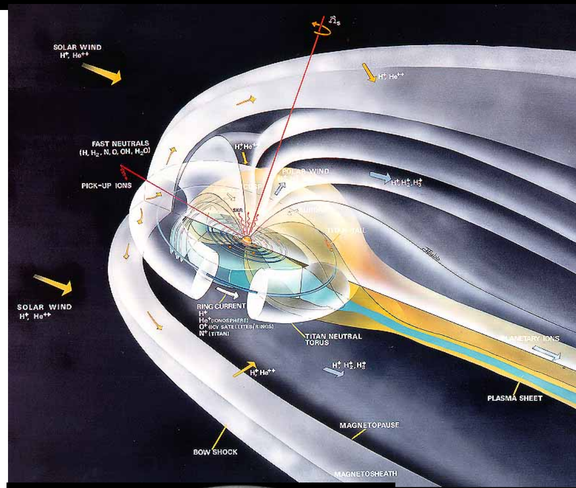
Close to Sun

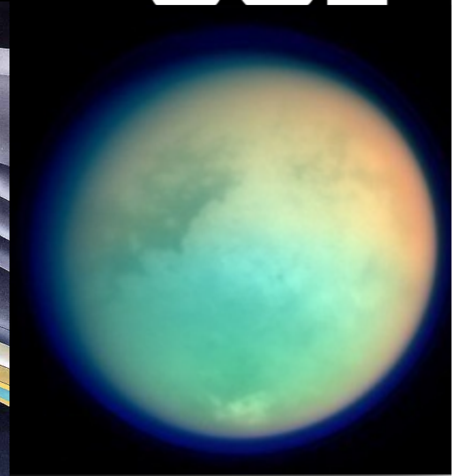


Pickup ions in both cases. Rosetta will study activity onset (2014).

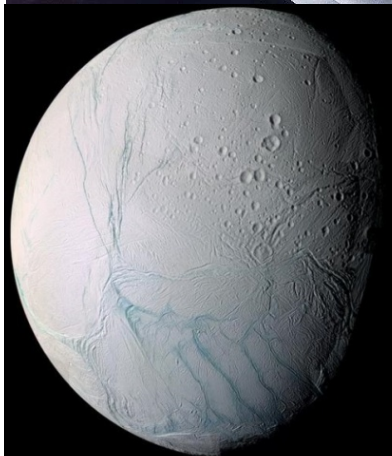
Titan

- Magnetosphere: M_{ms}<1, no shock. Draping, wake

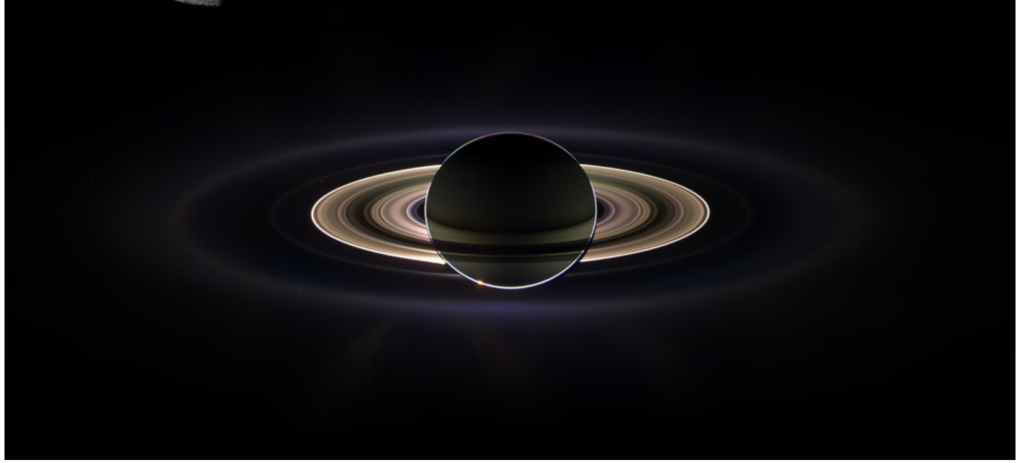




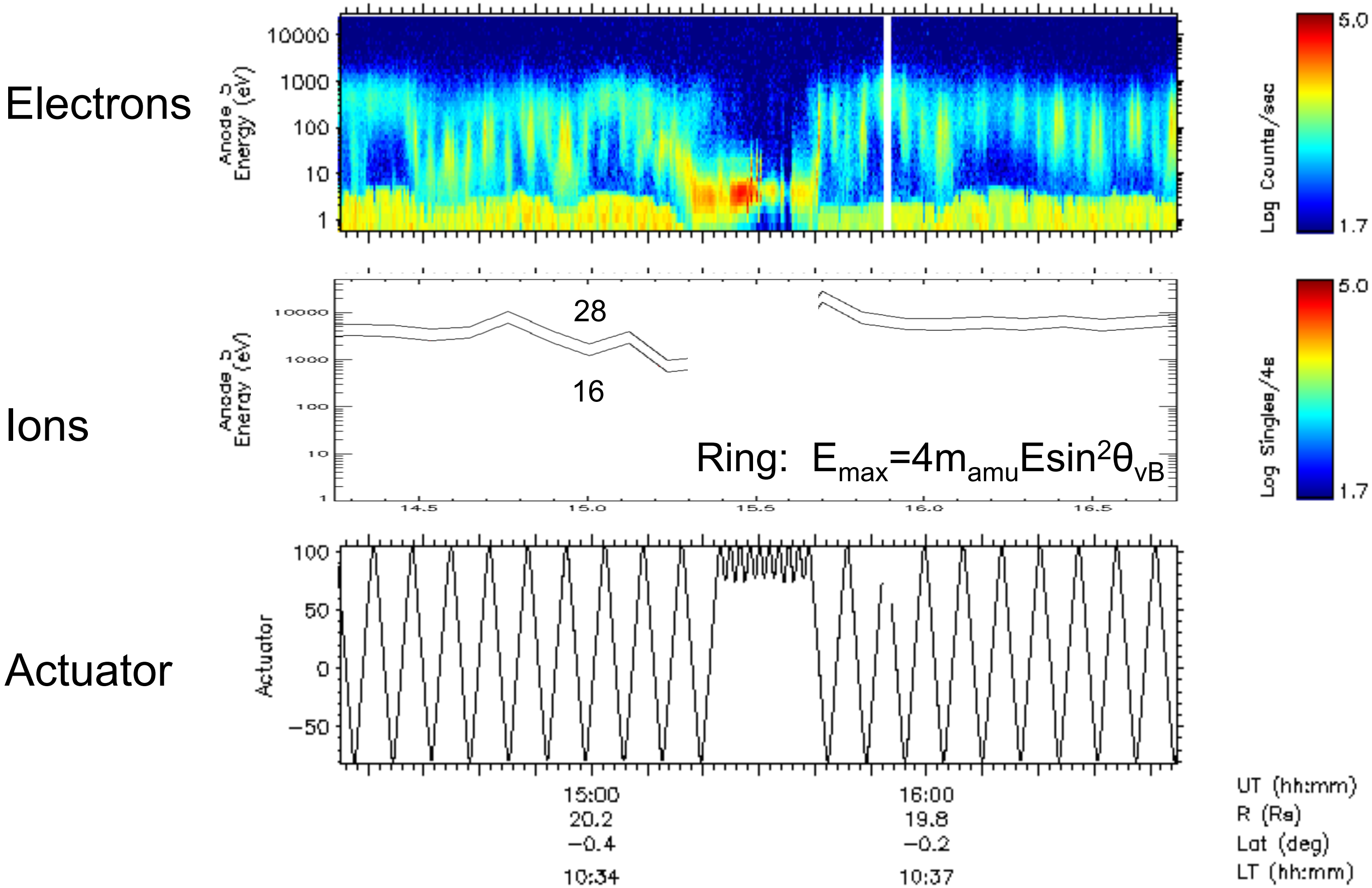
Icy satellites



- Enceladus, and E ring, are major sources for inner magnetosphere
- Plasma-surface access, modification



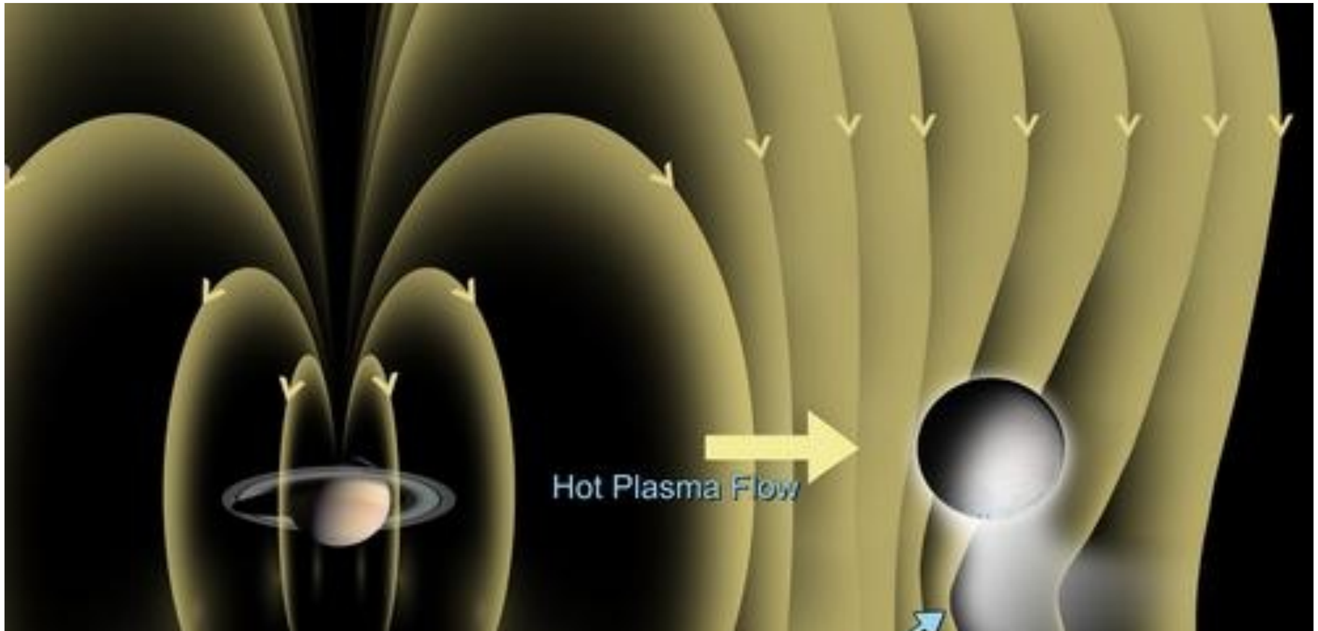
Pickup & magnetospheric ions 'TA' encounter

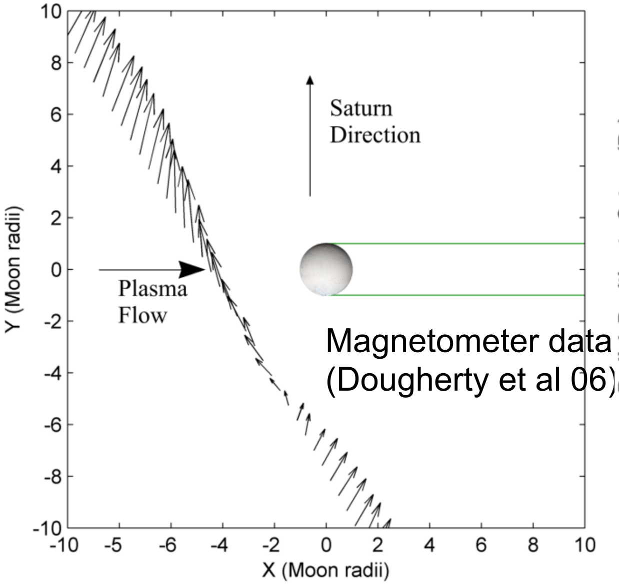


See also Hartle et al., 2006.

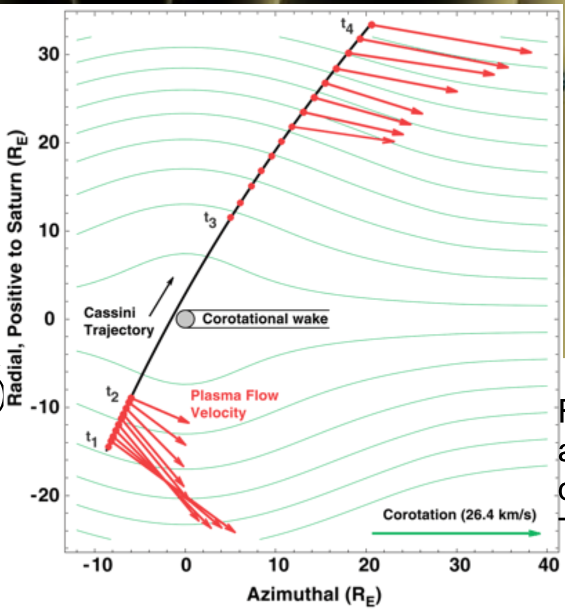
Production rate low ~10^{25} s^{-1} (Wahlund et al., 2005)

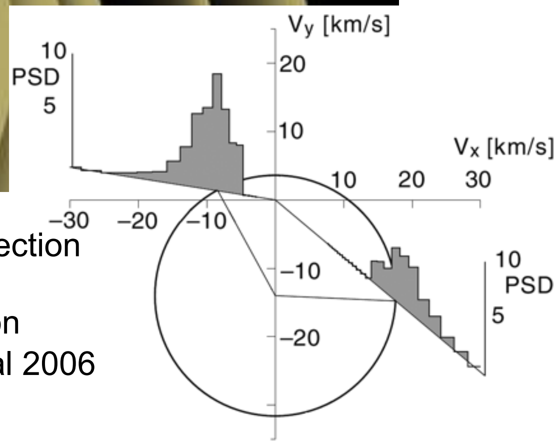
Enceladus atmosphere



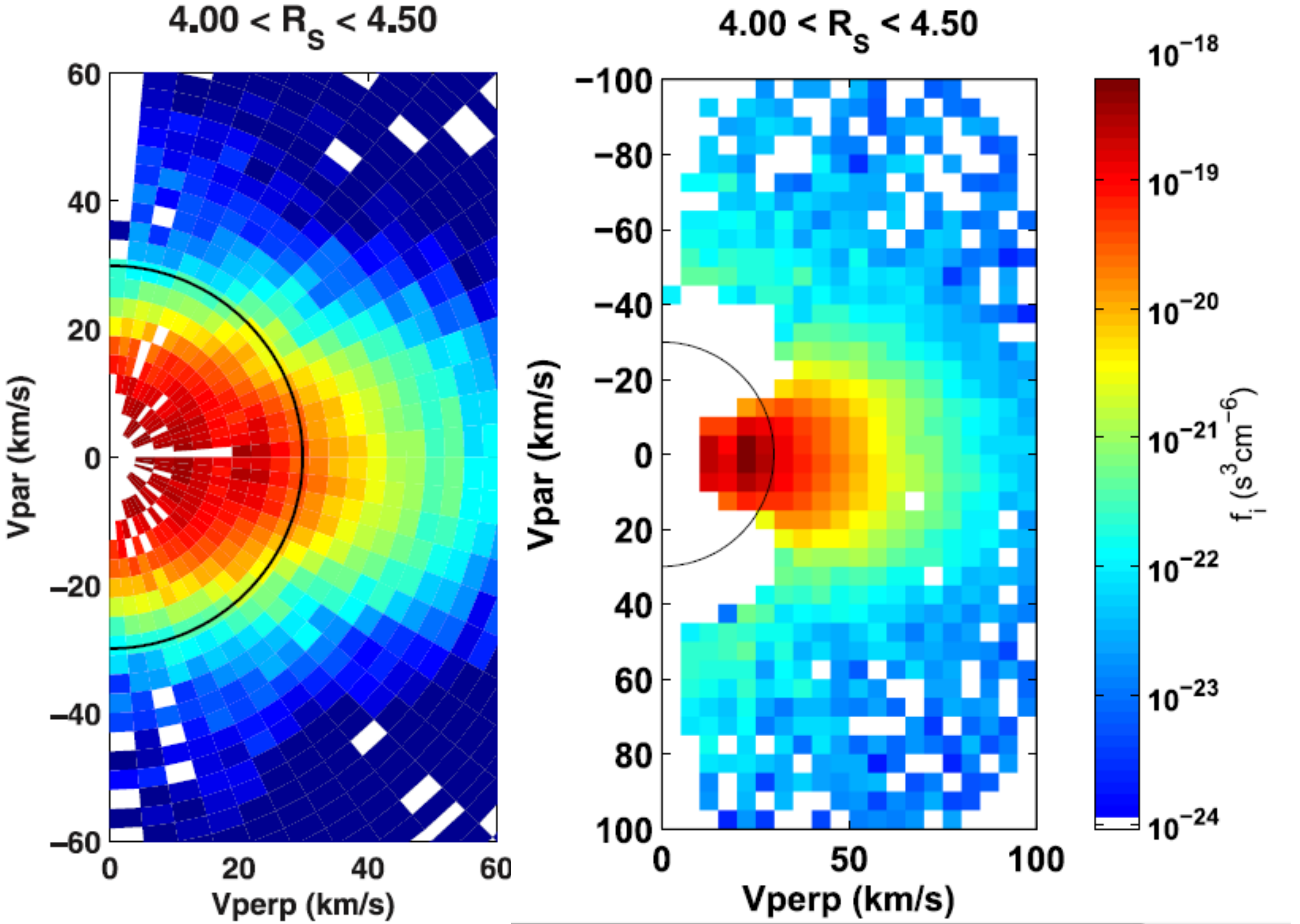


Magnetometer data (Dougherty et al 06)

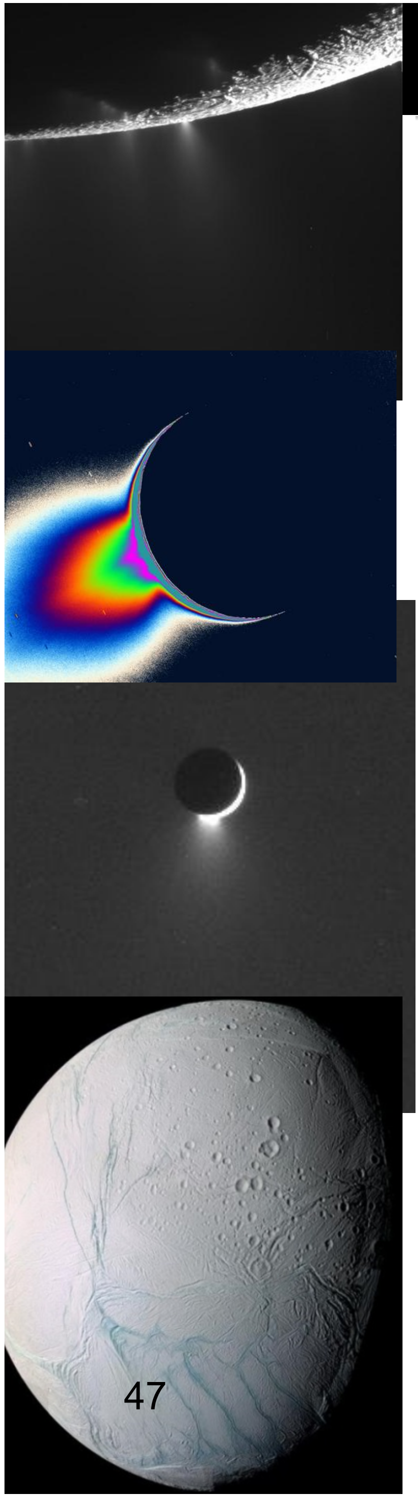


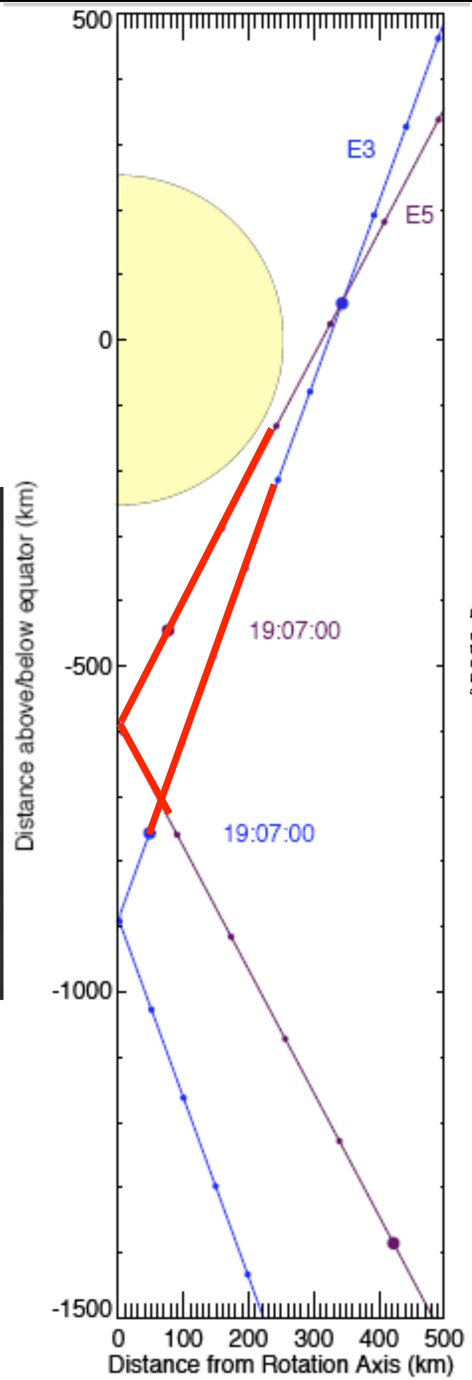


Flow deflection and ring distribution Tokar et al 2006

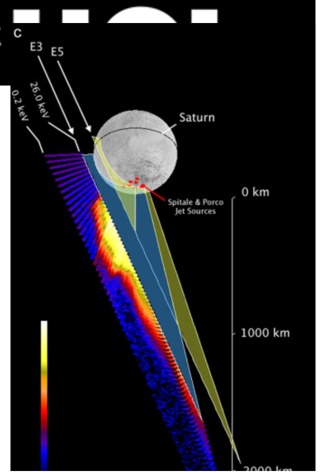


Water group ions near Enceladus,Tokar et al, GRL 2008
Inner magnetosphere dominated by water group ions from abundant neutrals, Young et al 2005





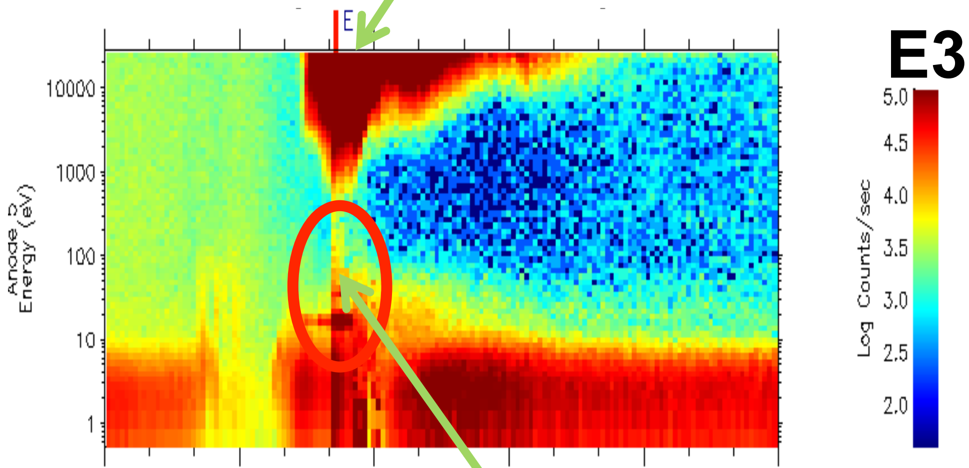
Some unexpected discoveries from Cassini at Enceladus

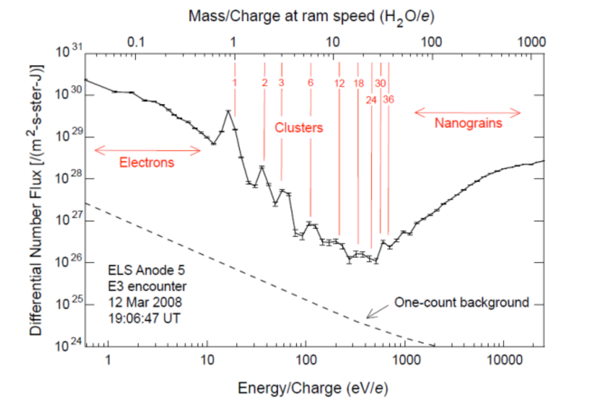


‘Pickup’ charged nanograins

Negative and positive

Jones et al., GRL, 2009

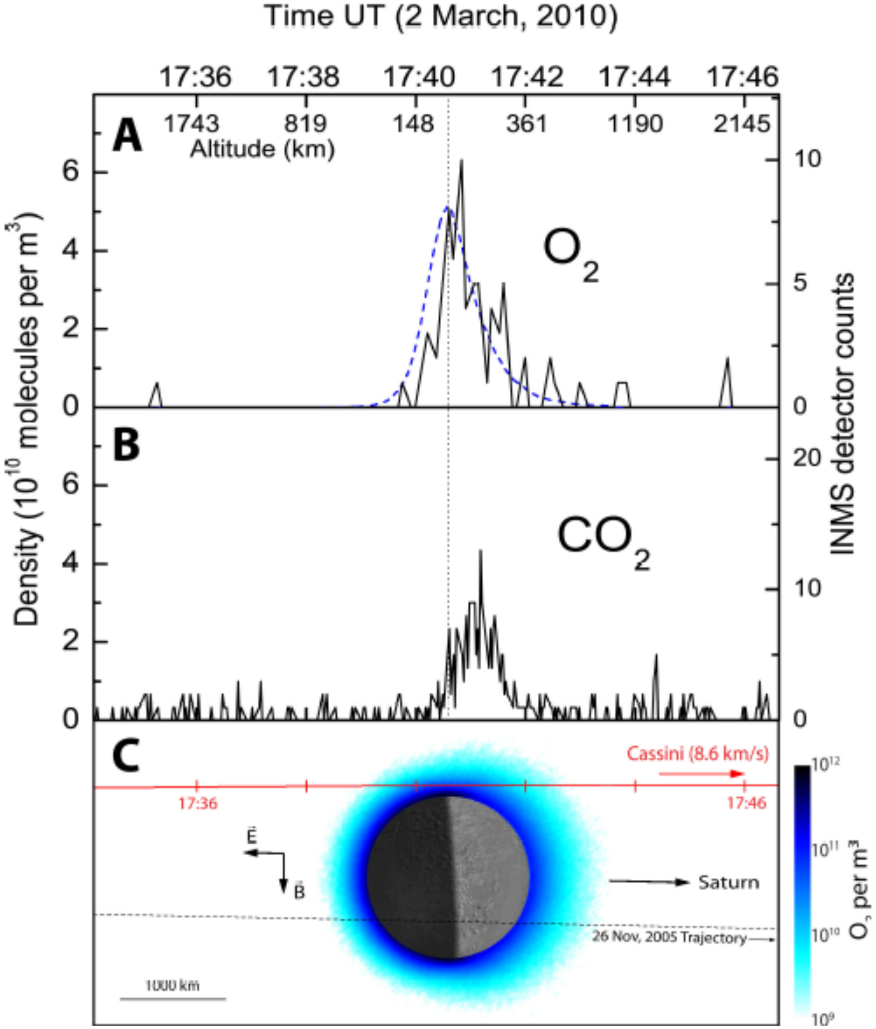


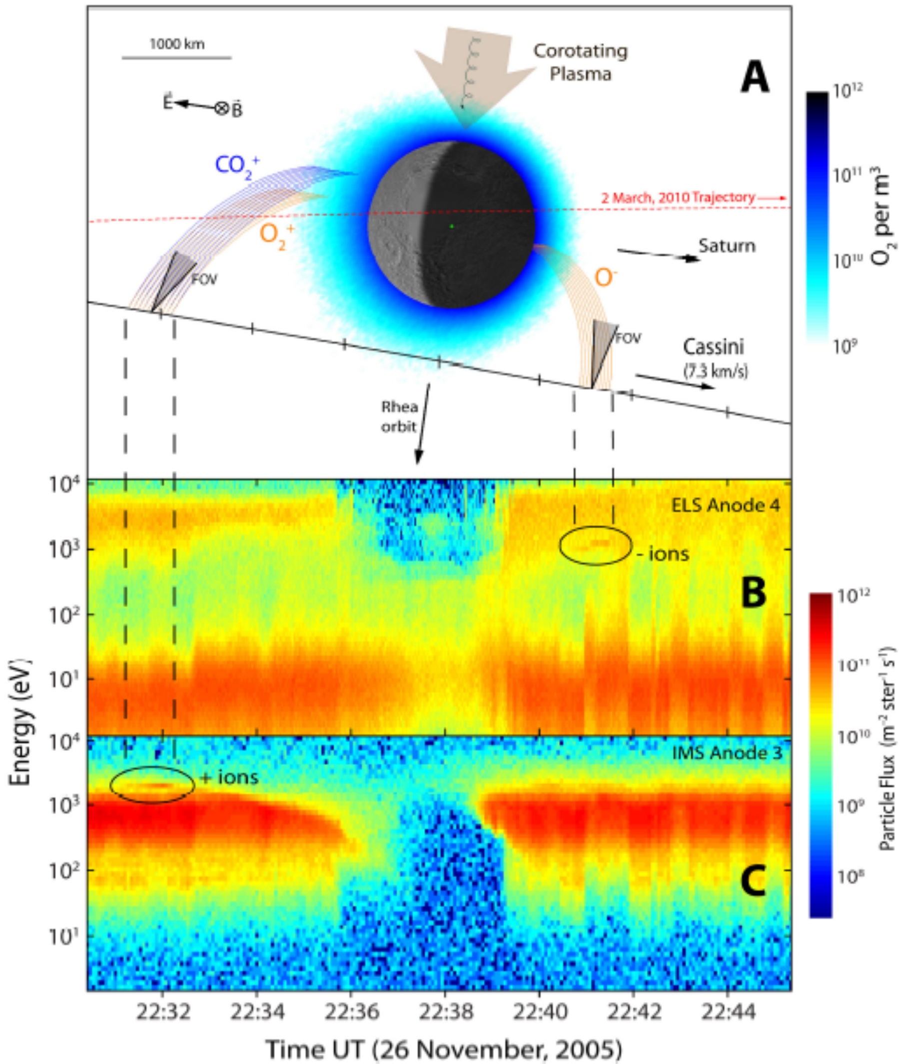


Negative ions in the plume

Coates et al., Icarus 2010, Faraday Discussions 2010

Rhea's O_2 and CO_2 atmosphere – from INMS and CAPS
Teolis et al., Science, Dec 2010



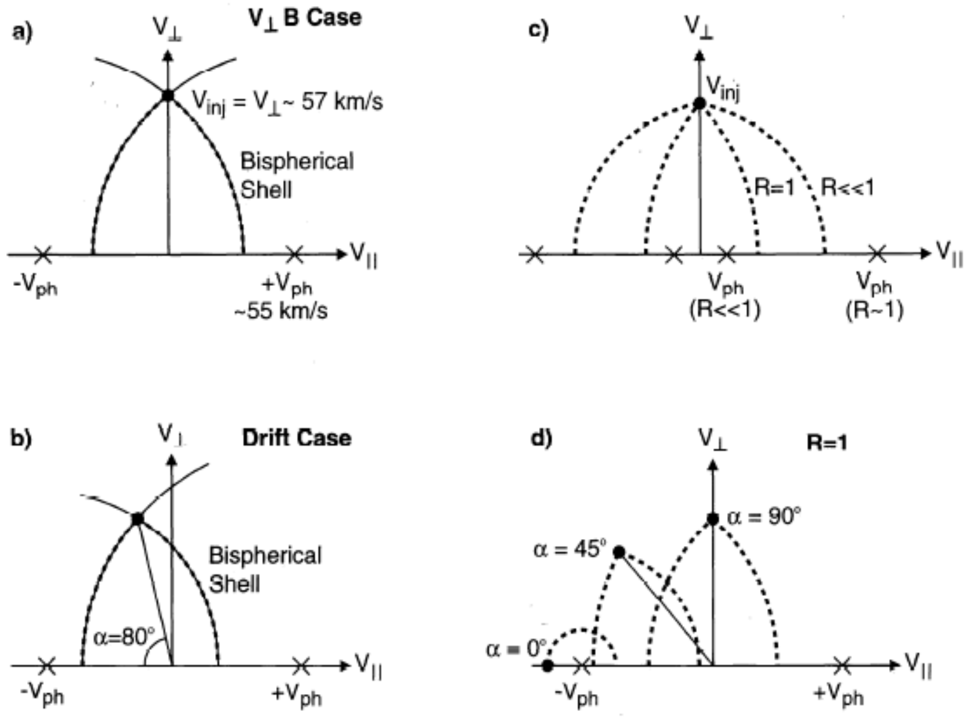


In-situ neutral atmosphere measurements (INMS)

Negative and positive ions picked up from atmosphere pinpoint near-surface source (CAPS)

Io, Jovian satellites

- Io a source of heavy (S, O based) neutrals
- Io well inside Jovian magnetosphere
- Corotation faster than orbital speed: wake ahead of Io
- Partially conducting, subsonic flow: Alfven wings
- Pickup ions modify this at a rate ~3×10^{28} s^{-1}
- Initial pickup ion distribution ring-like (~ $v \perp B$)
- Pitch angle scattering occurs as elsewhere in solar system, timescale few days here
- Ion pickup also observed at other Galilean satellites – neutrals from sputtering under plasma bombardment



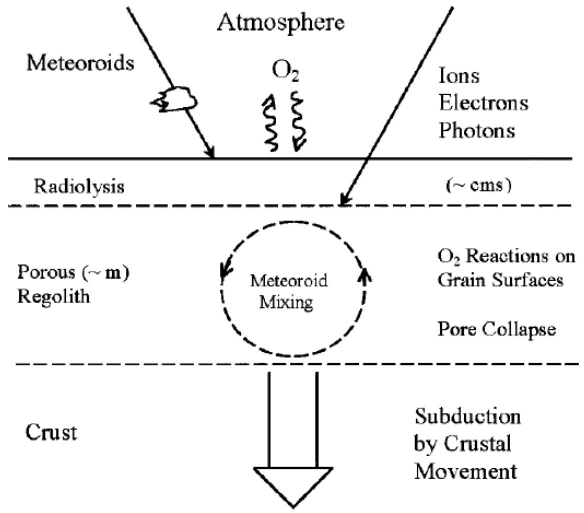
Pickup at Io: initial bispherical scattering followed by ion cyclotron wave growth. Huddleston et al 1998

Ganymede & Europa: JUICE

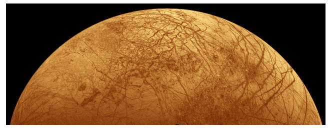
- Weak, O_2/H_2O atmospheres
- Ganymede magnetic field
- Ionospheres present

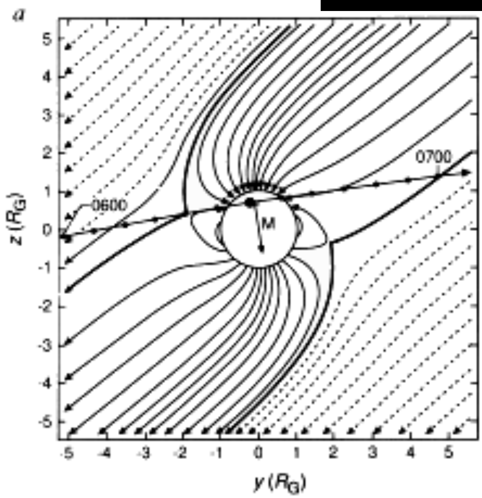
Need to measure:

- Upstream plasma conditions key for interaction
- Pickup ions can give information on exosphere and surface composition



Johnson et al 2003

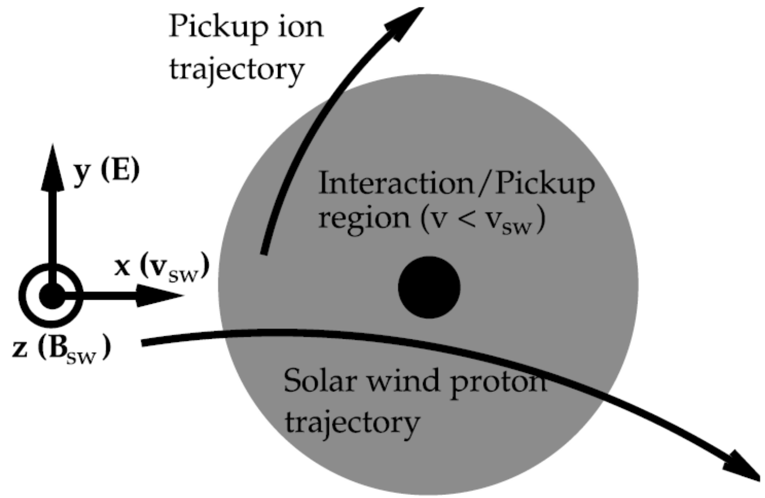




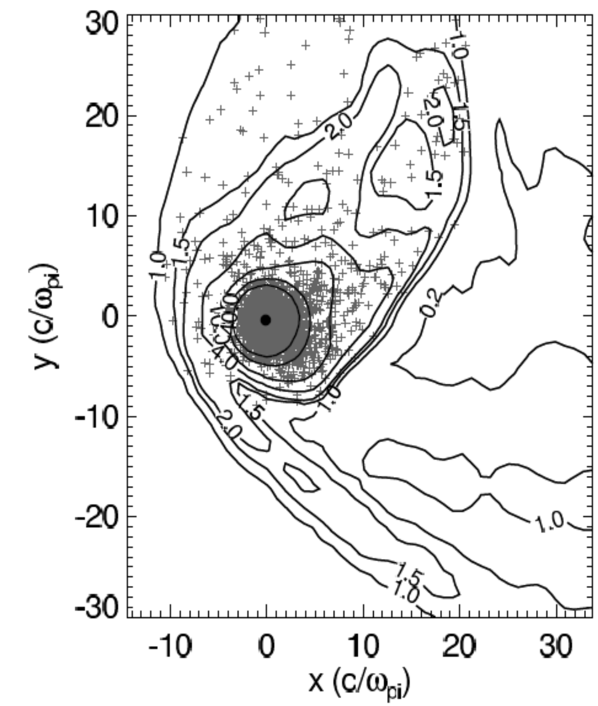
Khurana et al 1996

Pluto

- Solar wind Mach number high
- Solar wind interaction comet-like when Pluto nearest to Sun, and has an 'atmosphere'
- Estimated atmosphere loss 10^{25}-10^{27}s^{-1} (McNutt 1989)
- Large 'mass loading' region
- CH_4^+ gyroradius 250,000 km, N_2^+ 658,000 km!
- Bow shock at 2,000 to 28,000 km (Bagenal & McNutt, 1989)
- Nongyrotropic distributions probably important, as at weak comets

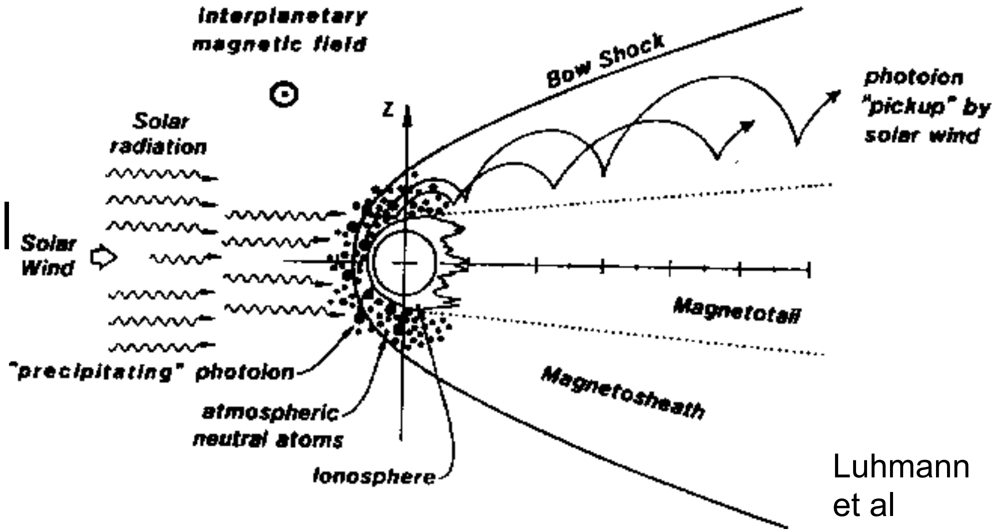


Delamere and Bagenal, 2004



Mars

- No global field
- Exosphere: ionization, pickup
- Gyroradius larger than planet
- Loss rate ~10^{25} s^{-1} (Lundin et al 89) – tens of % of Earth's atmospheric mass over 3.8GY
- Early measurements of loss from Mars Express factor 100 lower (Barabash et al 2007) now revised upwards
- Asymmetric pickup due to reabsorption by planet
- Mars Express looking at pickup ions and global loss rates
- See Lundin et al talk



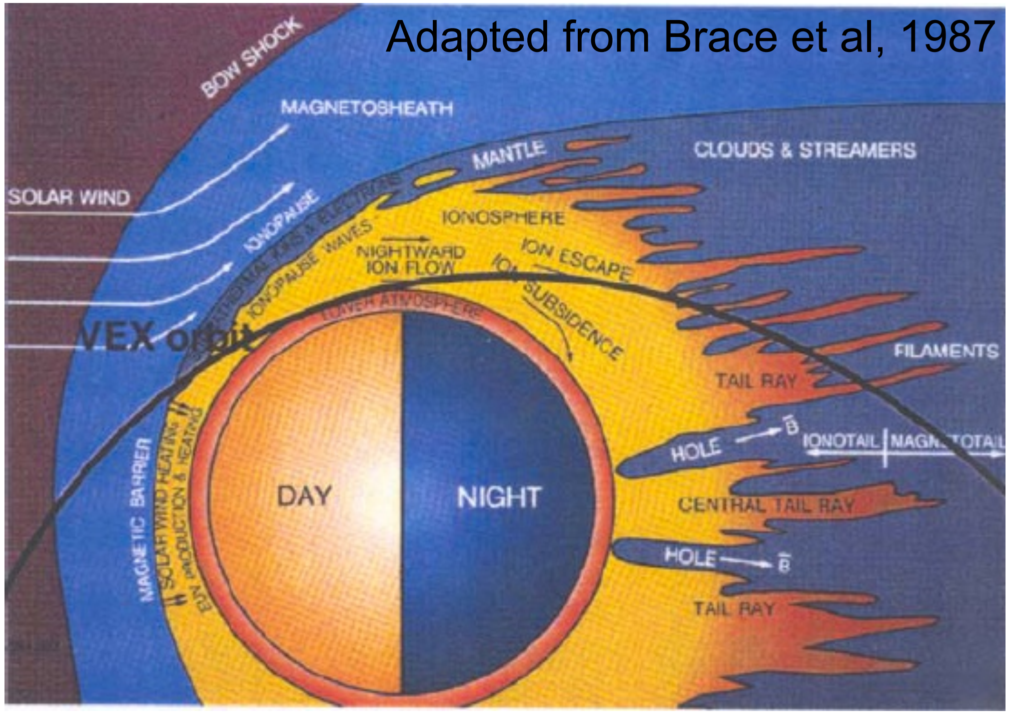
Luhmann et al

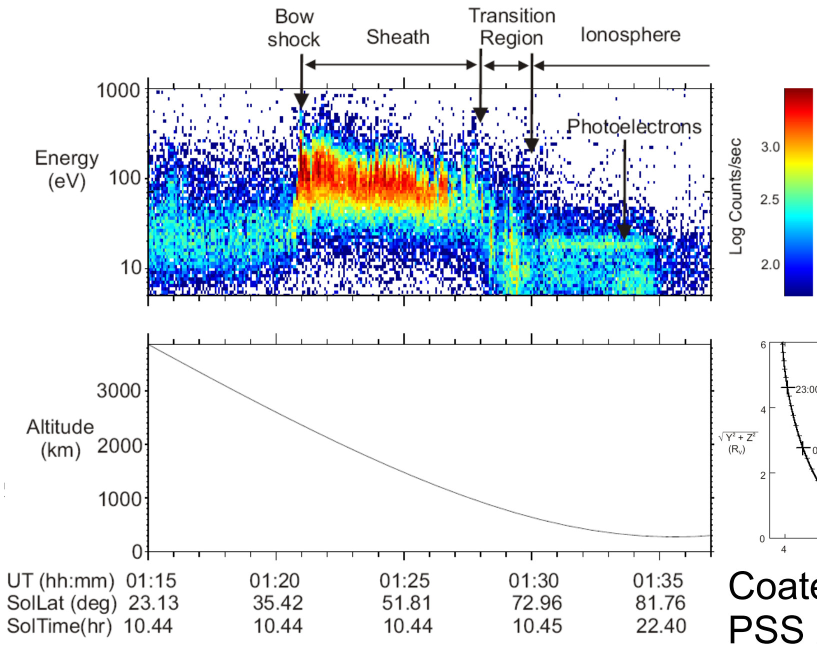
Venus similar but gyroradius smaller

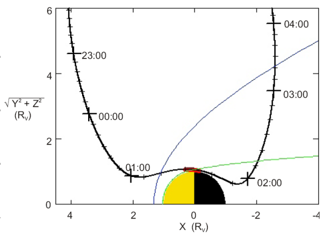
Pickup may be augmented by other processes e.g. ambipolar outflow due to ionospheric photoelectron escape (c.f. Coates et al, 2007 [Titan], 2008 [Venus])

Venus

- Gyroradius smaller than planetary radius
- Pickup ions (O^+) seen from PVO etc, now Venus Express
- Earlier estimated ~10^{24} s^{-1} steady loss down tail – impulsive value may make average 50x larger (Brace et al 1987)
- Venus Express measuring rate: ~10^{25} s^{-1} via tail, <10% via pickup(Barabash et al., 2007)
- Ambipolar effect may augment pickup (Coates et al 2008)







Coates et al, PSS 2008

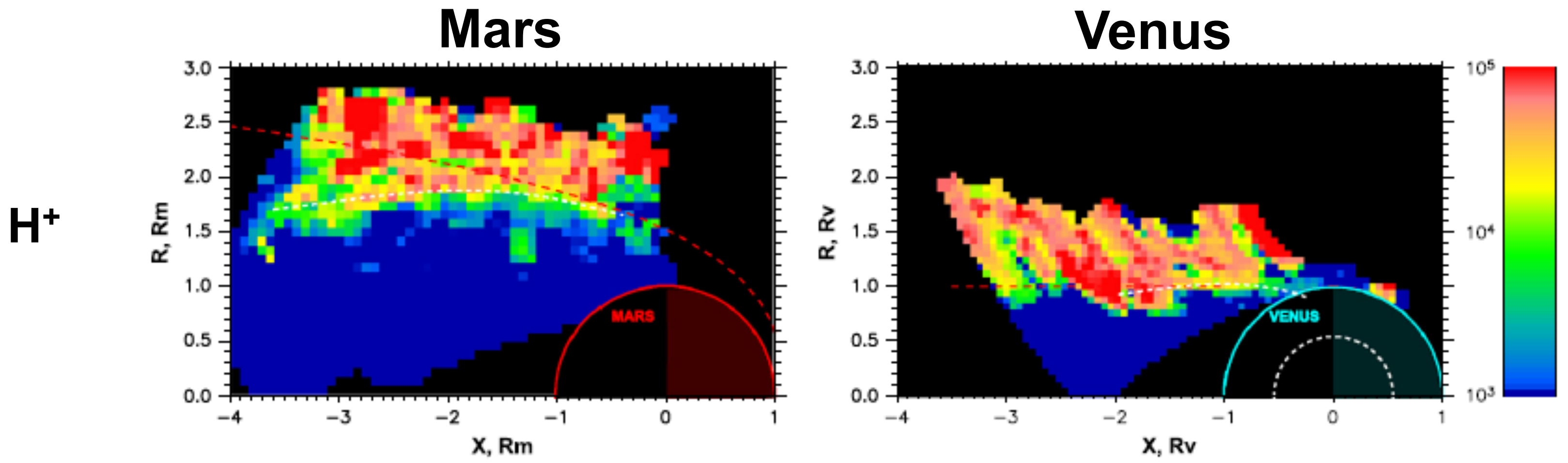


Fig. 1. Spatial distribution of the proton flux with energy greater than 300 eV in cylindrical coordinates: X connects the planet center and the Sun; $R = \sqrt{Y^2 + Z^2}$. All scales are in planet radii. The color scale is shown in arbitrary units. Blue color indicates zero flux, and black color shows the absence of the measurements. Left panel shows the Martian wake, and right panel shows the Venusian one. Red dashed curve in the left panel shows the theoretical position of the magnetosphere boundary after Kallio (1996). Similar dashed line in the right panel shows the wake boundary at Venus. White dashed curves are explained in the text.

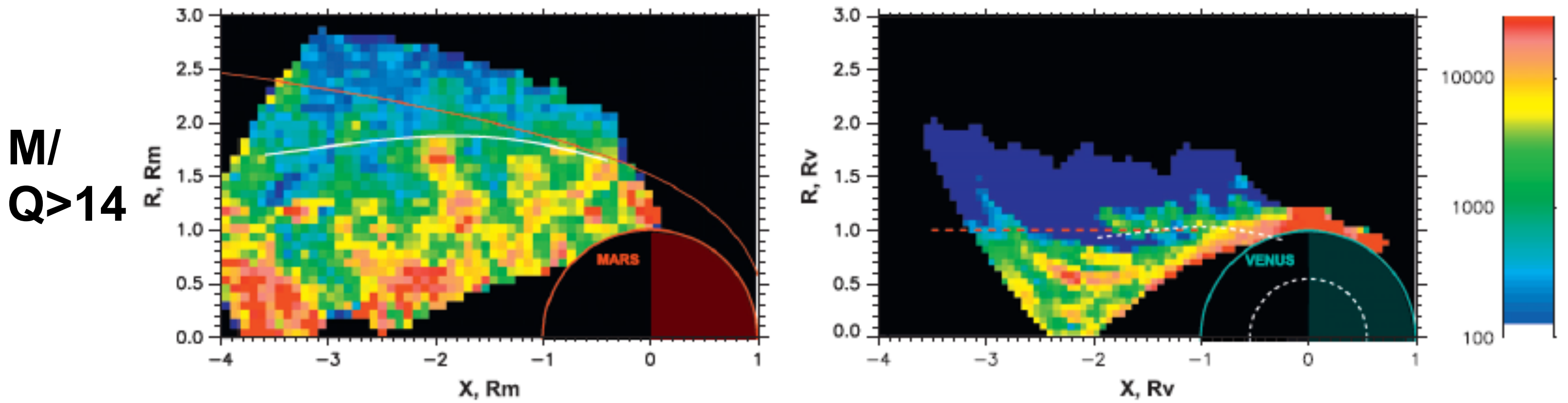
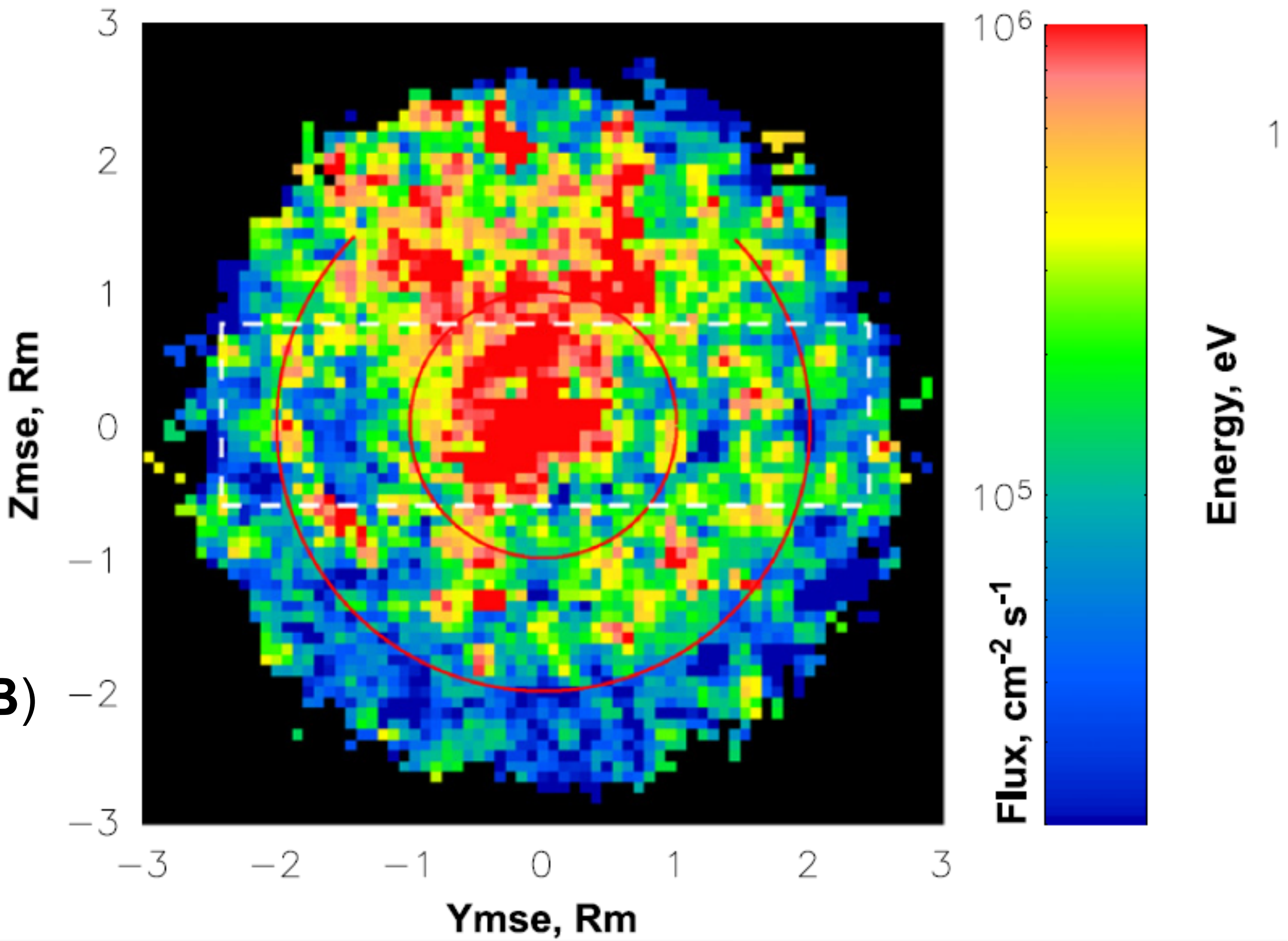


Fig. 2. The same as Fig. 1 but for ions of planetary origin with $M/Q > 14$.

Fedorov et al., PSS 2009

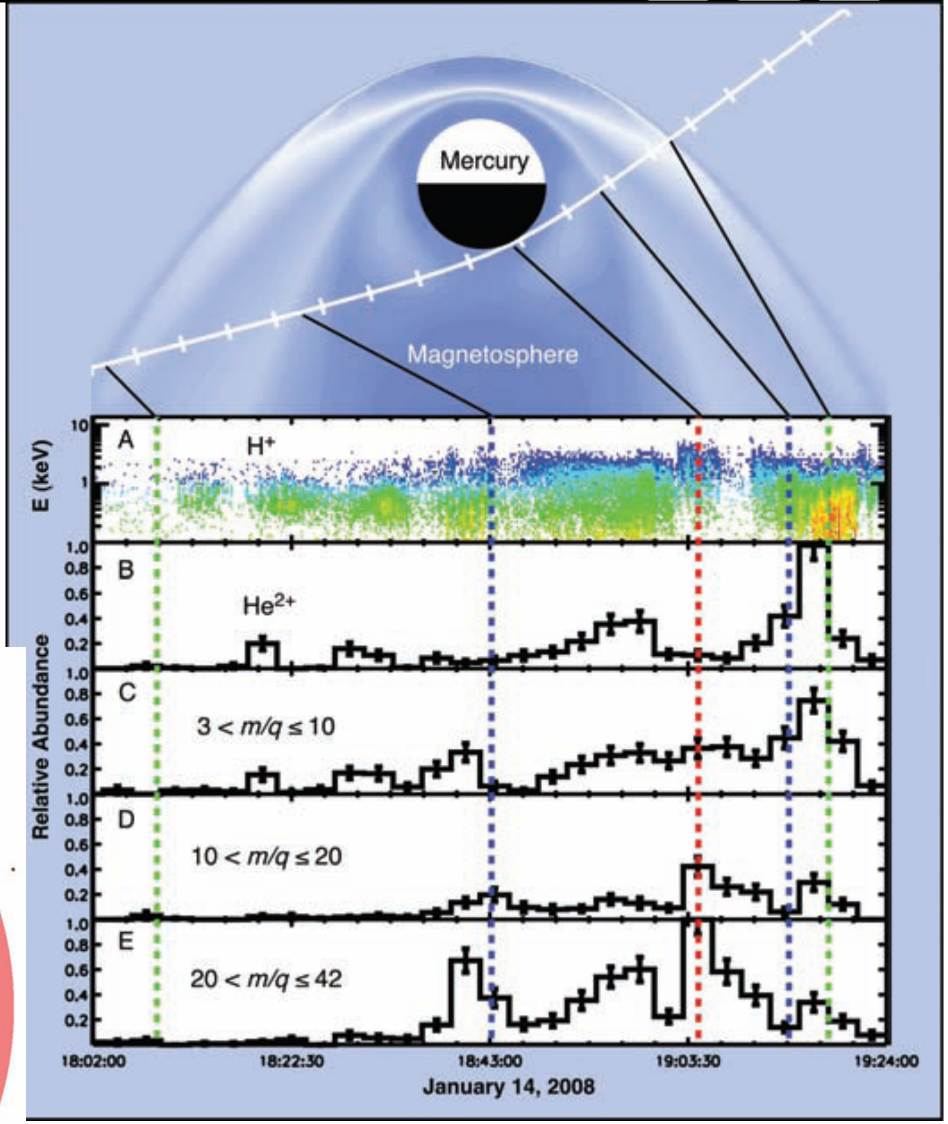
$\mathbf{E} =$
$-(\mathbf{v} \times \mathbf{B})$



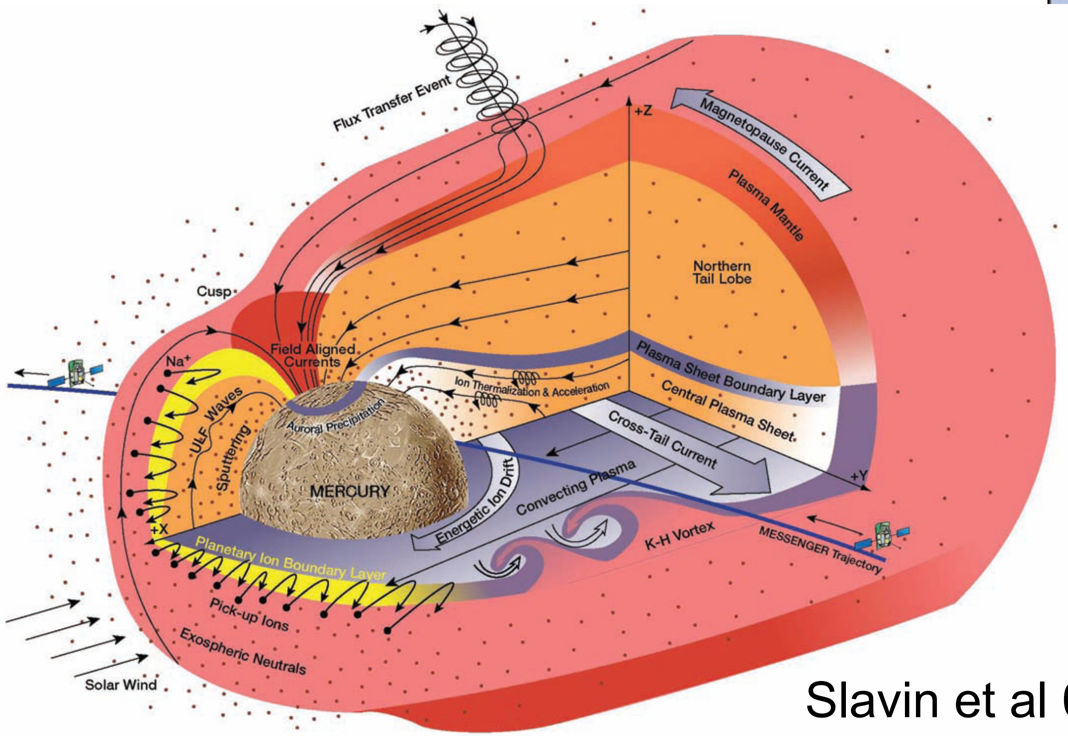
Mars – m/q>14 ion escape controlled by **E**, Fedorov et al., PSS 2009

Mercury

- Heavy pickup ions seen at Mercury
- From surface sputtering of particles
- Much more to come fom Messenger and BepiColombo



Zurbuchen et al 08



Slavin et al 08

The Moon - pickup of reflected and backscattered ions (‘self-pickup)

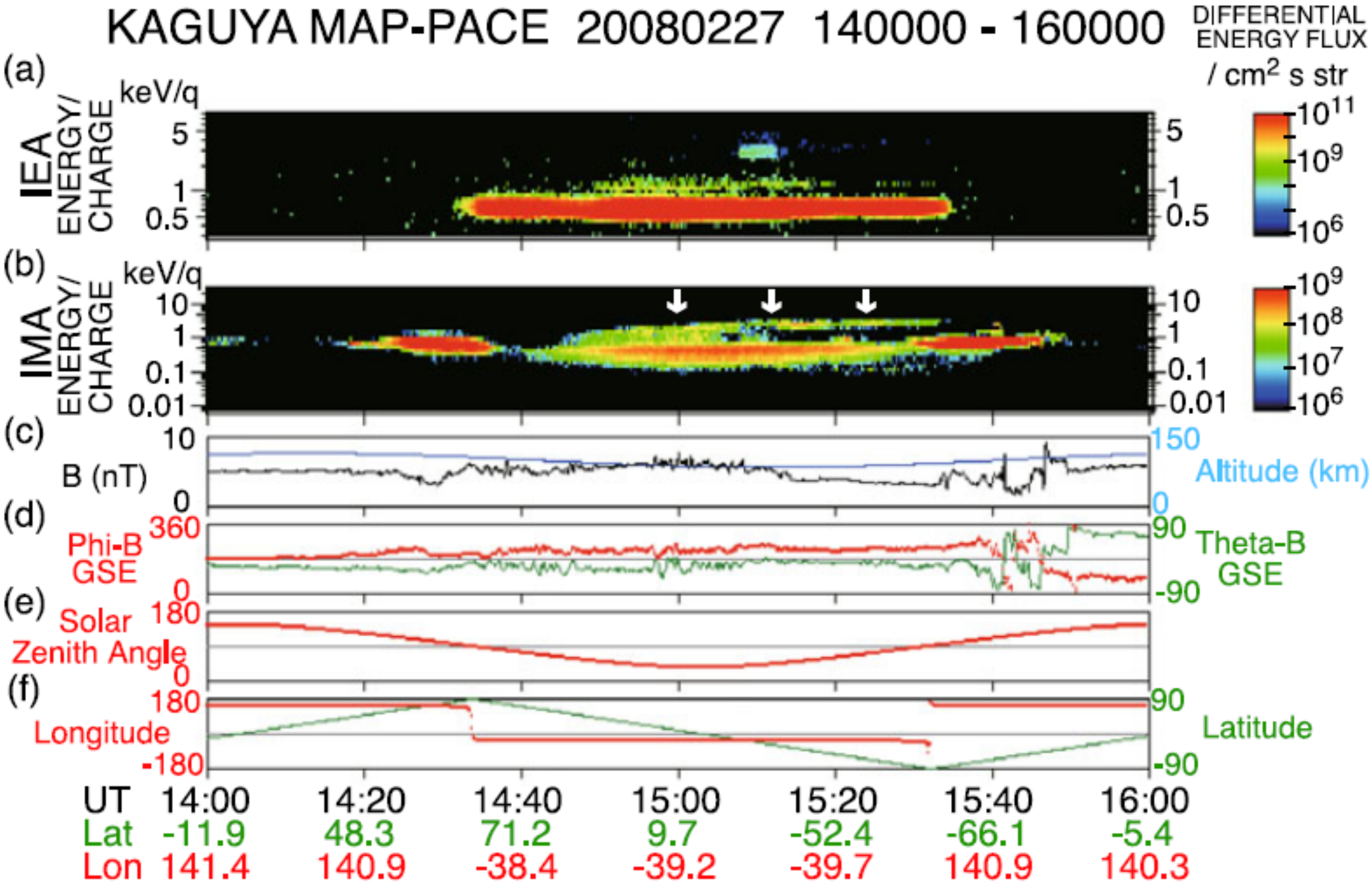
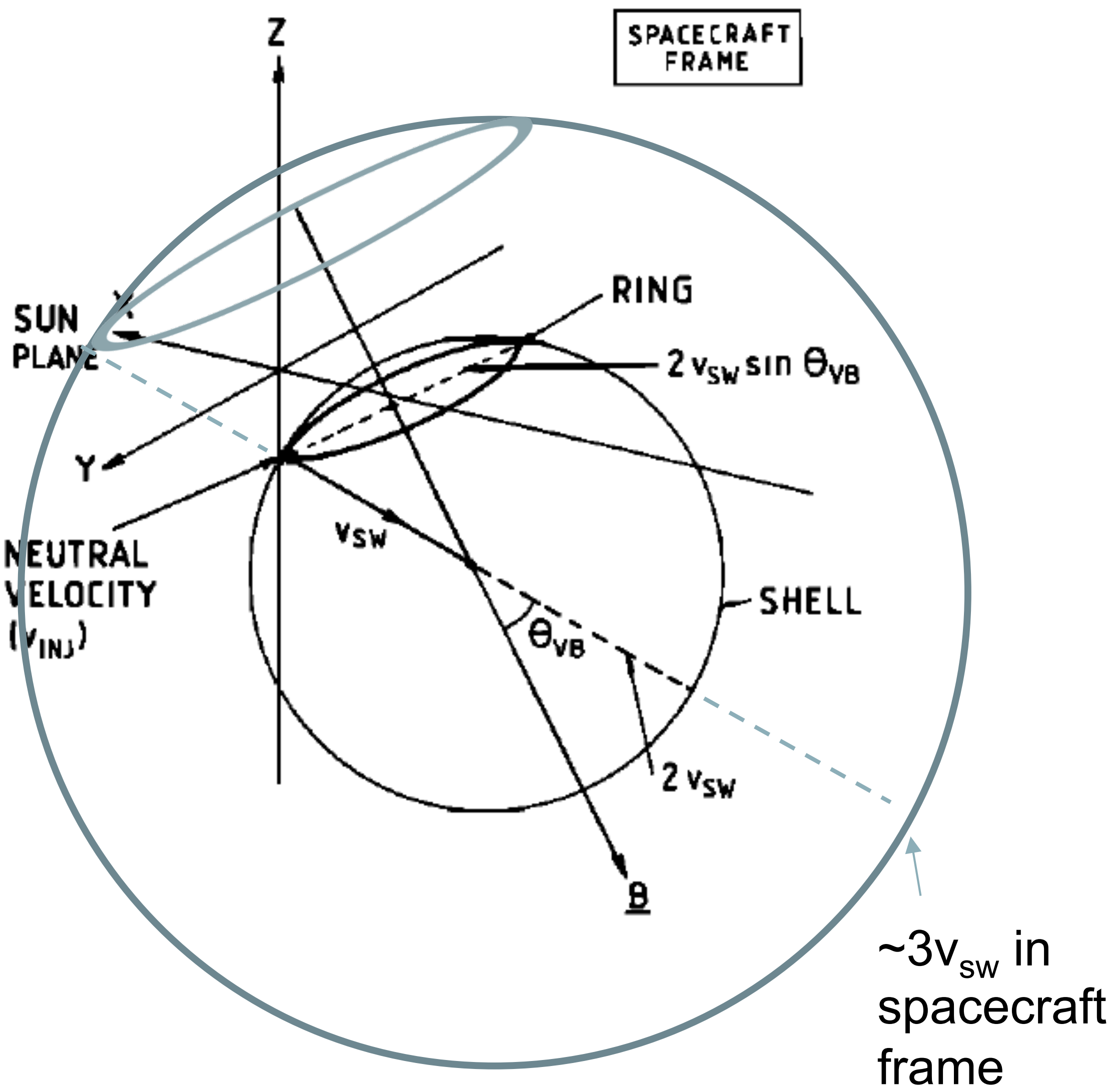


Fig. 26 An example showing self-pickup accelerated ions (indicated by white arrows). The format is the same as Fig. 20

‘Self-pickup’ at the Moon

- Recent results from Kaguya and Chandrayaan-1
- Two different types of pickup ions (see review by Saito et al., Space Sci Rev., 2010):
  - ‘Self-pickup’ from reflected ions (Saito et al., 2008) and from neutrals (Wieser et al., 2009, Bhardwaj et al., 2010)
  - Direct pickup from surface and exosphere (Yokota et al., 2009)
- Self pickup ions may penetrate deep in lunar wake (Nishino et al., 2009, 2010, Holmstrom et al., 2010)
- This interesting population can have speeds up to 3xsolar wind velocity (9x solar wind energy) in the spacecraft frame



Velocity space sketch for classical pickup and 'self-pickup' from reflected ions

Injection point of reflected ions at $-\mathbf{v}_{sw}$

Classical pickup:

$E_{max,\,ring} = 4m_{amu}\, E_{sw}\sin^2\theta_{vB}$

$E_{max,\,shell} = 4m_{amu}E_{sw}$

Self pickup:

$E_{max,\,ring} = 9m_{amu}\, E_{sw}\sin^2\theta_{vB}$

$E_{max,\,shell} = 9m_{amu}E_{sw}$

Adapted from Coates et al., 1989

Object	Spacecraft	Production rate (s^{-1})	Ratio (Halley=100)	Reference
Mercury	Ground based	10^{24}-10^{25}	$1.5x10^{-4}$-$1.5x10^{-3}$	Potter et al., 02
Venus	VEx, PVO	10^{24}-10^{25}	$1.5x10^{-4}$-$1.5x10^{-3}$	Brace et al., 87 Barabash et al., 07a
Mars	MEx, Phobos	10^{23}-10^{25}	$1.5x10^{-5}$-$1.5x10^{-3}$	Barabash et al., 07b Lundin et al., 08, 89
Io	Galileo	$3x10^{28}$	4.3	Bagenal, 94
Europa	Galileo	$2x10^{27}$	0.29	Smyth & Marconi, 06
Titan	Cassini	10^{25}	$1.5x10^{-3}$	Wahlund et al., 05
Enceladus	Cassini	$3x10^{27}$ – 1-$2x10^{28}$	0.43-2.9	Tokar et al., 06 Smith et al.
Enceladus L-shell	Cassini	3.8-$7.6x10^{26}$	0.06-0.12	Cowee et al., 09
Rhea	Cassini	$2.45x10^{24}$	$3.6x10^{-4}$	Teolis et al., 2010

From Coates, 2011, Ion Pickup and Acceleration: Measurements From Planetary Missions, AIP proceedings volume 'Physics of the heliosphere: a 10-year retrospective', 10th Annual Astrophysics Conference, in press, Sep 2011

Stages in ion pickup process

Stage in process	Timescale	Seen at
Nongyrotropic ring	<gyroperiod	C
Ring	~gyroperiod	C, Ma, Mo, V, Io, E, T, I
(Bispherical) shell	~10 gyroperiods	C, Io?, E?, I?
Acceleration, shell filling	~100 gyroperiods	C
Maxwellian	?	?

C=Comets, Ma=Mars, Mo=Moon, V=Venus, Io=Io, E=Enceladus, T=Titan, I=Interstellar

Conclusions

- Pickup process important in many solar system contexts, electric field controls initial particle trajectories
- Comets: pickup ions seen as gyrotropic and nongyrotropic rings, bispherical shells, accelerated particles. Distribution functions have time to evolve in extended interaction regions.
- Titan: Some rings seen
- Enceladus: Field, flow deflection, pickup rings seen
- Rhea: Positive and negative pickup ions
- Io: Rings seen
- Mars: Pickup ions seen as rings. Less time to evolve. Also tail escape controlled by **E**
- Venus: Pickup ions detected, distributions unknown (likely rings), also tail escape controlled by **E**
- Mercury: analysis starting

- Coates, A.J., et al., Ionospheric electrons in Titan's tail: plasma structure during the Cassini T9 encounter, Geophys. Res. Lett., 34, L24S05, doi:10.1029/2007GL030919, 2007.
- Coates, A.J., et al., Ionospheric Photoelectrons at Venus: Initial Observations by ASPERA-4 ELS, Planetary and Space Science, Volume 56, Issue 6, p. 802-806, May 2008.
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- Lavvas, P., et al., Energy deposition and primary chemical products in Titan’s upper atmosphere, Icarus, 213, 233-251, May 2011.
- Coates, A.J., Ion Pickup and Acceleration: Measurements From Planetary Missions, AIP proceedings volume ‘Physics of the heliosphere: a 10-year retrospective’, 10th Annual Astrophysics Conference, March 13-18 2011.
- Coates, A.J.,et al., Ionospheric photoelectrons: comparing Venus, Earth, Mars and Titan, Planet. Space Sci. 59 (2011), 1019-1027, doi:10.1016/j.pss.2010.07.016, Aug 2011.