Mass loading

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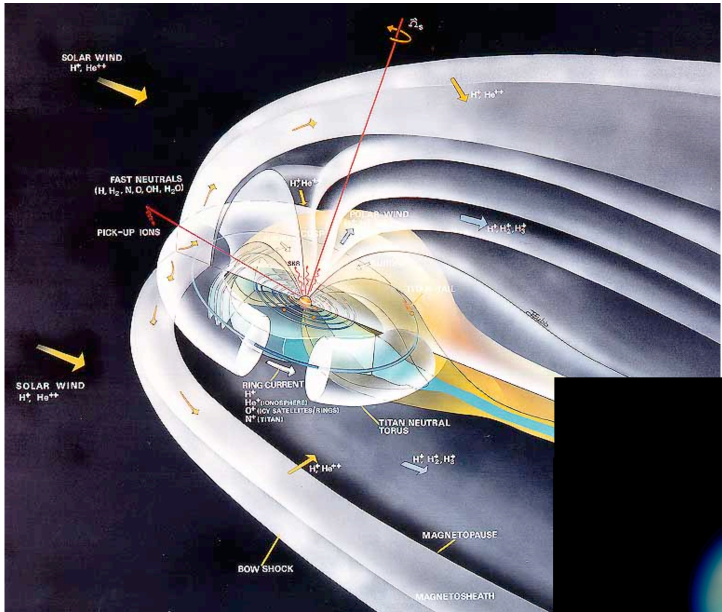
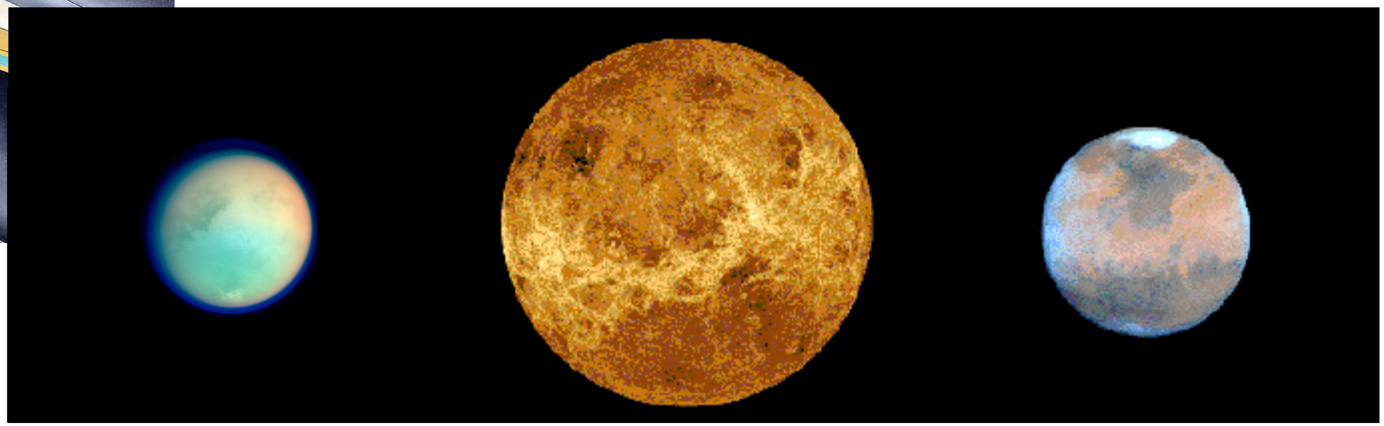
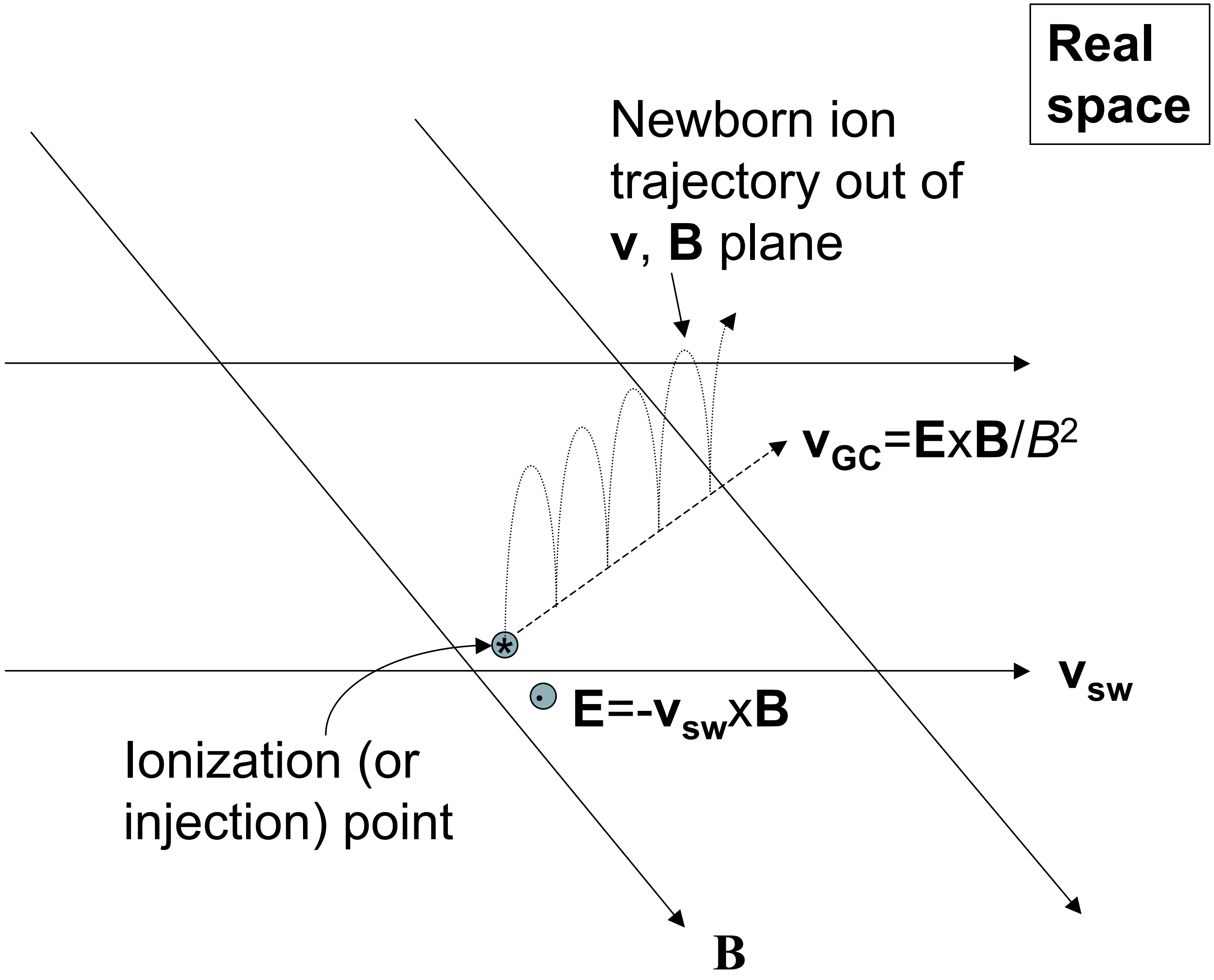




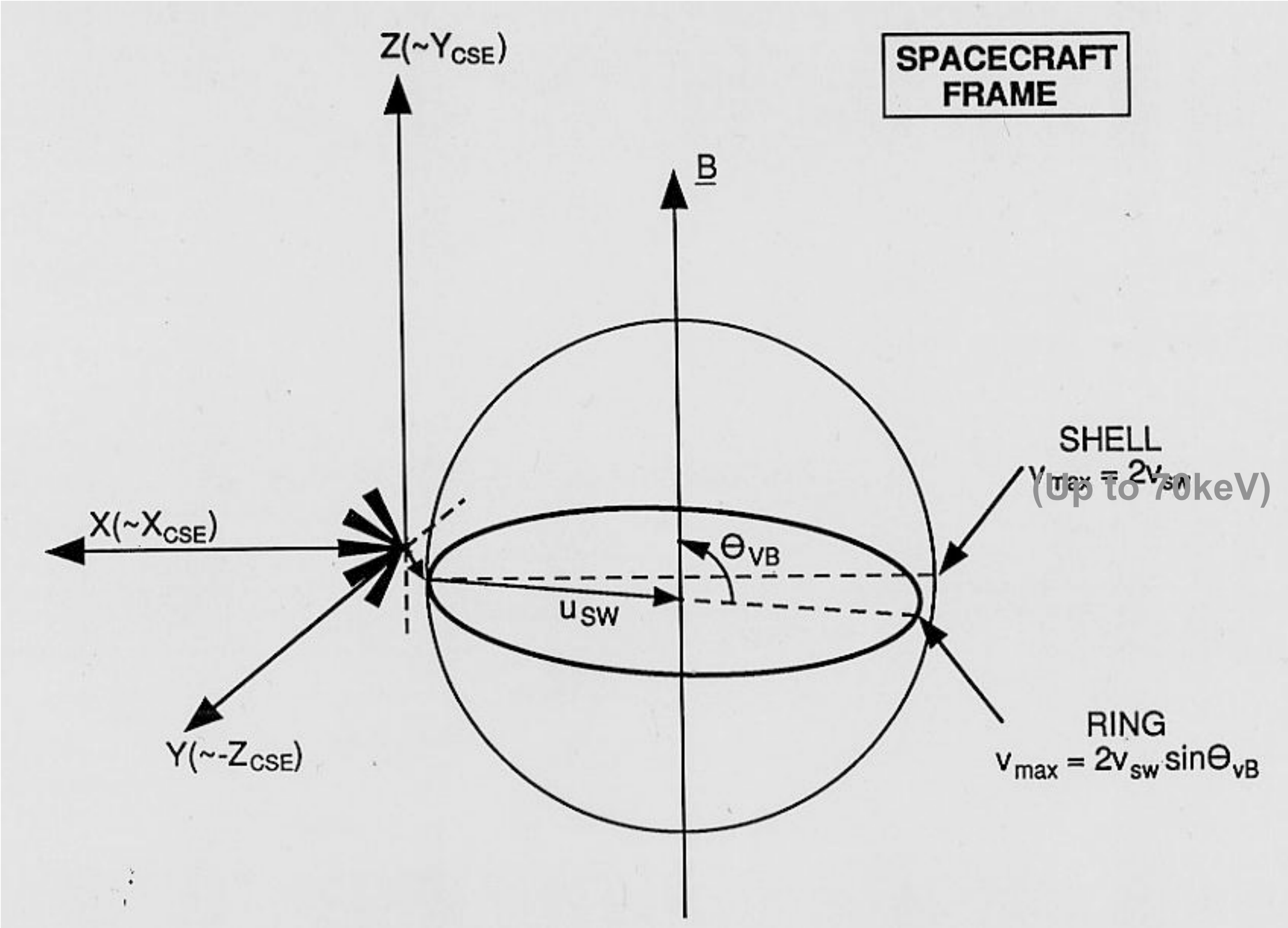
Ion pick-up process - 1

- Solar wind plasma is fully ionized, highly conducting
- Magnetic field ‘frozen in’ to flow
- Neutral particle (mainly water group) ionizes due to photoionization or charge exchange
- New born ion feels electric field $\mathbf{E} = -\mathbf{v}_{\mathbf{sw}} \times \mathbf{B}$
- Accelerates along electric field, gyrates around magnetic field
- Resultant motion a cycloid – ‘**E**x**B** drift’
- In comet frame maximum ion velocity given by $2v_{sw} \sin\alpha$ (where α is the angle between the solar wind velocity and the magnetic field)
- Maximum energy $2mv_{sw}^2 \sin^2 \alpha$. E.g. 1 keV solar wind, H_2O^+ ions gives 72 keV (for α=90°)

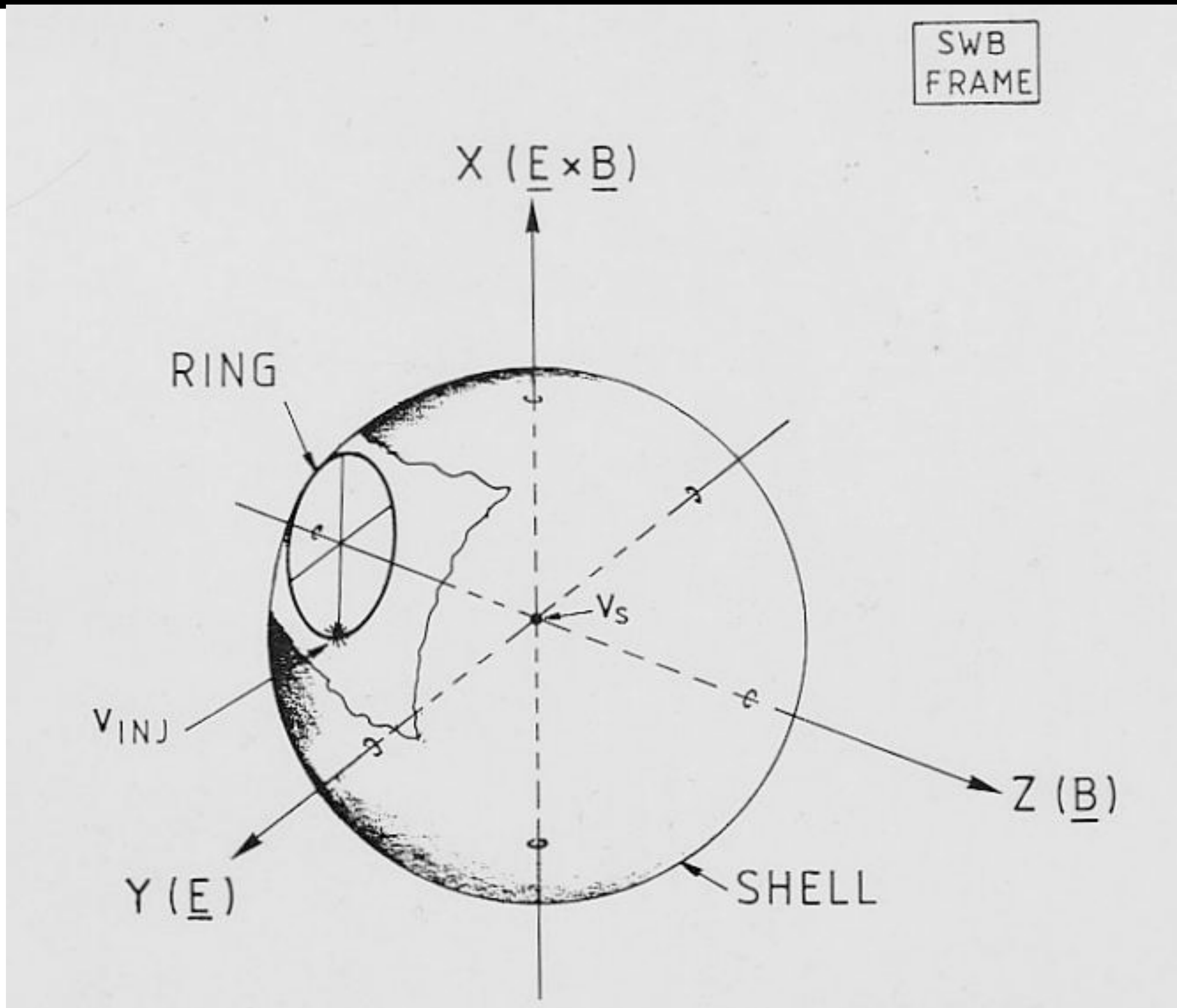

Real space
Newborn ion trajectory out of **v**, **B** plane
$\mathbf{v}_{GC}=\mathbf{E}\times\mathbf{B}/B^2$
$\mathbf{v}_{sw}$
$\mathbf{E}=-\mathbf{v}_{sw}\times\mathbf{B}$
Ionization (or injection) point
B

Ion pick-up process - 2

- In velocity space, cycloid translates to a ring
- Ring distribution is 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**
- Ion pickup implies accommodation of ions into the solar wind flow



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

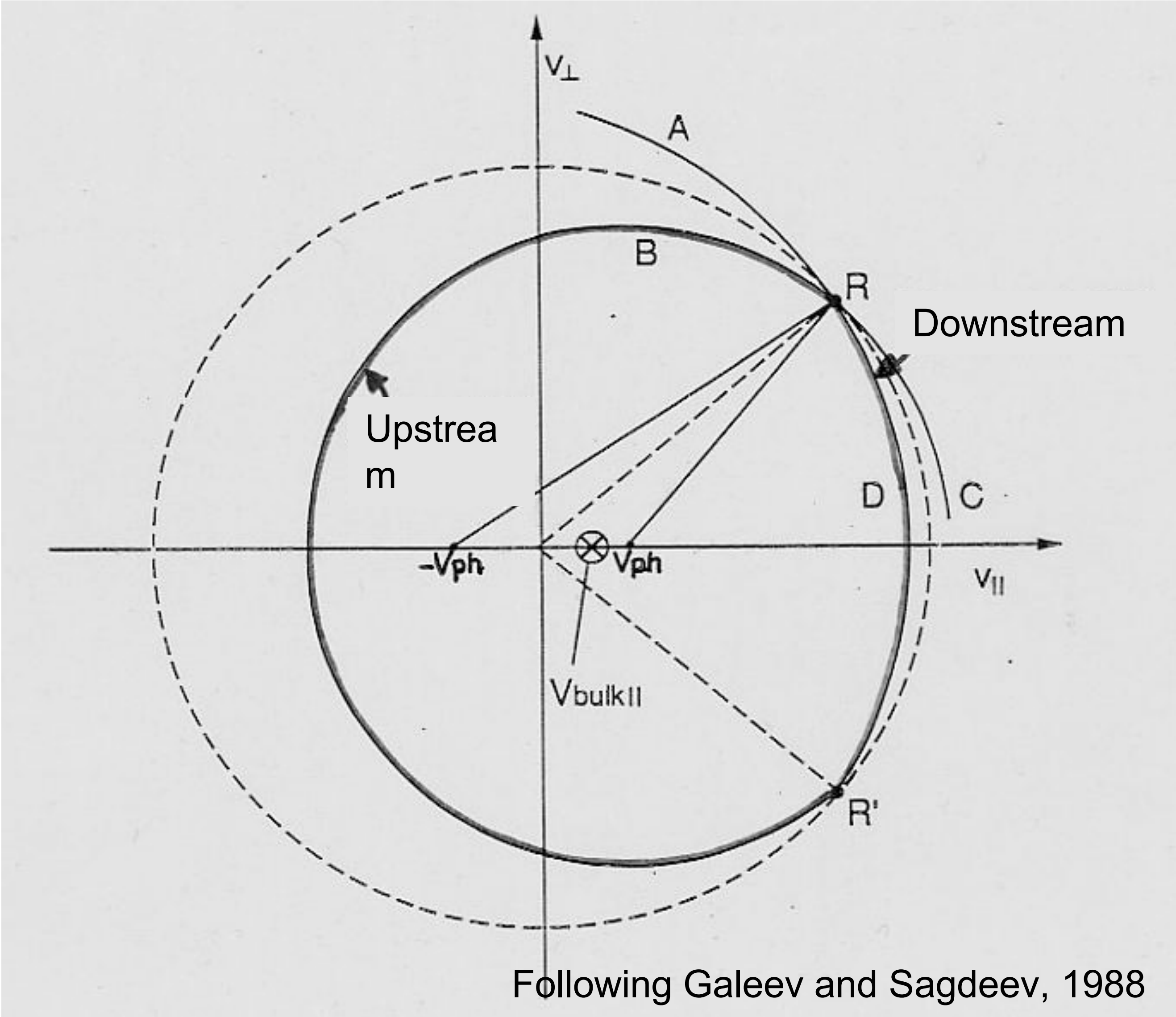


In this frame, $\mathbf{v}_{\mathbf{ring}}=(0,0,v_{||})$, $v_{||}=\mathbf{v}.\mathbf{B}/B$

$\mathbf{v}_{\mathbf{shell}}=(0,0,0)$ (Coates et al 1990)

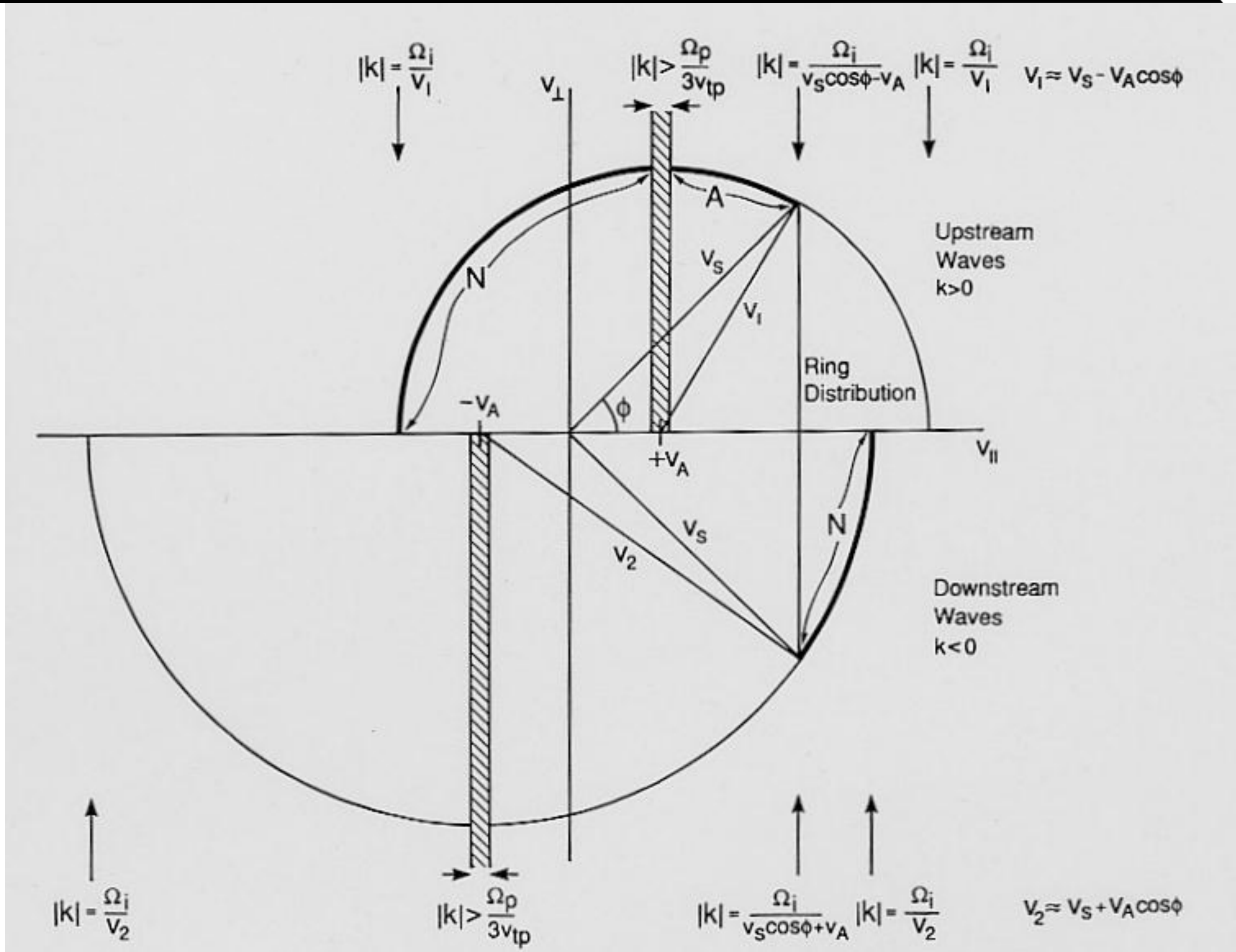
Pitch angle scattering

- Pitch angle scattering from ring to shell (predicted by Wallis 1970, Wu and Davidson 1972, etc)
- Maximum velocity of particles in shell $2v_{sw}$
- Simple shell an approximation
- Use solar wind, field aligned frame of reference
- More realistic distribution is a bispherical shell
- Two shells centred on upstream and downstream propagating waves, at $\pm v_{wave}$
- Pitch angle scattering follows these in velocity space
- Theoretically a problem appears in scattering through zero parallel velocity
- If scattering can happen this is first stage of accommodating pickup ions into the flow



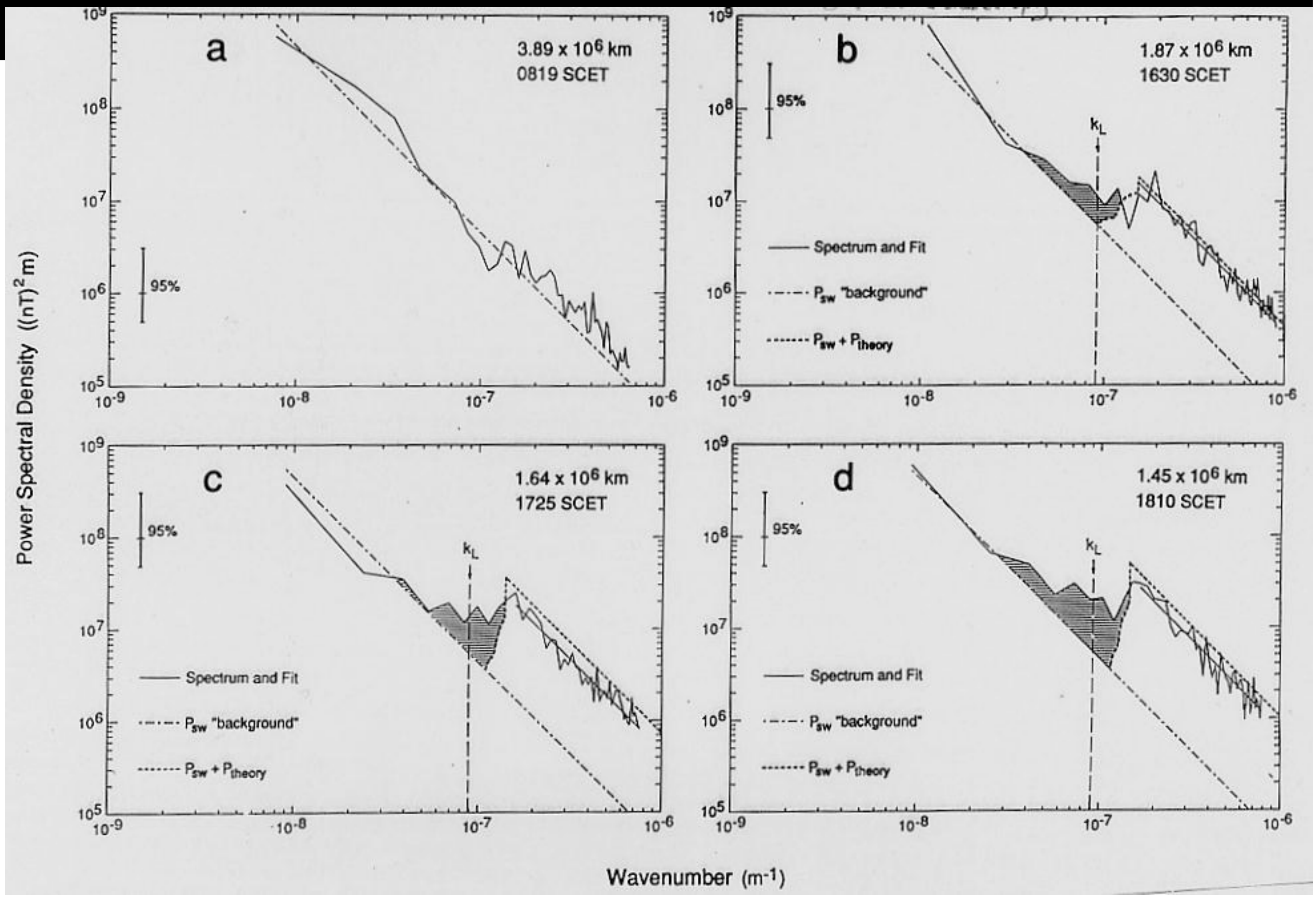
Bulk velocity now $(0,0,v_{bulk||})$

Coates et al 1990

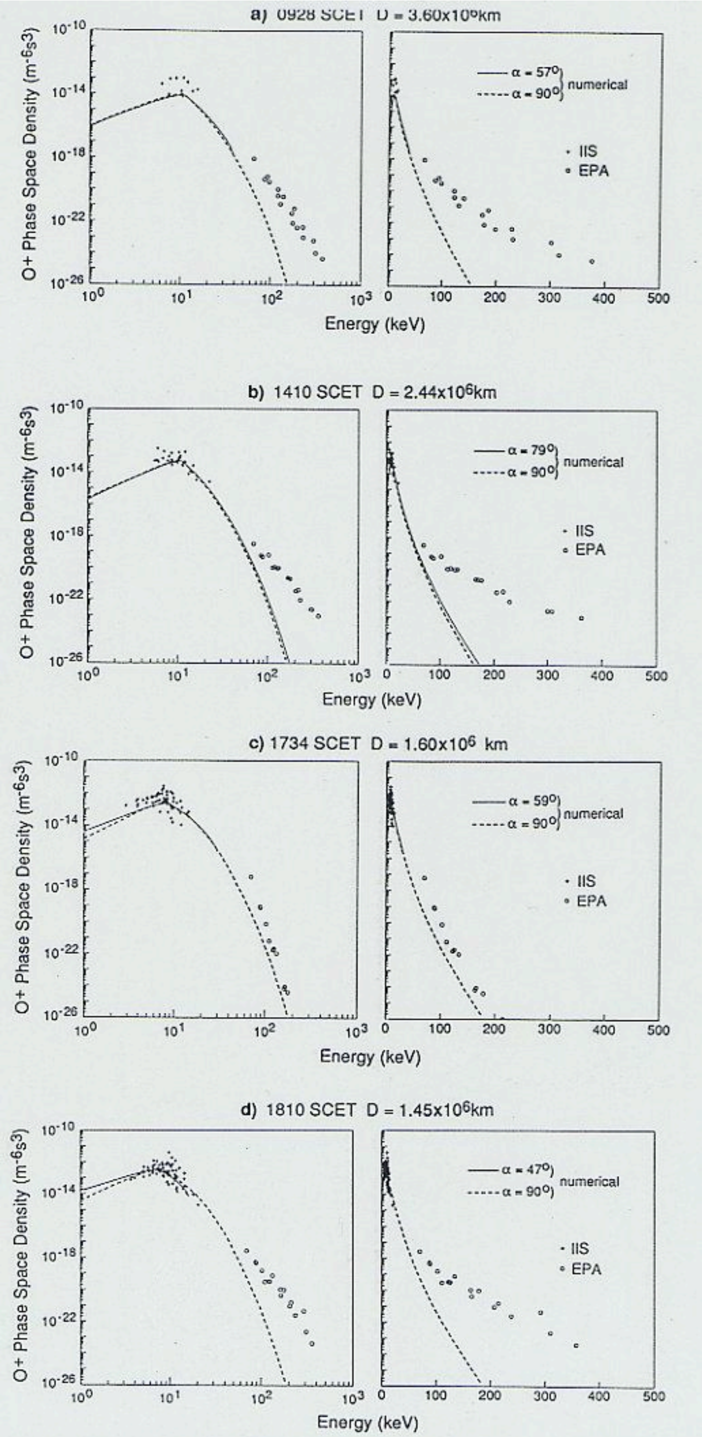


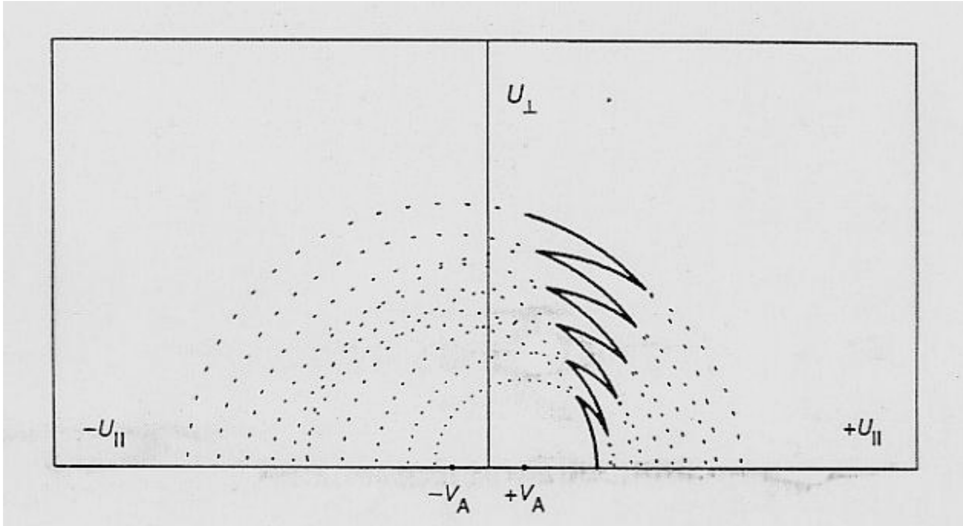
Resonant wave-particle interactions show that different parts of shell interact with particular waves (Johnstone et al, 1990)

1. Introduction
2. The cometary plasma environment
3. Ion pickup process
4. Mass loading
5. Recent results – Hyakutake, Borrelly, X-rays
6. Boundaries
7. Tail formation
8. Questions for Rosetta



Huddleston and Johnstone 1992





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)?

Stages in ion pickup process

Stage in process	Timescale
Nongyrotropic ring	<gyroperiod
Ring	~gyroperiod
Bispherical shell	~10 gyroperiods
Acceleration, shell filling	~100 gyroperiods
Maxwellian	?

Cometary plasma environment 1

- 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

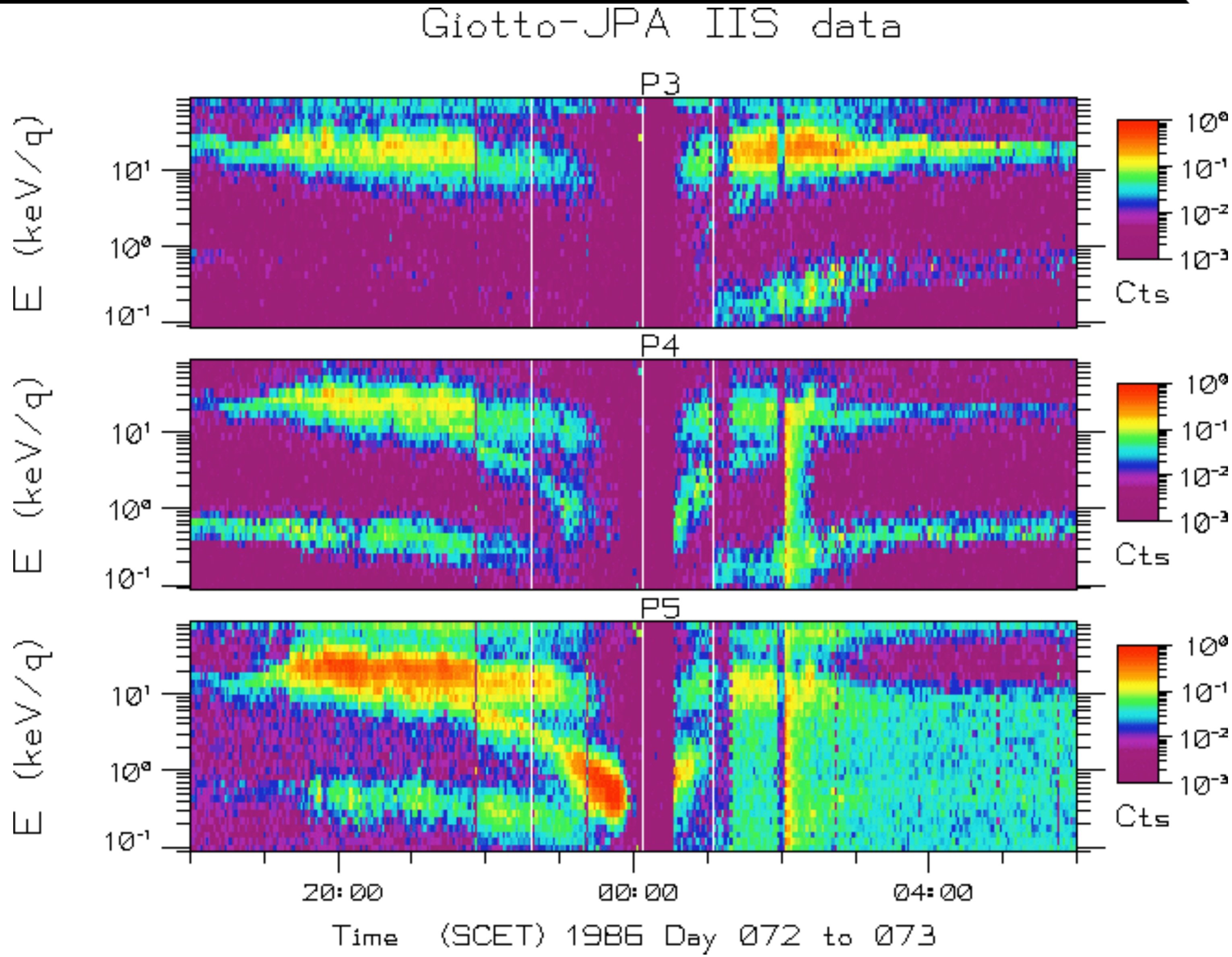
•Source term of form

$$Q = \frac{Q_0}{r^2} \exp\left(\frac{-r}{v_e t}\right)$$

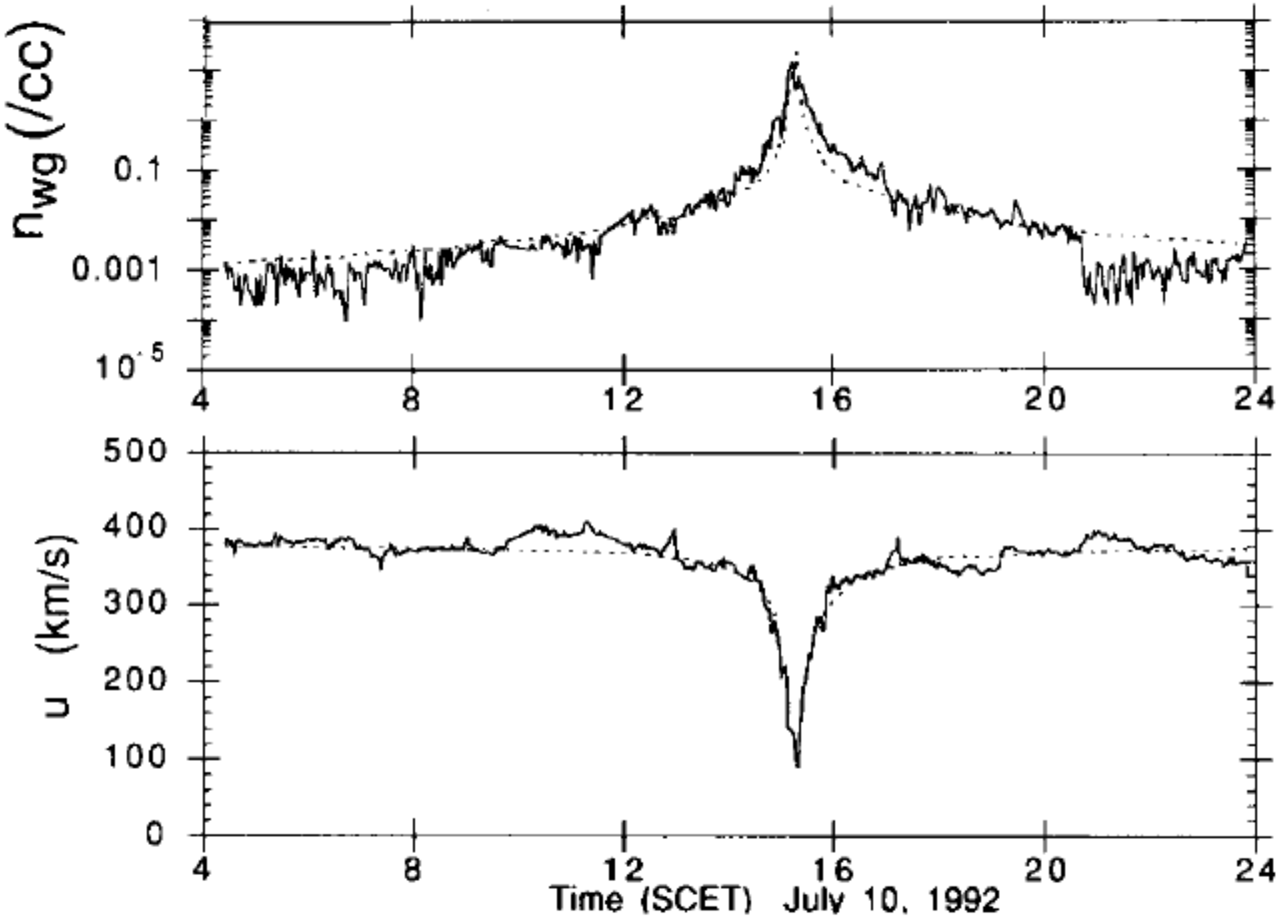
where v_e is expansion velocity. Describes spherical expansion of gas, and depletion due to ionization.

Cometary plasma environment 2

- On ionization, **ion pickup** process begins
- Heavy cometary ions added to flow, causing deceleration of solar wind by mass loading
- Magnetic field drapes around comet
- If rate of mass addition fast enough a shock forms
- Other predicted boundary prior to encounters was contact surface – pressure balance between solar wind and expanding cometary plasma
- Encounters provided a more complex picture – but different stages of ion pickup seen
- At small comets, nongyrotropic distributions are important; at large comets distributions evolve to bispherical shells and beyond
- Rosetta will examine inner regions in detail



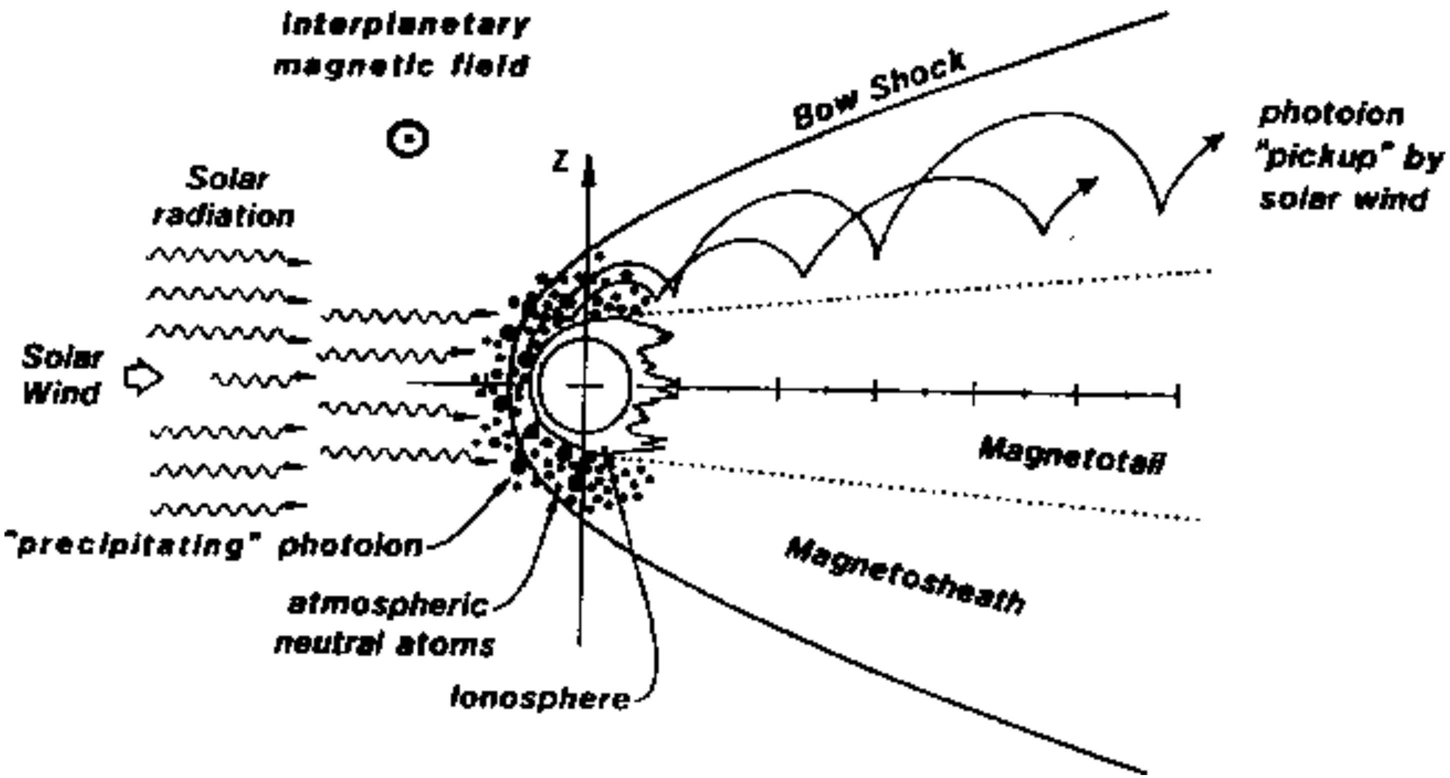
Giotto at Halley (Johnstone et al, 1986)



n_{wg} (/cc)
0.1
0.001
10^{-5}
4
8
12
16
20
24
500
400
300
200
100
0
u (km/s)
Time (SCET) July 10, 1992

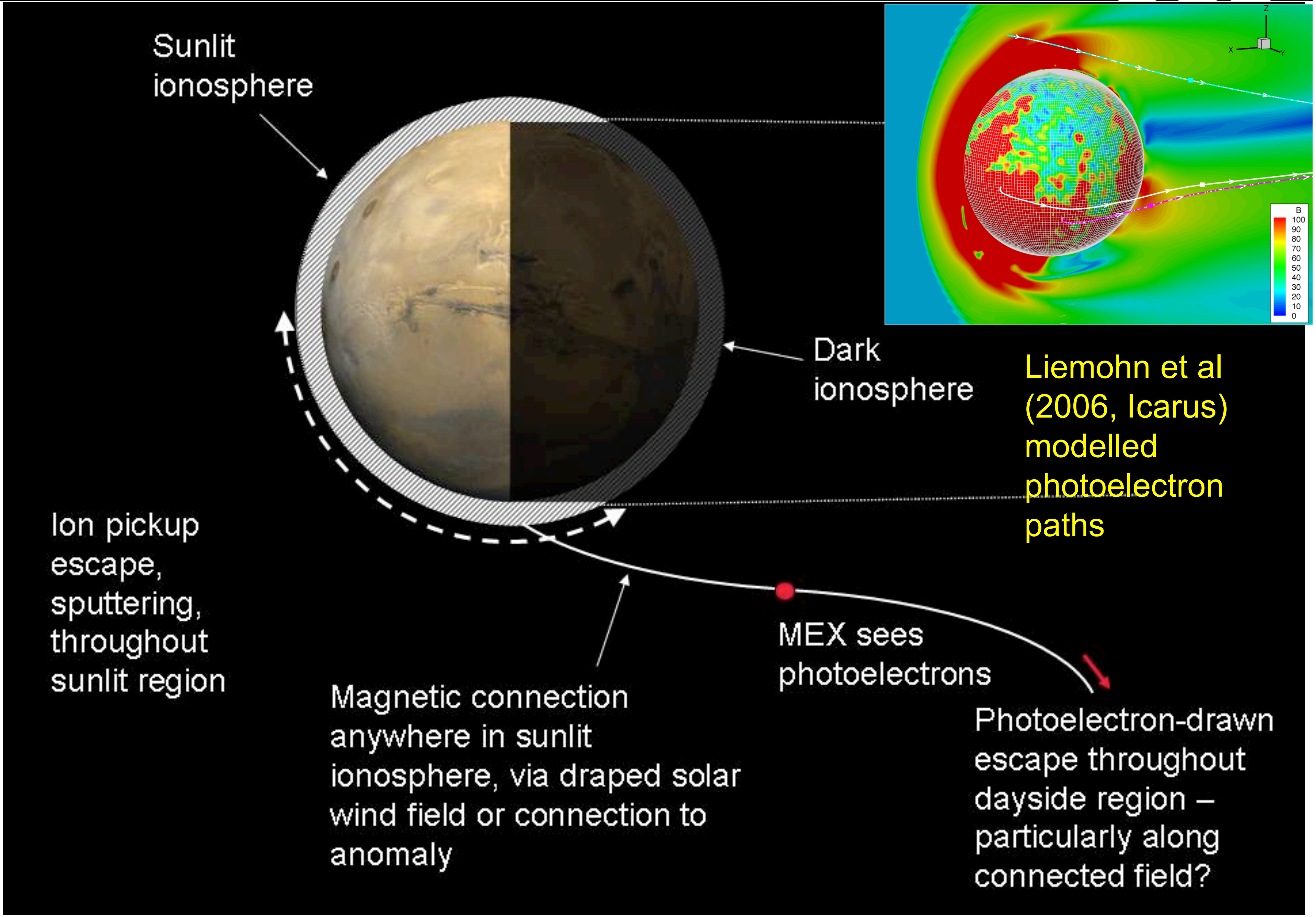
Mars

- Planet has no global magnetic field
- Exosphere of Mars; ionization and ion pickup
- Direct pickup from upper atmosphere also possible
- Gyroradius larger than planet size
- Solar wind scavenging important
- Estimated loss rate ~10^{25} s^{-1} (Lundin et al) – significant on solar system timescale
- Corresponds to tens of % of Earth's atmospheric mass
- Early measurements of loss rate from Mars Express factor 100 lower (Barabash et al 2007) – being revised
- Field draping forms barrier for bow shock formation
- Asymmetric pickup due to reabsorption by planet
- This produces further pickup ions
- Mars Express looking at pickup ions and global loss rates



Solar wind interaction with Mars (schematic)

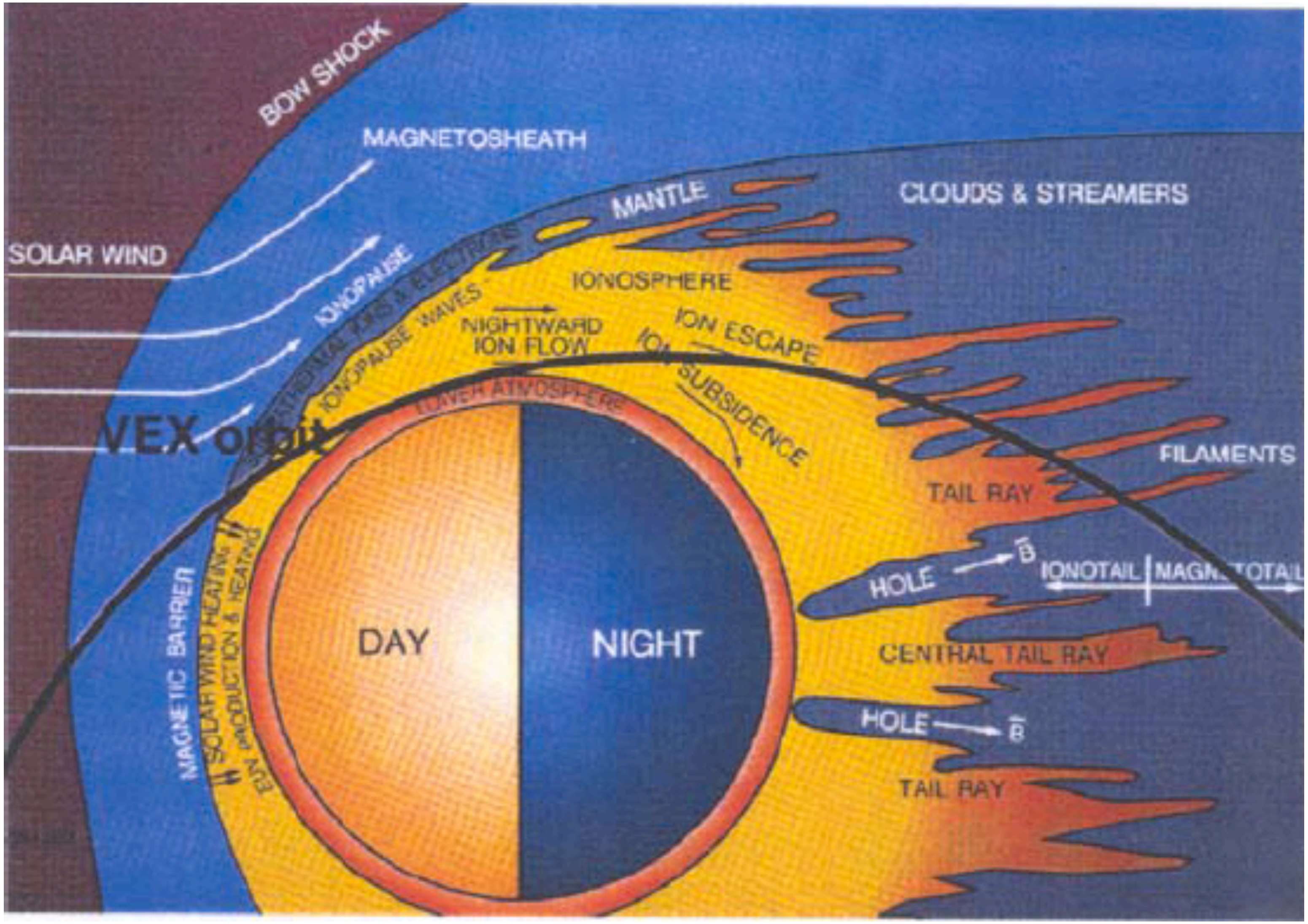
For Venus, similar picture but ion gyroradius is smaller


Sunlit ionosphere
Dark ionosphere
Liemohn et al (2006, Icarus) modelled photoelectron paths
B
100
90
80
70
60
50
40
30
20
10
0
Ion pickup escape, sputtering, throughout sunlit region
Magnetic connection anywhere in sunlit ionosphere, via draped solar wind field or connection to anomaly
MEX sees photoelectrons
Photoelectron-drawn escape throughout dayside region – particularly along connected field?

Venus

- Planet has no magnetic field. Thick ionosphere
- Ionopause position from pressure balance between ionosphere and solar wind (modified by pickup)
- Outside ionosphere, ionized neutrals picked up
- Gyroradius smaller than planetary radius
- Solar wind ‘scavenging’ – role in atmosphere evolution
- Pickup ions (O^+) seen from PVO etc, now Venus Express
- Gyroradius relatively smaller than at Mars – more mass loading?
- Earlier estimated ~10^{24} s^{-1} steady loss down tail – impulsive value may make average 50x larger (Brace et al 1987)
- Venus Express currently measuring rate and solar wind interaction, mass loading processes

Venus interaction with solar wind



ESA VENUS EXPRESS ASPERA-4

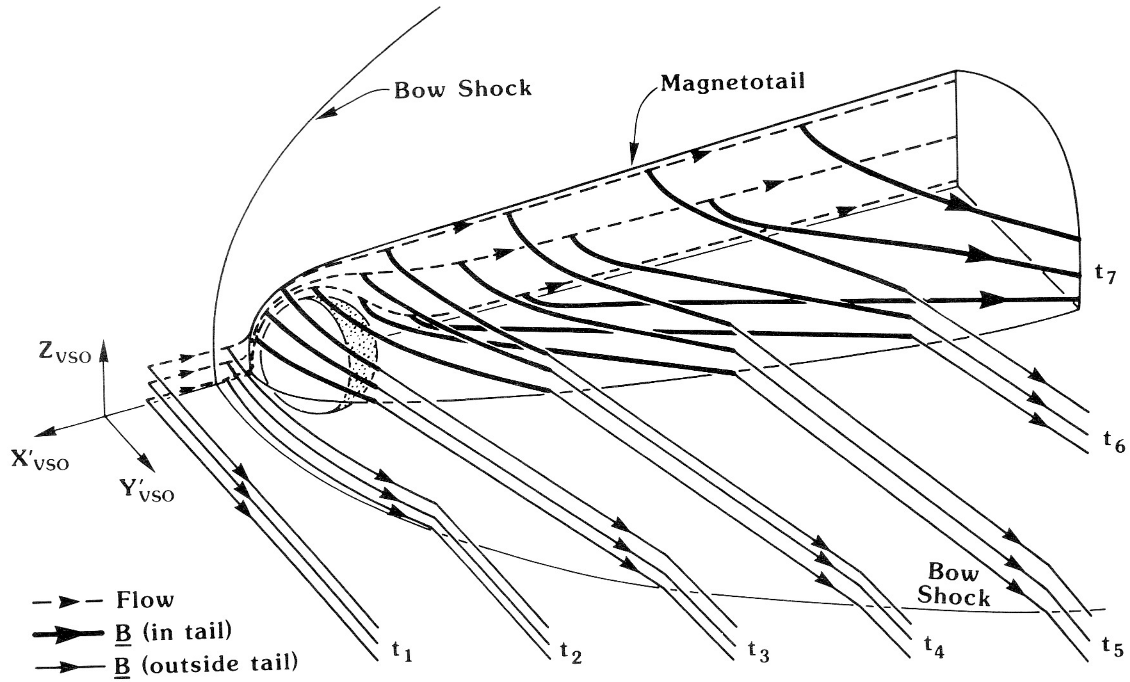


Fig. 17. The formation of the Venus tail. Magnetic field lines are carried to the planet by the solar wind flow. The plasma near the planet slows down while the ends of the magnetic field lines on the solar wind continue to move with the solar wind. This velocity shear bends the magnetic field lines. Field lines closest to the planet are bent the most. The flow passing closest to the planet also becomes more dense due to photo-ionization of the exosphere. This increases the bending of the field and enhances the tail [Saunders and Russell, 1986].

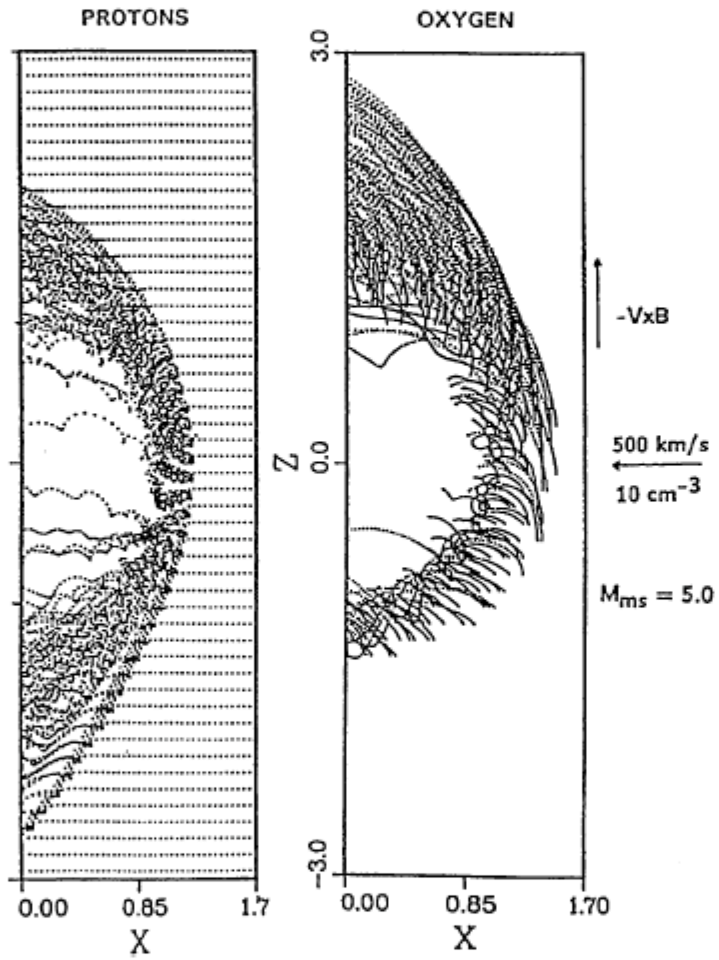
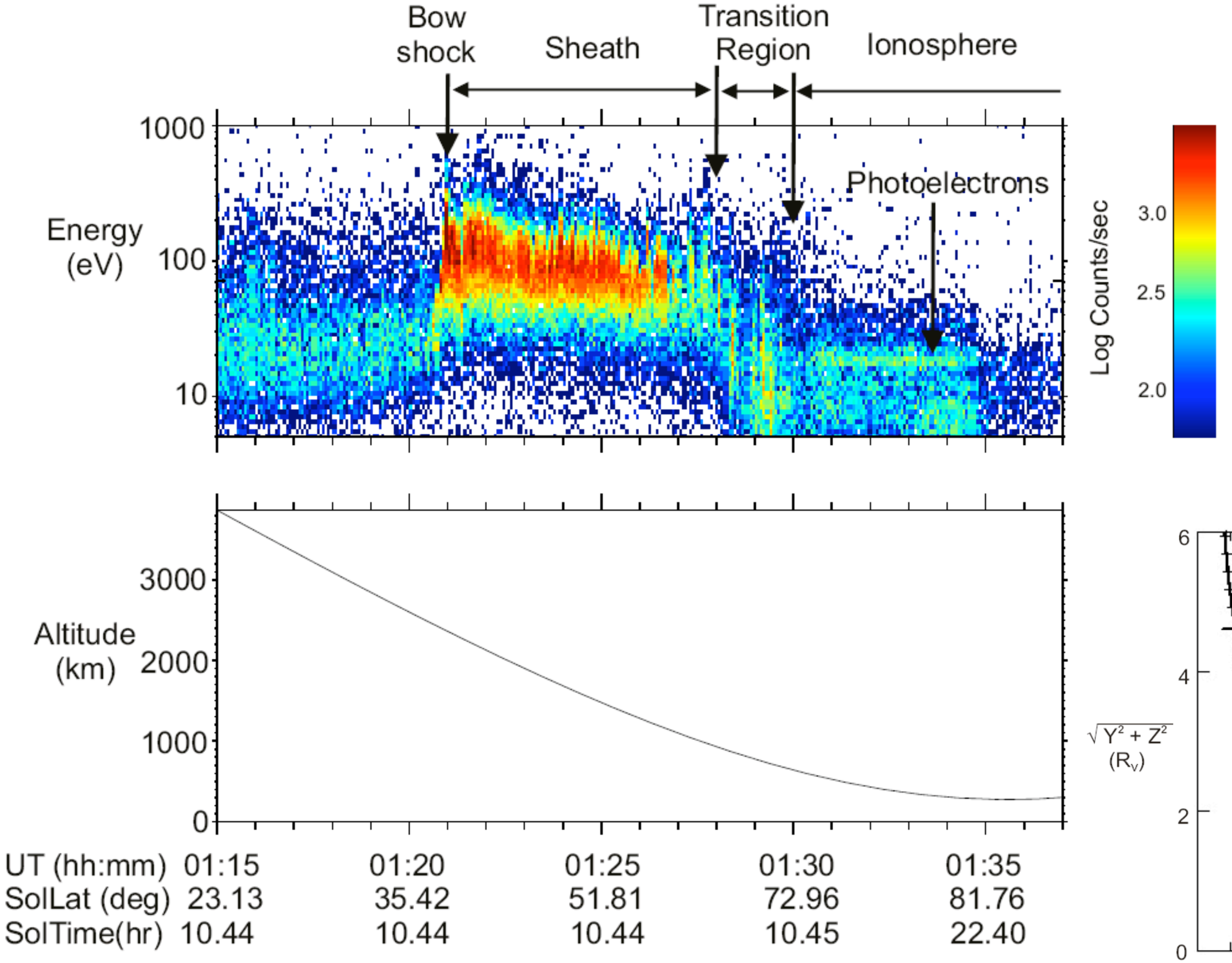
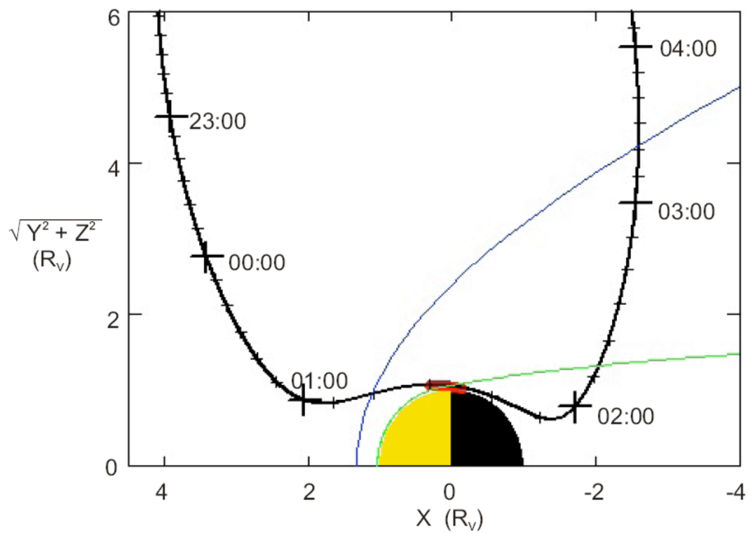


Figure 4.3.3. Proton and oxygen ion trajectories in the solar wind near Venus (from Moore et al., 1991).

Example of Venus-solar wind interaction



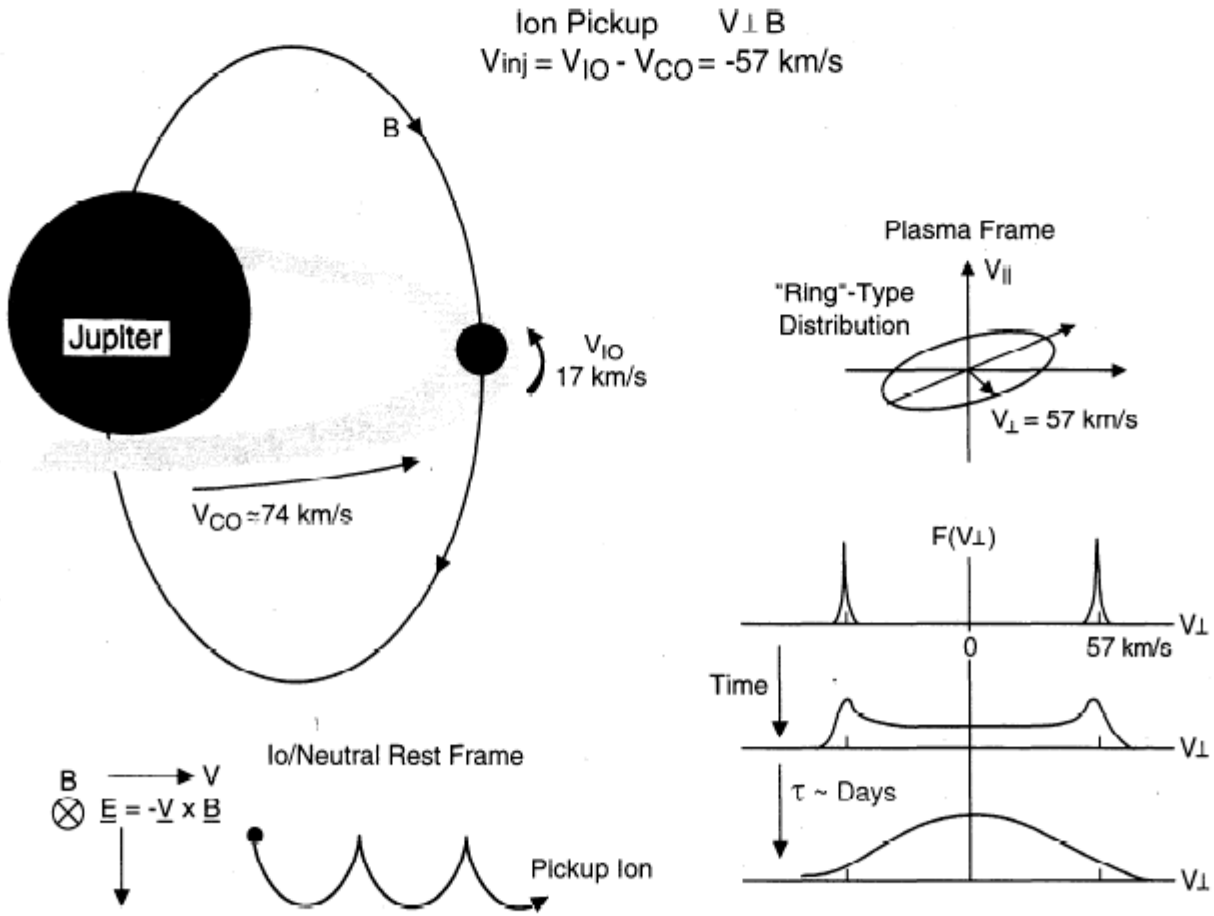


From Coates et al, PSS 2007

Ion escape: Barabash et al in prep.

Io, Jovian satellites

- Io volcanoes a source of heavy (S, O based) neutrals
- Major source of particles for the magnetosphere
- Io plasma torus from ionization of these
- 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

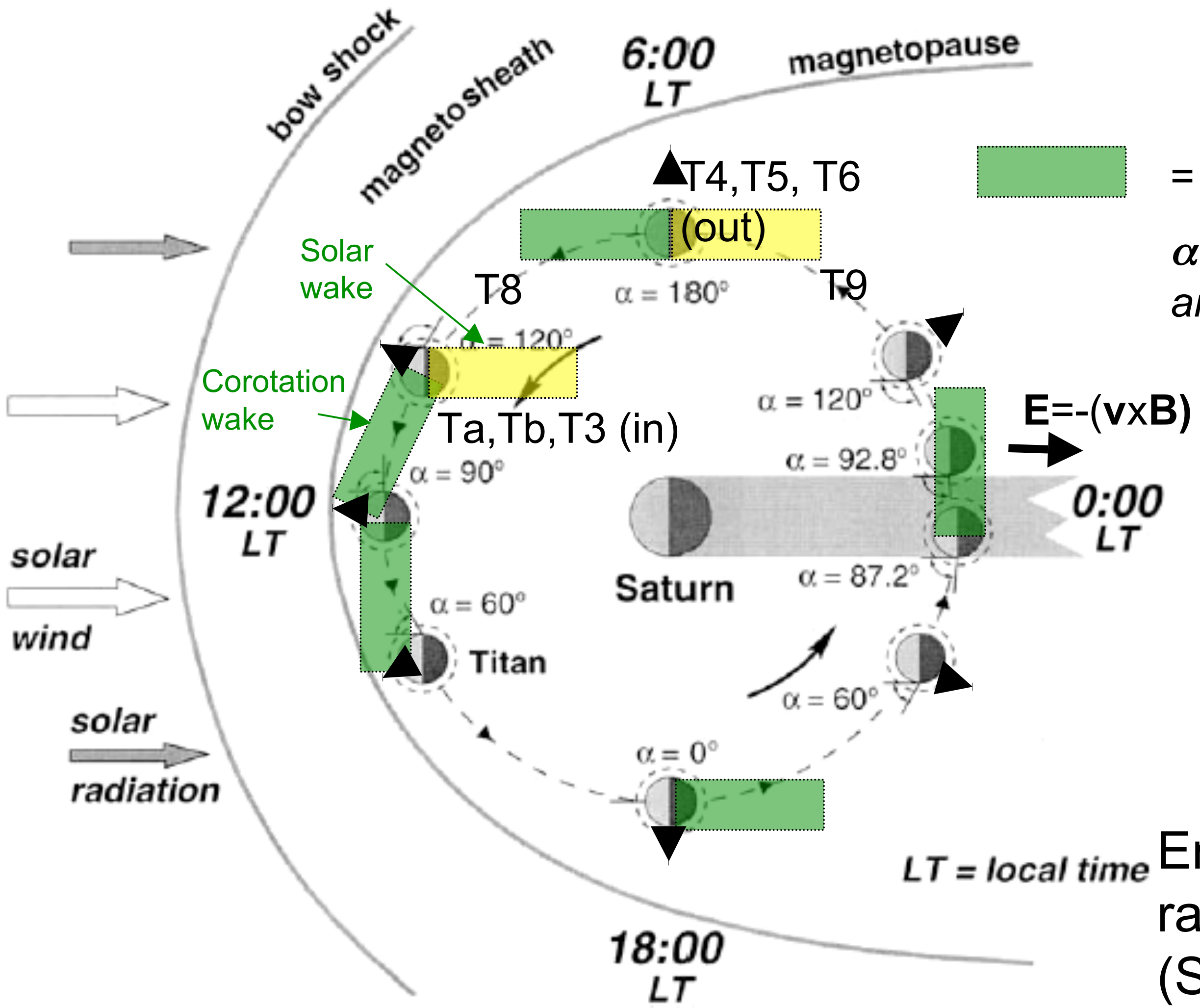


Ion Pickup V ⊥ B
Vinj = VIO - VCO = -57 km/s
B
Jupiter
VIO
17 km/s
VCO ≈74 km/s
Plasma Frame
"Ring"-Type
Distribution
V||
V⊥ = 57 km/s
F(V⊥)
V⊥
0
57 km/s
Time
V⊥
τ ~ Days
V⊥
Io/Neutral Rest Frame
B
V
E = -V x B
Pickup Ion

Titan, Kronian satellites

- Atmosphere, ionosphere of **Titan** source for Saturn’s magnetosphere - except when Titan in solar wind
- Magnetosphere: M_{ms}<1, no shock. Draping, wake.
- Mass loading occurs but no electron heating - instead ‘bite out’ of electrons - absorption?
- Effect of magnetospheric electrons on Titan aeronomy
- Evidence for localised precipitation - UV hot spots
- **Icy satellites**: plasma-surface access, modification
- Major ion source in inner magnetosphere
- Electron depletions. Absorption of energetic particles.
- Targets for Cassini-Huygens

Local time effects

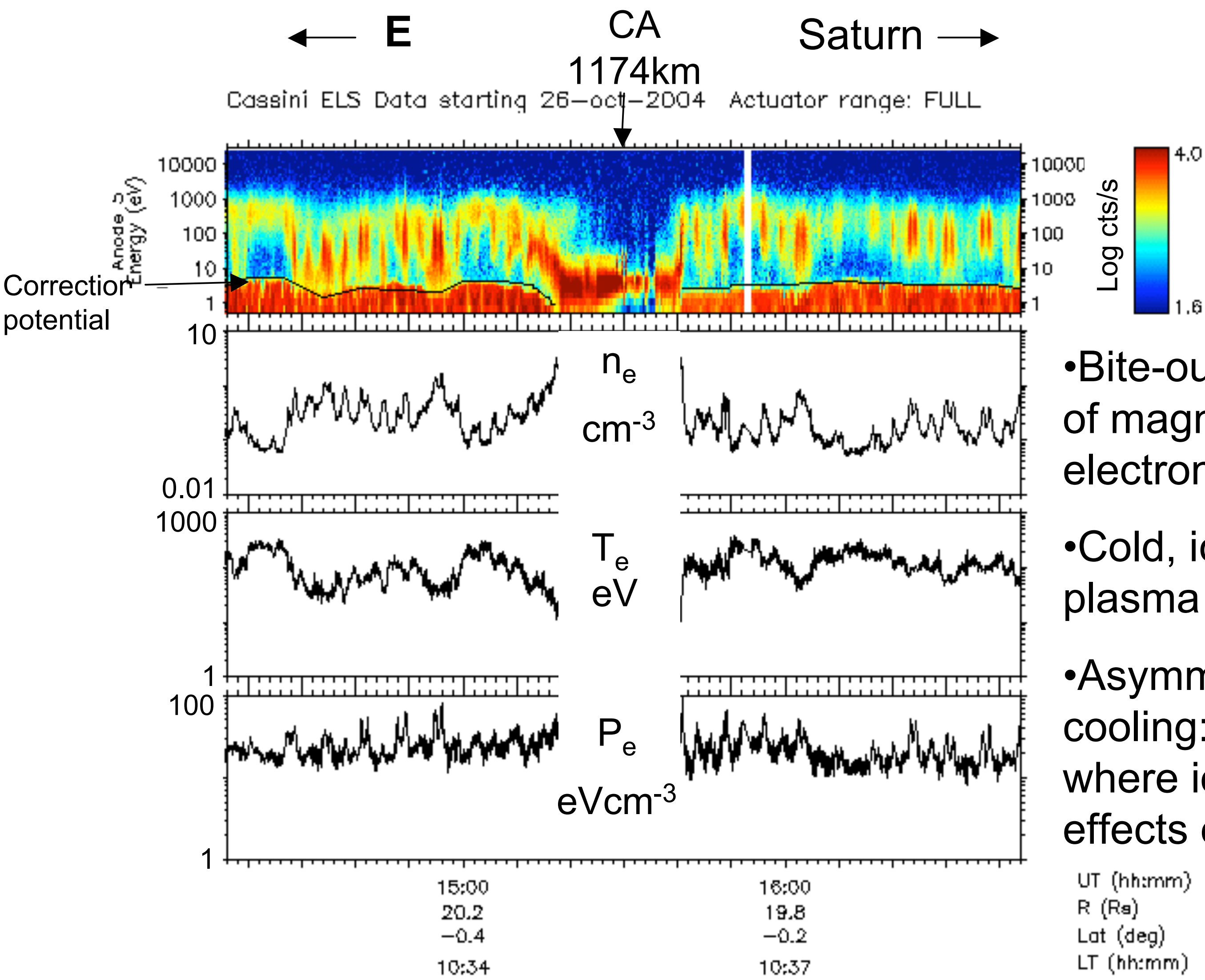


Electric field nominally away from Saturn

Encounters over wide range of local times (Saturn & Titan), altitudes

Adapted from Neubauer (1982)

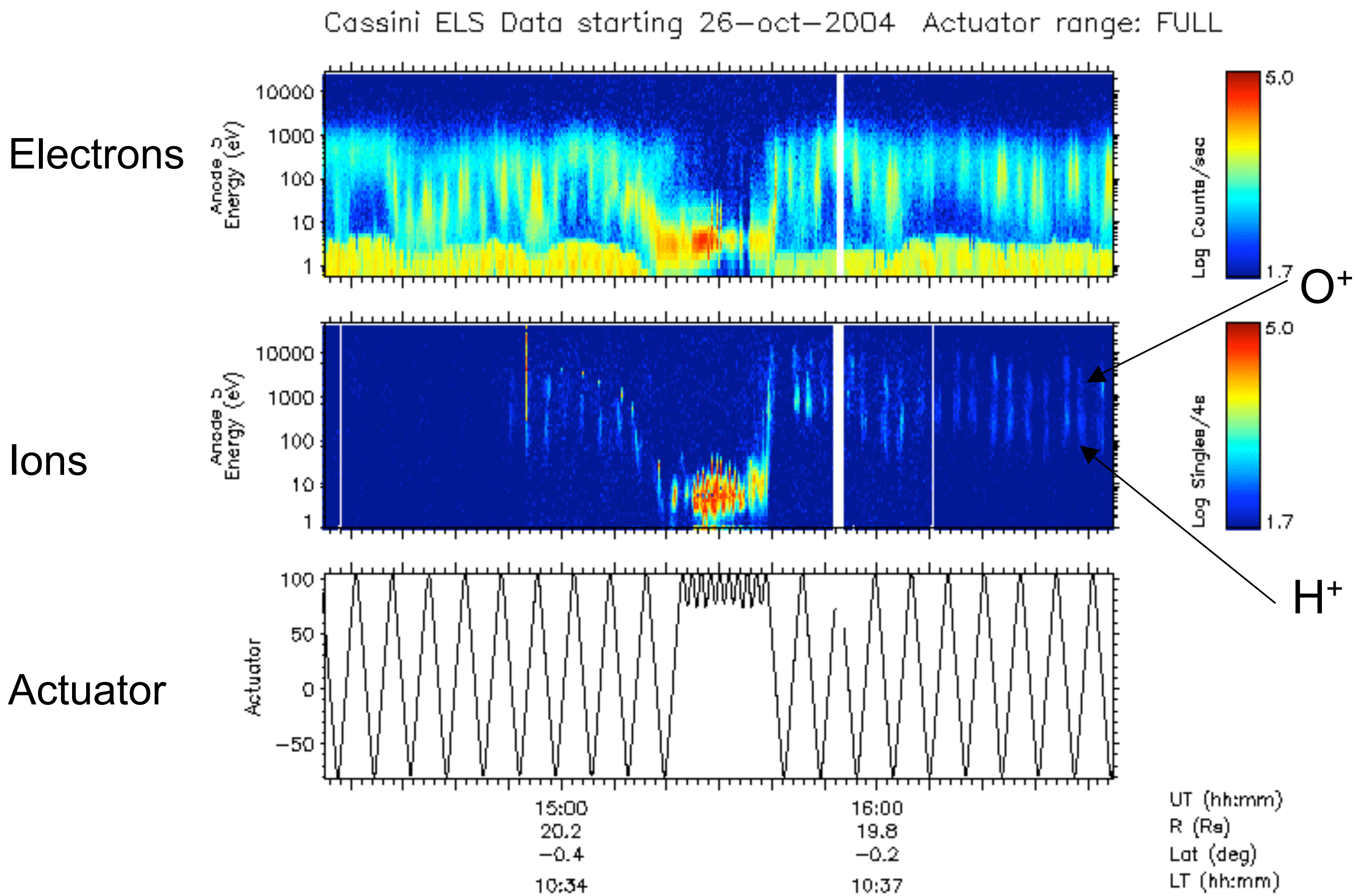
Electrons at Titan A: ±10 R_T



- Bite-out (incomplete) of magnetospheric electrons
- Cold, ionospheric plasma
- Asymmetry of electron cooling: less sharp where ion gyroradius effects expected

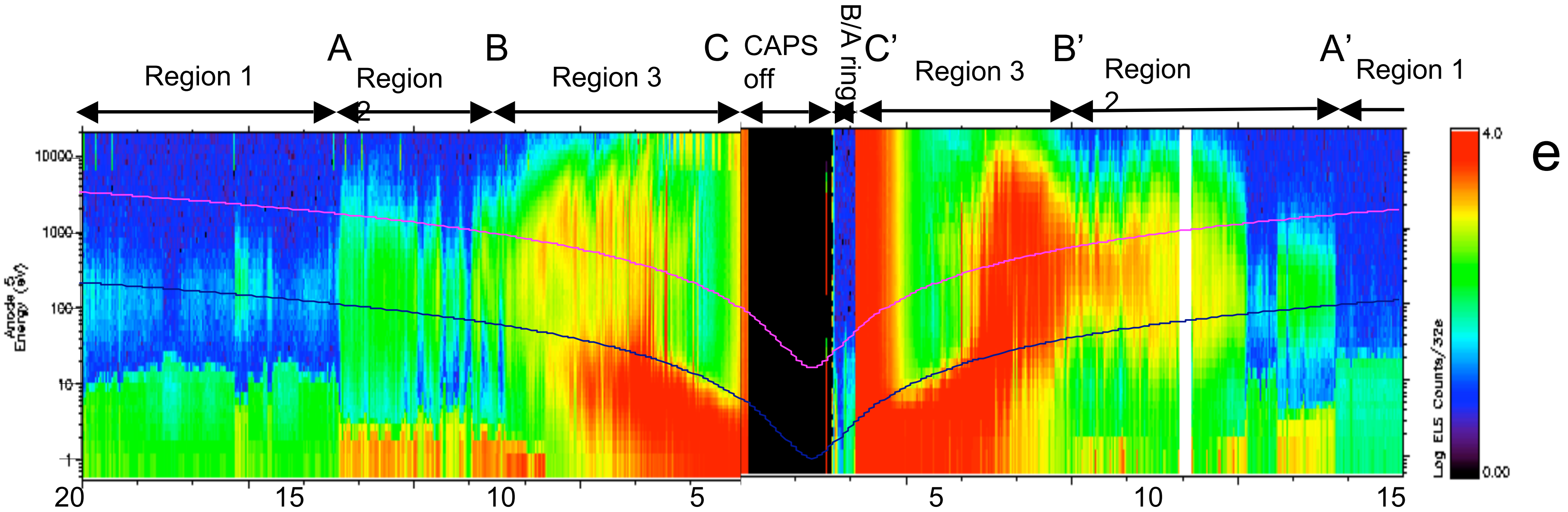
Coates et al 2007

Pickup & magnetospheric ions



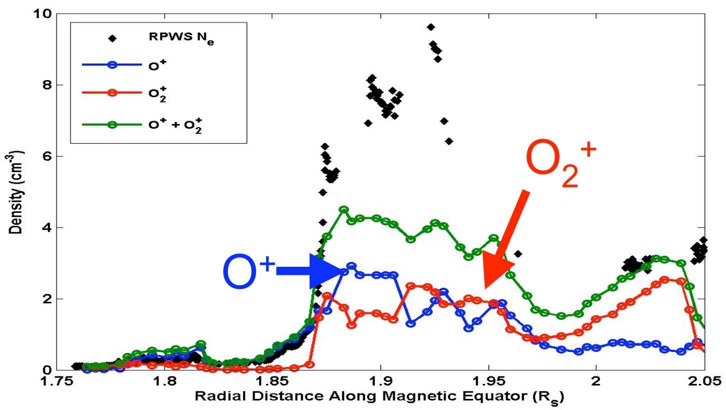
Ring distributions (Hartle et al 2006)

Adapted from Young et al 2005



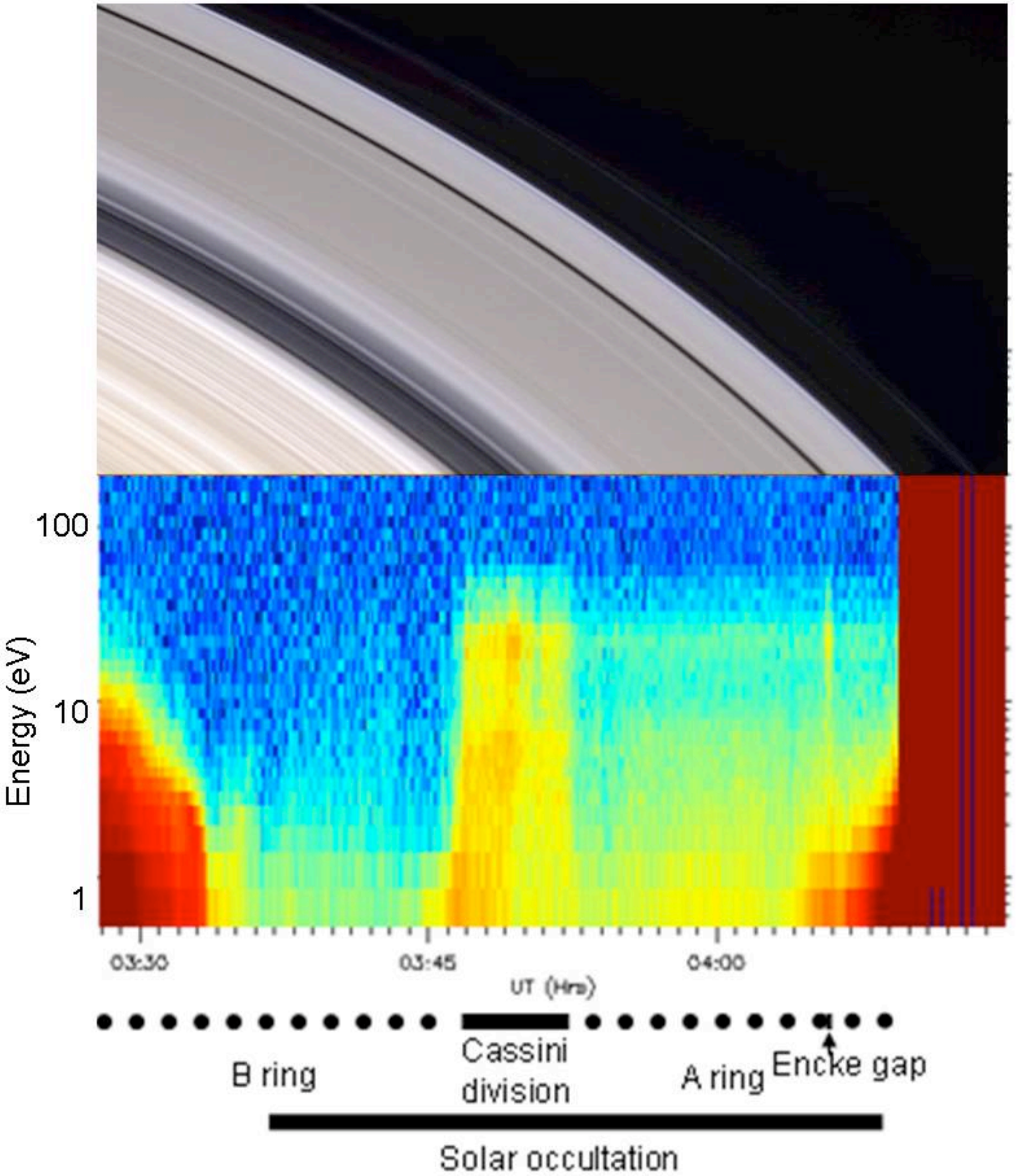
Rings through electron eyes

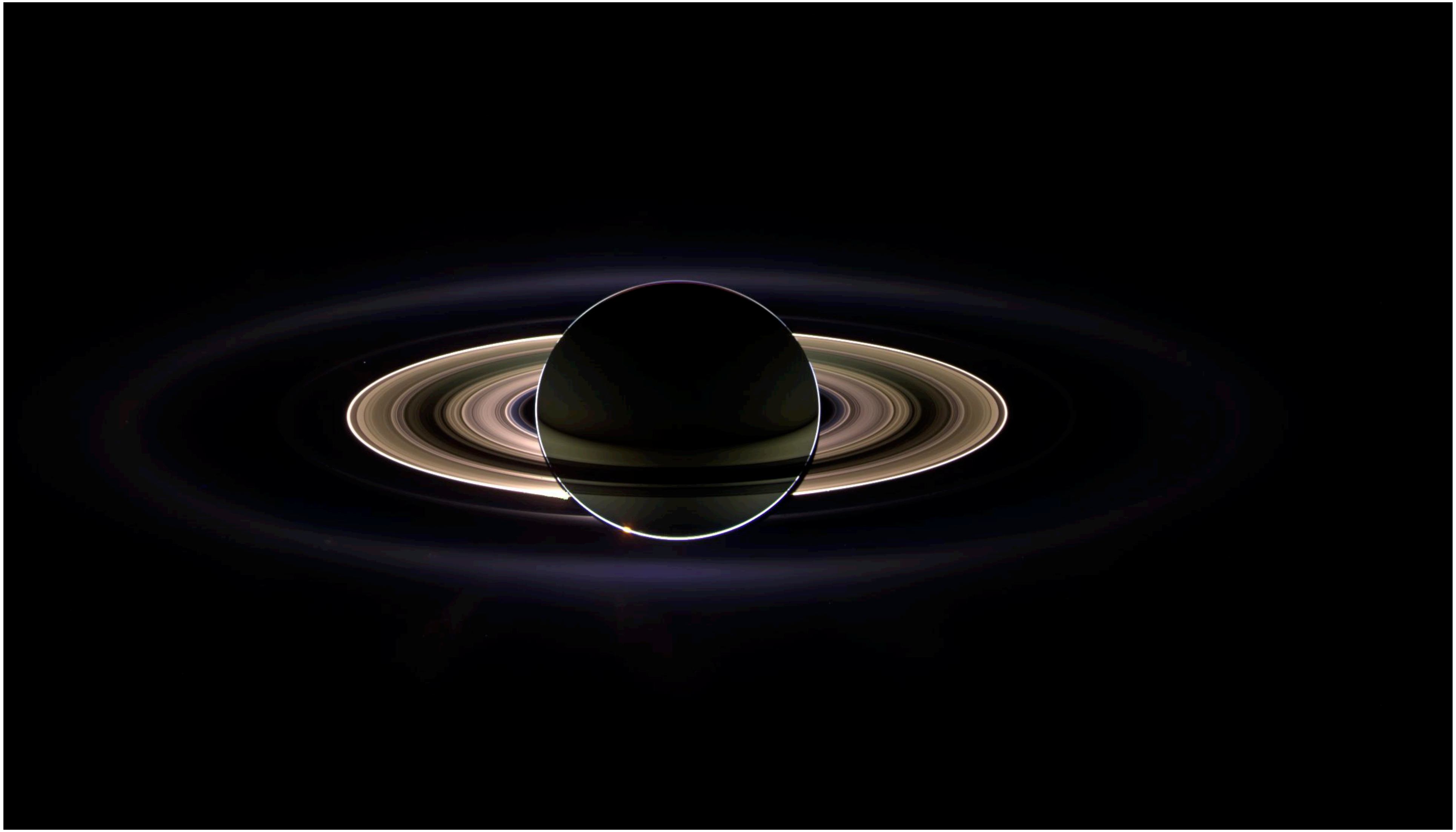
Rings have an atmosphere! (CAPS, INMS)



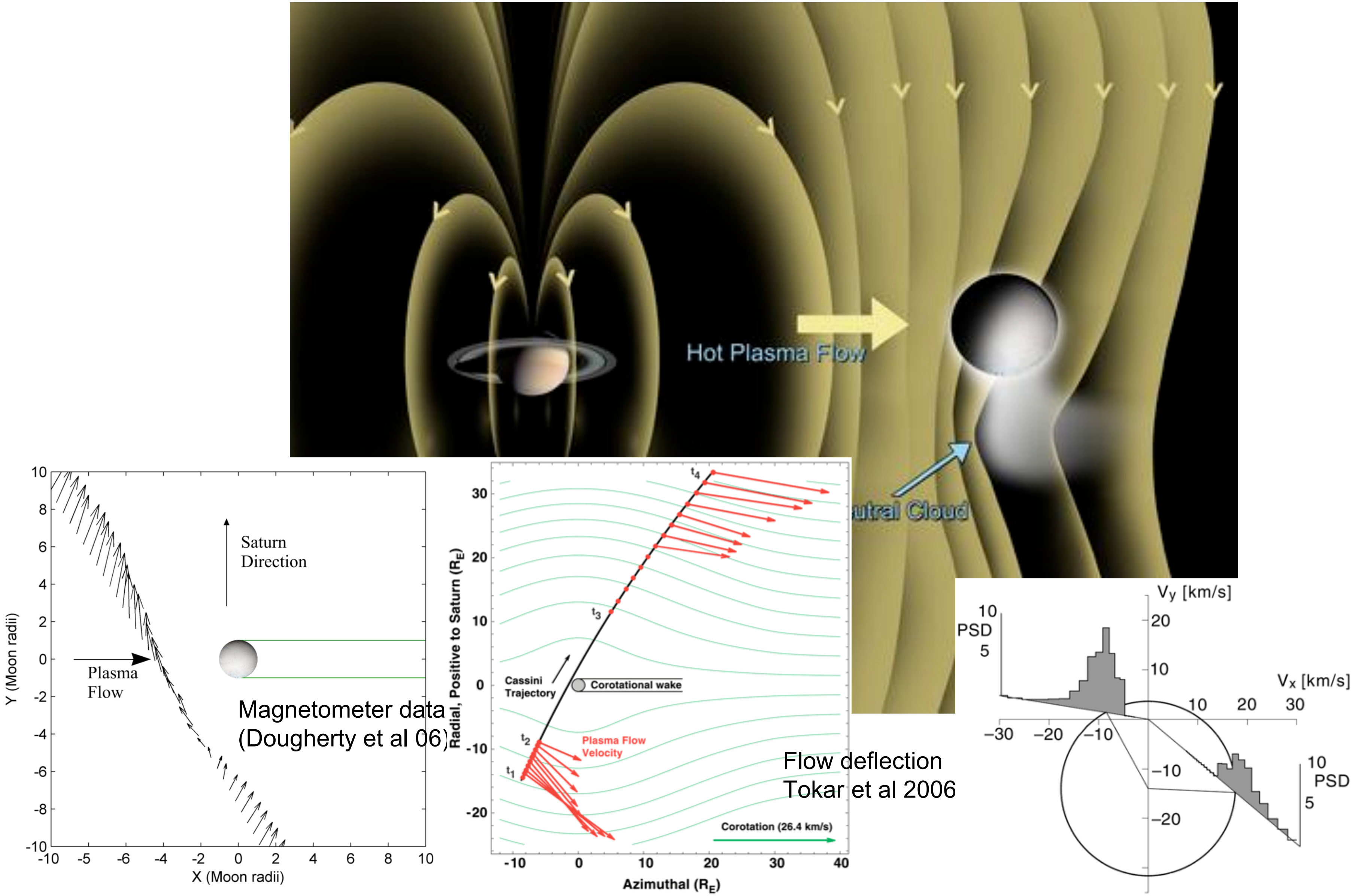
Coates et al, 2005

Tokar et al 2005



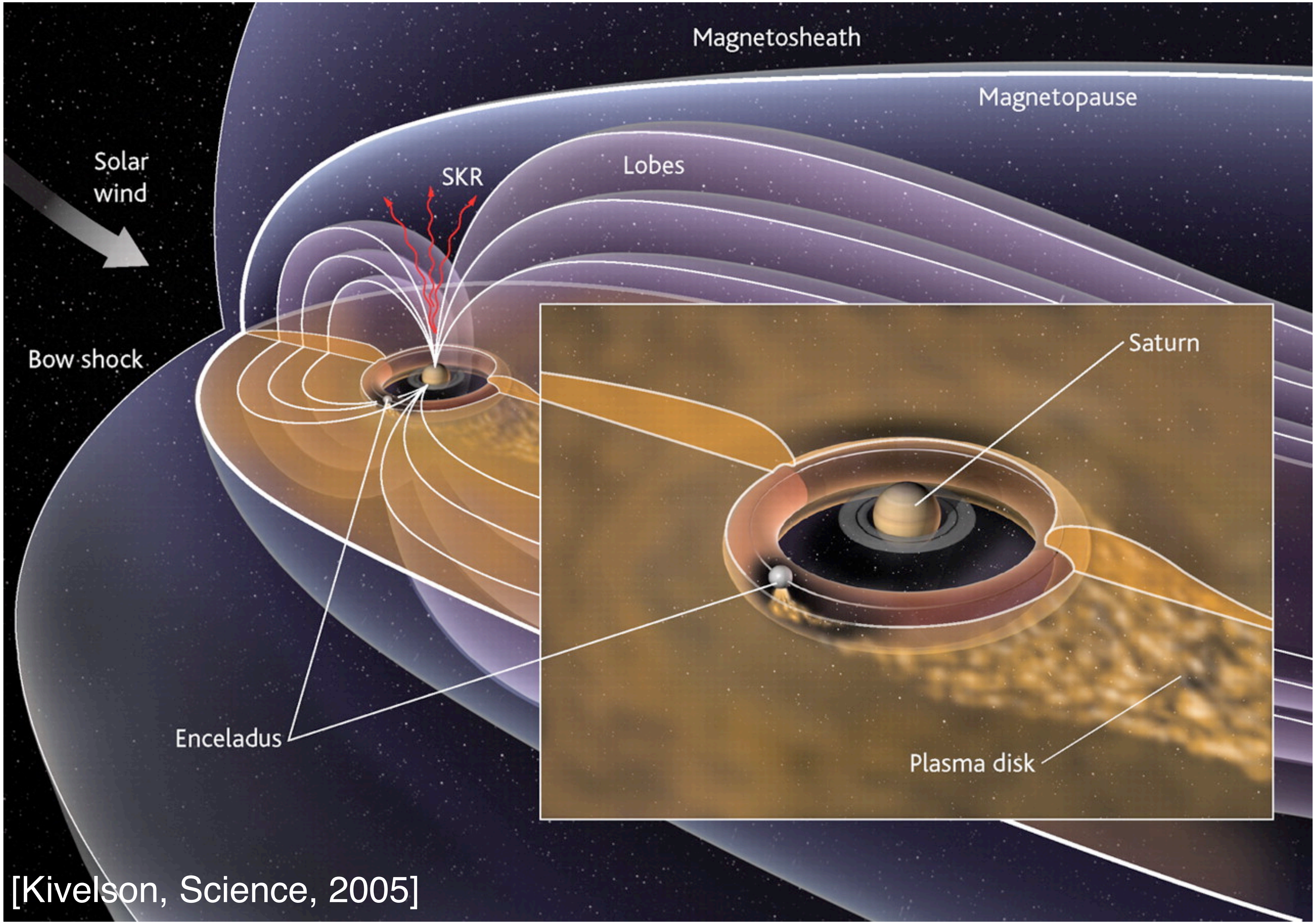


Enceladus atmosphere



Magnetometer data (Dougherty et al 06)

Flow deflection Tokar et al 2006


Magnetosheath
Magnetopause
Solar wind
SKR
Lobes
Bow shock
Saturn
Enceladus
Plasma disk
[Kivelson, Science, 2005]

Enceladus: source of gas and dust

Pluto

- Solar wind Mach number high
- Pluto, Charon icy (probably)
- Solar wind interaction comet-like during part of orbit nearest to Sun, when Pluto has an ‘atmosphere’
- Estimated atmosphere loss 10^{28} s^{-1}
- Large ‘mass loading’ region as an active comet
- Rest of orbit may resemble Venus interaction
- Methane gyroradius 250,000 km!
- Predicted bow shock at 2,000 to 28,000 km (Bagenal and McNutt, 1989)
- Nongyrotropic distributions probably important

Interstellar medium

- Neutral component of local interstellar medium enters solar system, ionizes
- Predicted in 1970s: He^+ measured by AMPTE (Moebius, 1985), H^+ by Ulysses (Gloeckler et al, 1993)
- Expected distribution isotropic: recent measurements (Gloeckler et al 1995) suggest significant anisotropies in both components
- AMPTE data show that incomplete scattering happened during times of almost radial IMF (Mobius et al 1998)
- Possible explanation is difficulty of scattering through zero parallel velocity
- Recent studies with Geotail indicate torus and shell-like distributions

Stages in ion pickup process

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

C=Comets, M=Mars, V=Venus, Io=Io, E=Enceladus, T=Titan, I=Interstellar

Conclusions

- Comets: pickup ions seen as gyrotropic and nongyrotropic rings, bispherical shells, accelerated particles. Distribution functions have time to evolve in extended interaction regions.
- Mars: Pickup ions seen as rings. Less time to evolve.
- Venus: Pickup ions detected, distributions unknown (likely rings) but may be shells in tail
- Io, Titan: Rings seen, shells at Io.
- Enceladus: Field, flow deflection
- Interstellar: torus distributions, shells
- Comparative studies just starting – more data needed

Martin et al (Nature, 2007) Galex result

13 ly tail behind Mira (red giant shedding C, O)

Relative speed 130 km/s

A big comet?