Planetary plasma environments

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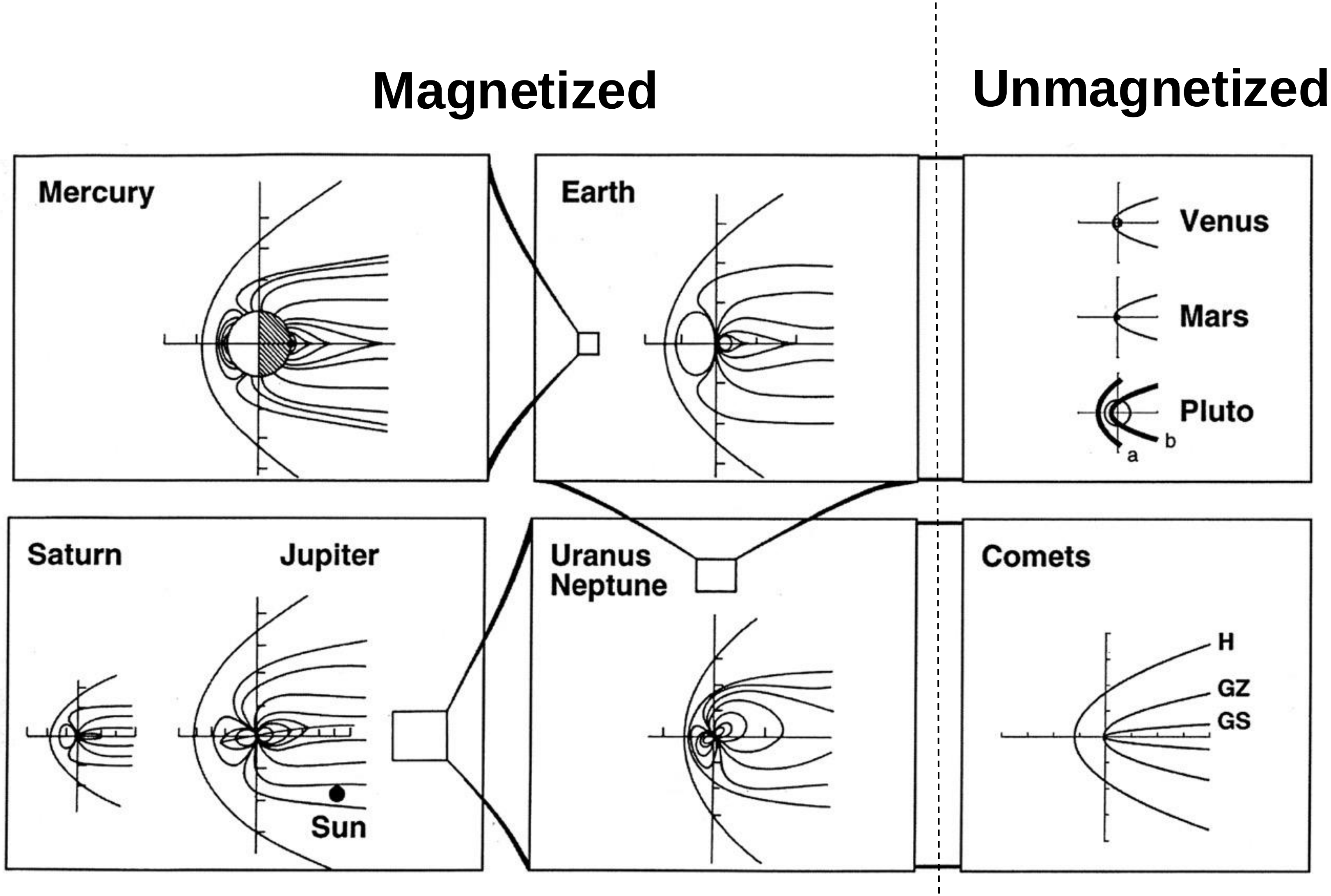
Outline

1. Space weather and solar wind
2. Plasma interaction with solar system objects
   - Inert – Moon (crustal fields)
   - Magnetized – Earth, Mercury, Jupiter, Saturn, Uranus, Neptune
   - Unmagnetized with an atmosphere – Venus, Mars (crustal fields)
   - Outgassing - comets
   - Moons in planetary magnetospheres: Titan, Enceladus, Io, Europa, Callisto
   - Magnetosphere within a magnetosphere: Ganymede
3. Conclusions and future missions

Plasma interactions in the solar system



Coates, 2001, adapted from Russell et al

Space weather - timescales

Earth's magnetic field shields us from solar, galactic particles – but some penetrate; radiation belts always present

Event from Sun reaches Earth (or planet at *R* AU) on 3 timescales:

1. 8 (x*R*) minutes: high energy X- or γ- rays, radio noise
2. Minutes - hours (x*R*), high energy charged particles
3. 2-3 days (x*R*), solar wind disturbances

Effects on spacecraft of 1 and 2 are computer upsets; 3 can distort and energise magnetic environments

Solar wind

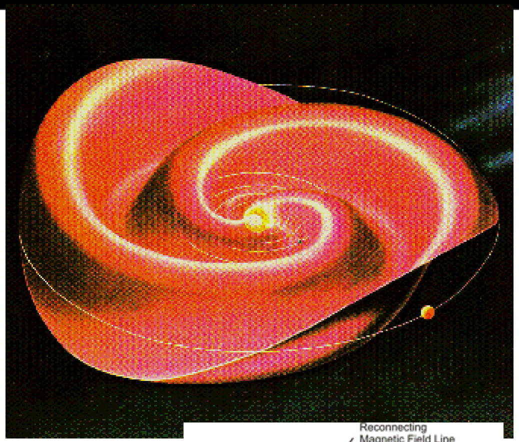
Gusty plasma from the Sun

Mainly H^+, ~4% He^{++}, other fully & multiply ionized ions e.g. O^{6+}, up to Fe

At Earth's orbit conditions variable:

- Density ~10 cm^{-3}
- Speed 300-800 km s^{-1}
- Temperature ~10^5 K
- Magnetic field ~10 nT

Gusty due to solar flares and ICMEs which fling huge amounts (10^{13} kg) of material into space



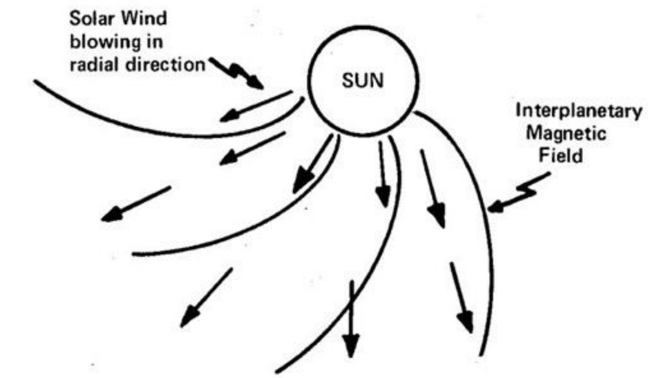
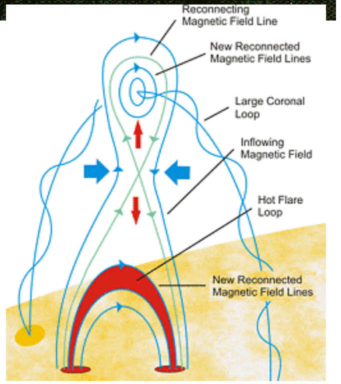
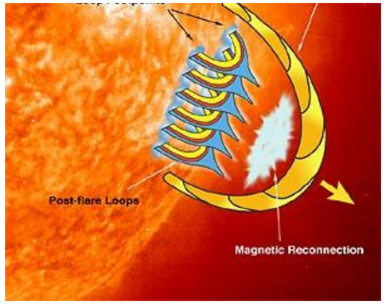


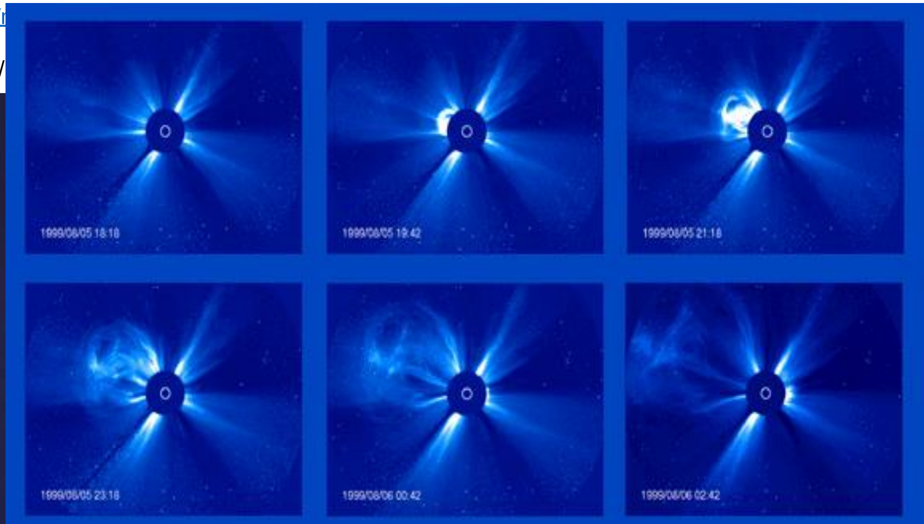
Figure 3.3 Spiral structure of the interplanetary magnetic field resulting from the fact that the ends of the field—being carried outward with the solar wind—remain attracted to the rotating Sun.

From Tascioni Introduction to the space environment

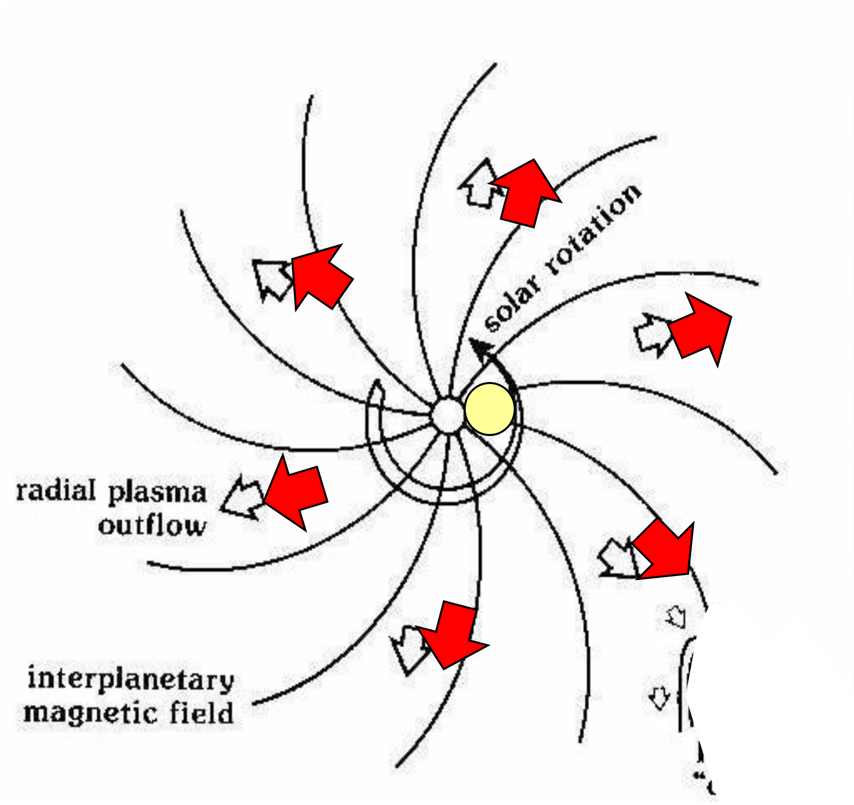




http://science.nasa.gov/
/08/31/
31aug_mms_resources/



Average solar wind conditions



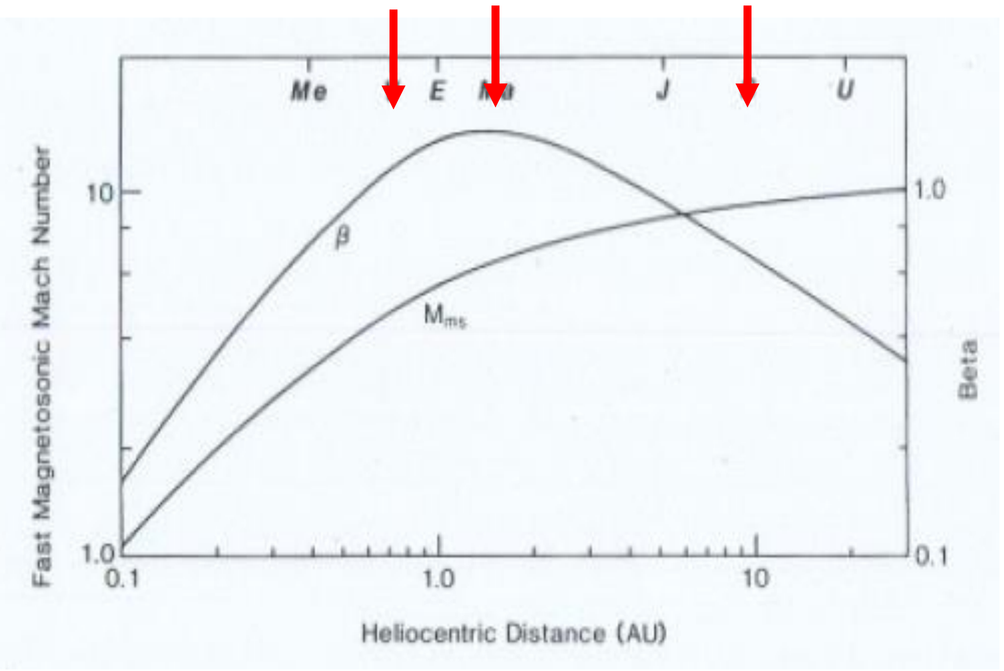


Diagram from Kivelson and Russell

Solar wind density and $B_r \propto R_{AU}^{-2}$, $B_\phi \propto R_{AU}^{-1}$, leading to Parker spiral

Actual conditions highly variable as solar wind conditions change

Interaction of the solar wind with solar system bodies

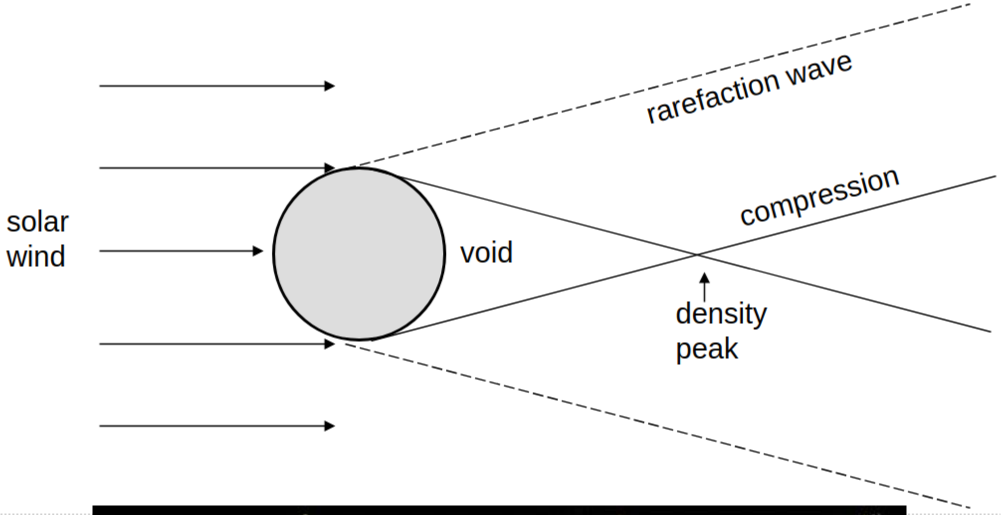
How does the solar wind interact with bodies in the solar system? Four types:

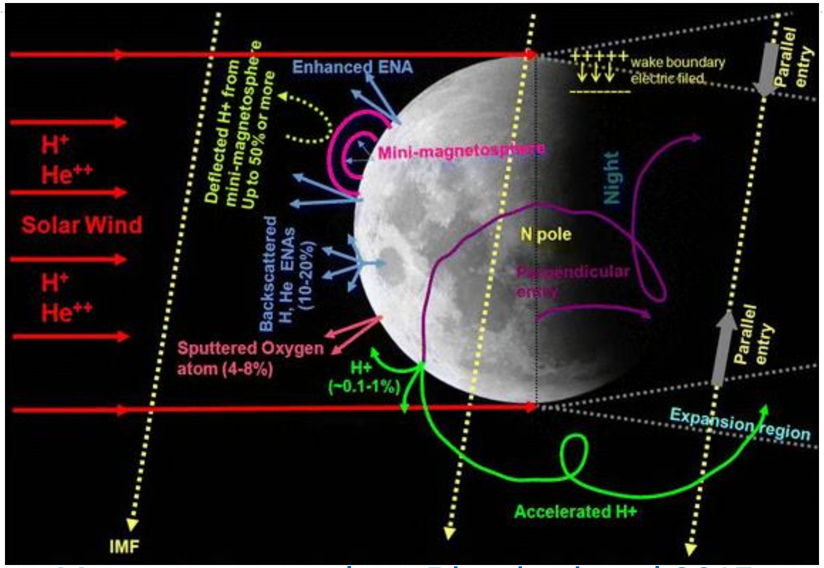
- Inert bodies
- Magnetised bodies
- Bodies without magnetic field but with an atmosphere
- Outgassing objects

Inert bodies

- e.g., asteroids, Earth's moon, spacecraft
- Body absorbs the impacting flow, creates void in its wake
- No shock wave is formed

Illustration of the solar wind impacting with an inert body.





Moon more complex - Bhardwaj et al 2015

The Moon - pickup of reflected and backscattered ions ('self-pickup) Saito et al 2010

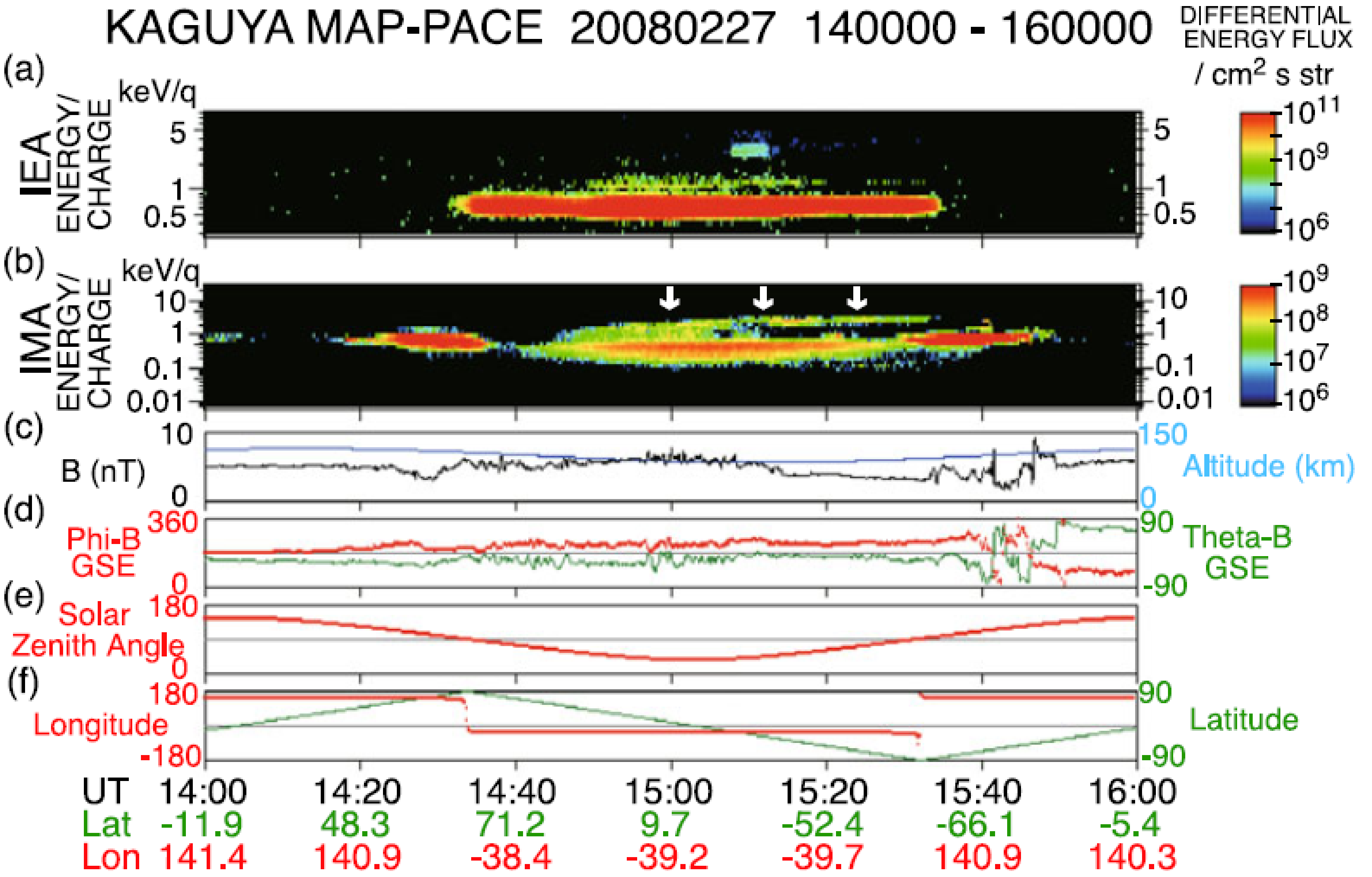
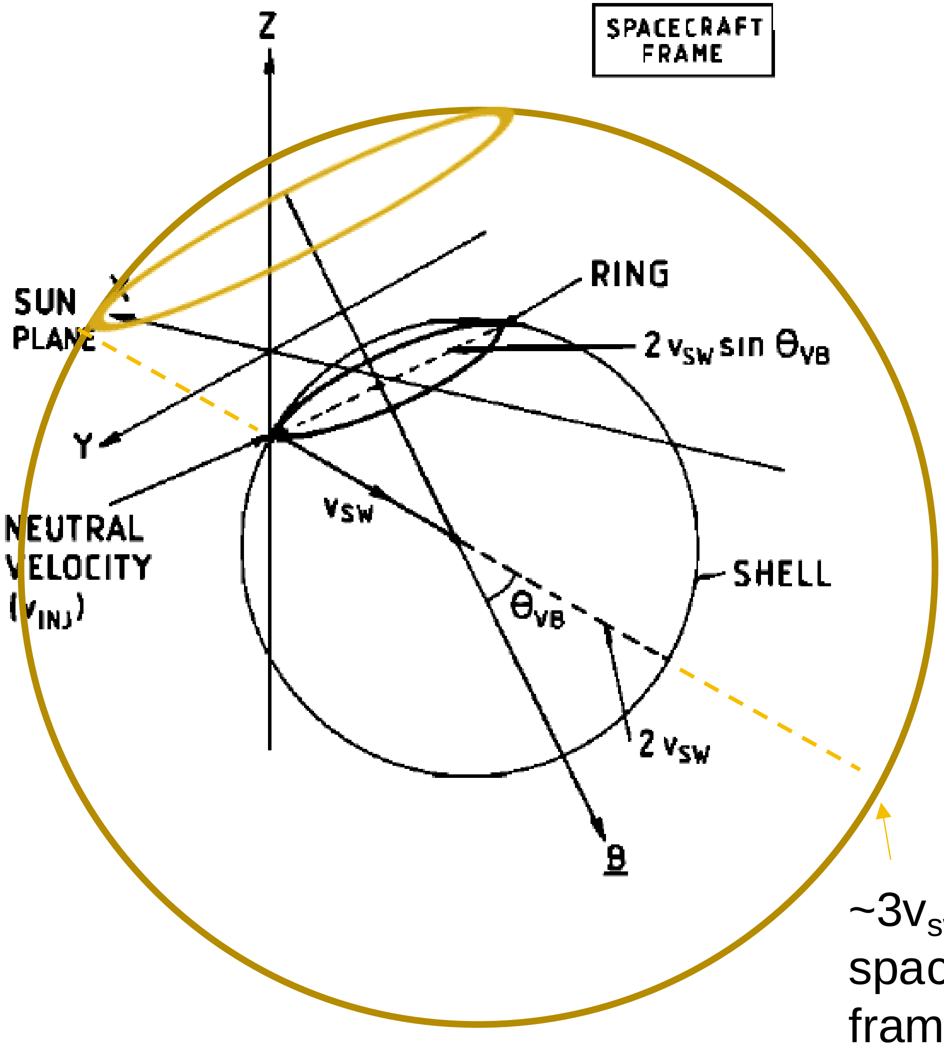


Fig. 26 An example showing self-pickup accelerated ions (indicated by white arrows). The format is the same as Fig. 20



~$3v_{sw}$ in spacecraft frame

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

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

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

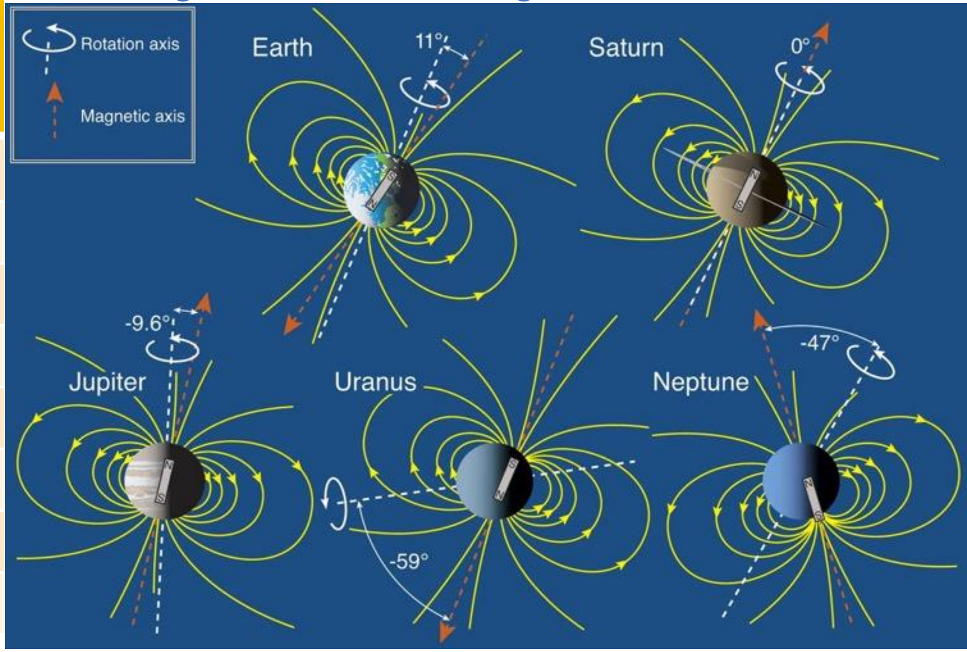
Interaction of the solar wind with solar system bodies

Magnetised bodies

- Mercury, Earth, Jupiter, Saturn, Uranus, Neptune
- Recall Earth's magnetic polarity is such that south magnetic pole is in Northern Hemisphere

	Rotation period (days)	Dipole moment (Earth=1)	Field at equator (uT)	Polarity same as Earth's?	Angle between spin & magnetic axes	Typical magnetopause distance (Rp)
Mercury	58.65	0.0007	0.3	Y	14	1.5
Venus	243.02	<0.0004	0.003	-	-	-
Earth	1.00	1.00	30.5	Y	10.8	10
Mars	1.03	<0.0002	<0.03	-	-	-
Jupiter	0.41	20,000	428	N	9.6	80
Saturn	0.44	600	22	N	<1	20
Uranus	0.72	50	23	N	58.6	20
Neptune	0.67	25	14	N	47	25

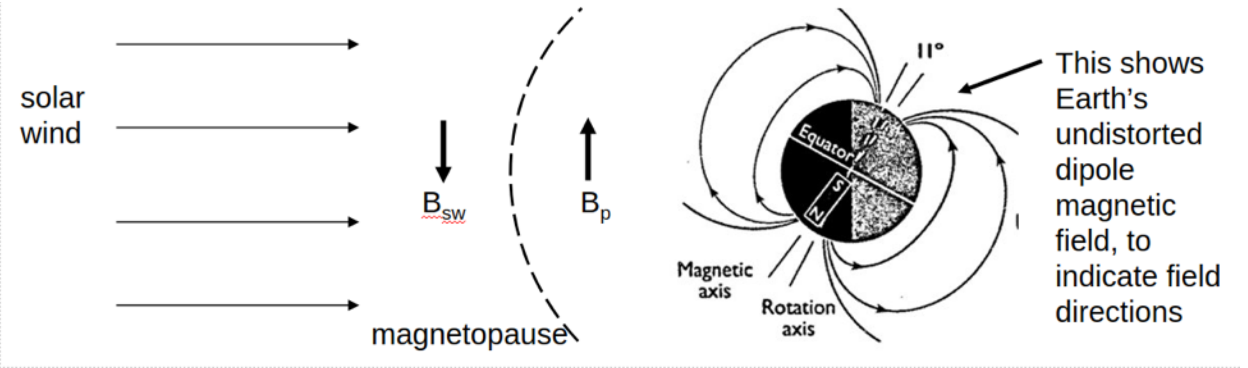
Figure credit Fran Bagenal & Steve Bartlett.

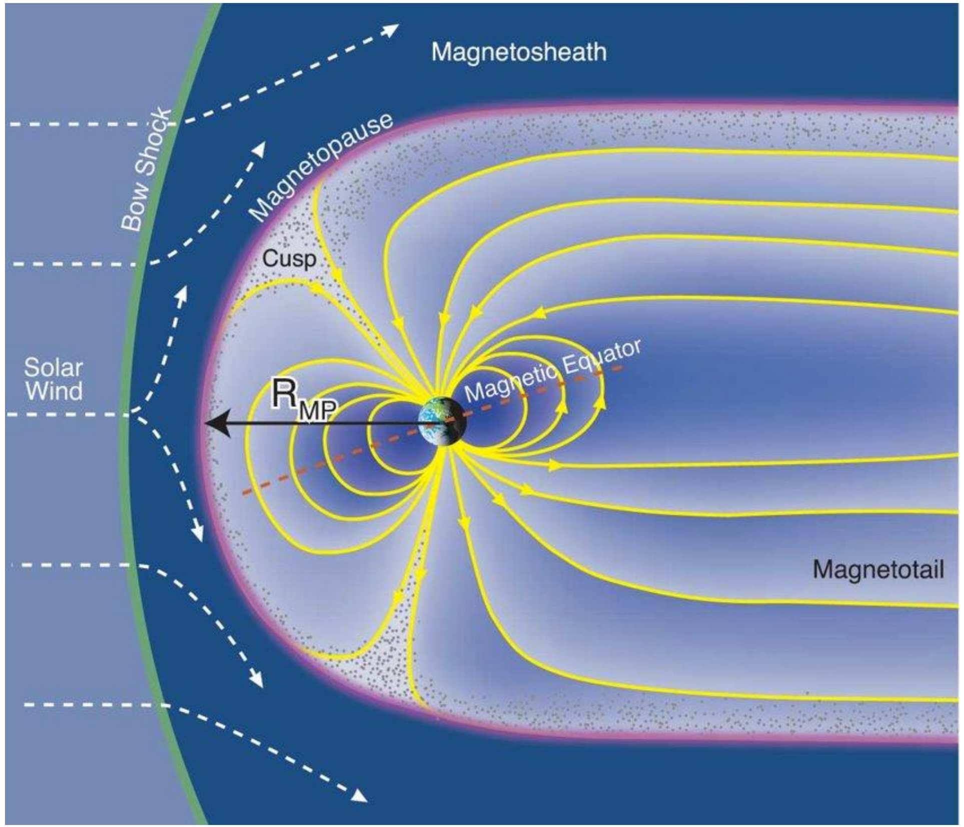


Interaction of the solar wind with solar system bodies

Magnetised bodies

- Solar wind plasma is highly conducting and is deflected by the magnetic field
- Plasma moves from supersonic to subsonic, and thermalises: bow shock.
- Magnetopause boundary forms where magnetic pressure from planetary magnetic field balances the solar wind pressure
- Planet's field is confined to magnetosphere
- In the direction of solar wind flow, magnetic field is increased and compressed
- A long magnetic tail can form (up to 10^6 km)



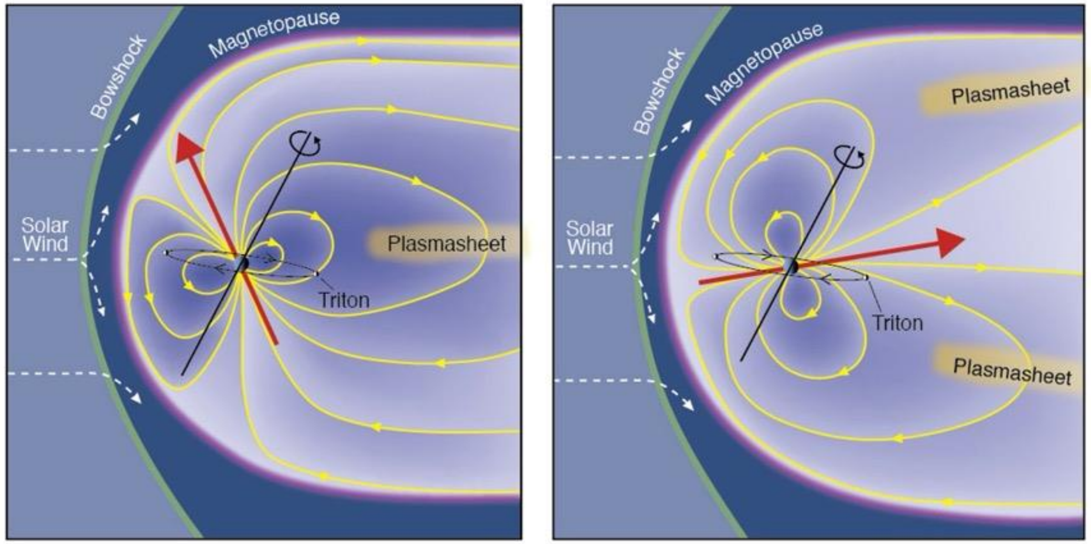


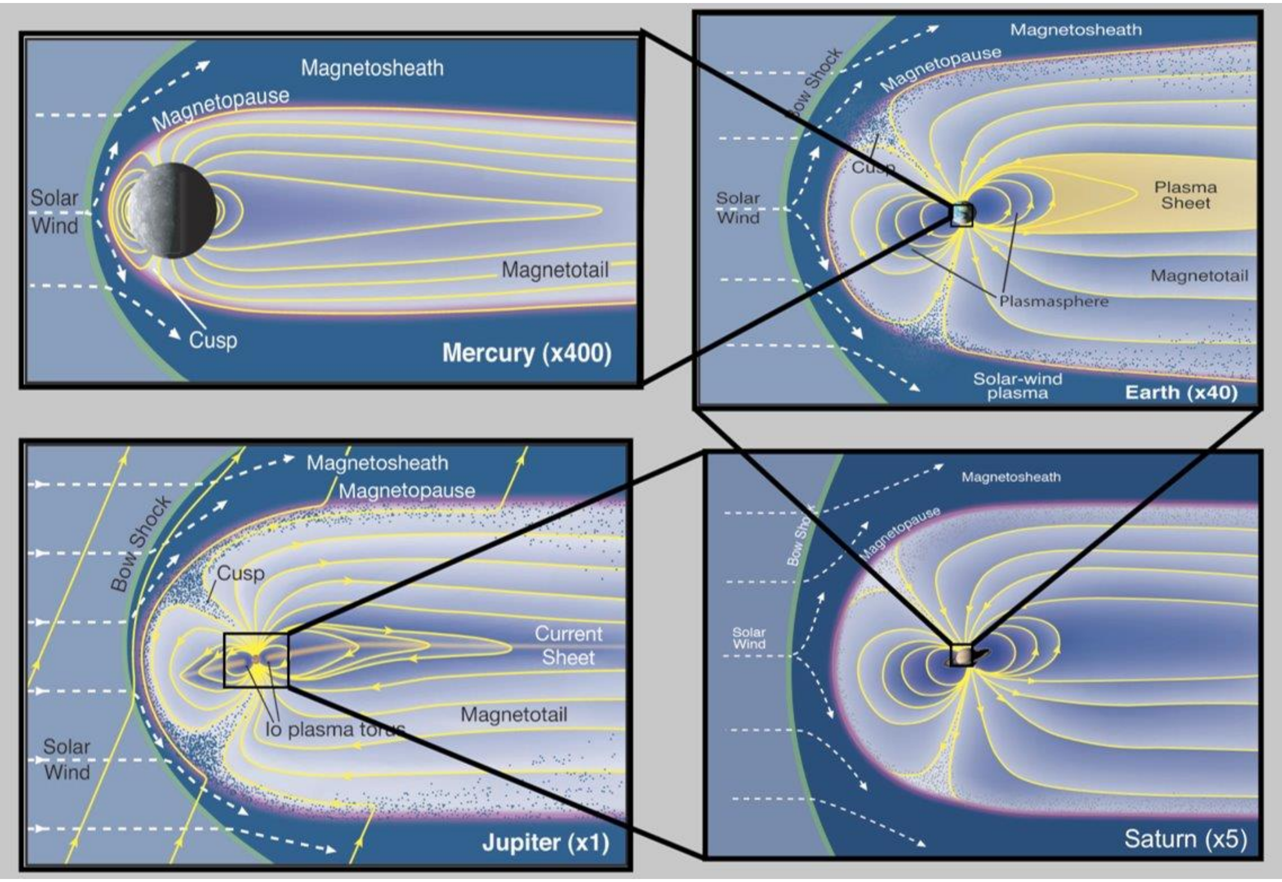
The formation of a bow shock as the solar wind interacts with magnetic field. Figure credit Fran Bagenal & Steve Bartlett.

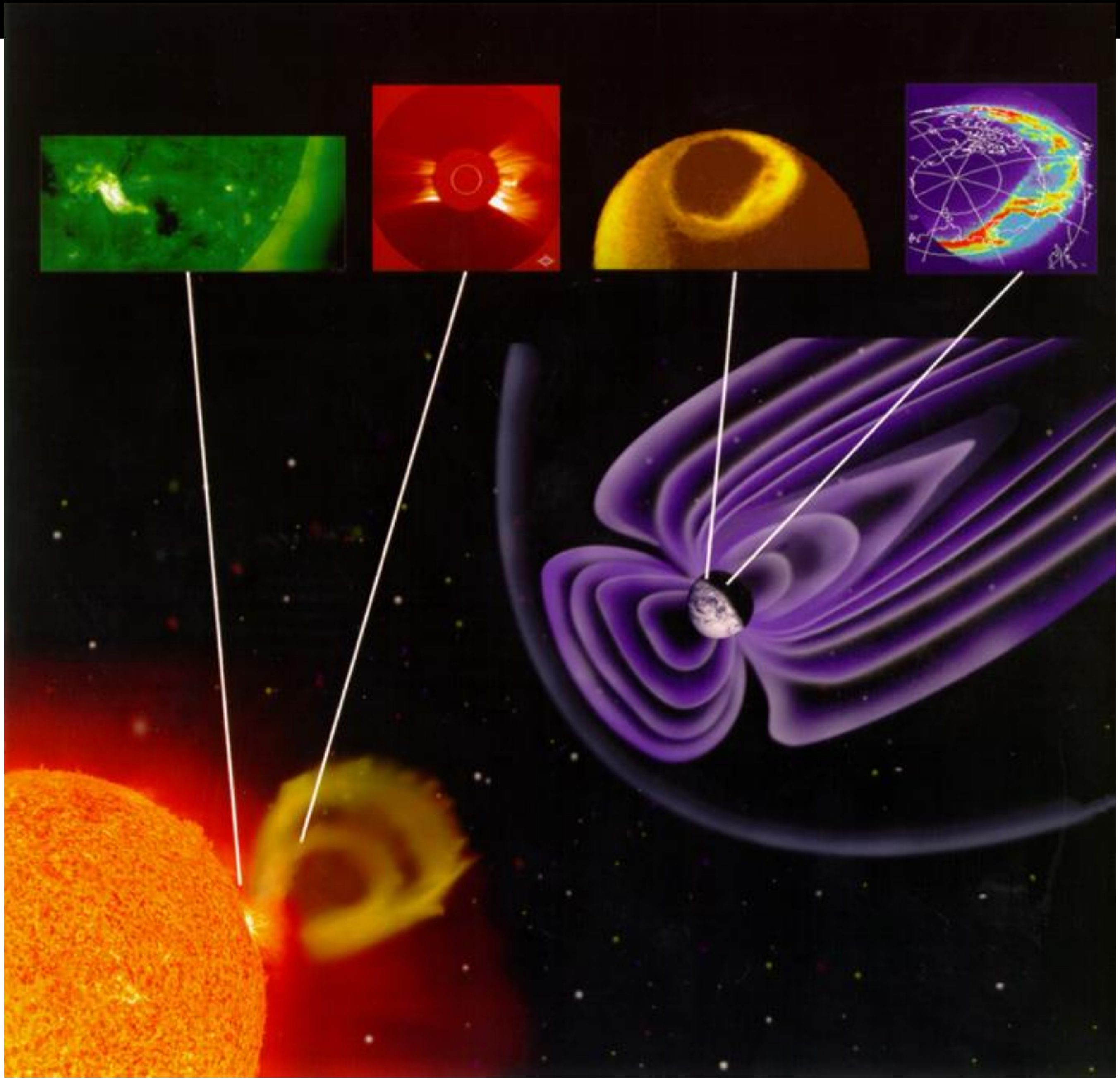
Interaction of the solar wind with solar system bodies

Magnetised bodies

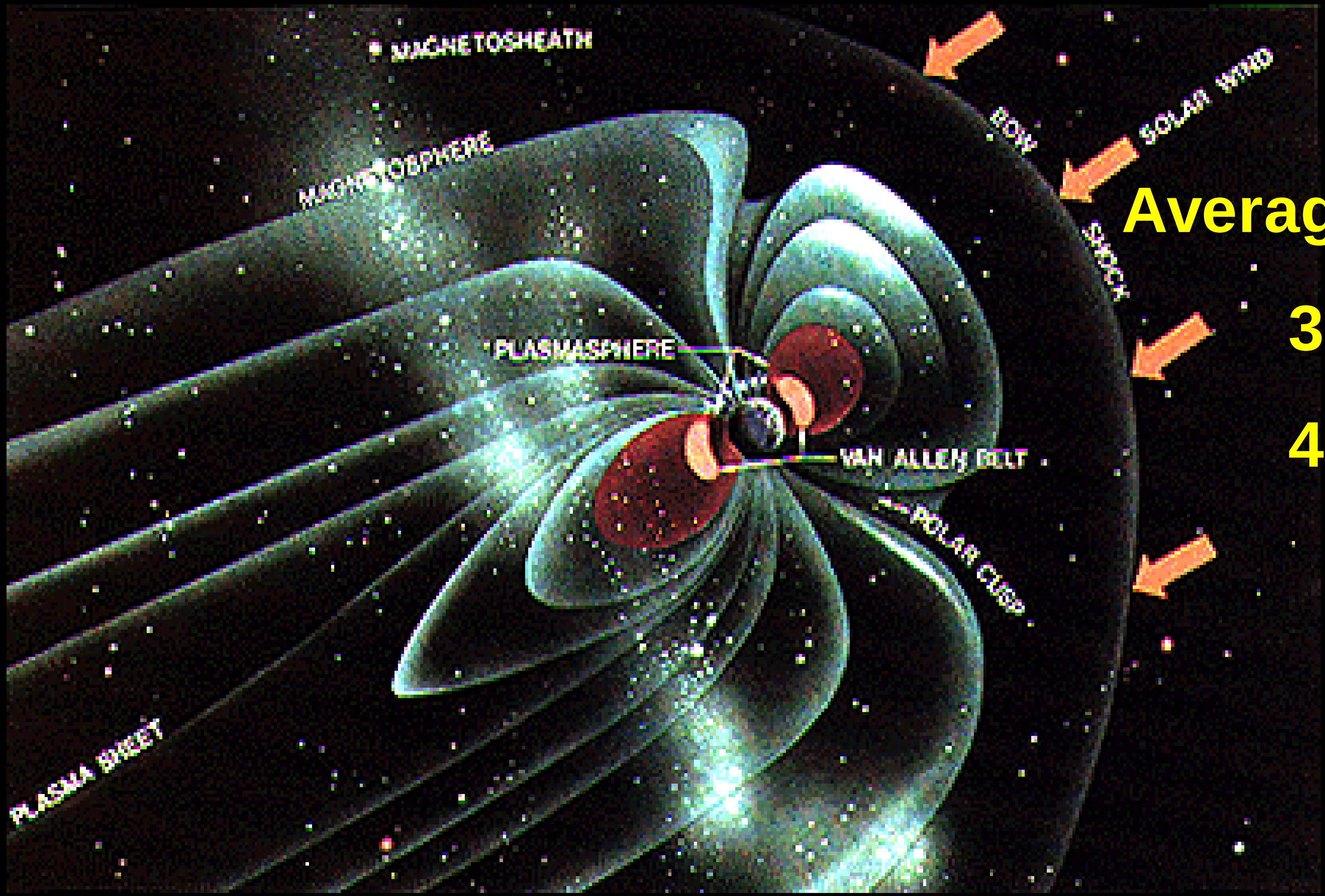
Left figure shows the magnetosphere for Neptune at different phases of rotation. On the right, the sizes of magnetospheres for four different planets are compared (dipolar lines show the planetary magnetic field). Figure credit Fran Bagenal & Steve Bartlett.







Earth's magnetosphere



Average input:

$3x10^{12}$ W

40 kg s^{-1}

Earth's radiation belts: energetic charged particles

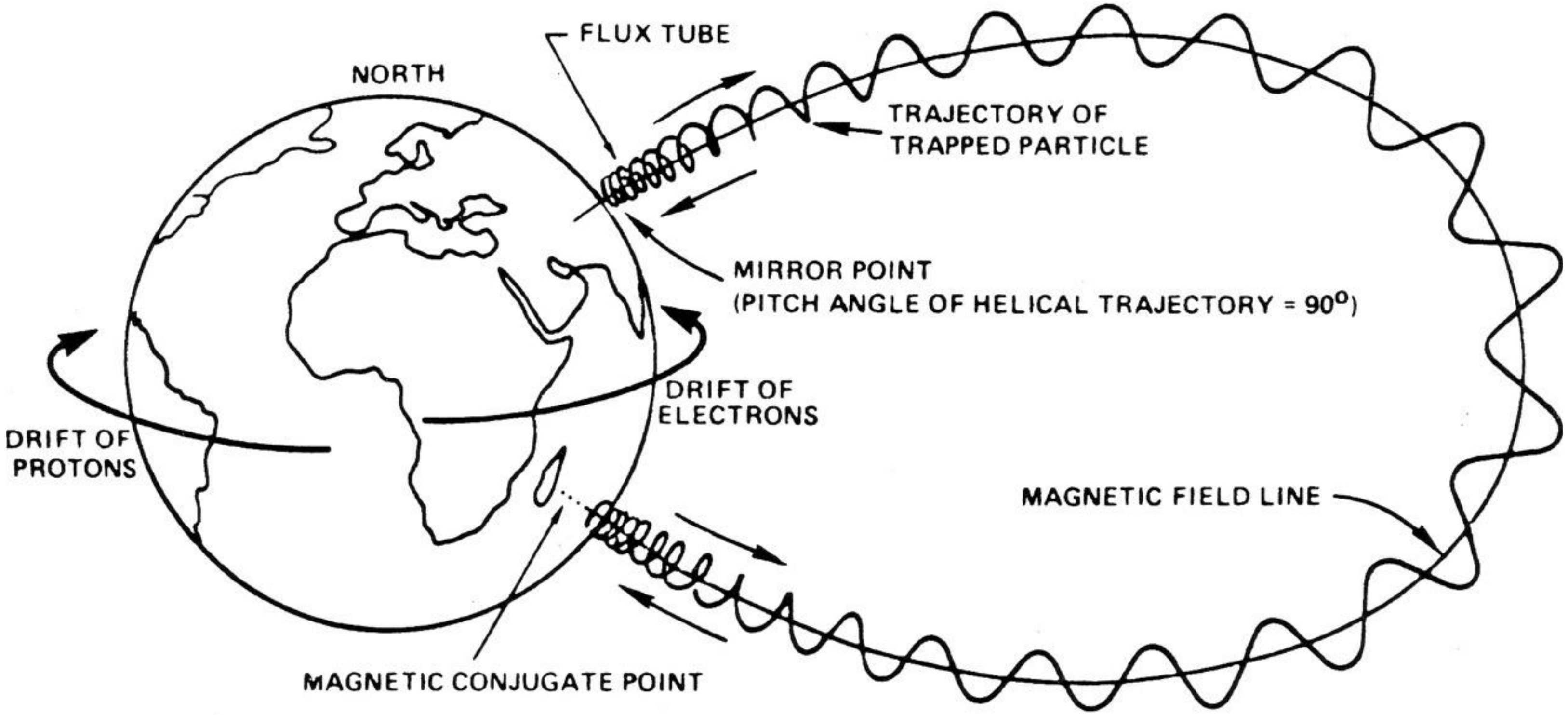


Figure 5-10. A descriptive drawing of the three types of motion of particles trapped in the earth's magnetic field.

Planet. Space Sci., Vol. 33, No. 11, pp. 1267 1275, 1985
Printed in Great Britain.
0032-0633/85 $3.00 + 0.00
Pergamon Press Ltd.

IONOSPHERIC PHOTOELECTRONS OBSERVED IN THE MAGNETOSPHERE AT DISTANCES UP TO 7 EARTH RADII

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Mullard Space Science Laboratory, Department of Physics and Astronomy, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, U.K.

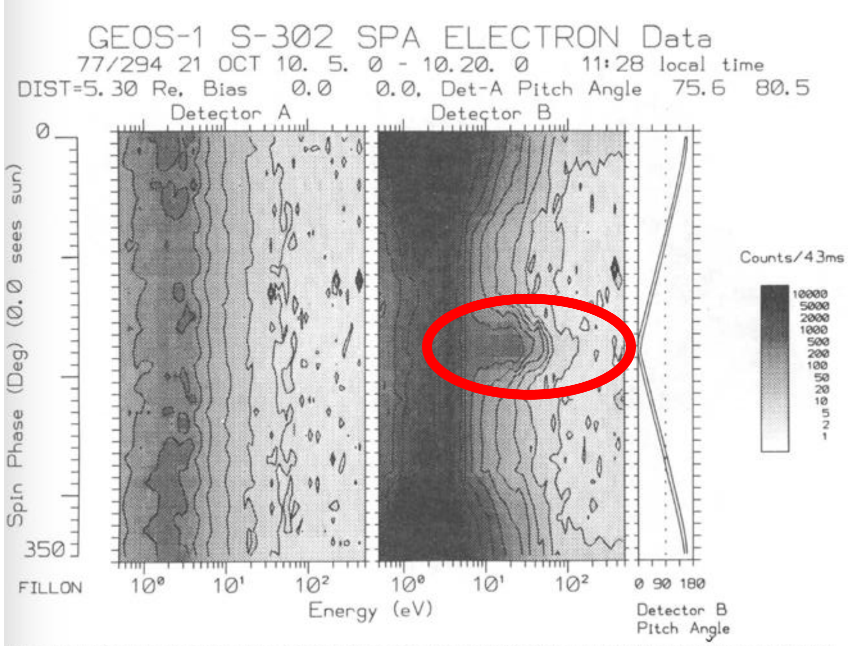

FIG. 1. GREY-SCALED COUNT SPECTROGRAMS FROM ANALYSER A (LEFT PANEL) AND ANALYSER B ON GEOS-1, WITH SPIN PHASE AS THE ORDINATE AND ENERGY THE ABSCISSA.
The analyser B pitch angle variation is shown on the right side of the two spectrograms. Analyser B, which views nearly perpendicular to the spin axis, sees photoelectrons at zero pitch angle.

1985 - Ionospheric photoelectrons seen at 7 R_E – gives upper limit of 2V for ambipolar potential driving polar wind

Article

Earth's ambipolar electrostatic field and its role in ion escape to space

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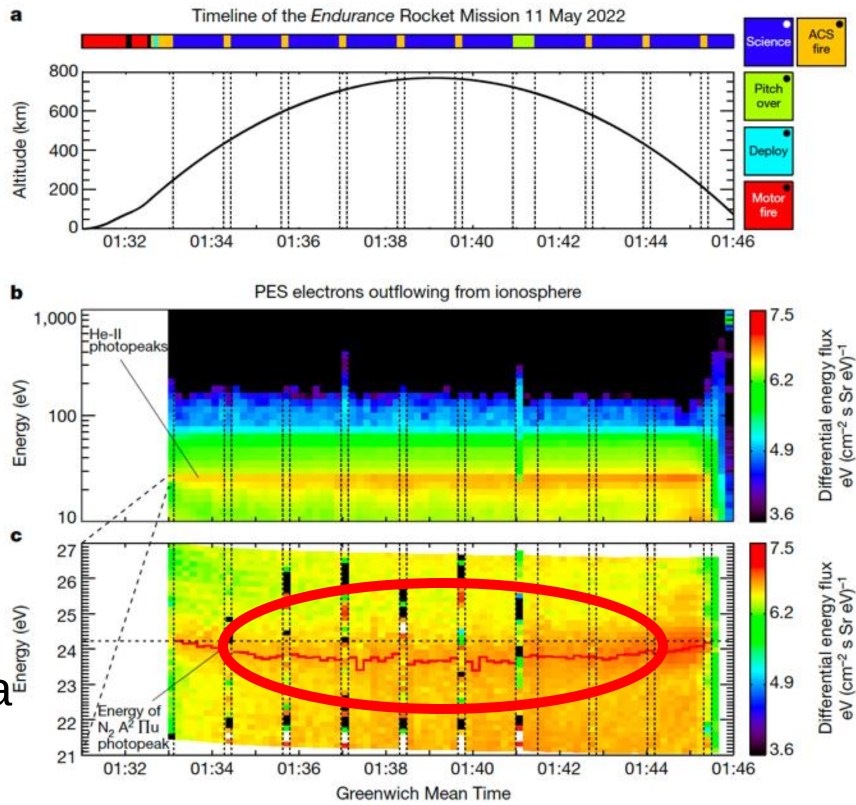
Glyn A. Collinson[1,2,3], Alex Glocer[1], Robert Pfaff[1], Aroh Barjatya[4], Rachel Conway[4], Aaron Breneman[1], James Clemmons[5], Francis Eparvier[6], Robert Michell[1], David Mitchell[7], Suzie Imber[8], Hassanali Akbari[1,2], Lance Davis[4], Andrew Kavanagh[9], Ellen Robertson[1], Diana Swanson[5], Shaosui Xu[7], Jacob Miller[1,10], Timothy Cameron[1], Dennis Chornay[1], Paulo Uribe[1], Long Nguyen[1], Robert Clayton[4], Nathan Graves[4], Shantanab Debchoudhury[4], Henry Valentine[4], Ahmed Ghalib[11] & The Endurance Mission Team*

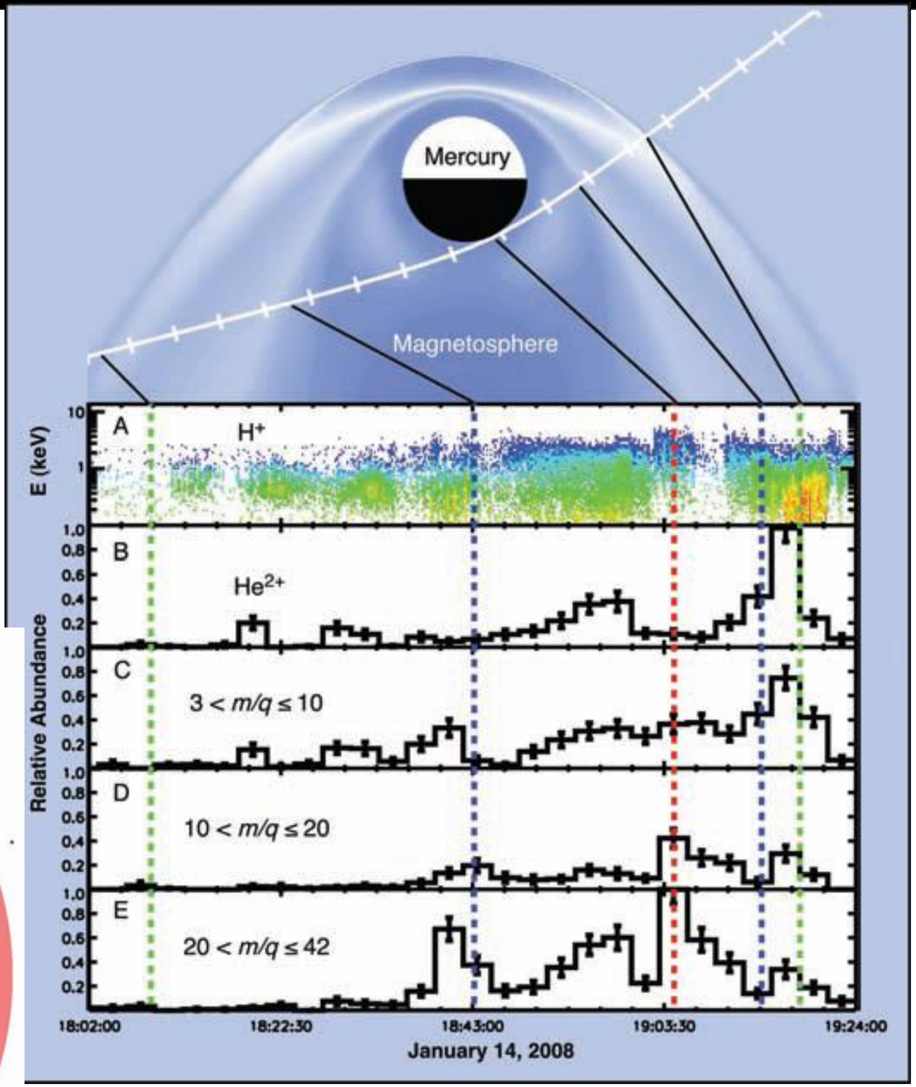
Nature,
28 August 2024



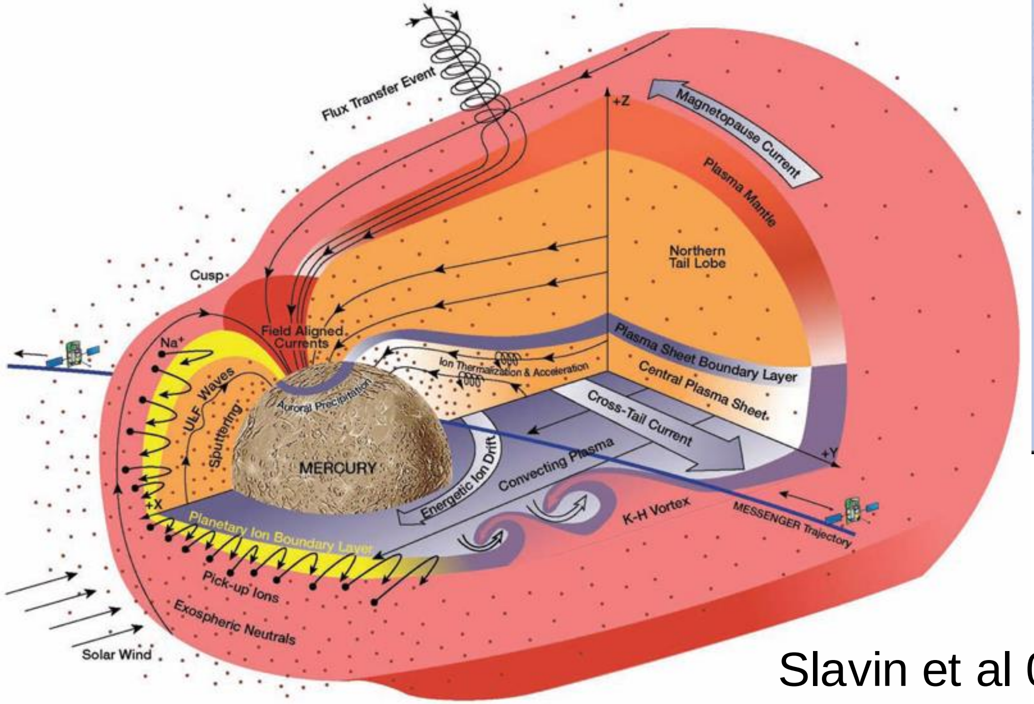
2024 - NASA Endurance rocket led by ex-PhD student Glyn Collinson (GSFC) measures ambipolar potential ~0.55 V – source of cold plasma in magnetosphere

Mercury

- Very small magnetosphere, no radiation belts
- Heavy pickup ions from surface sputtering by magnetospheric or solar wind particles

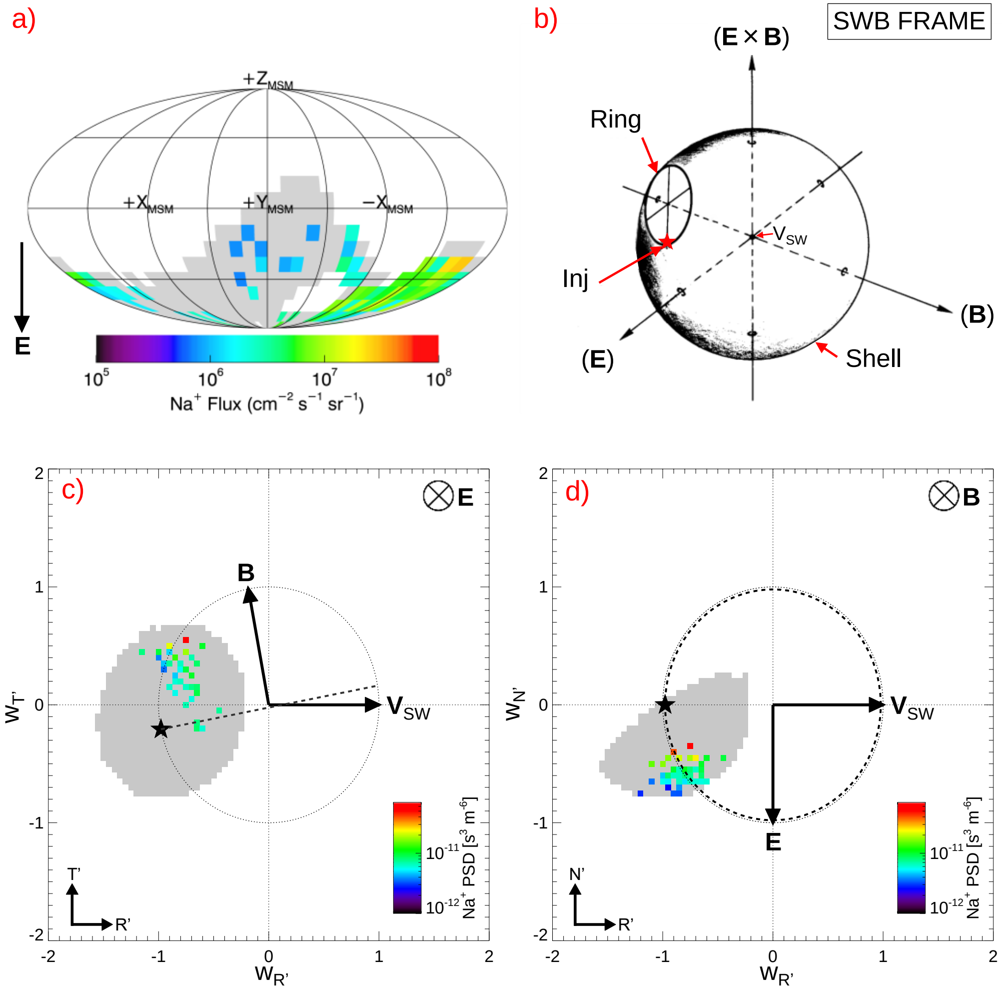


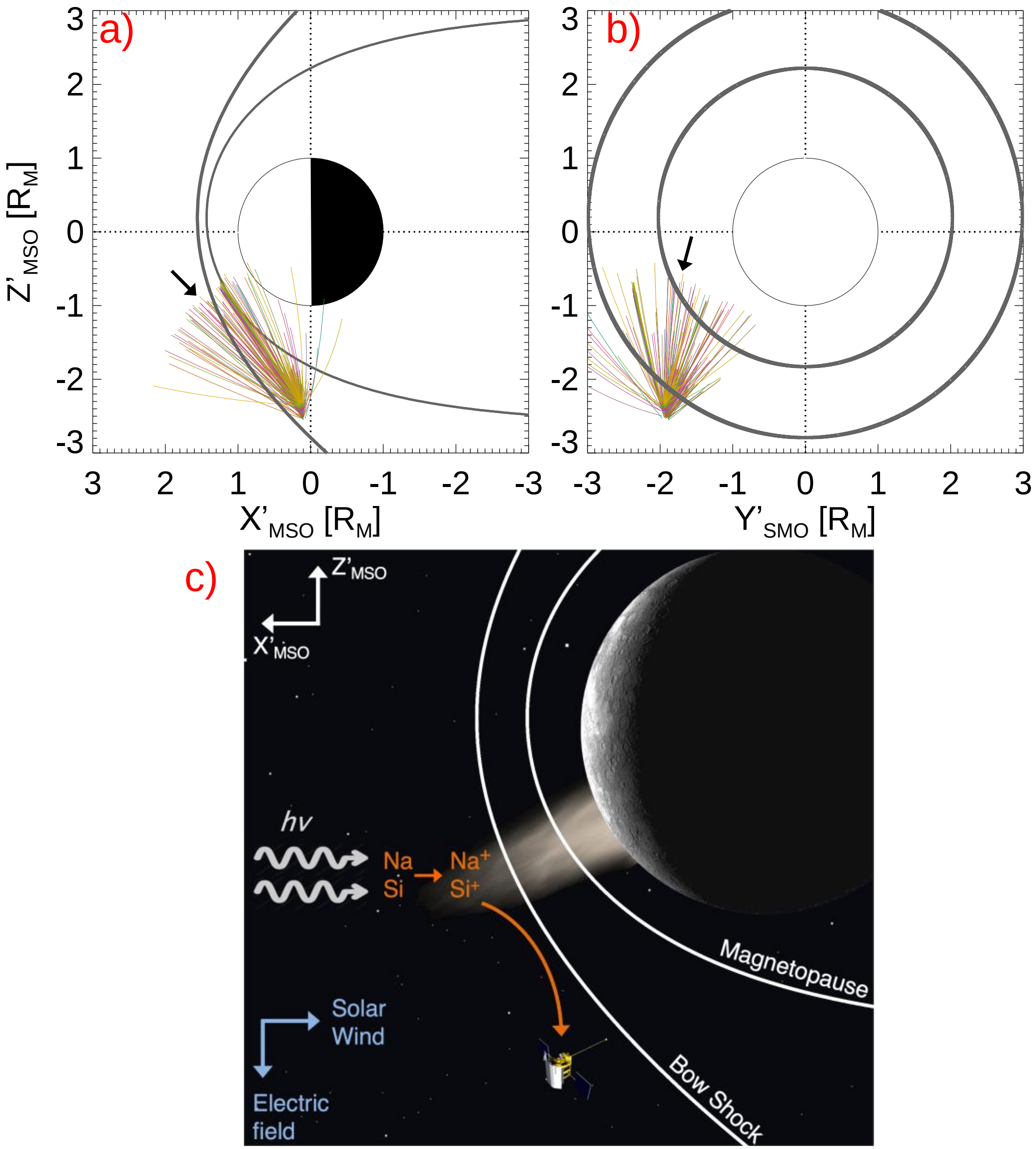
Zurbuchen et al 08



Slavin et al 08

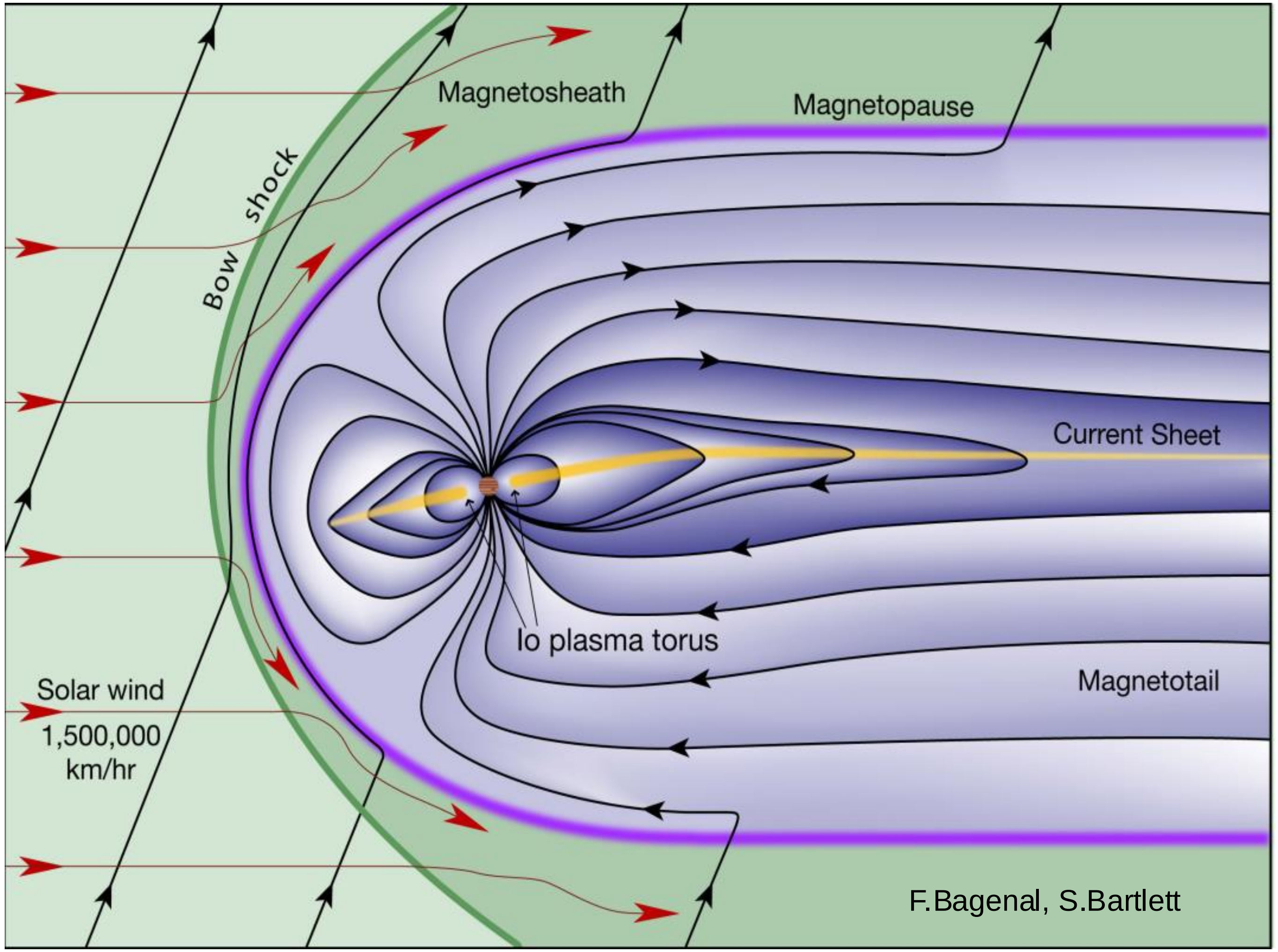
Early stage pickup at Mercury From meteor impact on surface
Jasinski et al., Nat. Comm., 2020

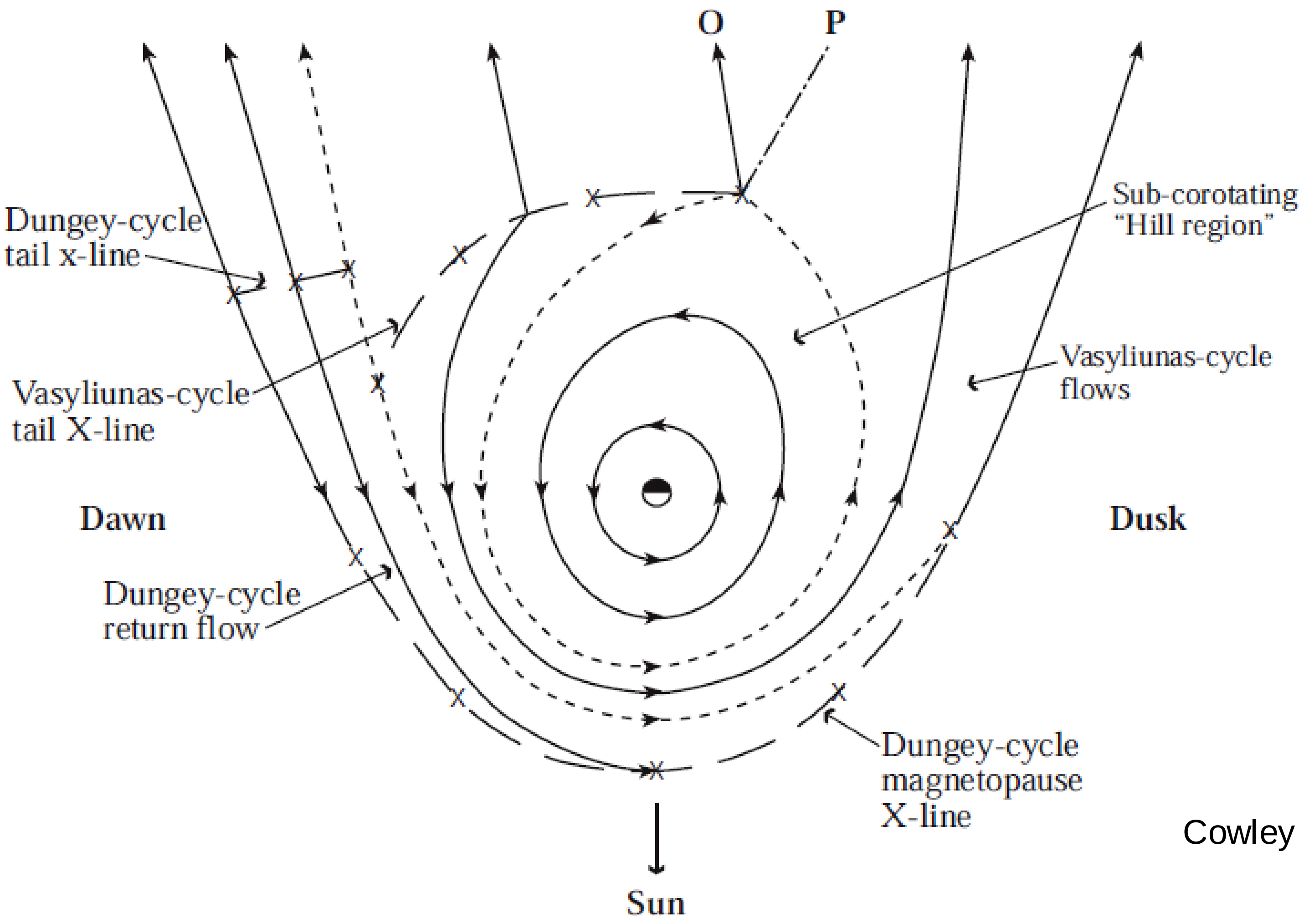




Jupiter’s magnetosphere

- Rapidly rotating magnetosphere
- Filled with sulphur from Io’s volcanoes, water and oxygen from ice
- Slowly turned into sulphur, oxygen, water ions
- Ions are picked up by the rapidly rotating magnetosphere and eventually lost into the solar wind



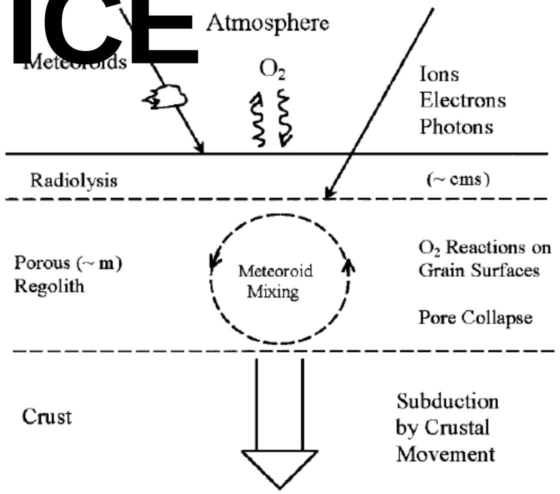


Cowley et al., 2003

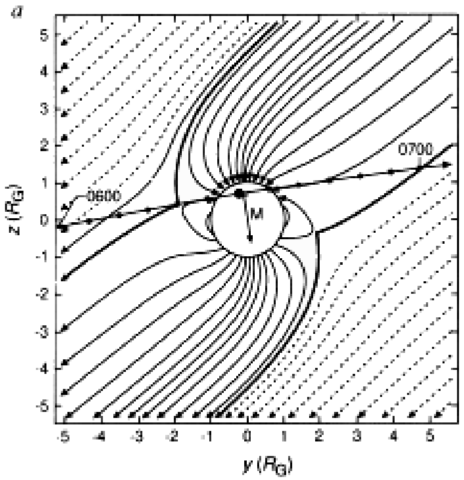
Solar wind-driven and rotation-driven reconnection?

Ganymede & Europa: JUICE

- Weak, O_2/H_2O atmospheres
- Ganymede – magnetosphere within a magnetosphere
- Ionospheres present
- Upstream plasma conditions key for interaction
- Pickup ions can give information on exosphere and surface composition



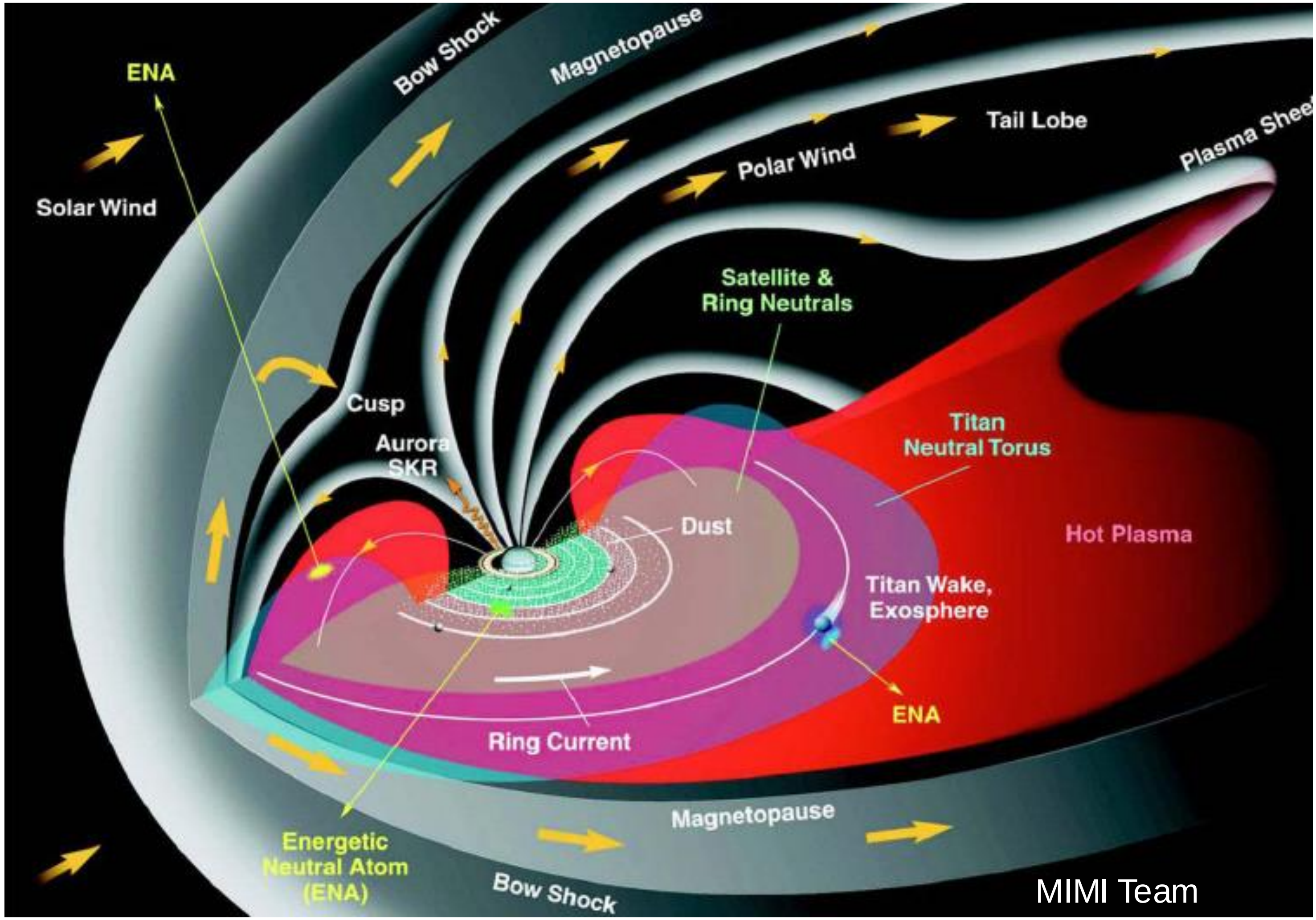
Johnson et al 2003



Khurana et al 1996

Saturn’s magnetosphere

- Rapidly rotating
- Filled with **water-group molecules** (O, OH, H_2O, H_3O) from the major sources (Enceladus, main rings, others)
- Slowly turned into **water-group ions.**
- Ions are picked up by the rapidly rotating magnetosphere and eventually lost



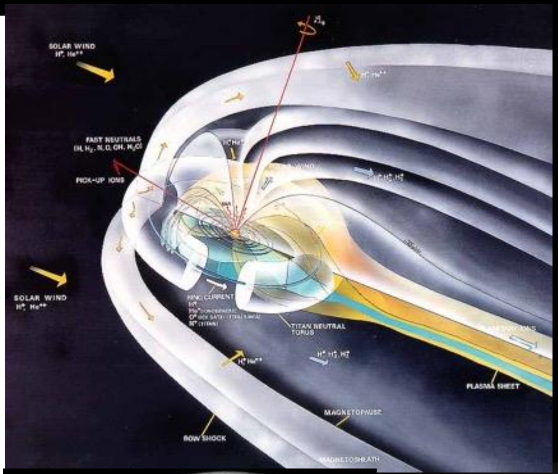
MIMI Team

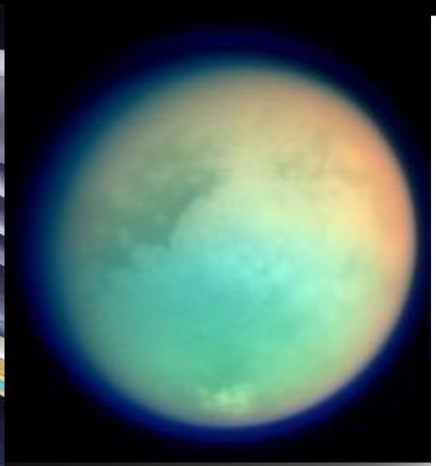
Titan

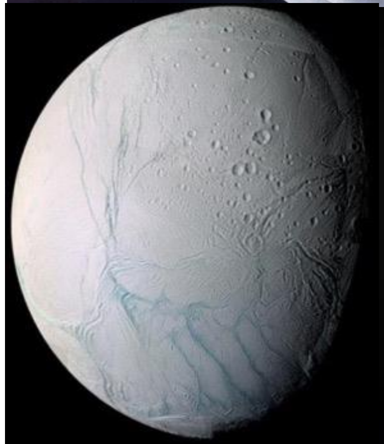
- Magnetosphere: M_{ms}<1, no shock. Draping, wake

Icy satellites

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



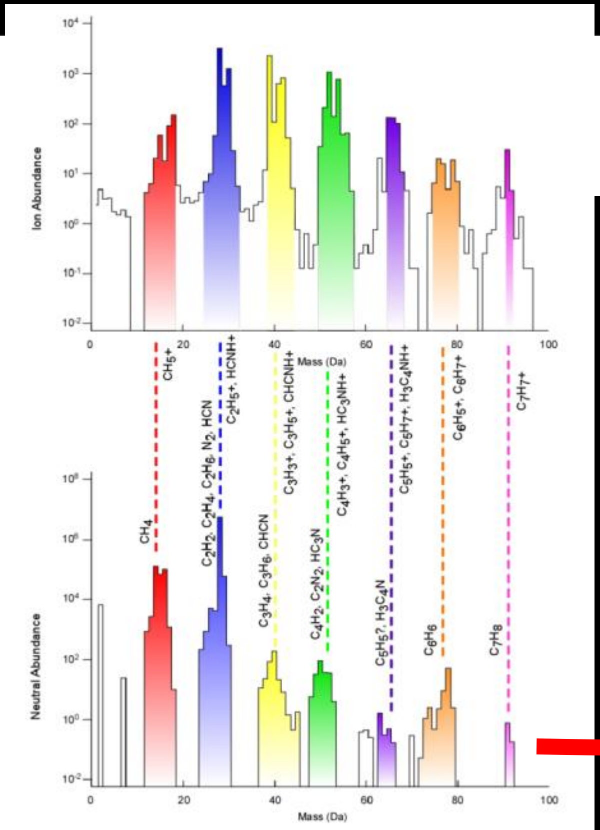




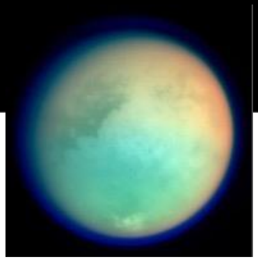
Titan's atmosphere: a rich chemical environment revealed by Cassini

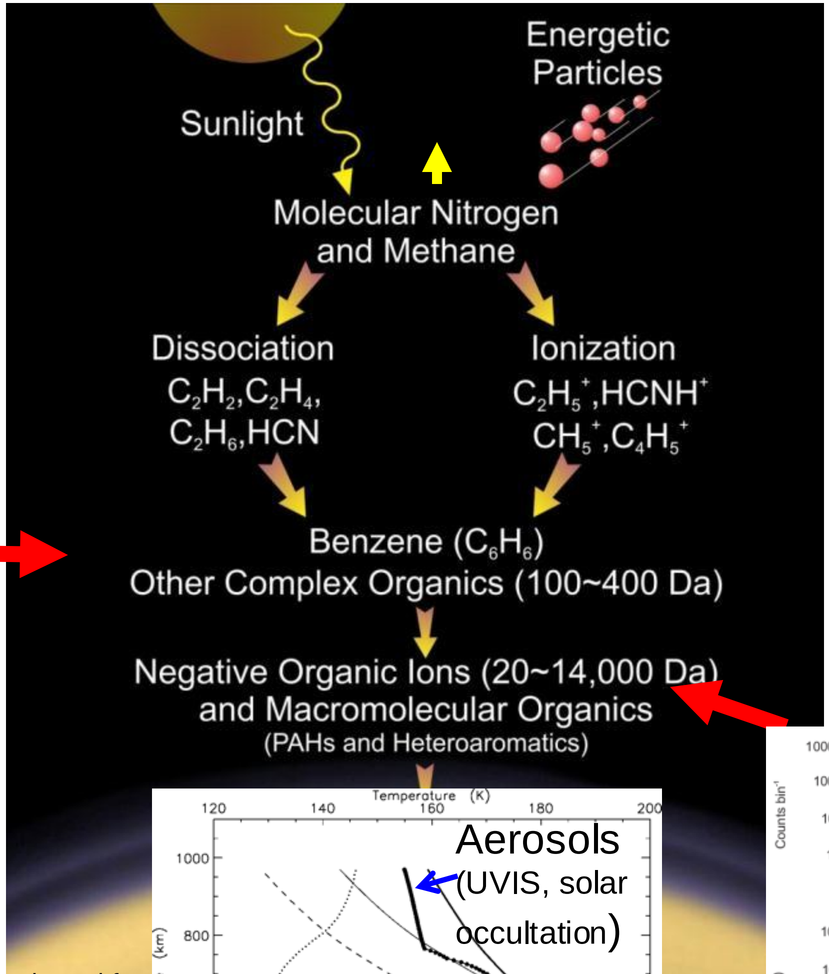
Unexpected heavy **anions**: Coates+ 2007, 2009, 2010, 2011, Wellbrock+ 2013, Sittler+ 2009, Vuitton+ 2009, Michael+ 2011, Lavvas+2012, Ali+ 2015, Lindgren+ 2017, Desai+ 2017, Mukundan & Bhardwaj 2018, Dubois+, 2019, Wellbrock+2019, Haythornthwaite+ 2021

Escape - Coates et al 2012, 2016

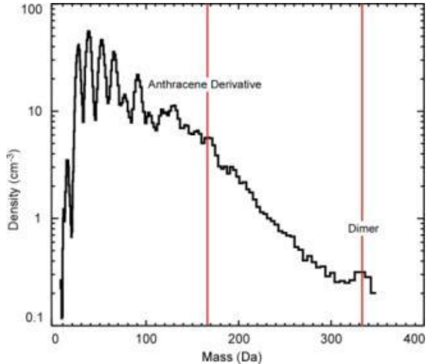


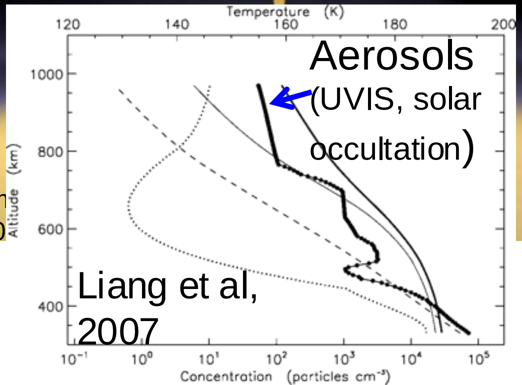
Heavy **neutrals and positive ions**: Waite et al, 2007, Crary et al 2009



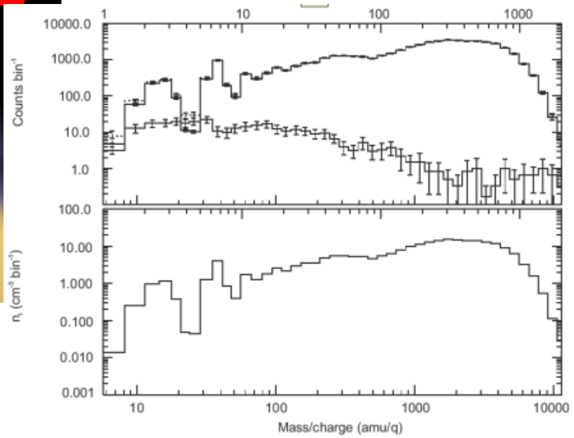


Adapted from Waite et al 07





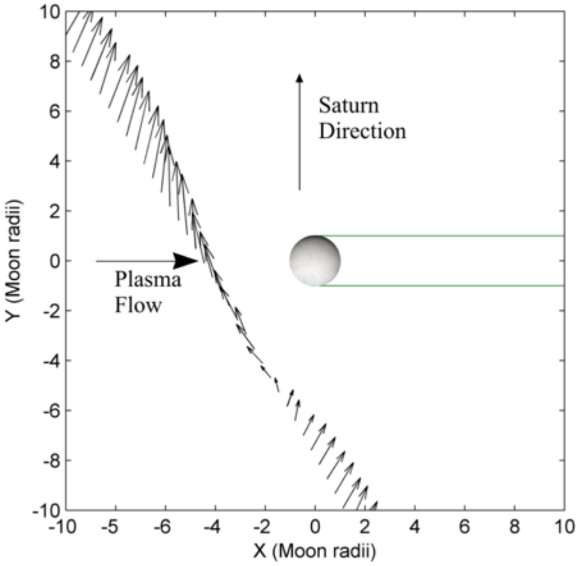
Liang et al, 2007

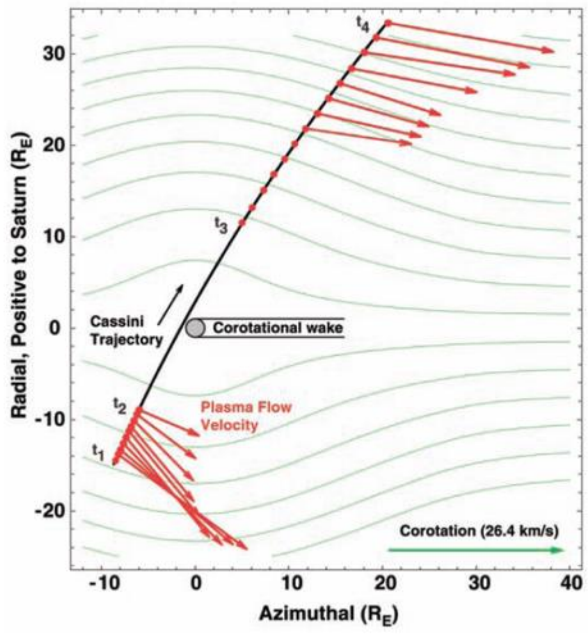


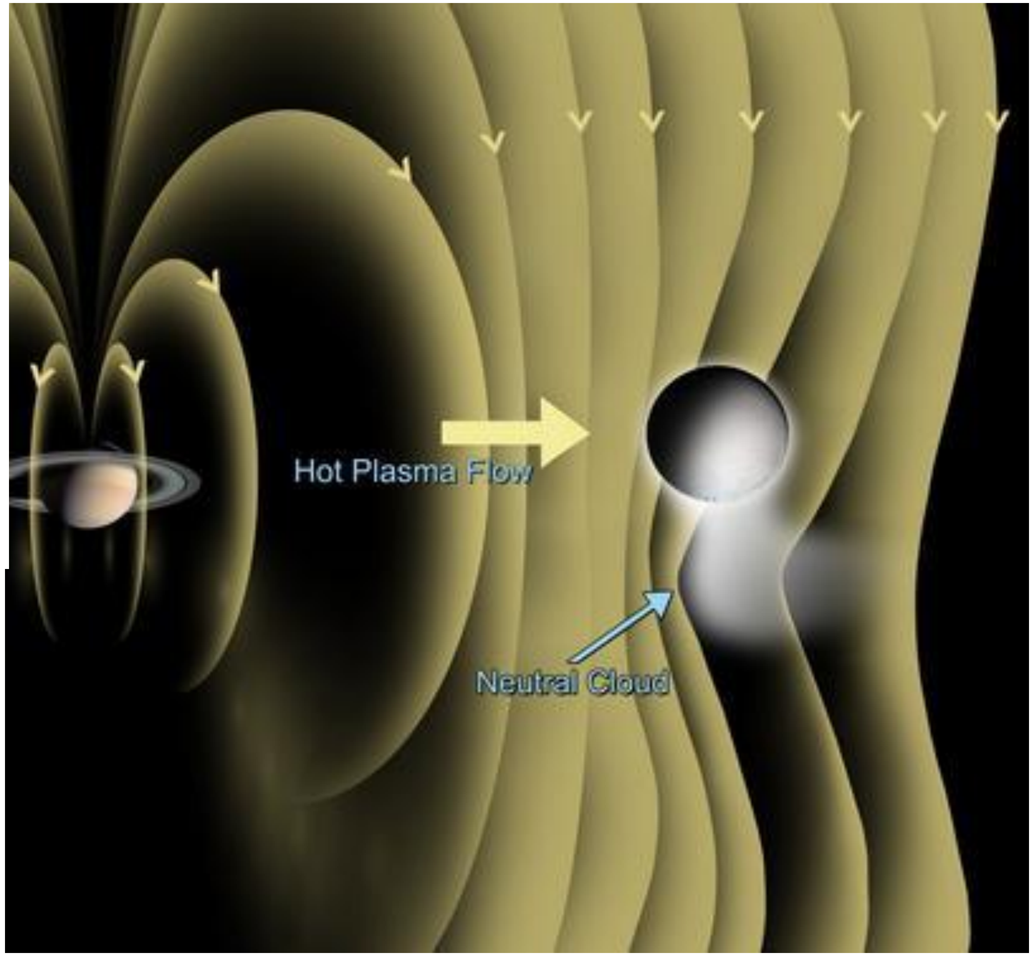
Titan space weather effects

- Mostly inside Saturn’s magnetosphare
- Dependent on upstream conditions
- Encounters at different local times and positions within magnetosphere – building up picture of hoe interaction varies with conditions
- Heating of upper atmosphere
- Photoelectron production
- Production of heavy hydrocarbons, positive and negative ions – seed particles for aerosols, tholins
- Escape of Titan atmosphere
- Nitrogen isotope ratio (INMS – Waite et al.) indicates loss over time
- Observations in tail (Coates et al., 2012) indicate significant loss of Titan atmosphere (7 tonnes/day average)

Enceladus plume discovery

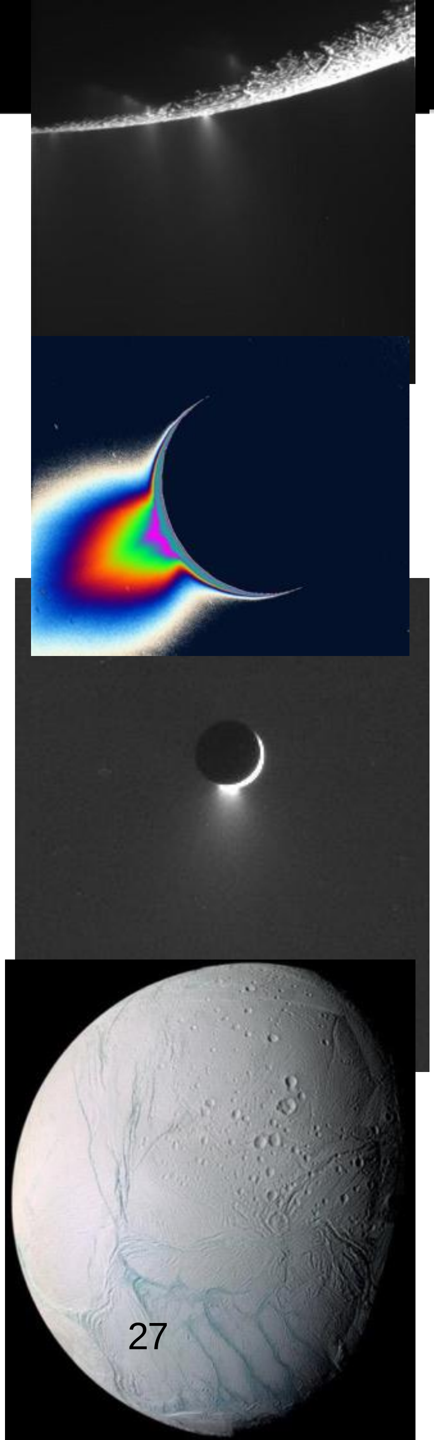


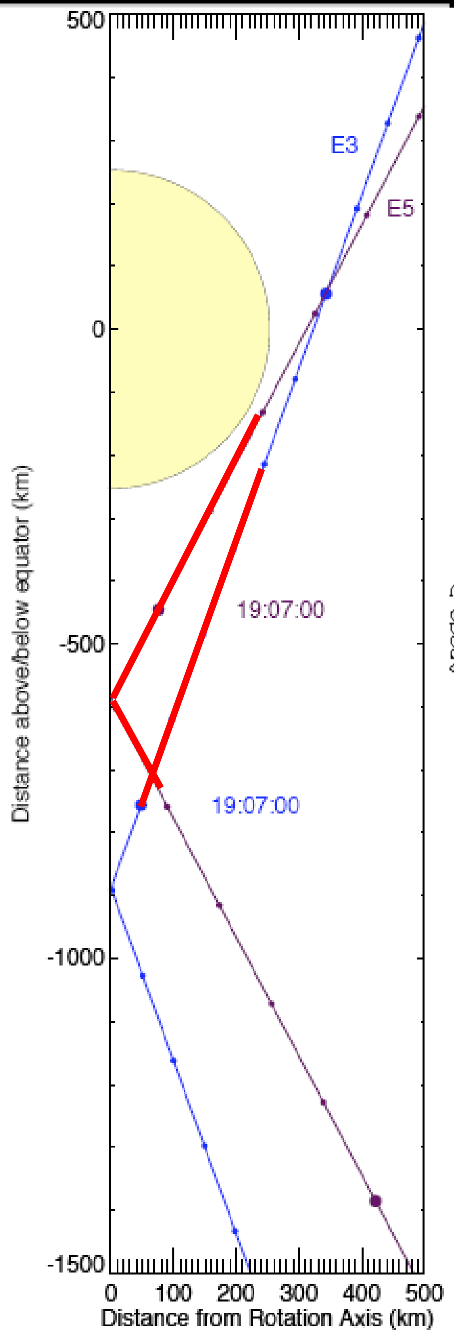




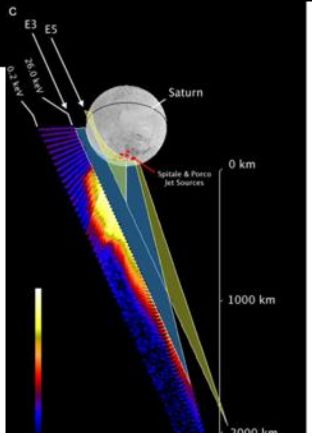
Magnetometer data (Dougherty et al 2006)

Plasma data showed production rate ~ 100 kg/s (Tokar et al., 2006)

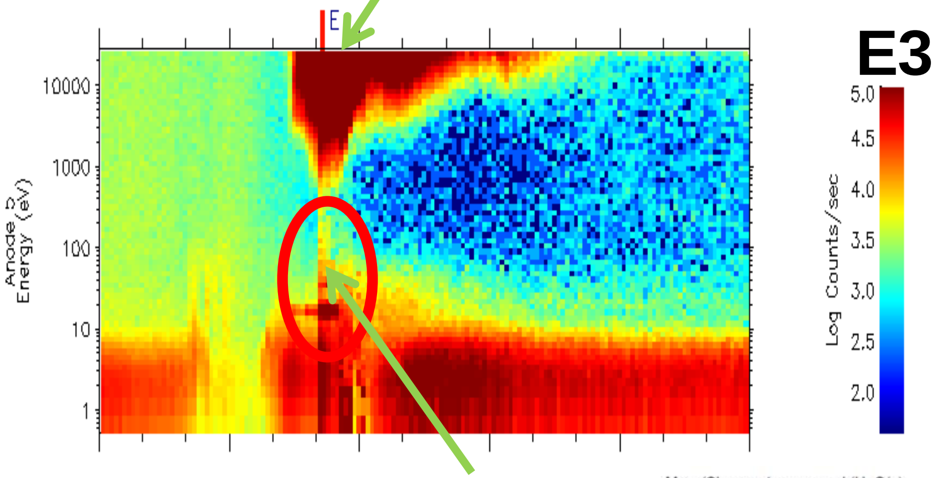




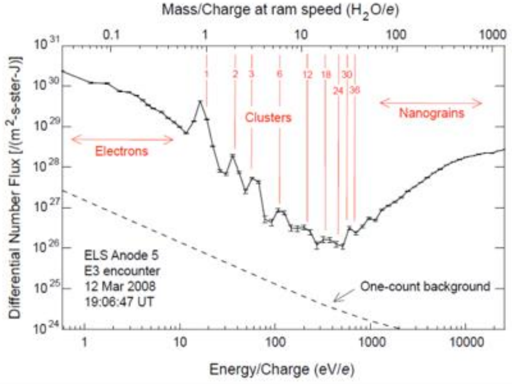
Unexpected discoveries from Cassini at Enceladus



Charged nanograins
Jones et al., GRL, 2009,
Hill et al., 2012



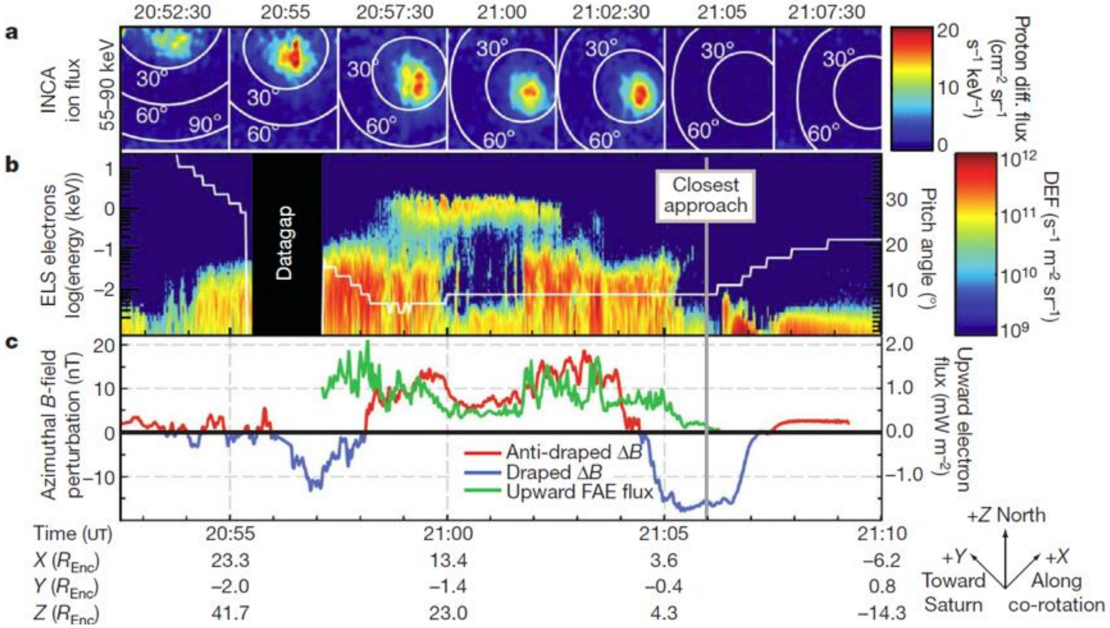
Negative ions
in the plume

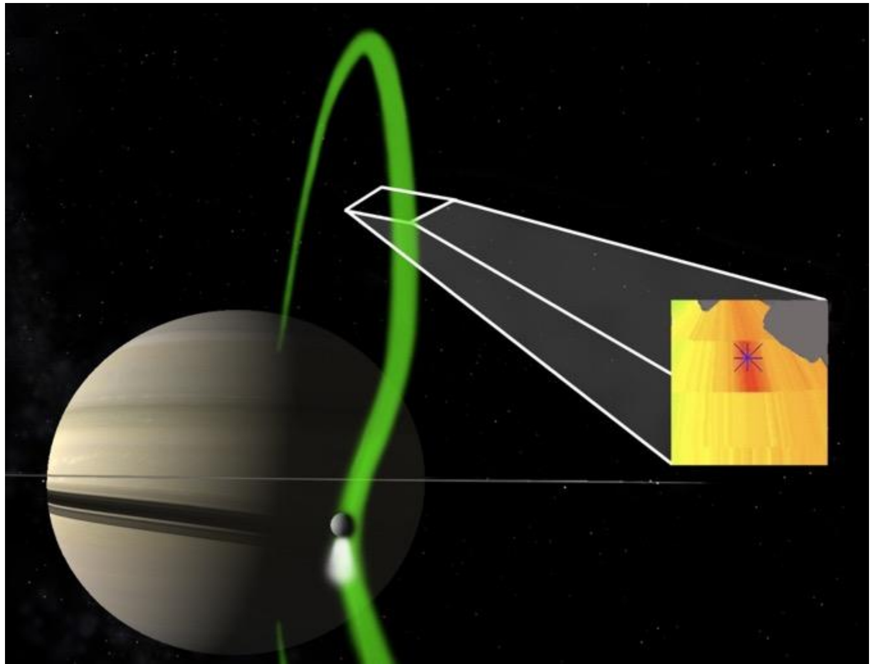


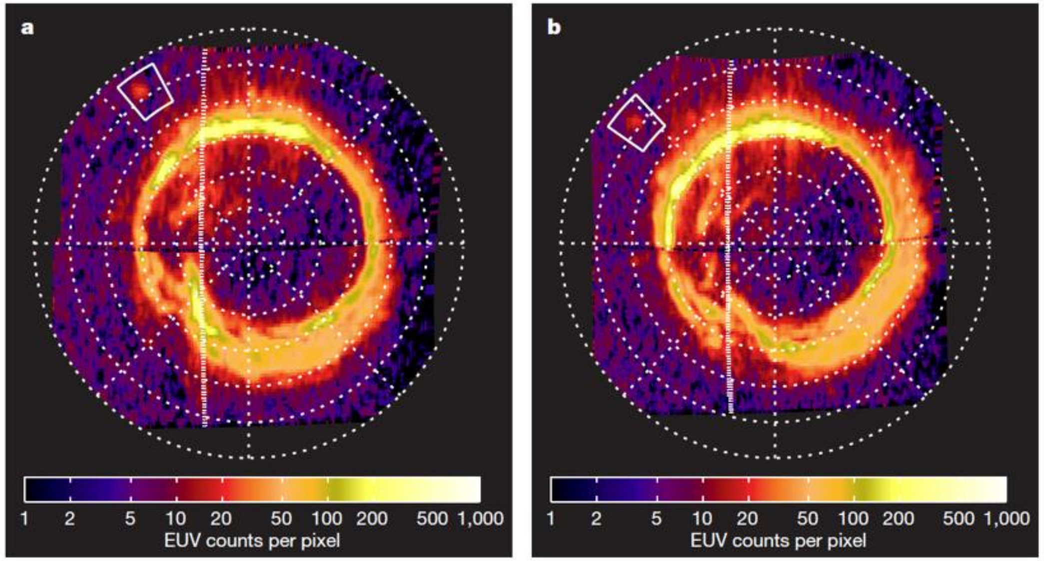
Coates et al., Icarus 2010,
Faraday Discussions 2010

Enceladus' auroral spot

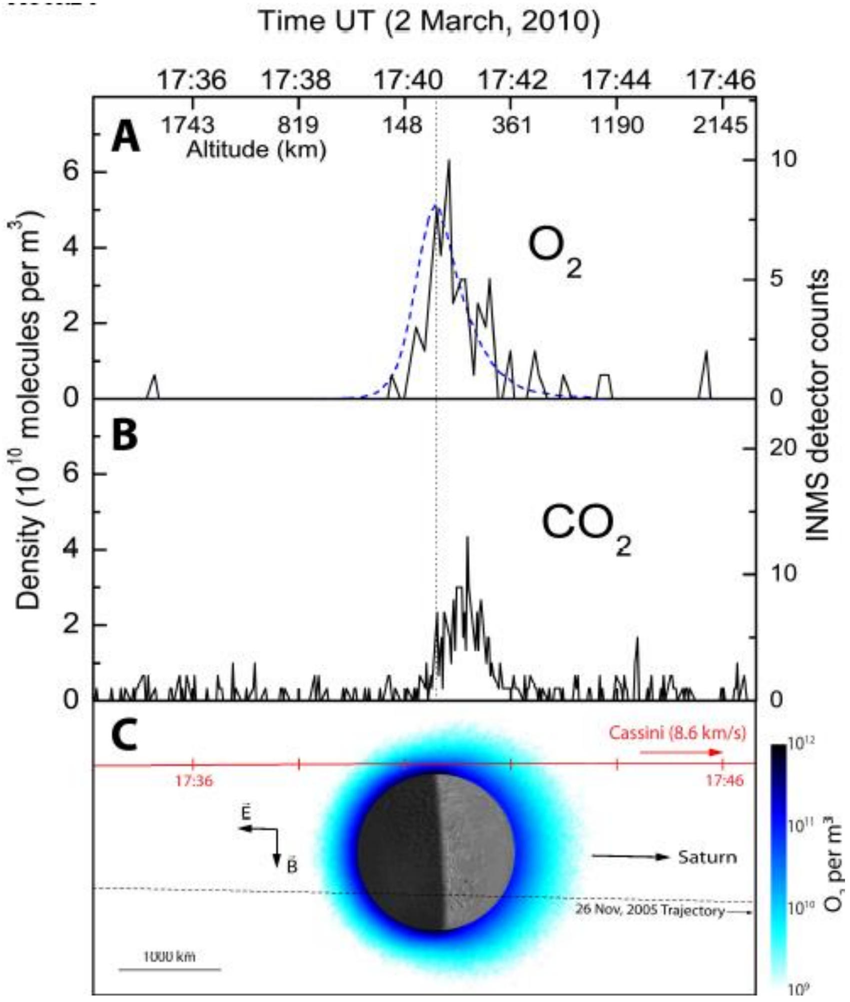
Pryor, Rymer et al., Nature 21 April 2011

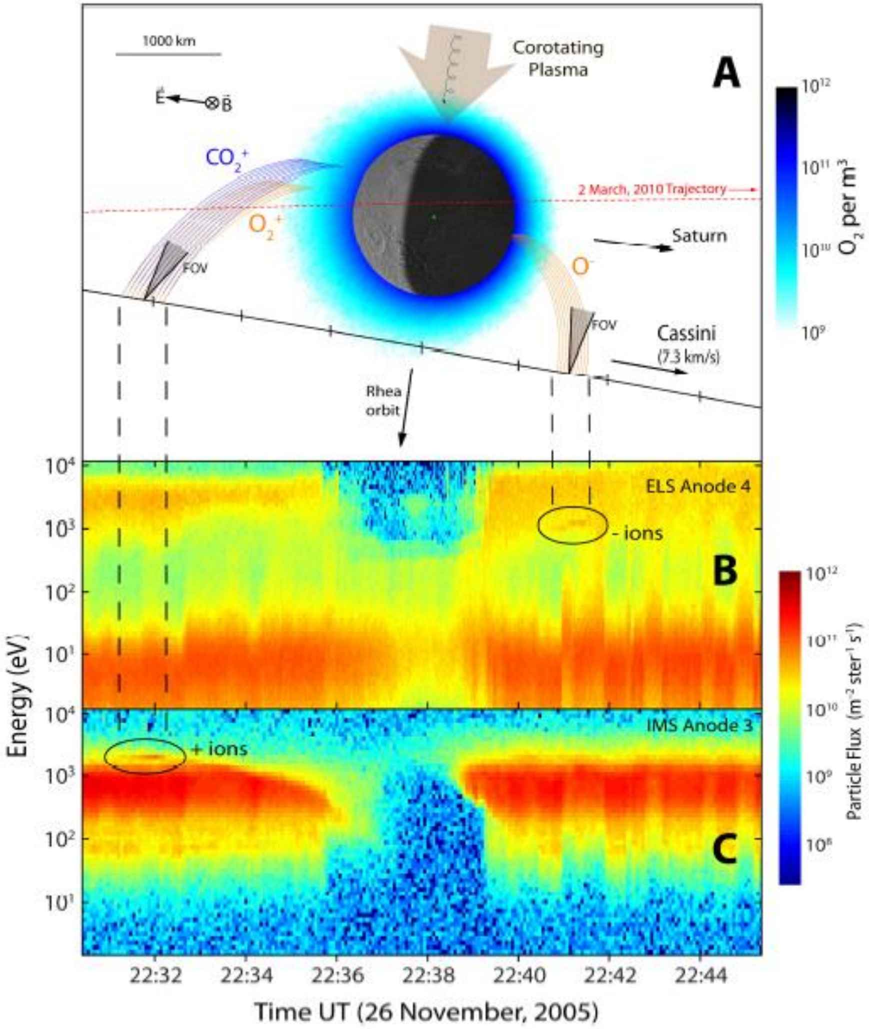






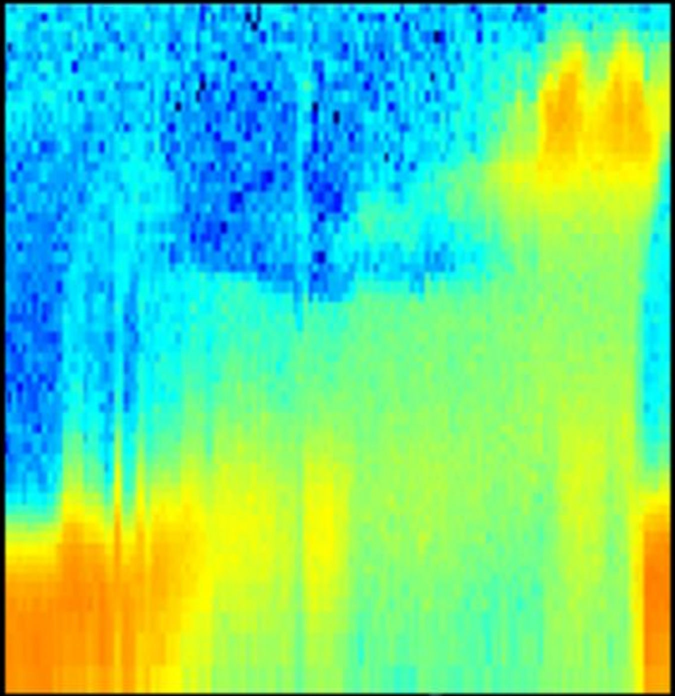
Rhea's O_2 and CO_2 atmosphere – from INMS and CAPS
Teolis et al., Science, Dec 2010

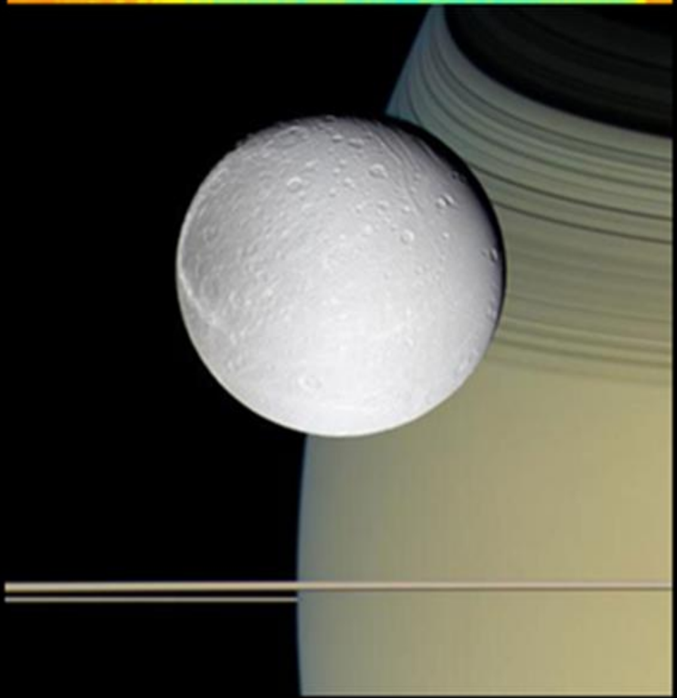




In-situ neutral atmosphere measurements (INMS)

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

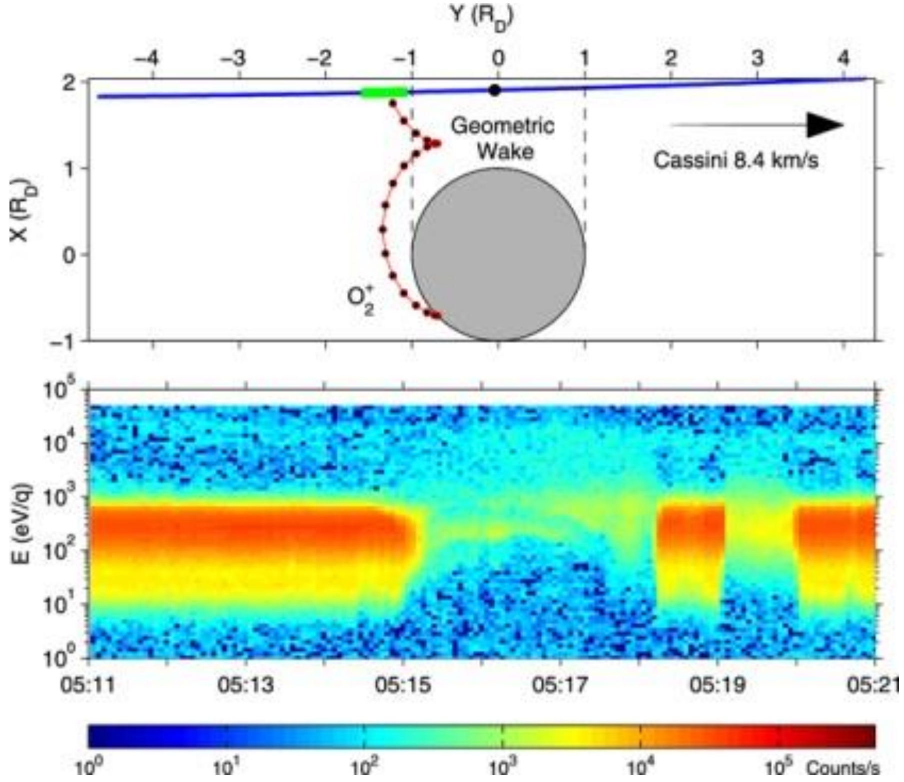




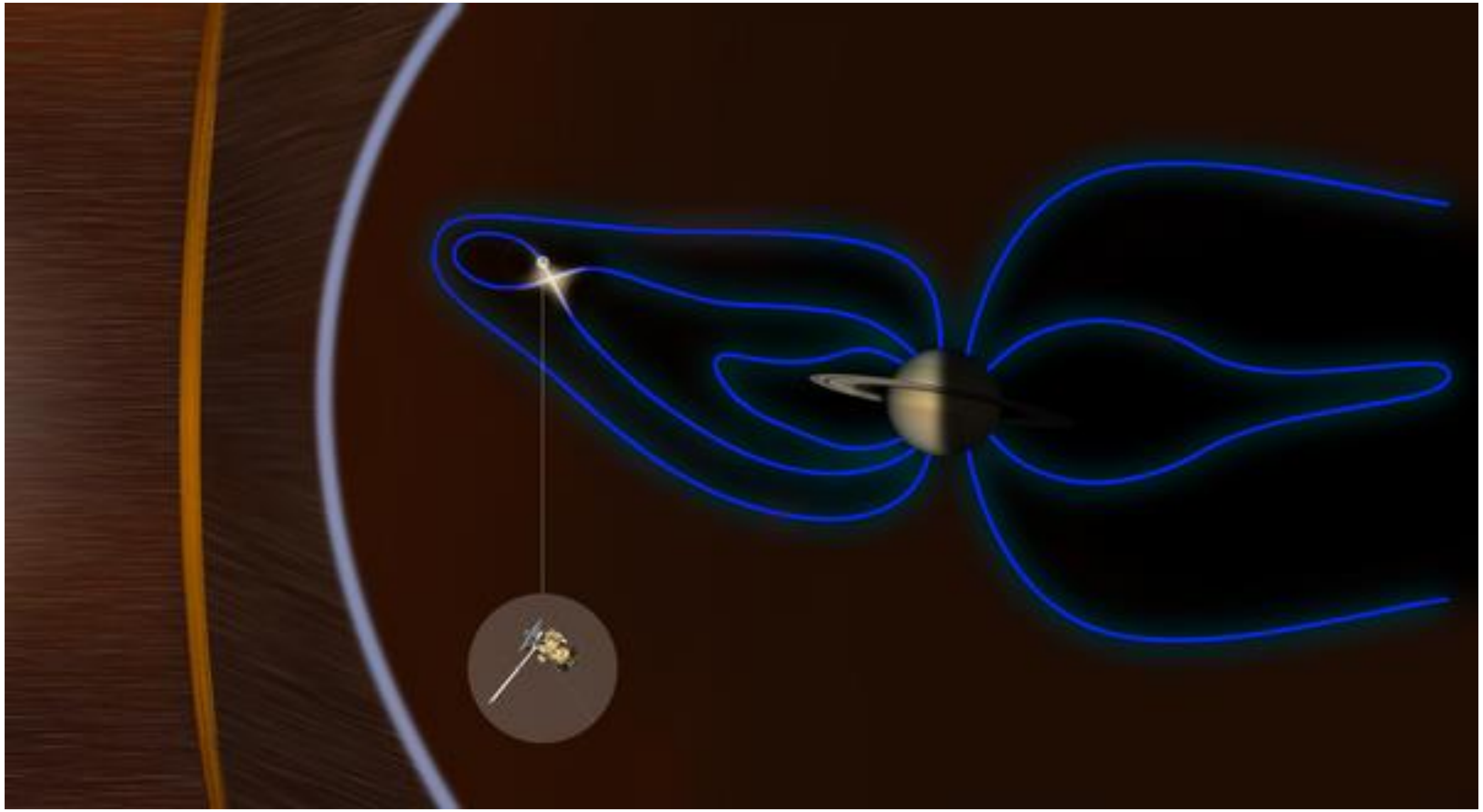
Dione's oxygen exosphere
Tokar et al., Geophys Res Lett., Feb 2012

Icy Dione is within Saturn's trapped radiation belts – oxygen forms and is recycled via the surface

Process occurs at Dione, Rhea and Saturn's main rings, also at Ganymede, Europa and Callisto in Jupiter's - targets for ESA's JUICE (JUpiter ICy moons Explorer) mission arriving 2031



Reconnection inside Saturn's magnetosphere



Guo et al., Nature Astronomy, June 2018
Supplements reconnection at magnetopause (e.g. Jasinski et al., 2016), and in tail (e.g. Jackman et al., Hill et al. 2008, Arridge et al., 2016)

Interaction of the solar wind with solar system bodies

Atmospheres but no magnetic field

e.g., Venus and Mars

Magnetic field of solar wind induces currents in the ionosphere which deflect the solar wind

Similarly to before, a shock wave forms.

The boundary where thermal pressure and solar wind pressure balance is the ionopause

Tail is formed (studied by e.g., Mars Express, MAVEN and Venus Express).

- In the tail of Mars, oxygen ions stream away, at ~0.1 kg/s.
- From NASA Maven mission, atmospheric loss appears to occur in the tail (75% of the loss), a polar plume (25%) and extended cloud surrounding Mars (minor)
- Coronal mass ejections on the Sun increase the mass loss rate

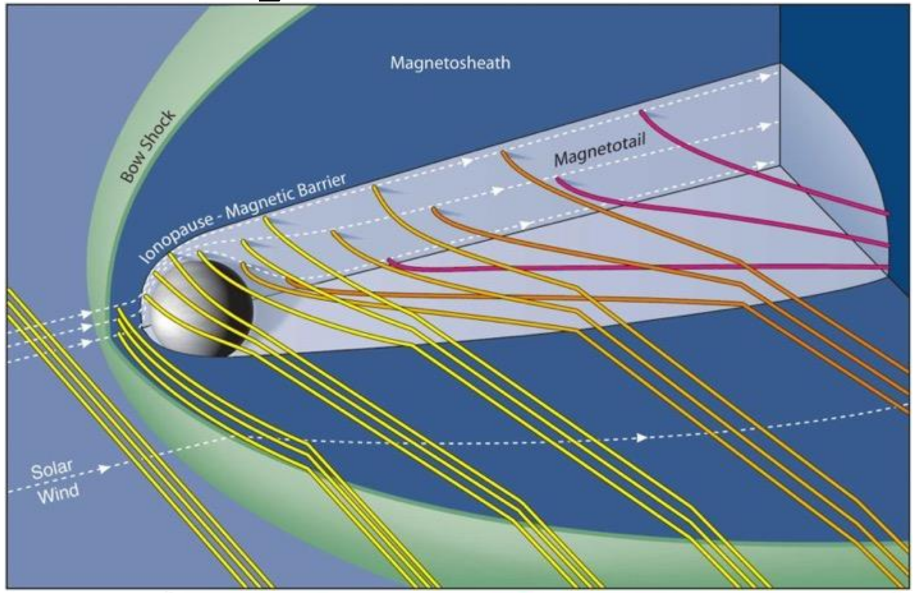
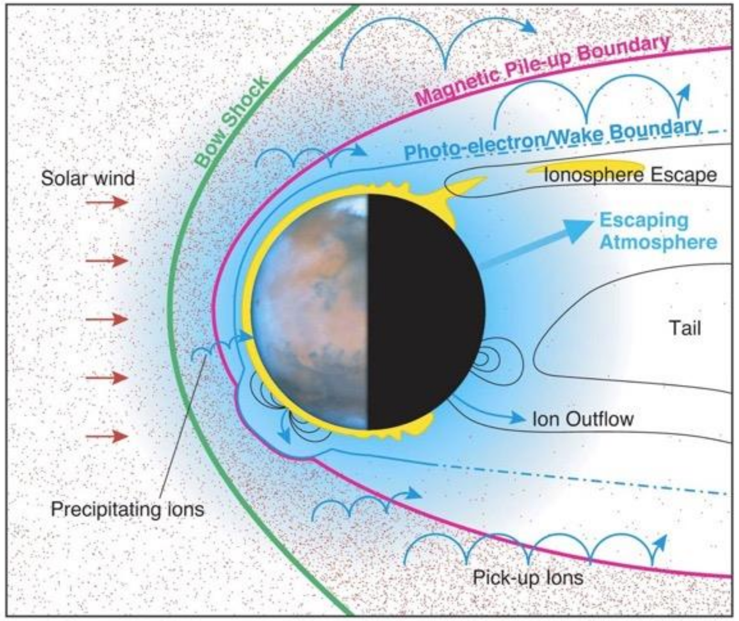
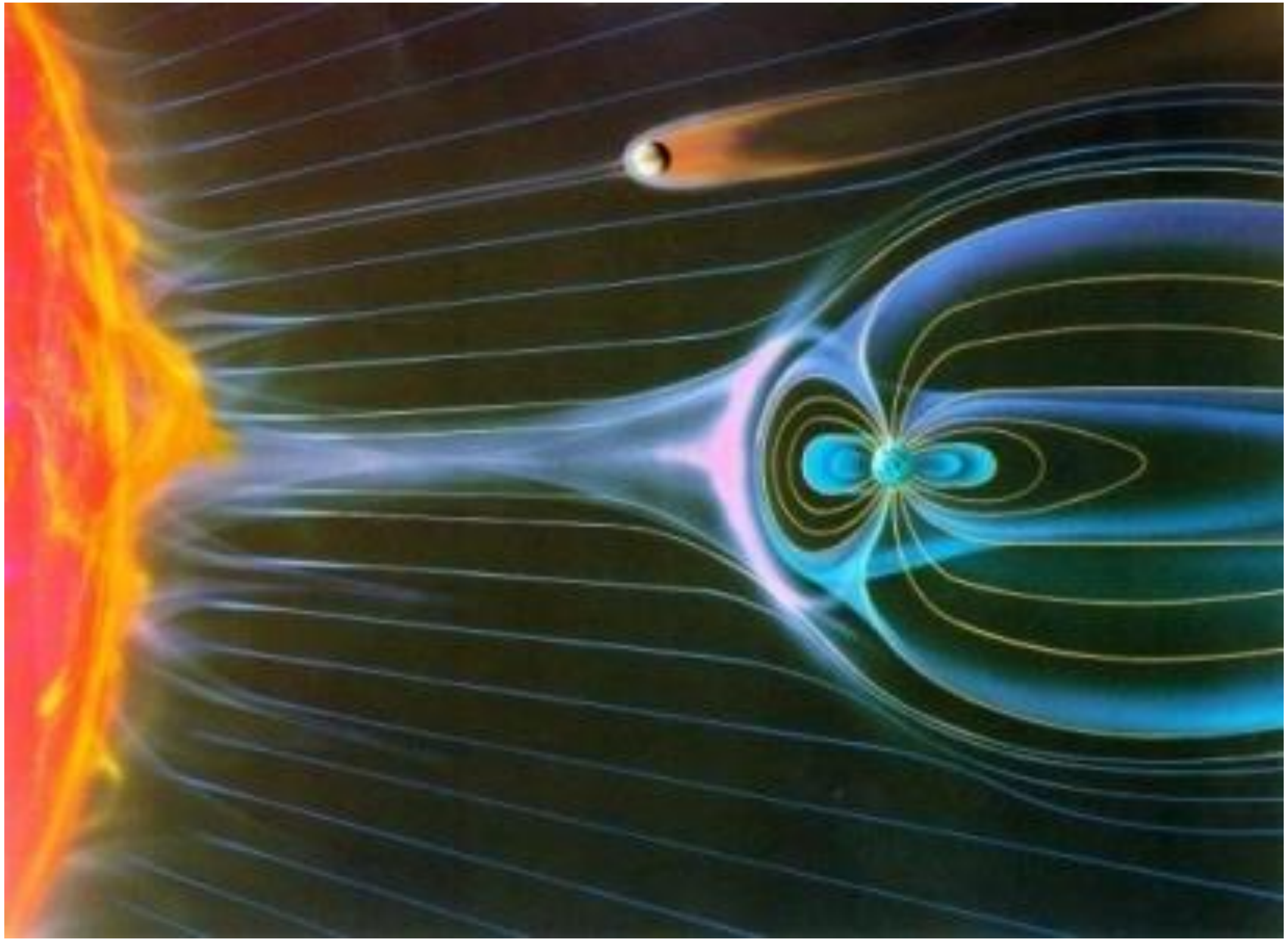


Figure credit Fran Bagenal & Steve Bartlett.



Venus interaction



Venus - solar wind interaction

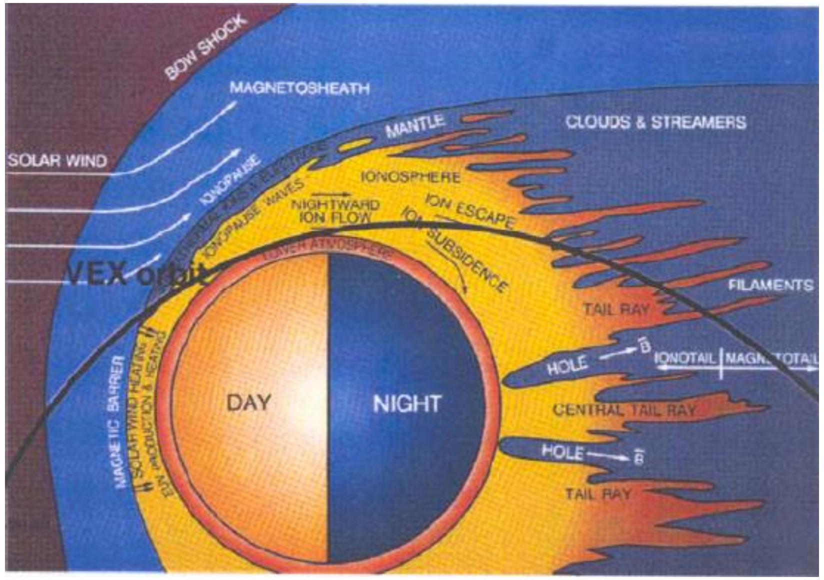
Venus has no magnetic field

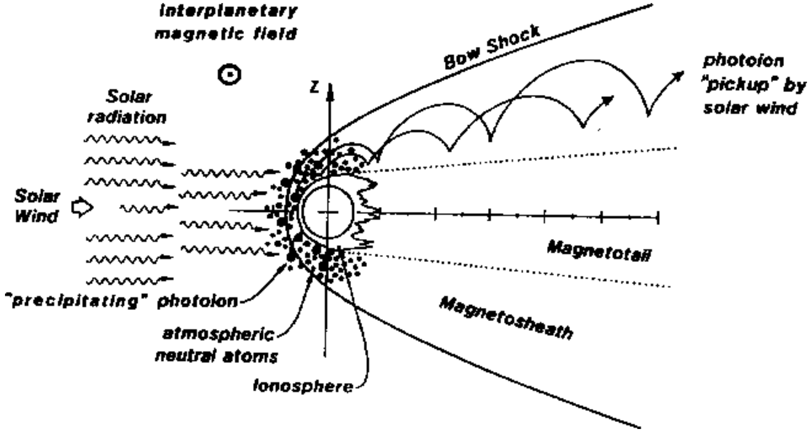
Gyroradius smaller than planetary radius

Solar wind erodes the Venus atmosphere

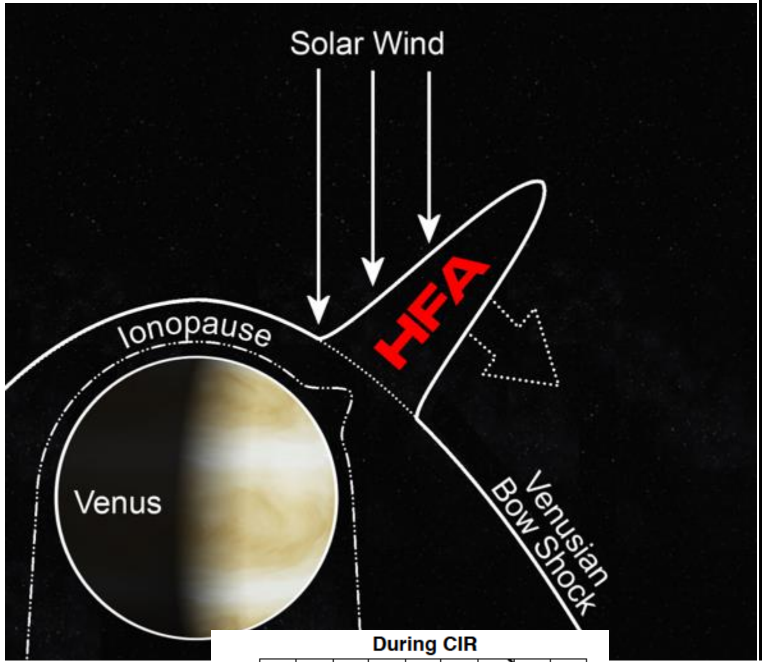
Venus Express measuring rate: ~10^{25} s^{-1} via tail, <10% via pickup(Barabash et al., 2007)

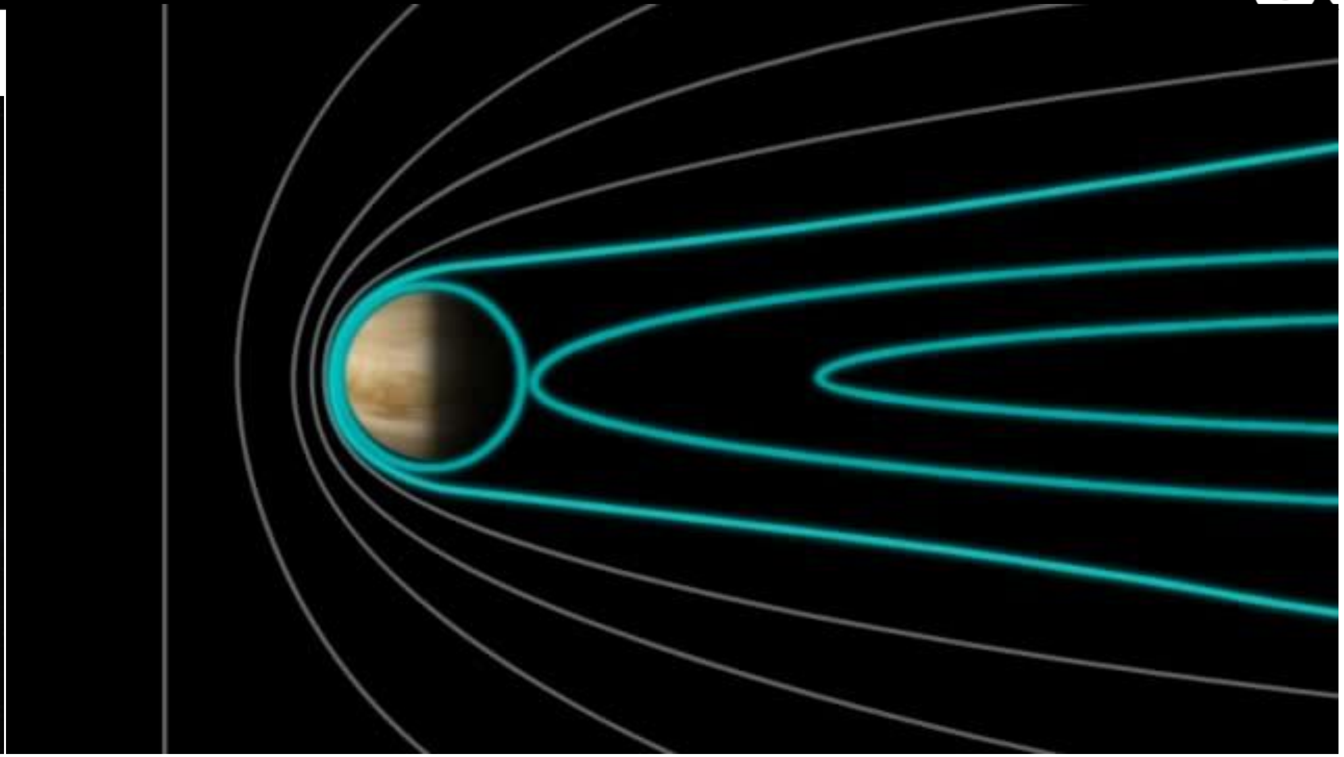
Ambipolar effect may augment escape (Coates et al, 2008, 2011, Collinson et al 2016)

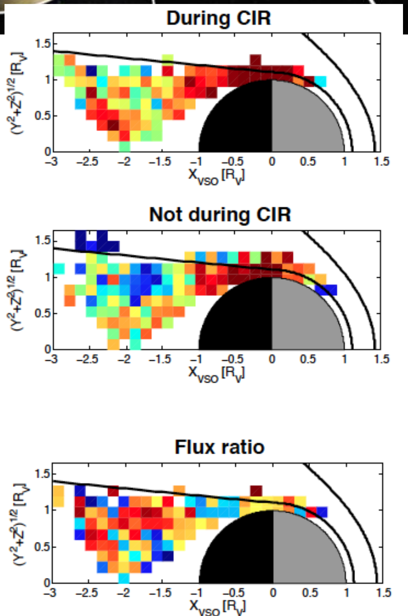




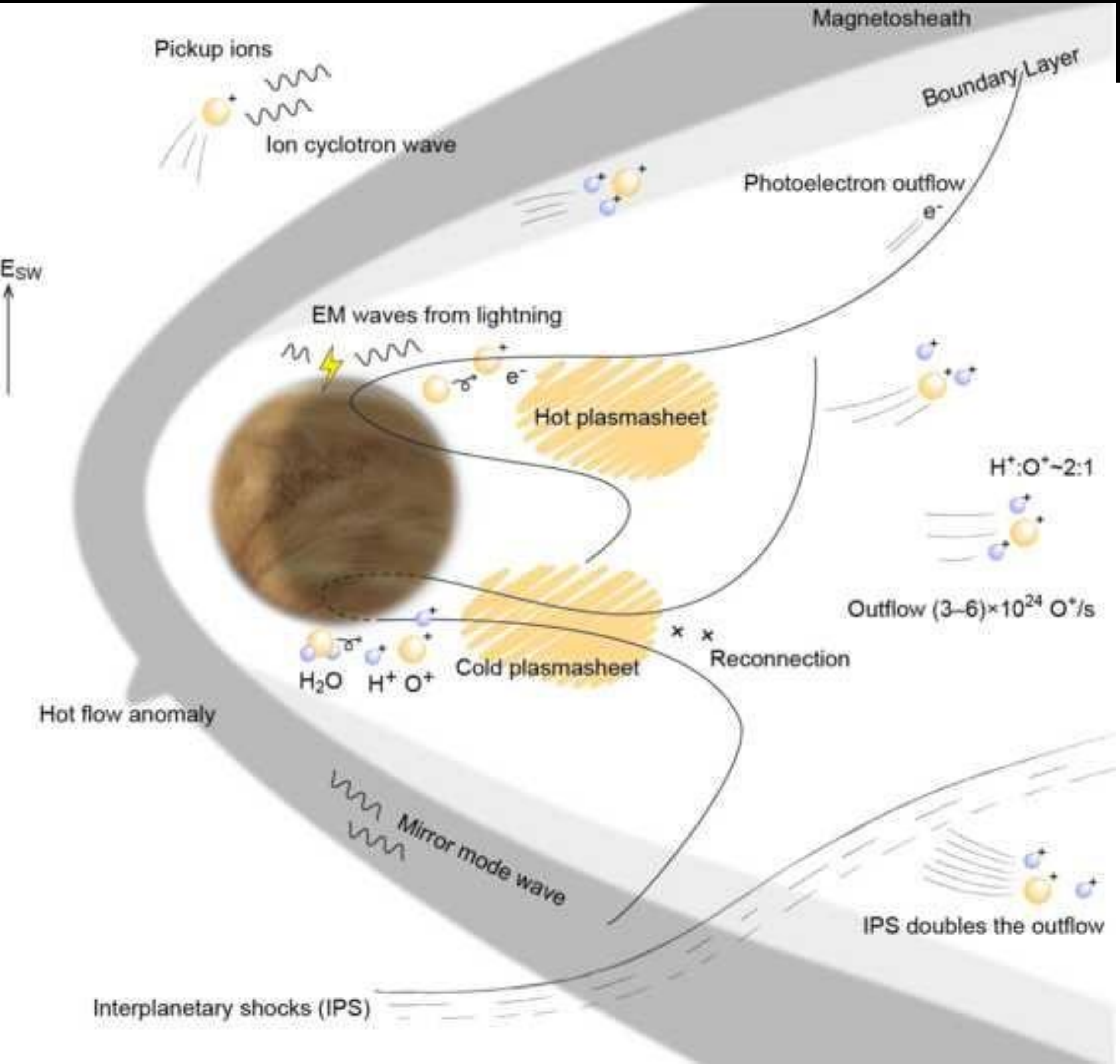
Some VEx results







- Magnetic reconnection in tail (Zhang et al., 2012)
- Hot flow anomalies (Collinson et al., 2012)
- Escape rate increases by factor ~1.9 during CIR (Edberg et al., 2011) and up to 100x during CME (Luhmann et al., 2007)0

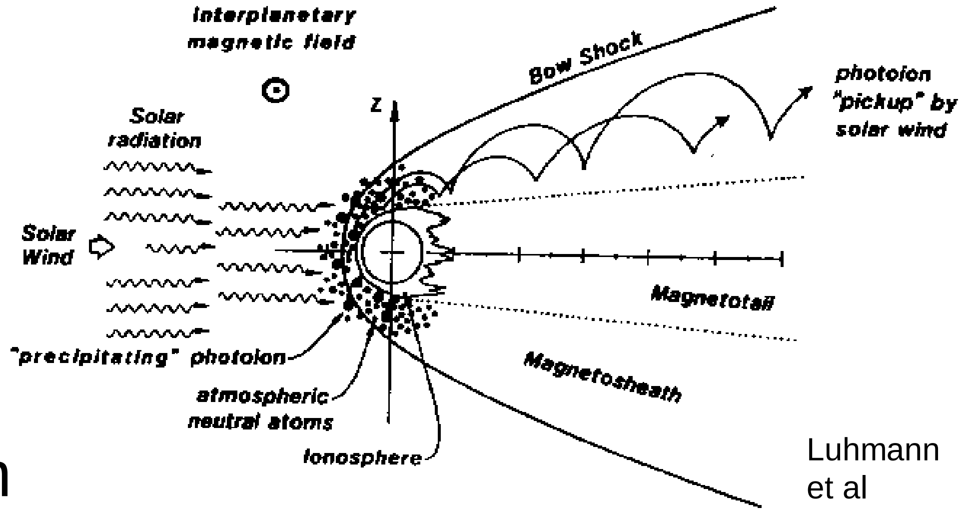


Venus Express discoveries

Futaana et al., SSR 2017

Mars

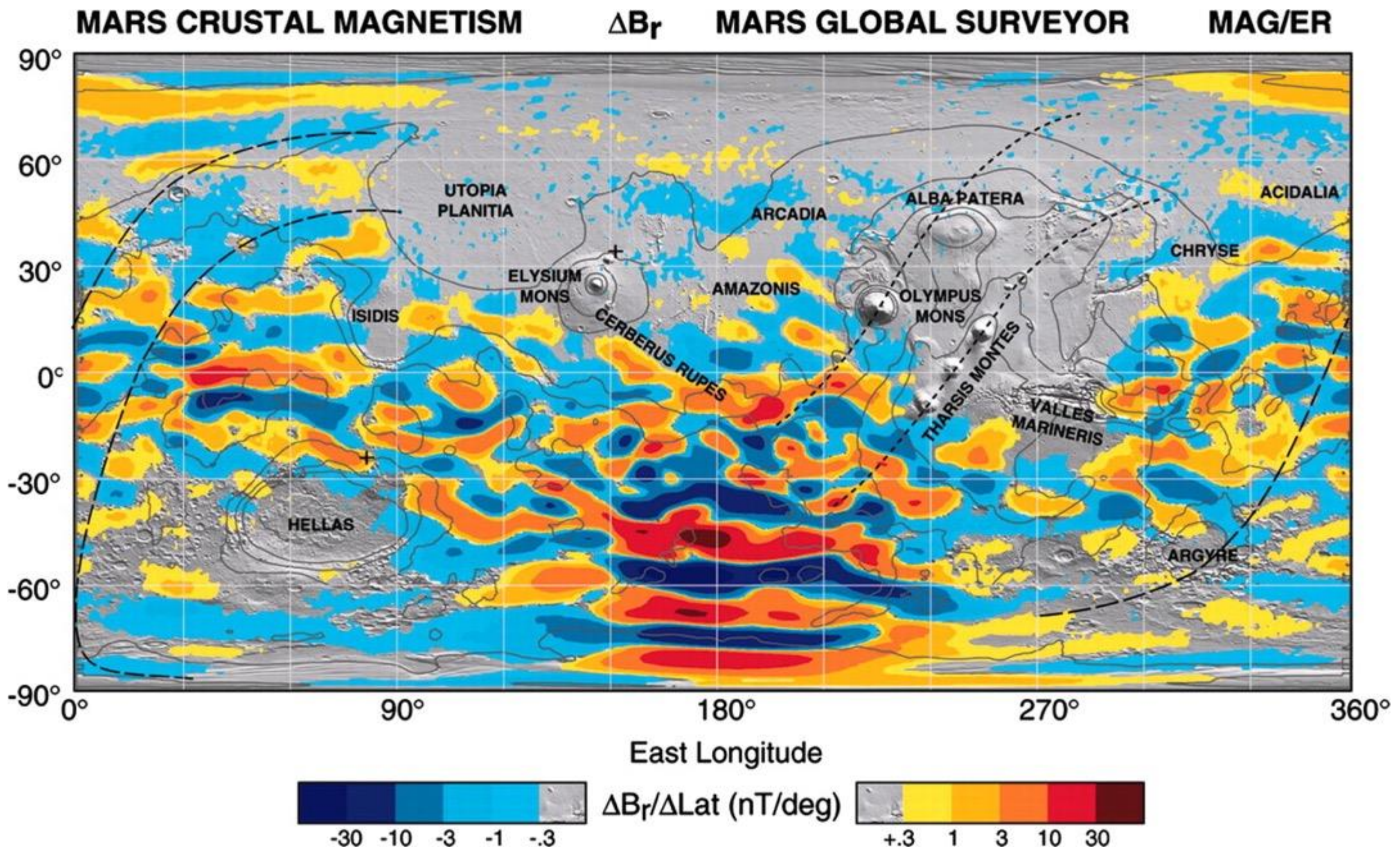
- No global field
- Exosphere: ionization, pickup
- Gyroradius larger than planet
- Loss rate ~10^{25} s^{-1} (Lundin et al 89) – tens of % of Earth's atmospheric mass over 3.8GY
- Early measurements of loss from Mars Express factor 100 lower (Barabash et al 2007) now revised upwards
- Asymmetric pickup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



Luhmann et al

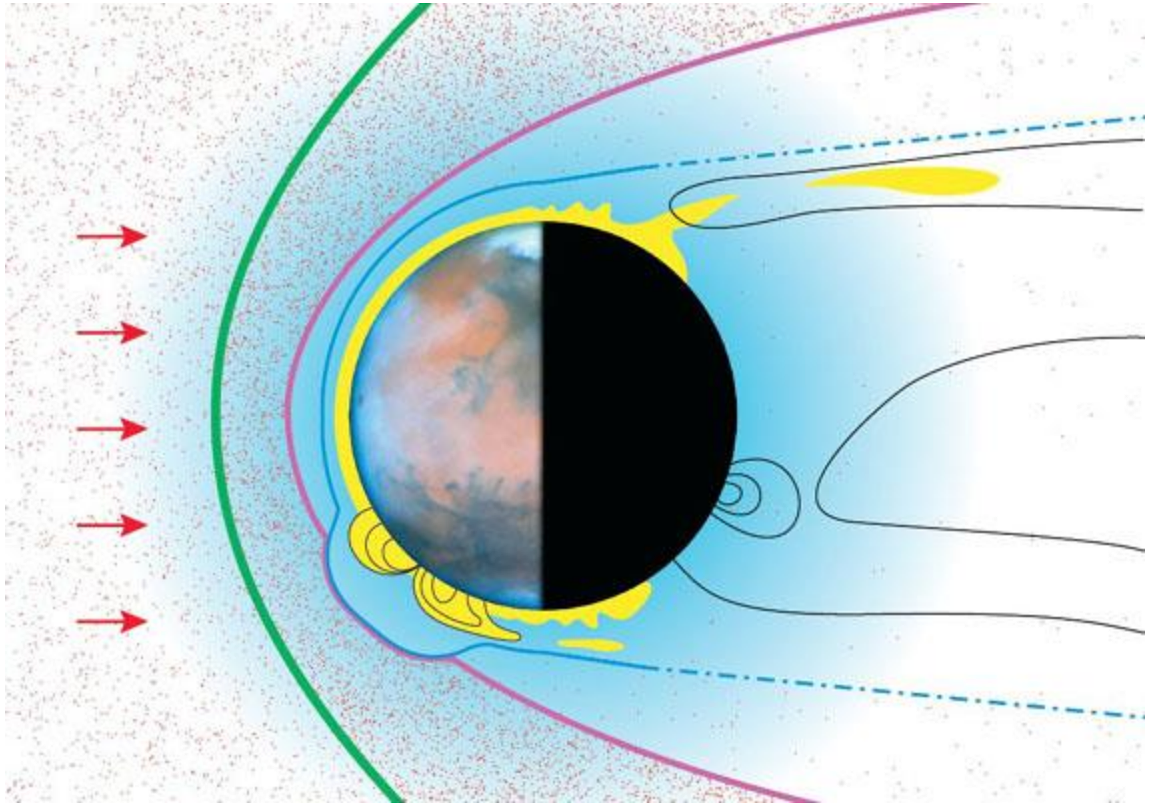
Venus similar but gyroradius smaller

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])



Connerney, J. E. P. et al. (2005) Proc. Natl. Acad. Sci. USA 102, 14970-14975

Solar Wind Interaction with Martian Mini-Magnetospheres

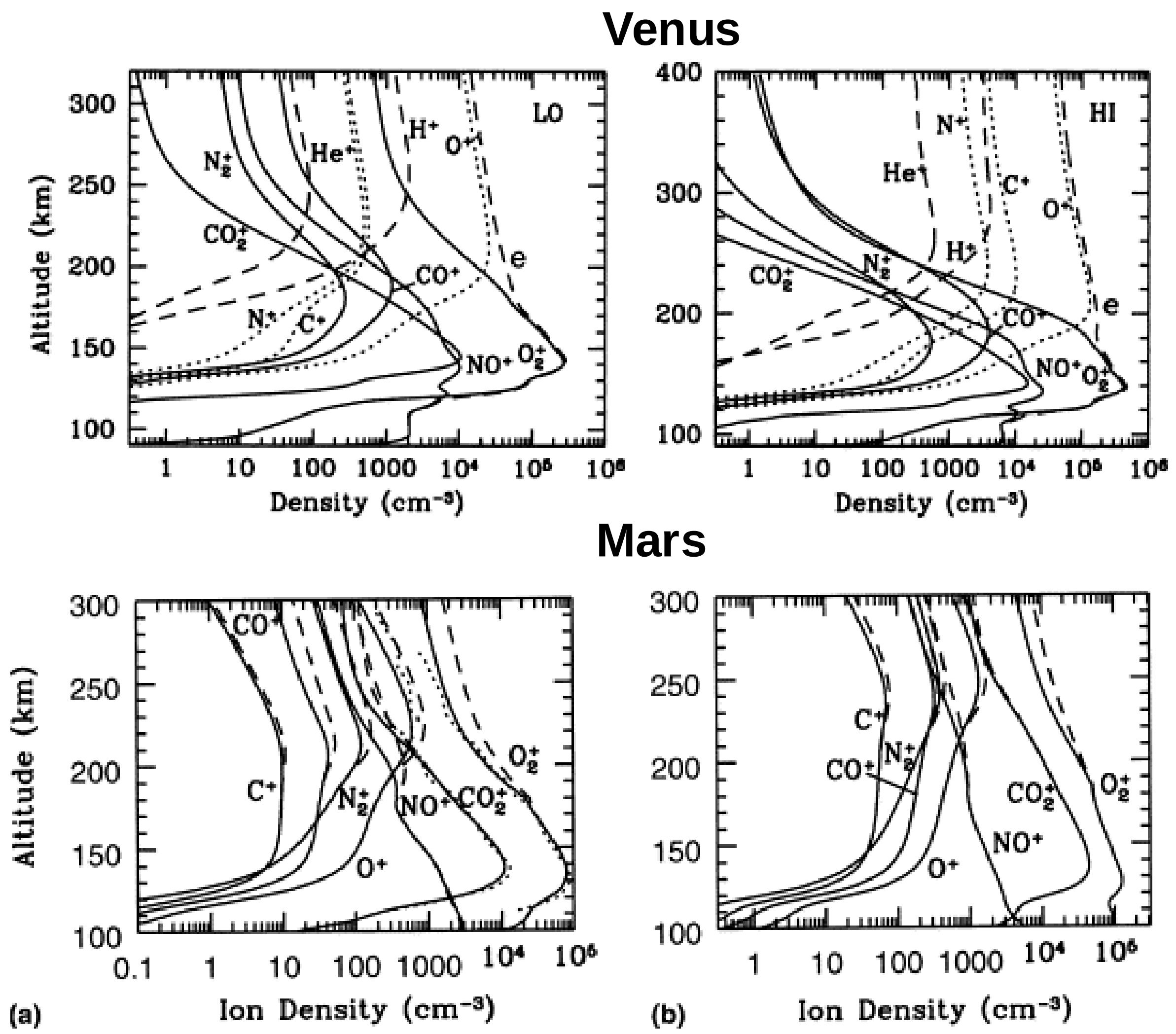


http://mepag.jpl.nasa.gov/science/5_Planetary_Magnetism/mars_plasmoid_Steve_Bartlett_NASA_sm.jpg

Venus & Mars ionospheres

Major ions in the Venus (top) and Mars (bottom) ionosphere for low (left) and high (right) solar activity. From Fox, Adv. Space Res. 33, 132, 2004.

- Chapman type ionospheres
- CO_2^+ is a major species:
  - Photoionisation
    - $CO_2 + h\nu \rightarrow CO_2^+ + e$ (at < 90 nm)
  - Dissociative recombination
    - $CO_2^+ + e \rightarrow CO + O$
- Observations of Venus
  - High level of nightside ionisation (x 100 from expected)
  - With slow rotation, ionisation should decay rapidly after sunset
  - Mechanism unclear, possibly ion transport from dayside
- Observations of Mars
  - Viking, Mars Express, Maven



Space Weather at Mars

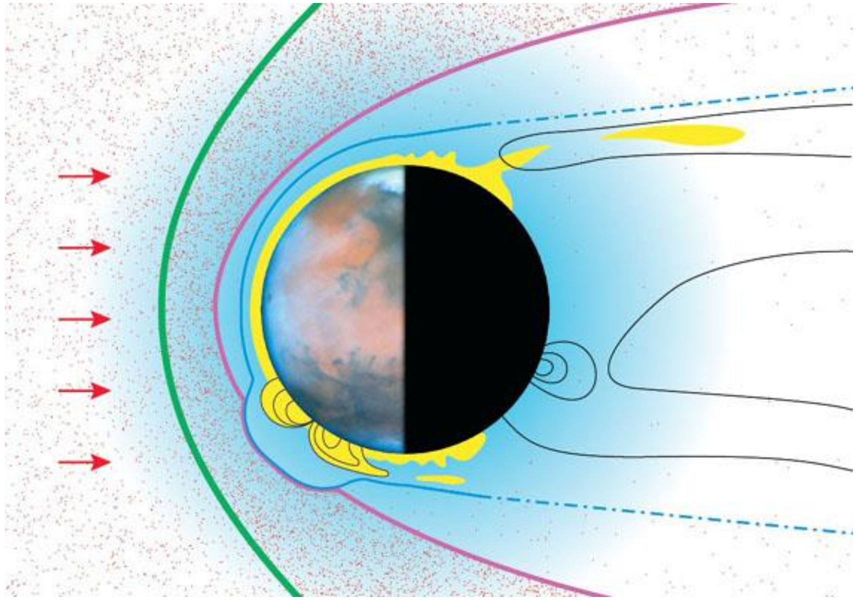
- Magnetospheric and ionospheric disturbances (T1, T3)
- Disruption of radio communication (T1)
- Disruption of satellite operations (T1, T2, T3)

Timescales:

T1 – electromagnetic radiation reaches Mars (12 minutes)

T2 – SEPs reach Mars (30-80 minutes)

T3 – Plasma reaches Mars (1.5-4.5 days)

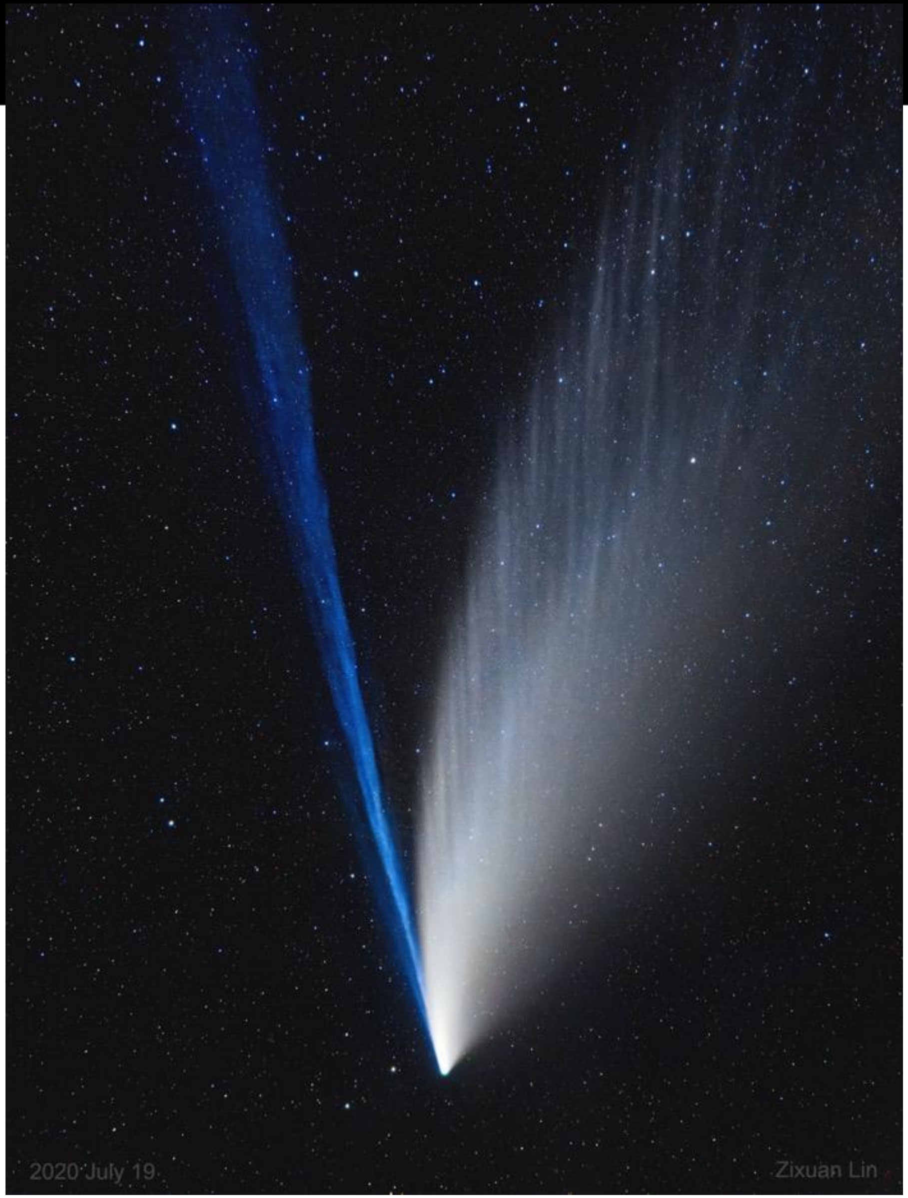


http://mepag.jpl.nasa.gov/science/5_Planetary_Magnetism/mars_plasmoid_Steve_Bartlett_NASA_sm.jpg

Interaction of the solar wind with solar system bodies

Outgassing objects

- e.g., comets, some planetary satellites
- Neutral gas particles stream away from the object when it is heated by the Sun, which then become photo-ionised
  - Once charged, they can be accelerated by the solar wind to solar wind velocities
  - Solar wind is decelerated in the process
- A weak bow shock forms, distance depends on gas production rate
  - Measured at 1,000,000 km from comet Halley
  - Measured at 20,000 km from comet Grigg Skjellerup
- Small region around the nucleus that the interplanetary magnetic field cannot penetrate

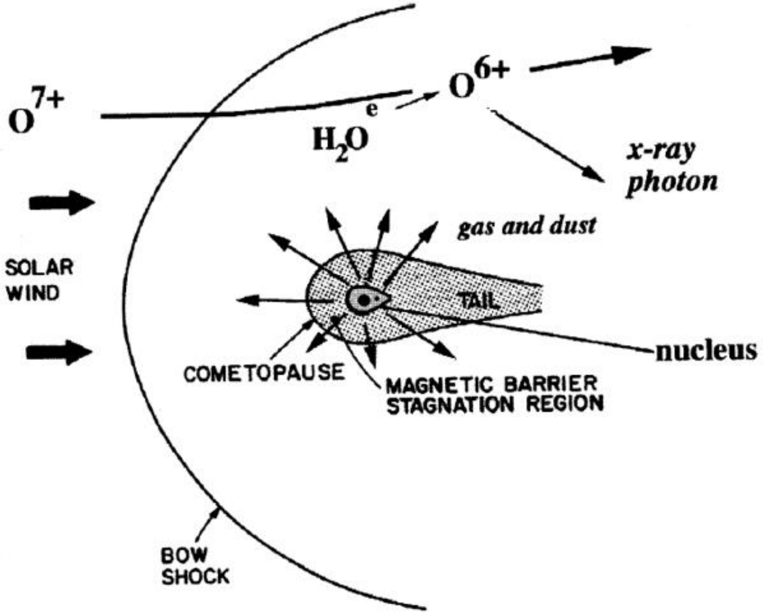


Tails of comet NEOWISE (July 2020). Blue ion tail is seen on the left, pointing directly away from the Sun, pushed out by charged solar wind. White dust tail on the right.
Image credit Zixuan Lin (Beijing Normal U.).

Comet-solar wind interaction

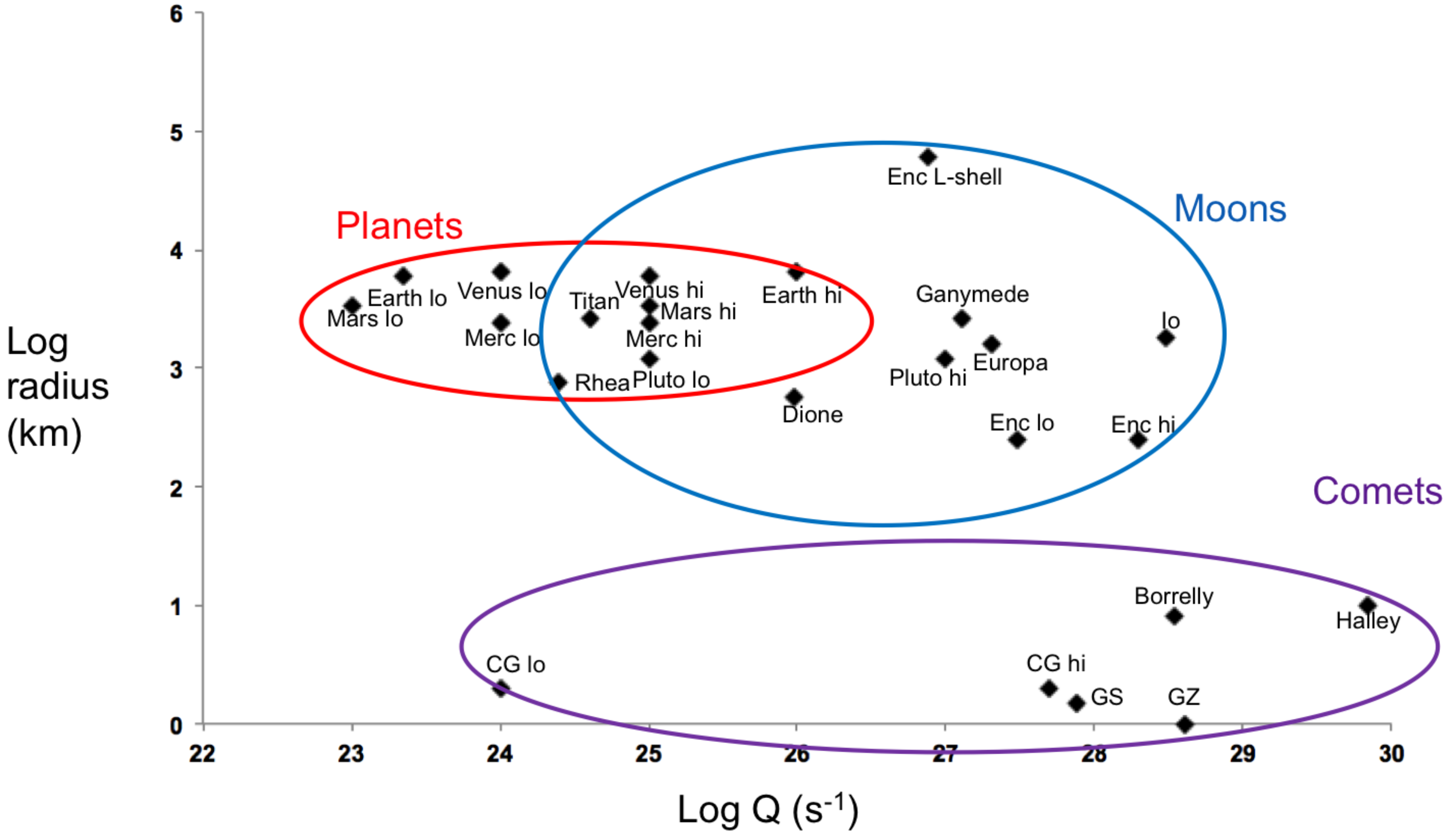
- Comet tail observations led to idea of the solar wind (Biermann, 1951), magnetic field draping suggested by Alfven (1957)
- In-situ observations (including by Giotto) have shown importance of ion pickup by the solar wind

Comet Halley, 1986

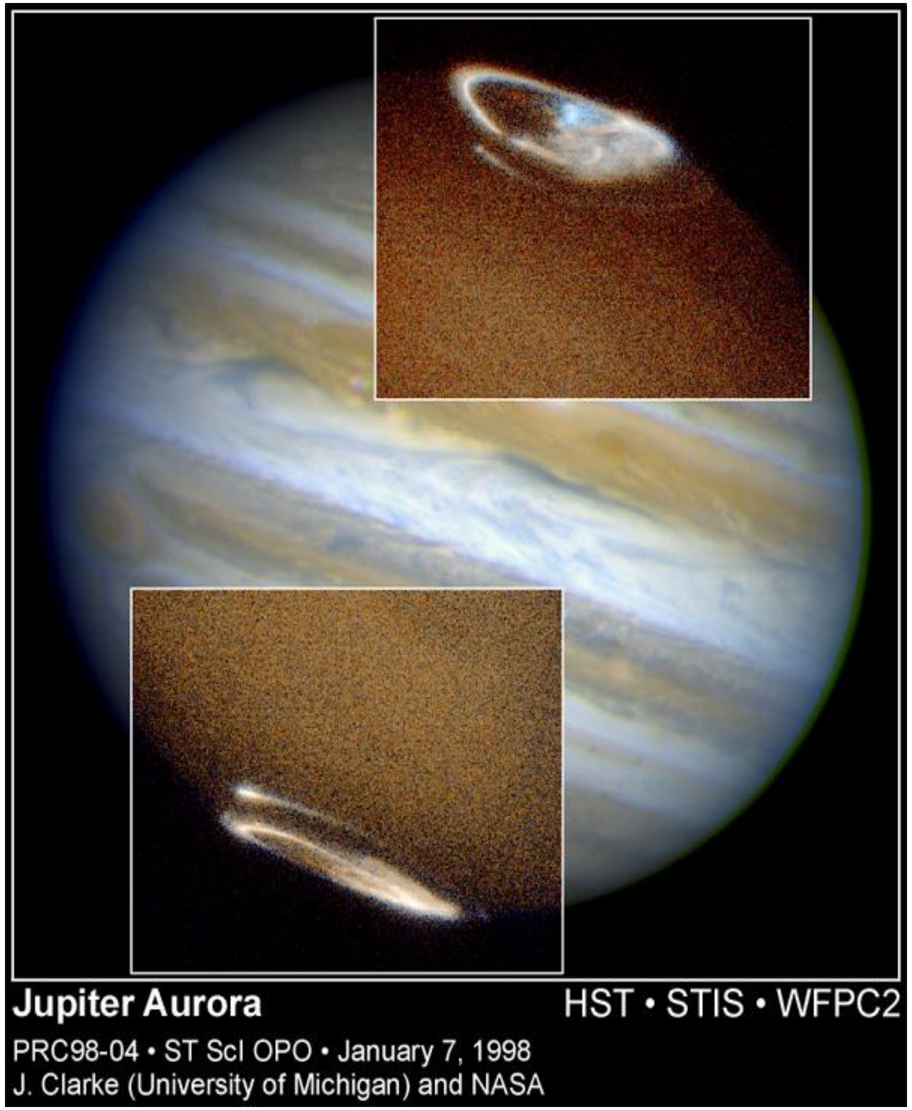


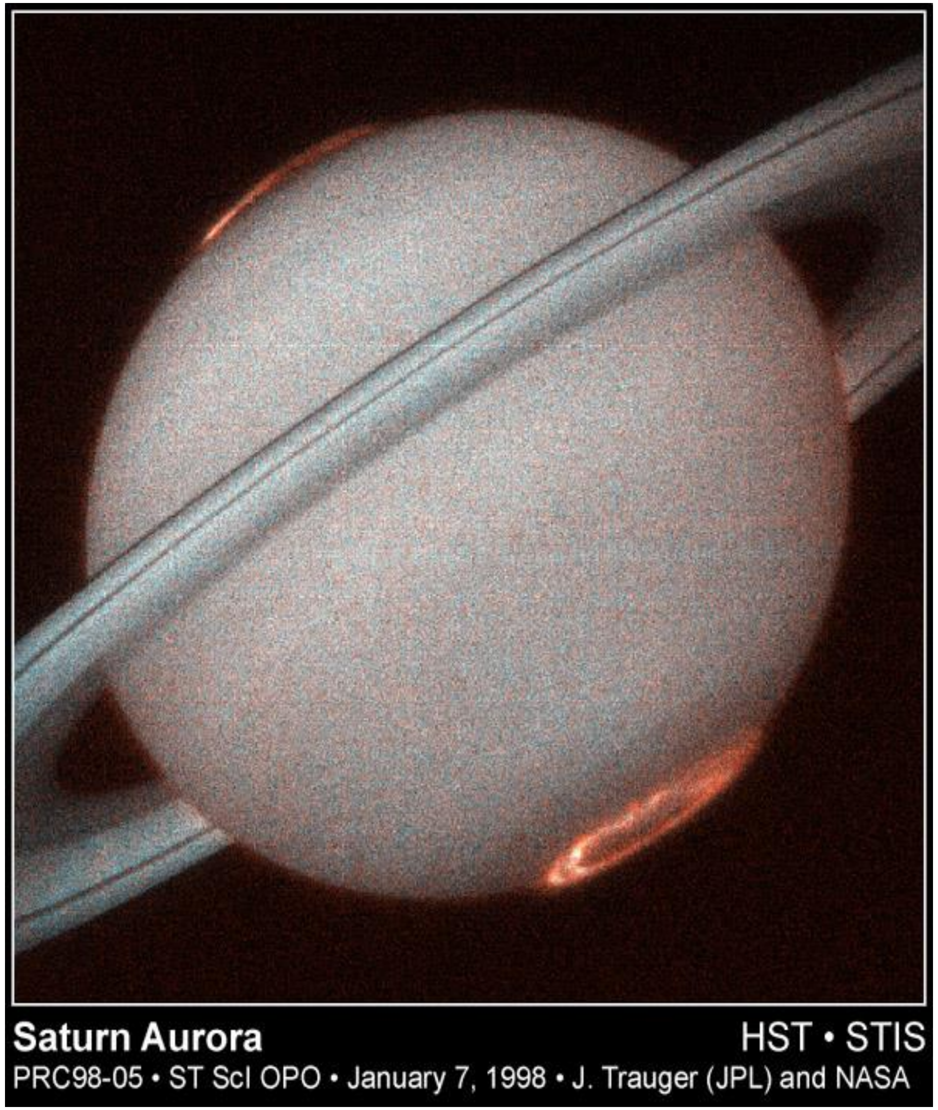
Cravens & Gombosi, 2004

Gas production rates of some solar system objects



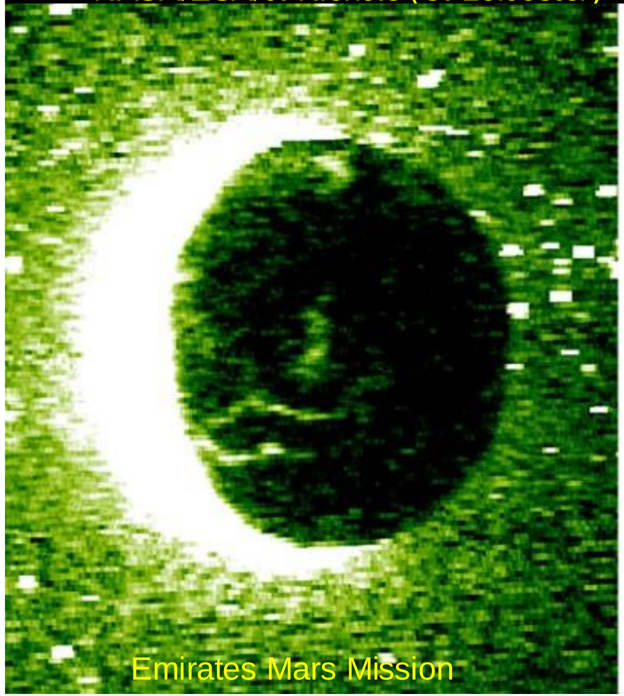
Coates et al., PSS 2015, Coates AGU monograph 2016


Jupiter Aurora
HST • STIS • WFPC2
PRC98-04 • ST ScI OPO • January 7, 1998
J. Clarke (University of Michigan) and NASA

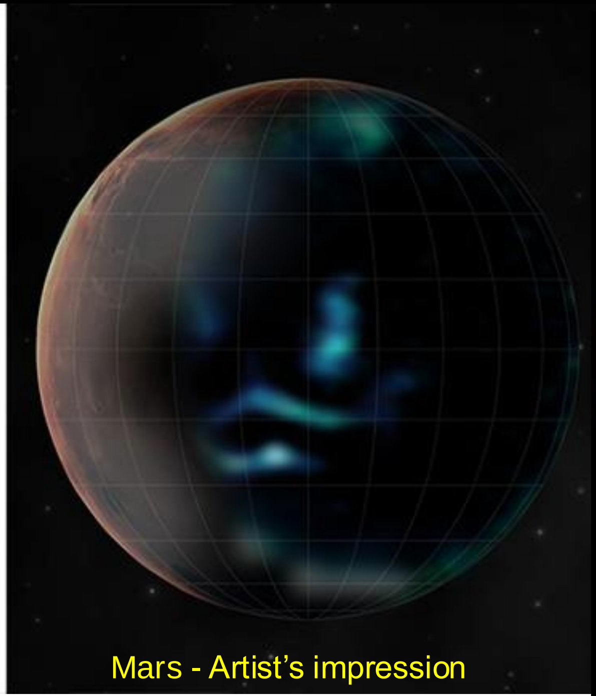

Saturn Aurora
HST • STIS
PRC98-05 • ST ScI OPO • January 7, 1998 • J. Trauger (JPL) and NASA

NASA/ESA/J. Nichols (U. Leicester)

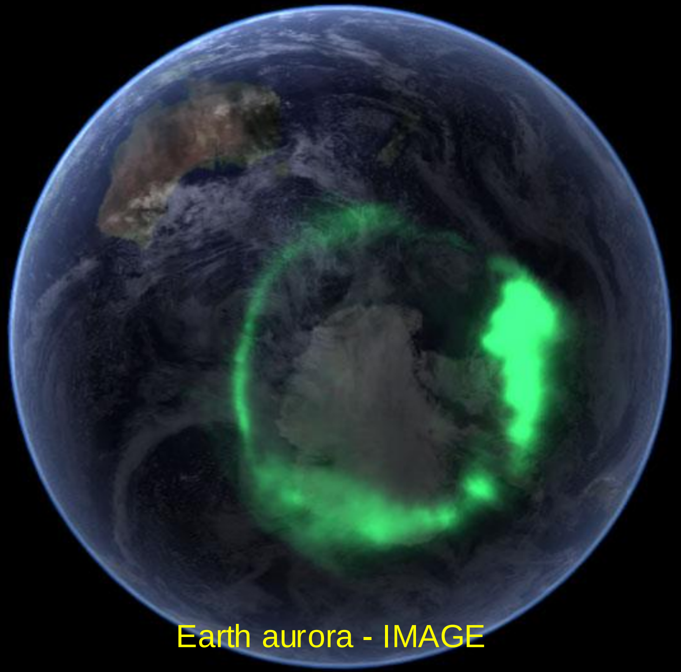
NASA, ESA & L. Lamy



Emirates Mars Mission



Mars - Artist’s impression



Earth aurora - IMAGE

Guildford, 10 May 2024 A.Coates

Summary photoelectrons

- Ionospheric photoelectrons (IPE) have distinctive energy spectra
- IPE seen at large distances from sunlit ionospheres at V, M, T & in Earth's magnetosphere sensitive 'tracer' of magnetic connection to sunlit ionospheres
- IPE drive ambipolar E field, enhances ionospheric escape - analogous to Earth's polar wind (c.f. Hartle & Grebowsky, 95); supplements other mechanisms e.g. ion pickup and outflow

Object	'Polar wind' escape rate	References
Venus	~2 $x10^{24}$ amu s^{-1}	Coates et al., PSS 08, 11, *15*, Tsang et al. PSS 15, Collinson et al., GRL 16
Mars	~3.1 $x10^{23}$ s^{-1}	Frahm et al., Icarus 06, PSS *09*, Coates et al., PSS 11
Titan	~2-9 $x10^{25}$ amu s^{-1}	Coates et al., GRL 07, PSS 11, JGR *12*, GRL 15, Wellbrock et al., JGR 12, Sittler et al. 10

Conclusions

- Space weather effects important at solar system bodies including atmospheric evolution
- Solar wind effects important, e.g. reconnection processes
- Rapid rotation controls magnetospheres of Jupiter, Saturn, associated reconnection
- Effects on plasma boundaries due to upstream dynamic pressure
- Escape rates depend on upstream conditions
- Ionospheres depend on UV
- Europa, Ganymede (magnetized), Callisto, Enceladus bombarded by energetic particles
- Surface modification and effects from plasma and SEPs
- Work continuing on Cassini data and looking toward future missions

Recent, current & future missions with plasma instrumentation

Mercury: BepiColombo – 4th flyby last night! 2 more before arrival in Nov 2026

Venus: Venus Express

Earth: Cluster, MMS, SMILE, Plasma observatory?

Moon: Chandrayaan 1,2, Kaguya, Chang’E 6, 1

Mars: Mars Express, MAVEN, MoM, Tianwen-1, Escapade, M-Matisse?

Jupiter: JUNO, JUICE, Europa Clipper

Saturn: Cassini-Huygens

Uranus: Uranus flagship?

Neptune:

Comets: Rosetta, Comet Interceptor