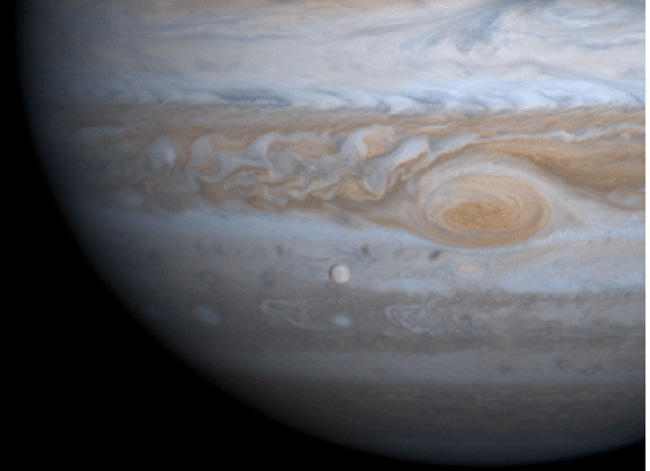
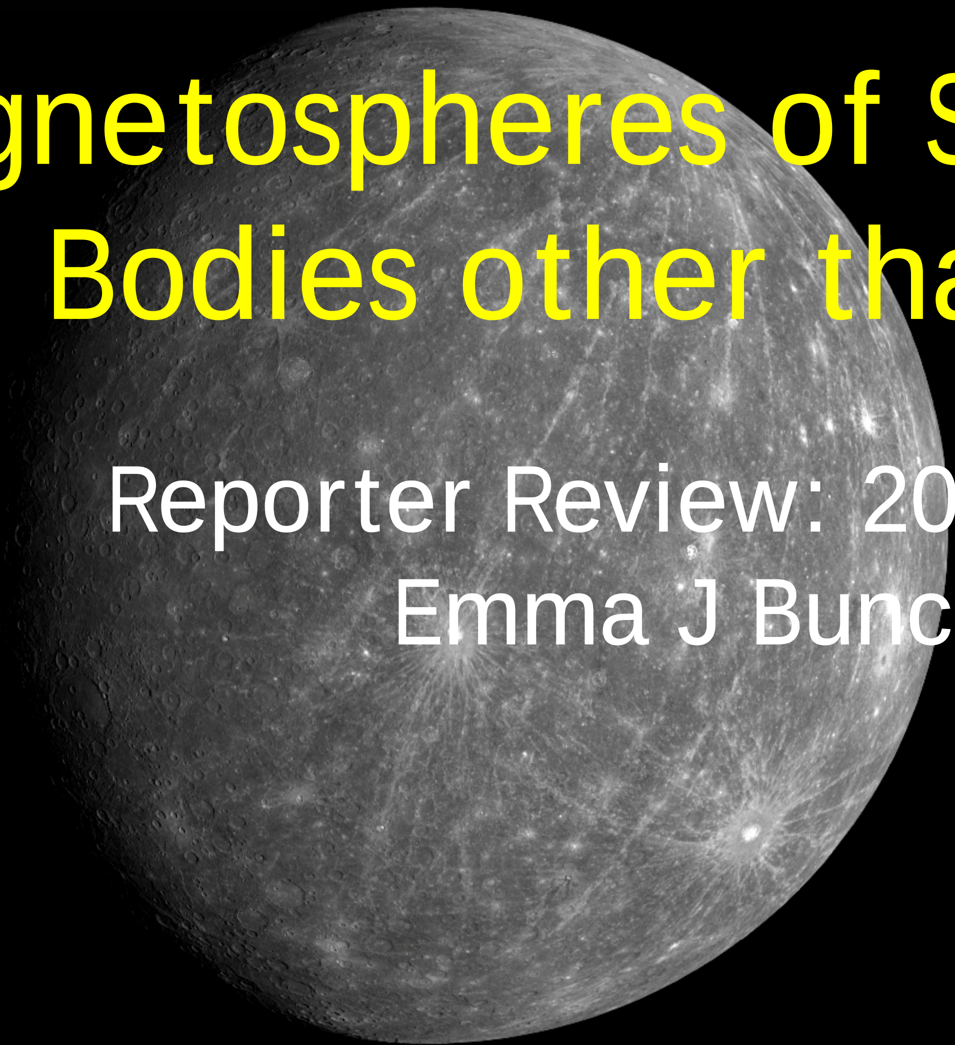




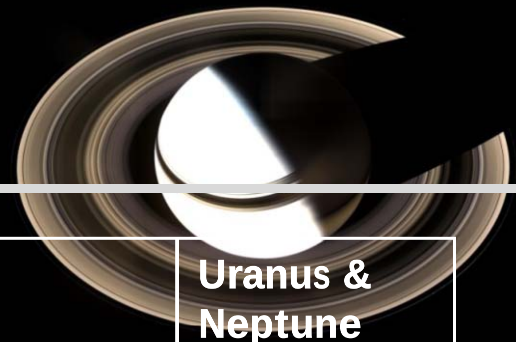
Magnetospheres of Solar System Bodies other than Earth

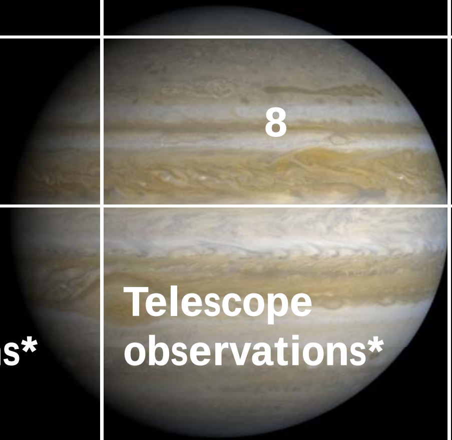
Reporter Review: 2009-2011

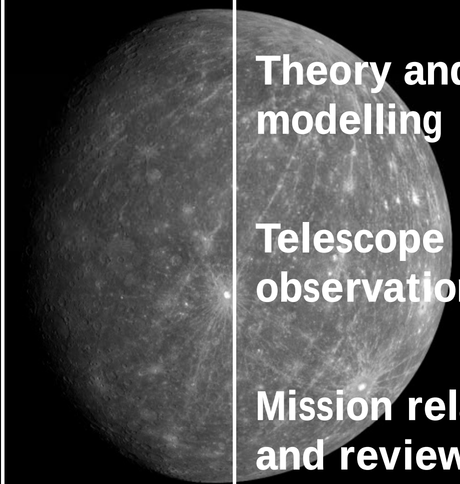
Emma J Bunce

University of Leicester

Publication Statistics from the Web of Knowledge for 2009-2011
Search keywords: planet/body + magnetosphere





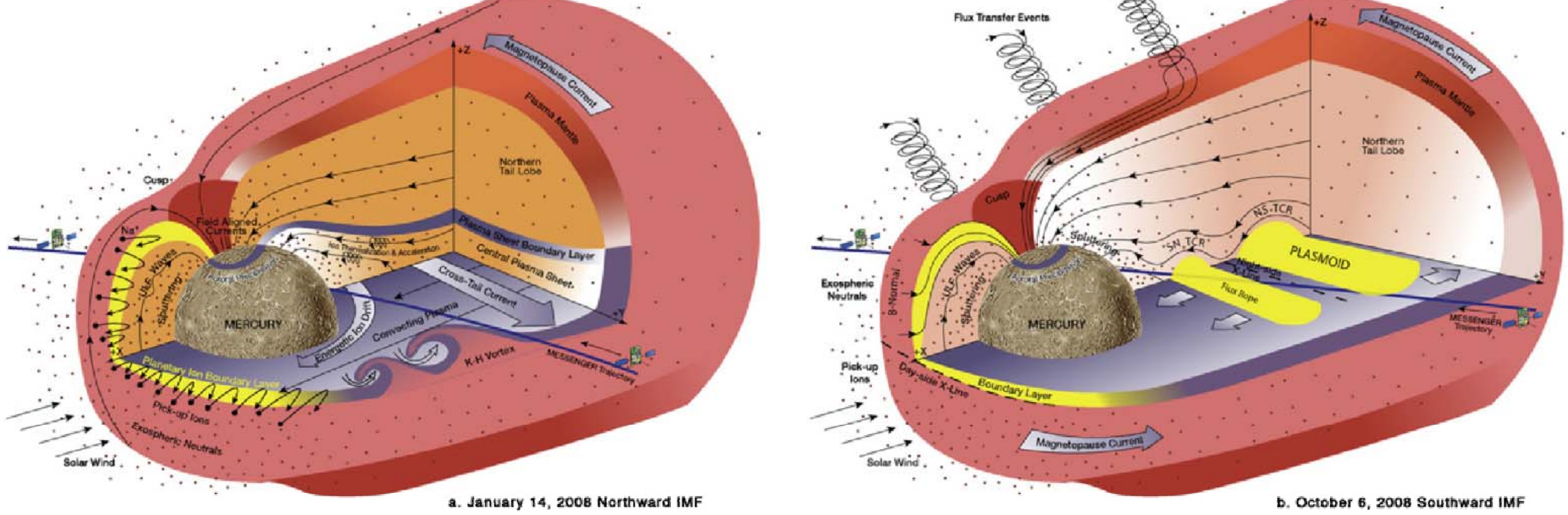


Planet/ Moon	Mercury	Jupiter	Ganymede	Saturn	Uranus & Neptune
In abstract or title	54	55	8	152	2
	Messenger in situ observations Theory and modelling Telescope observations* Mission related and reviews	Telescope observations* New Horizons Flyby Galileo/Ulysses Theory and modelling	Telescope observations* Simulations Galileo data	Cassini in situ observations Telescope observations* Simulations Theory and modelling	Theory and modelling

*e.g. Hubble Space Telescope, IR telescopes, radio telescopes

To obtain full list of references as a pdf file please email emma.bunce@ion.le.ac.uk

Schematic views of Mercury's magnetosphere for IMF N (left) and IMF S (right)



During northward IMF MESSENGER observed the planetary ion boundary layer, large flux transfer events (FTEs), flank Kelvin–Helmholtz vortices, and ultra-low-frequency plasma waves (see Slavin et al., 2008) &

During southward IMF MESSENGER saw strong magnetic field normal to the dayside magnetopause, large FTEs, and a reconnection line in the near-tail region, leading to plasmoid ejection and south–north (SN) sunward-moving and anti-sunward-moving north–south (NS) travelling compression regions (TCRs) (see Slavin et al., 2009).

What is the nature of Mercury's internal magnetic field?

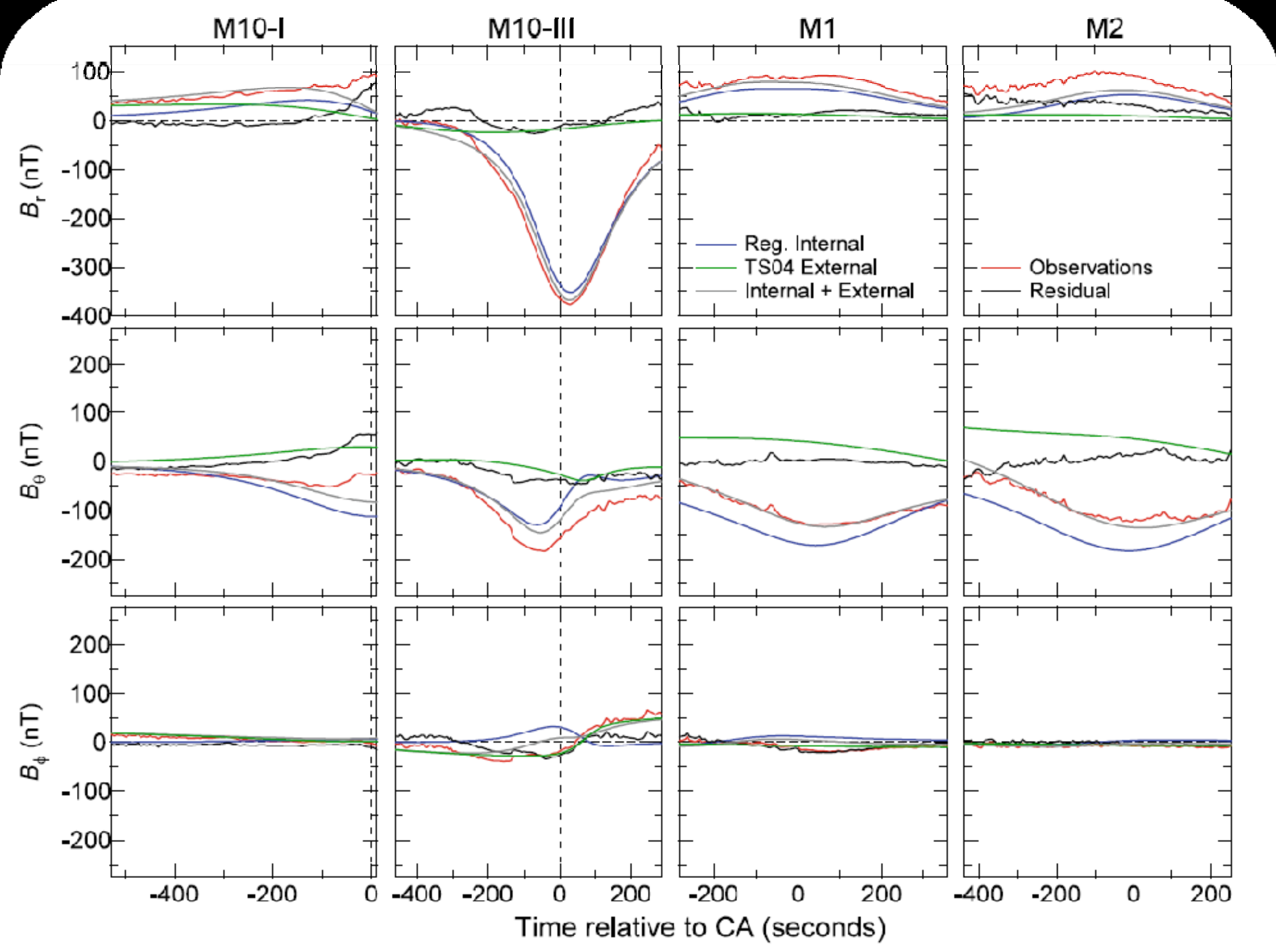


Fig. 8 Overview of Mariner 10 and MESSENGER observations of Mercury's magnetic field. Results are plotted in MBF coordinates: radial (B_r), polar angle θ (B_θ), and azimuth angle ϕ (B_ϕ) versus time relative to closest approach (CA). *Lines* show observations (*red*), internal field model from regularized solution (*blue*), TS04 external field model (*green*), sum of the internal and external models (*grey*), and residuals (*black*). The span of magnetic field values plotted is 550 nT for all three components

- Magnetic field strength of Mercury at the planet's surface is ~1% of Earth's
- Challenging to understand how it is generated, and how to separate it from "external current systems" associated with the solar wind-magnetosphere interaction
- The tilt of the magnetic moment is ~5 deg from the rotation axis.
- Considered as a dipole the strength of the moment is 240-270 nT-R_M^3
- Considered as a multipole the dipole term is smaller (180-220 nT R_M^3) plus higher order terms giving surface field strength at equator of 250-290 nT.
- The cross-tail current extends to within 0.5 Rm of surface on nightside, which may account for low field recorded near equator.

Anderson et al., 2010, The magnetic field of Mercury, Space Sci. Rev.

How do field-aligned current systems close in Mercury's magnetosphere?

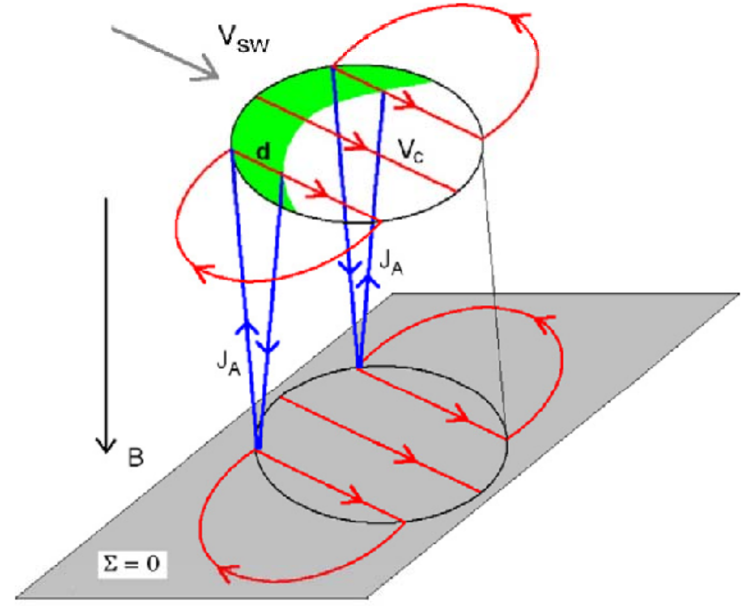


Fig. 3. Transport of the convection pattern (shown in red) and currents (shown in blue) of the Alfven wave from the upper boundary of the cylinder, where it is generated, to the planet surface and back with accounting for a shift of the propagating wave along the convection flow. While returning back to the upper boundary, the reflected Alfven wave appears shifted with respect to its original position by a distance *d*. The region between the initial and reflected *FACs* is shown as a green area. Other denominations are the same as in Fig. 2. We note that the currents of the Alfven wave J_A, are inclined to the magnetic field, *B*; this effect is known as the "Alfven wings".

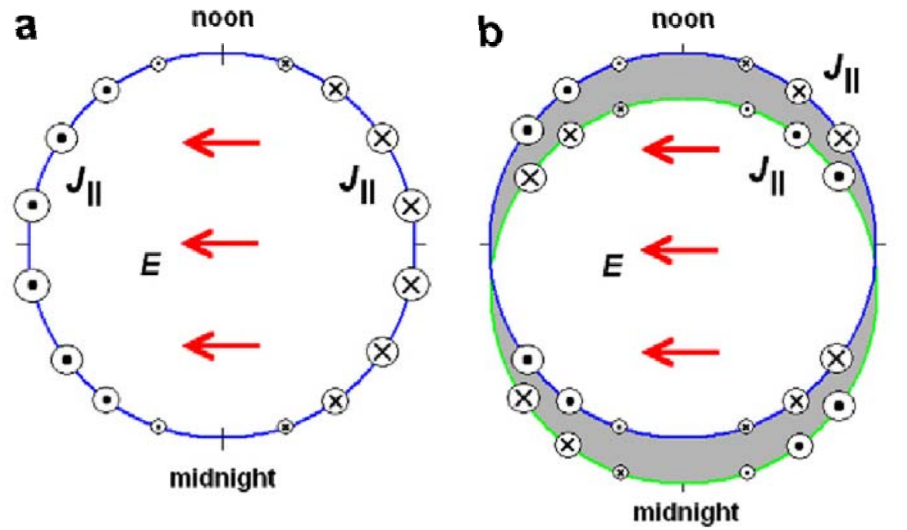


Fig. 4. The electric field (*E*) and *FACs* ($J_{||}$) over the polar cap when: (a) there is a substantial ionospheric conductance and no reflected wave, and (b) there is a reflected wave but no ionospheric conductance (the latter corresponds to the *AWR* model). The blue circle shows the region of open magnetic field lines. On the panel (a), *FACs* flow on the boundary of open field lines and are closing the ionospheric currents. On the panel (b), the *FACs* flow on the boundaries of the crescent areas (shown in gray) between the incident and reflected Alfven waves. The *FACs* increases to dawn and dusk though the width of the areas between the upward and downward currents is reduced. This picture does not include the substorm currents.

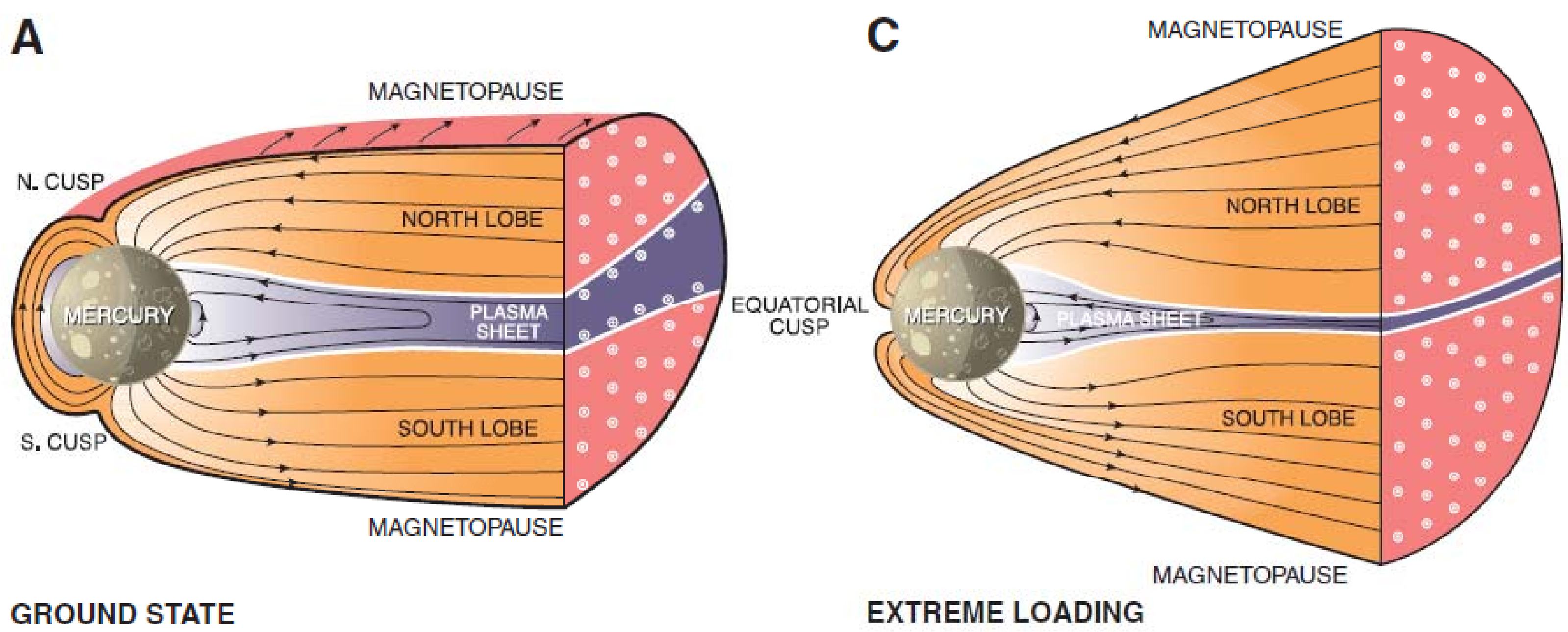
See Lyatsky et al., 2009, Alfven Wave Reflection model of field-aligned currents at Mercury, Icarus

- Mercury has no significant conducting ionosphere or surface conductance
- Need a mechanism whereby Mercury's field-aligned currents can be closed
- Proposed Alfven Wave Reflection (AWR) model is proposed
- Takes into account low ionospheric/surface conductivity, capable of carrying total FAC~500 kA

Mercury

Introduction | Magnetosphere | Exosphere

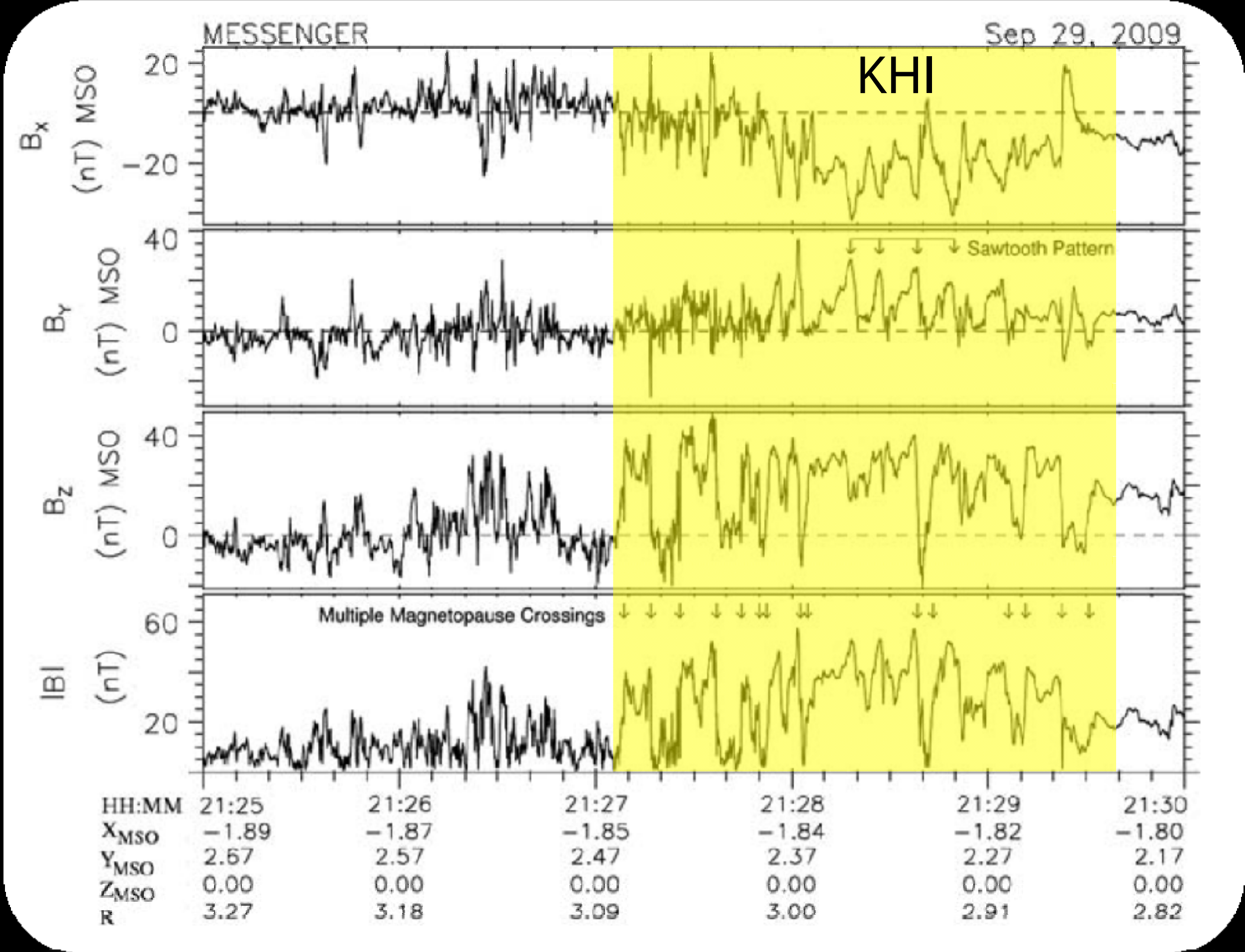
How do magnetospheric dynamics at Mercury compare to the Earth?



Slavin et al., 2010, Extreme Loading and Unloading of Mercury's Magnetic Tail, Science

- During second flyby MESSENGER observed large boundary normal component of the magnetic field, implying cross-magnetosphere potential of ~30 kV. This implied a Dungey-cycle time for Mercury of just 2 min!
- During the third flyby MESSENGER observed 4 loading/unloading events in the magnetotail lasting 2-3 mins in duration, with the magnitude of the tail field increasing and decreasing by factors of ~2-3.5
- Extreme case indicated a peak tail magnetic flux content of ~10 MWb – 50% more than expected from modelling work

How do magnetospheric dynamics at Mercury compare to the Earth?



Kelvin Helmholtz Instability observed at Mercury
(see Sundberg et al., 2010,2011 & **Boardsen** et al., 2010)

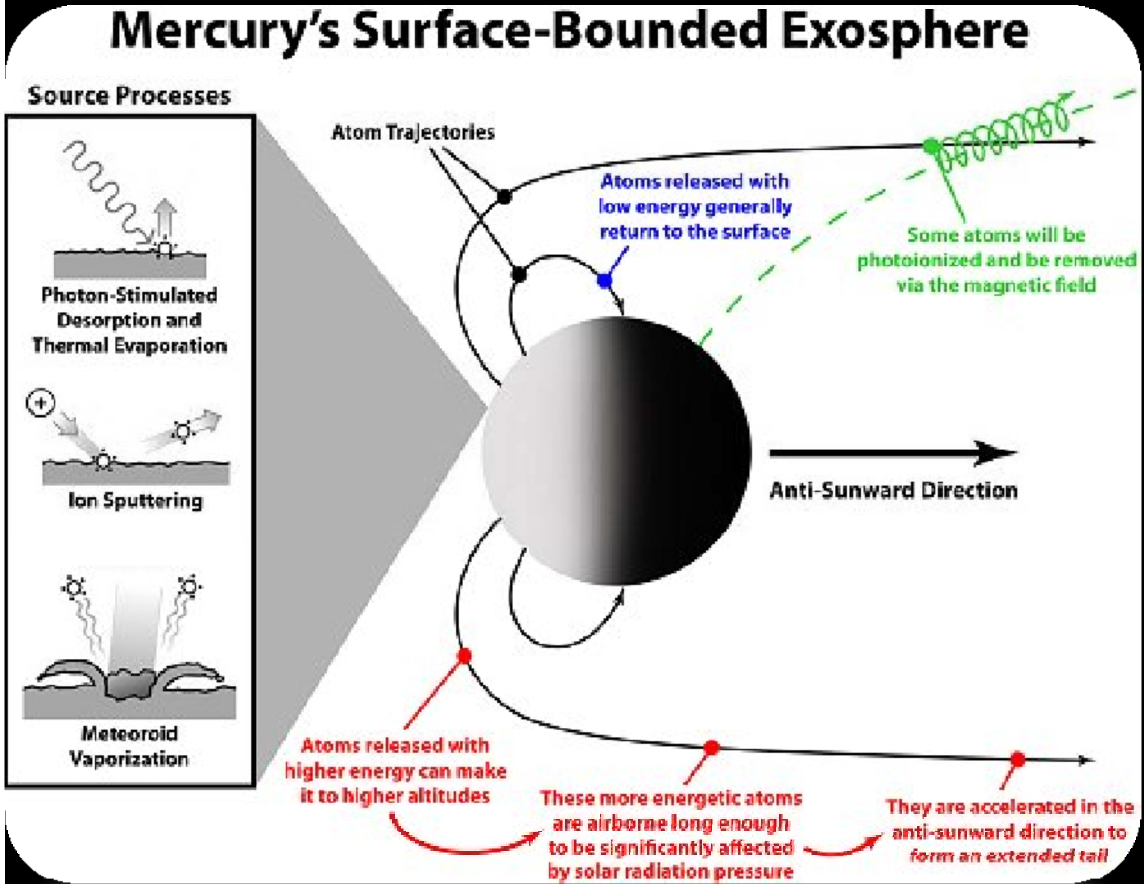
During the third flyby of Mercury, 15 magnetopause crossings were observed on the dusk-side during 2 minutes.

The crossings were quasi-periodic, with time separations of ~16 s between pairs of crossings.

Suggested to be indicative of surface waves arising from the KHI.

This work by Boardsen et al., (2010) supports and complements similar studies by Sundberg et al., (2010 and 2011).

Mercury



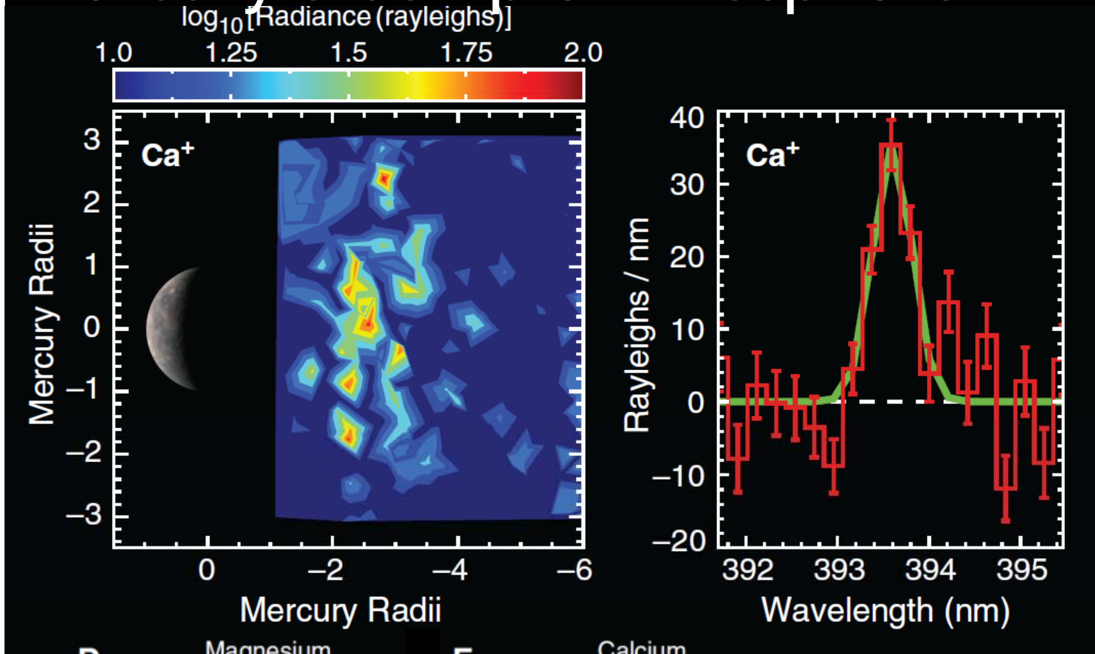
Mercury has a surface-bound exosphere in which constituent atoms and molecules travel on collisionless trajectories.

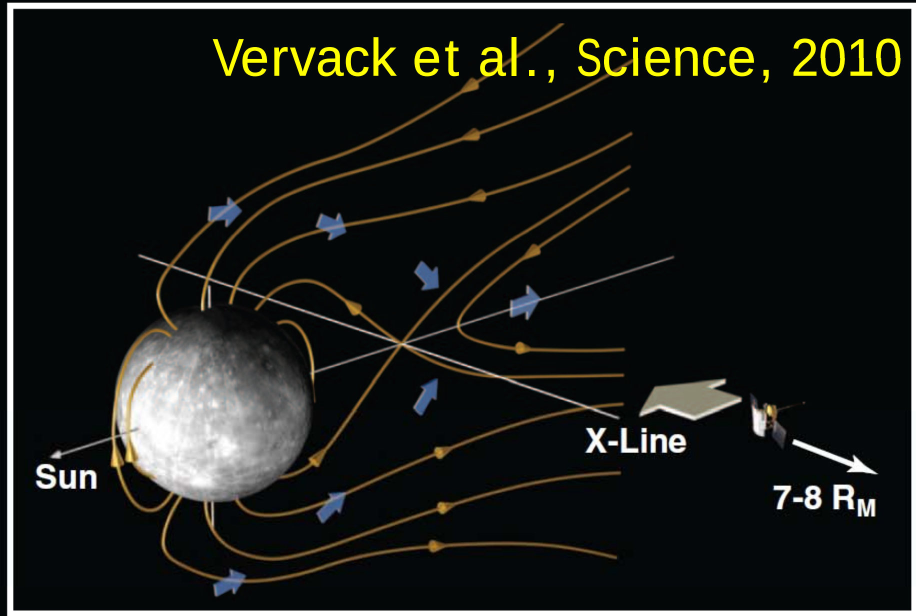
The exosphere experiences strong seasonal variations, and varies according to the solar wind interaction with the magnetosphere.

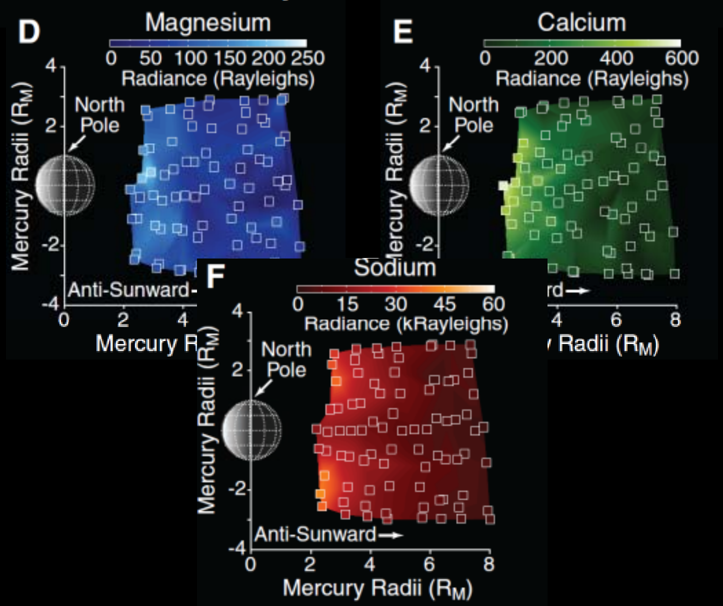
Neutral species are released from the surface through a variety of mechanisms: thermal desorption, photon-stimulated desorption, meteoroid impact vaporisation and ion sputtering.

Once released from the surface the distribution of species is determined by gravity, radiation pressure, and photoionisation – and then magnetic/electric field transportation ending in loss on open field lines or impact with the surface

Mercury's Complex Exosphere





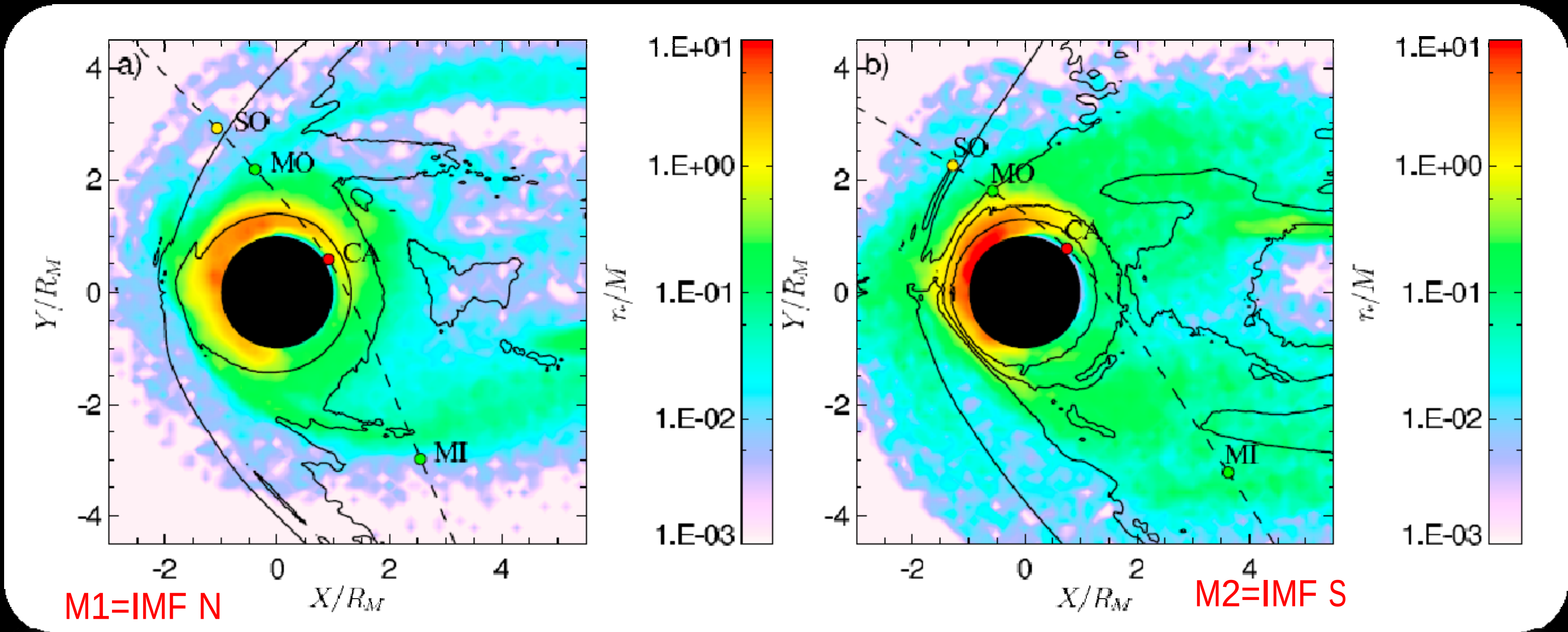


McClintock et al., Science, 2009

- Exosphere known to contain sodium, calcium and potassium, new measurements also show presence of magnesium.
- Calcium emission peaks near to dawn equator while the sodium peaks near to high latitudes (which may be a result of the solar wind sputtering process)
- Calcium ion observations show peak near 2 R_M thought to be the results of rapid ionisation in active magnetospheric conditions

Mercury's Complex Exosphere

- MESSENGER experienced different IMF conditions for M1 and M2 flybys
- The effects of this difference on the distribution of sodium ions has been modelled using the hybrid simulation code
- They assume photon-stimulated desorption and ion sputtering are the two main sources of sodium ions
- The first peaks at sub-solar point and the second is highly dependent on IMF orientation – peaks for IMF S



Paral et al., 2010, Sodium ion exosphere of Mercury, GRL
Travnicek et al., 2010, Mercury Hybrid Model, Icarus

Telescope observations of Mercury's sodium tail

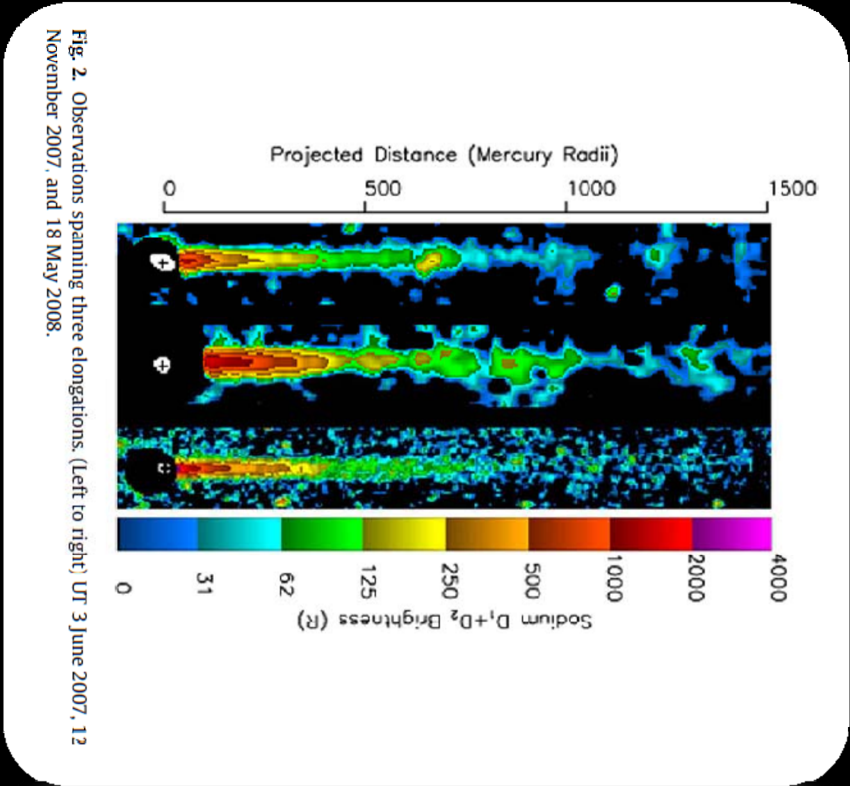


Fig. 2. Observations spanning three elongations. (Left to right) UT 3 June 2007, 12 November 2007, and 18 May 2008.

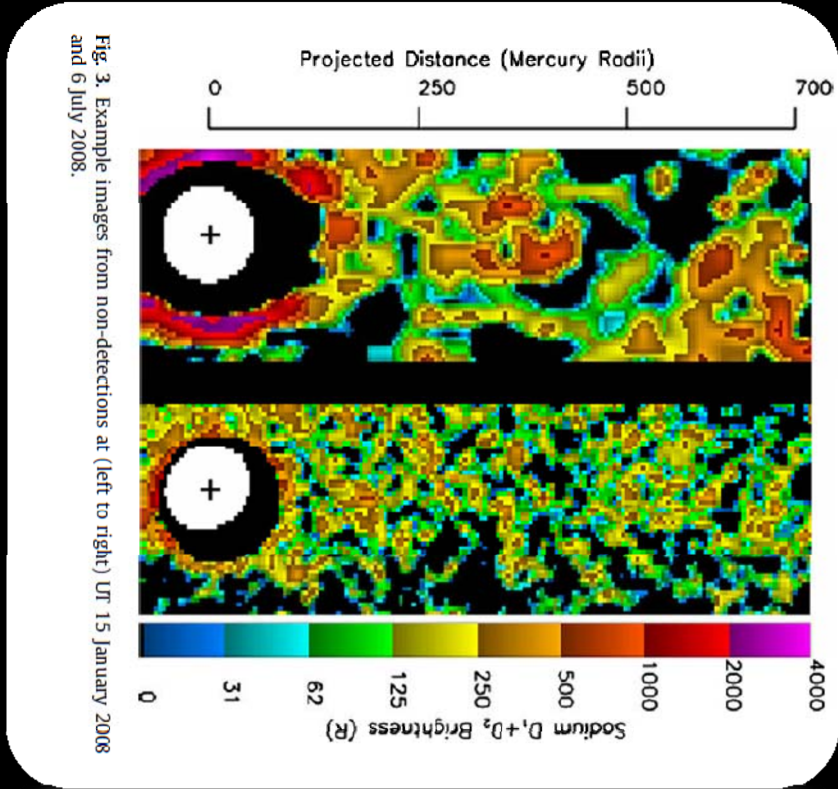
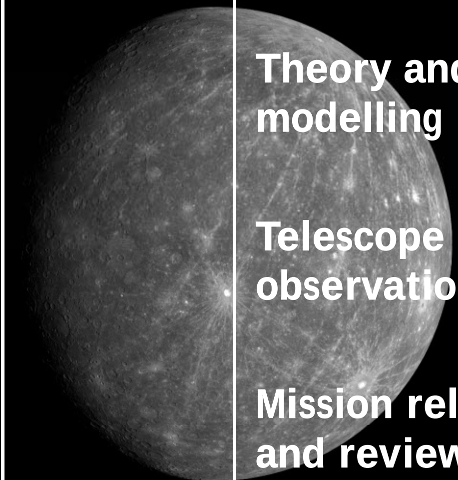


Fig. 3. Example images from non-detections at (left to right) UT 15 January 2008 and 6 July 2008.

Schmidt et al., 2010, Orbital effects on Mercury's escaping sodium exosphere, Icarus

- Multiple observations from the McDonald Observatory around May 2007 are used to study the neutral sodium tail extending to >1000 R_M
- When MESSENGER performed flyby in Jan 2008 (similar orbital phase) there was no evidence of a tail beyond ~120 R_M
- Differences are thought to be associated with changes in solar flux and radiation pressure due to changes in Mercury's heliocentric radial velocity – rather than surface source rates

Publication Statistics from the Web of Knowledge for 2009-2011
Search keywords: planet/body + magnetosphere



Planet/ Moon	Mercury	Jupiter	Ganymede	Saturn	Uranus & Neptune
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*e.g. Hubble Space Telescope, IR telescopes, radio telescopes

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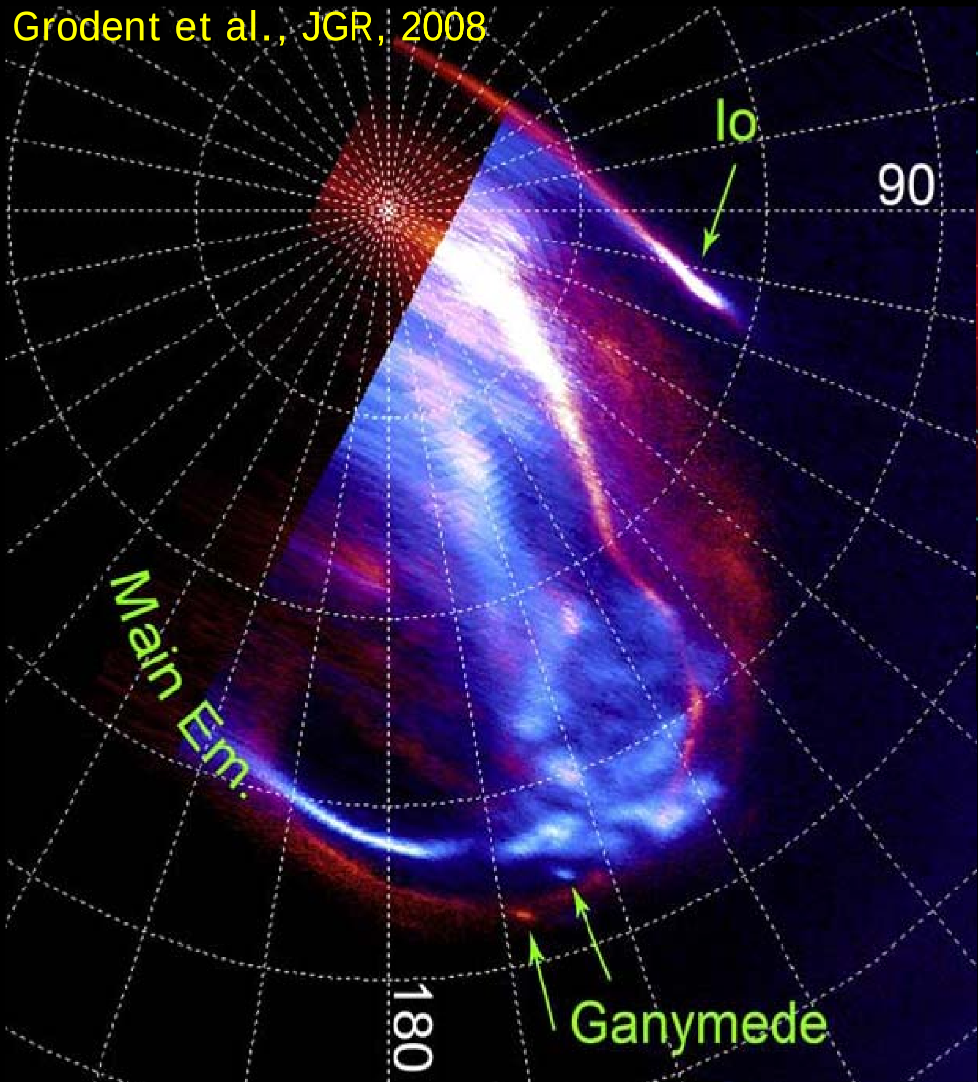
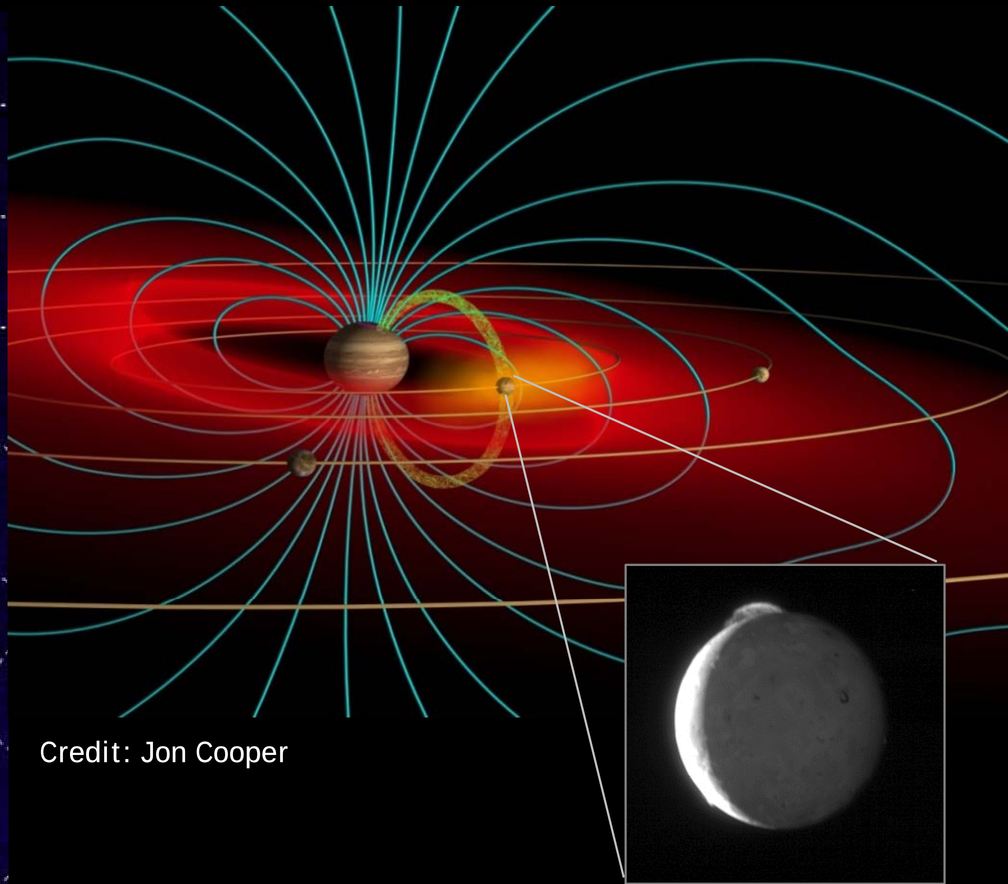
Jupiter

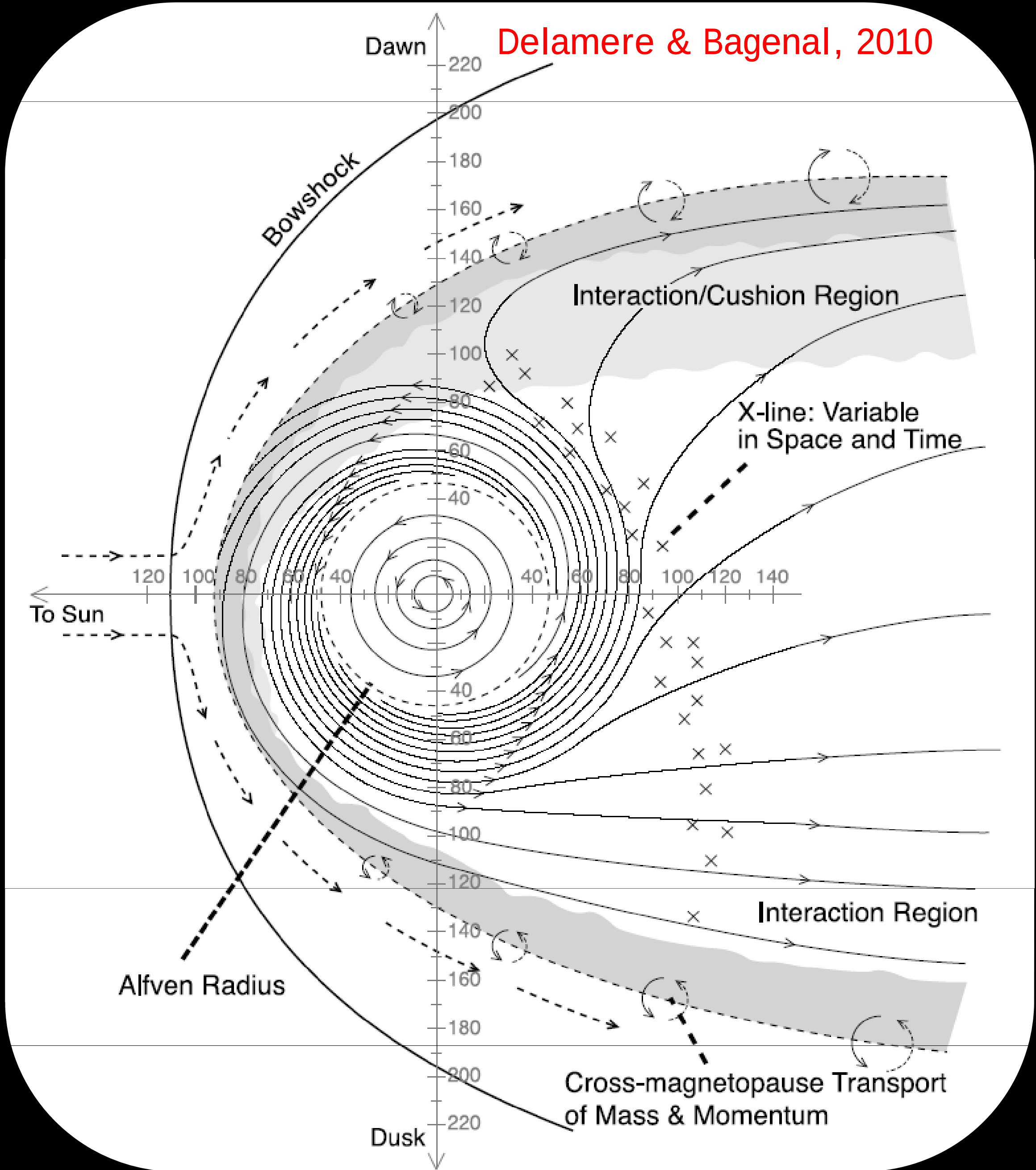




Credit: Jon Cooper

Jupiter's magnetosphere is driven by rapid planetary rotation, main source of plasma is the volcanic moon Io. Complex coupled system involving strong interactions between moons and magnetosphere.

Jupiter

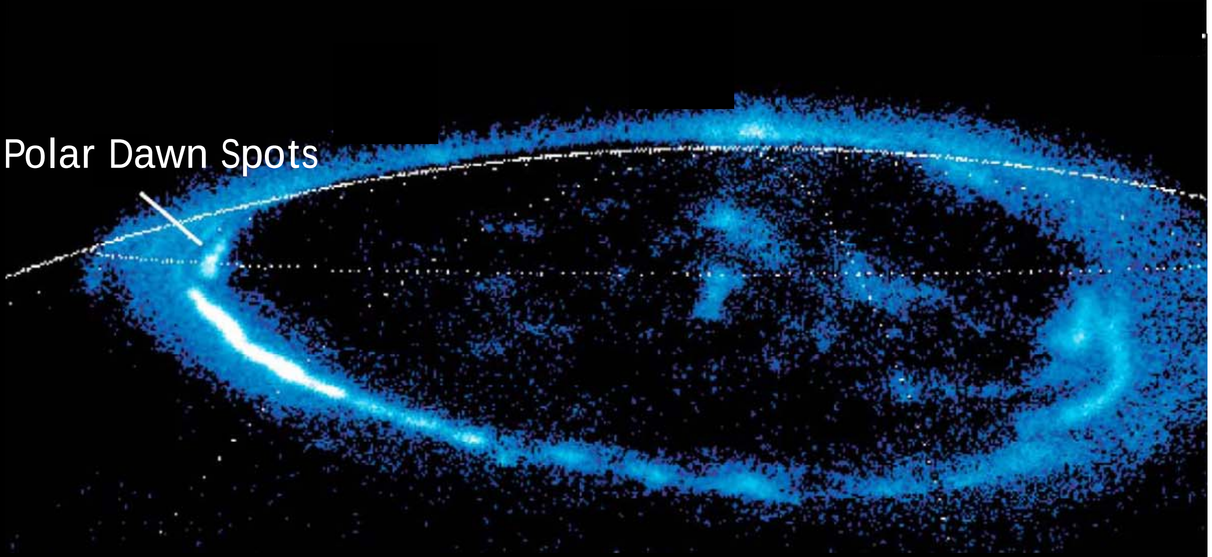


Argue that Jupiter's solar wind–driven magnetospheric flows are due primarily to viscous processes at the magnetopause boundary.

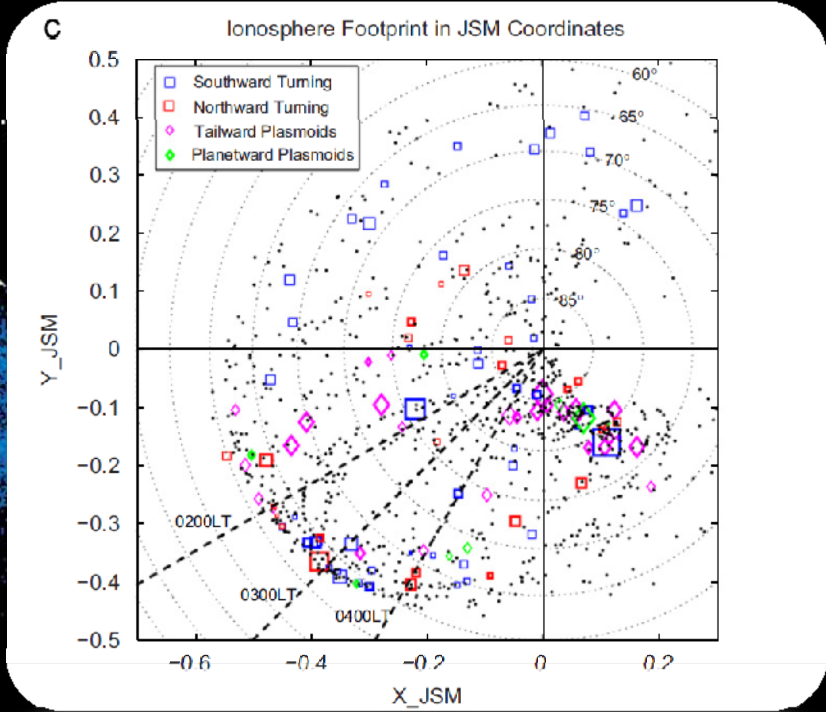
They discuss how such a plasma-on-plasma interaction generates solar wind–imposed magnetic stresses that:

(1) Generates the dawn-dusk asymmetry observed in plasma flows and magnetic field,
(2) Dictates the location of the magnetic x line in the tail,
(3) Enhances the escape of Jovian plasma down the magnetotail, &
(4) Drives global plasma flows that are consistent with Jupiter's complex polar aurora without the requirement for a persistent region of open flux.

Signatures of tail reconnection



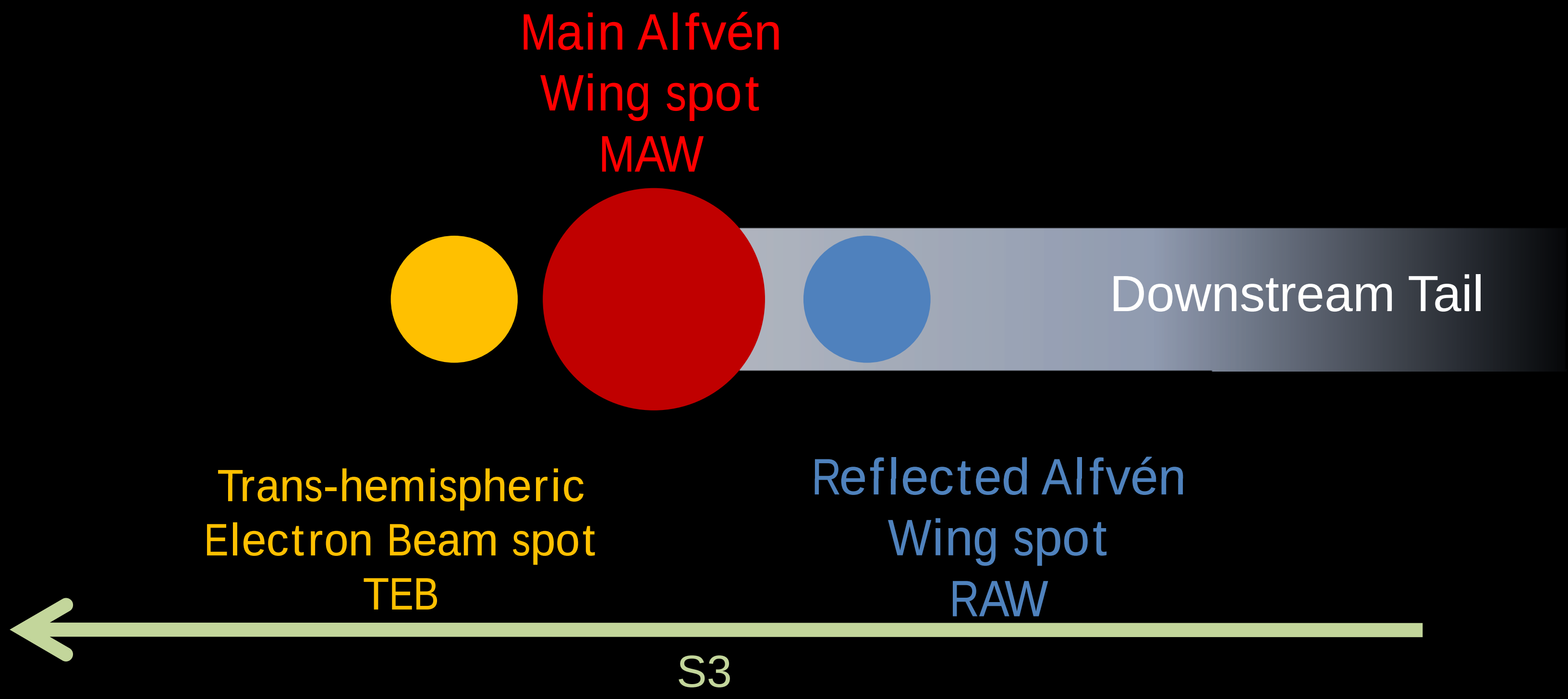
Radioti et al., JGR, 2011



Ge et al., JGR, 2010

- Signatures associated with tail reconnection are observed over a large area of local time – both in terms of remote sensing data (e.g. HST) and in situ (e.g. Galileo)
- Radioti et al. (2011) attribute both dawn and nightside polar "spots" in UV aurora to near-simultaneous measurements of inward moving flows in the magnetosphere
- Ge et al. (2010) show that signatures of dipolarisation in the tail most likely map to the dawn spots – and suggest an x line location of 02:00 LT at 80 R_J downtail
- Vogt et al., (2010) perform a similar study, but interestingly point out that the previously identified recurrence rate of 2-3 days is intermittent and not statistically significant

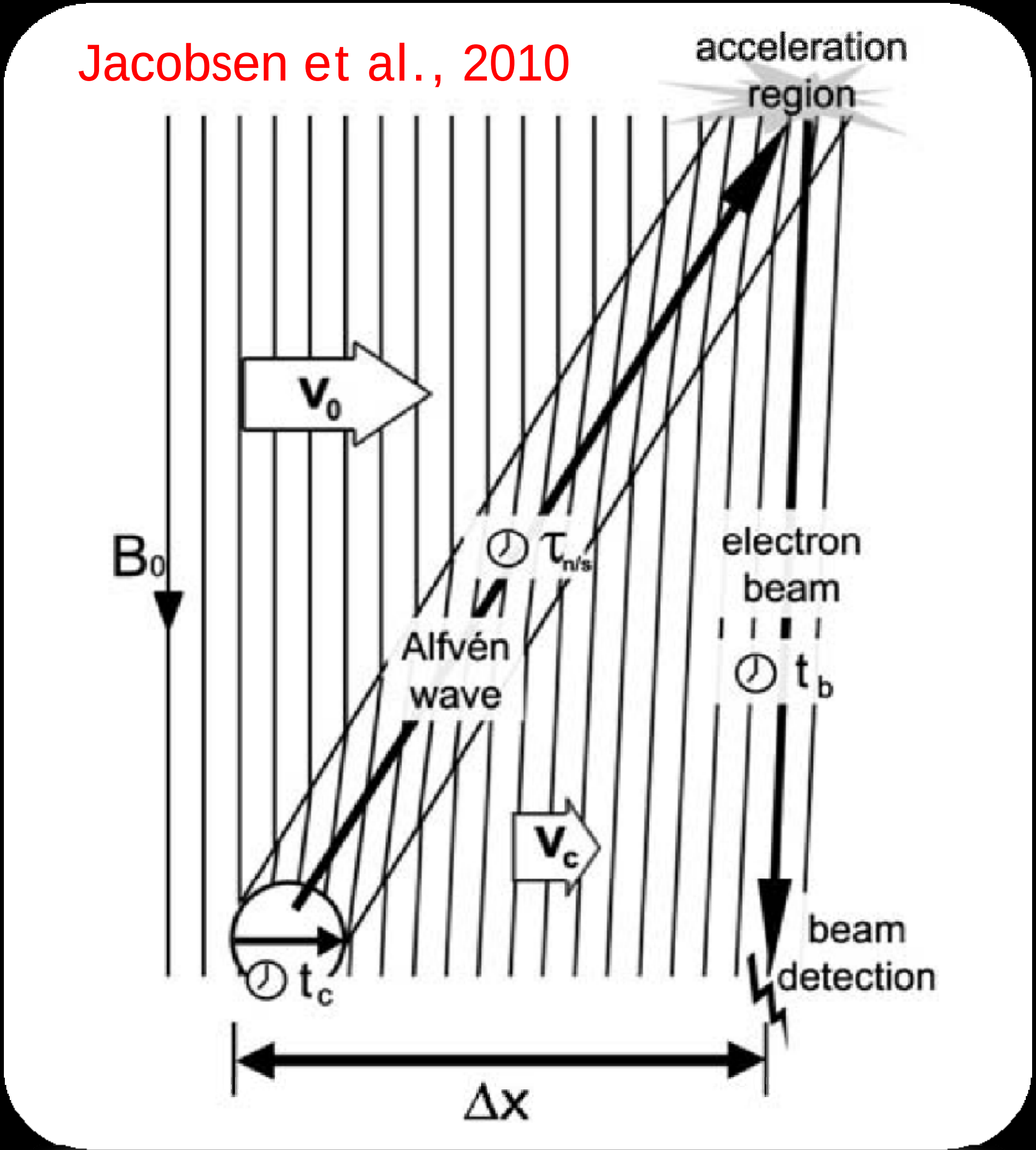
The extent of the Io-Jupiter interaction region

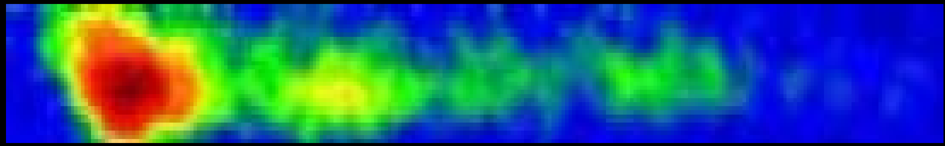


- The Io footprint aurora consists of one or several spots observed in both hemispheres and is related to the electromagnetic interaction between Io and the magnetosphere
- The spots are followed by an auroral curtain, the tail, which extends up to 90° in longitude
- The footprint brightness, spot multiplicity, and inter-spot distance depends on Io's location in the plasma torus
- Recently Bonfond et al. (2010) have shown the size of the spots to be 850 km long x 200 km wide, at an altitude of 900 km. This is important as it indicates the size of the interaction region at Io.

See Bonfond et al., JGR, 2009 & 2010 (and references therein)

The extent of the Io-Jupiter interaction region





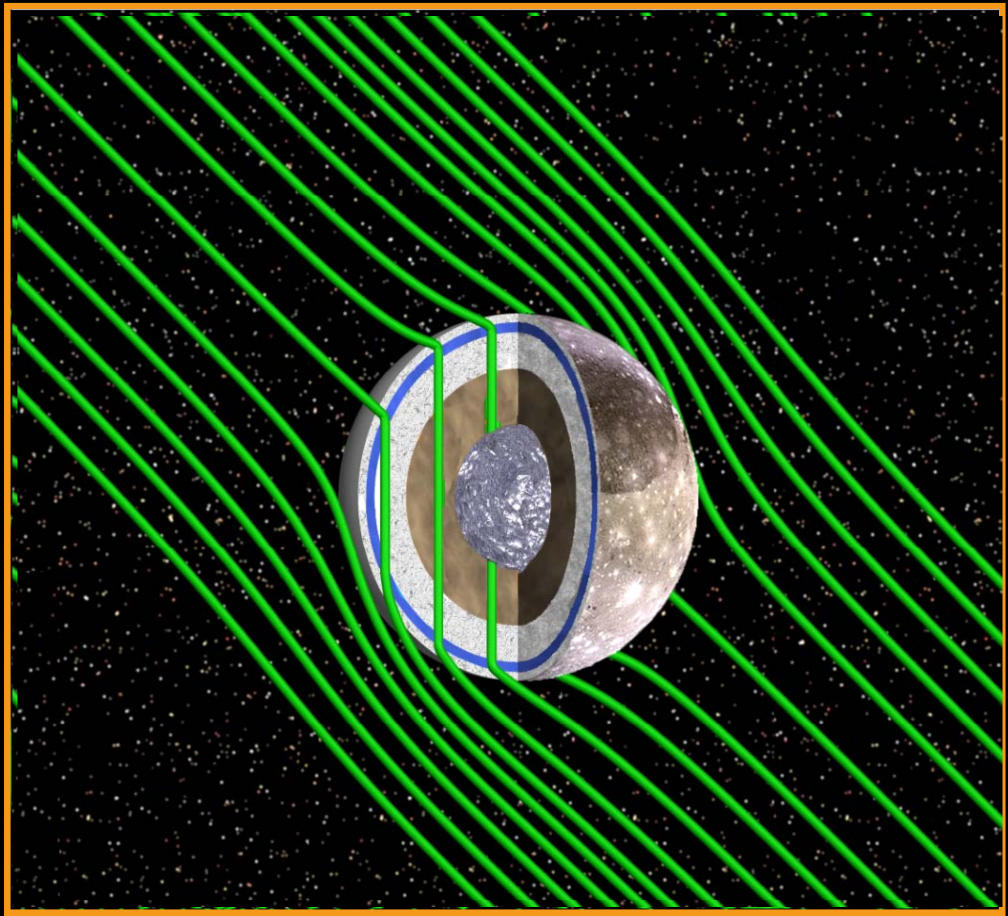
Io footprint seen in Jupiter's atmosphere

Jacobsen et al. (2010) apply a three-dimensional MHD model of the far-field Io-Jupiter interaction to simulate the location and spatial shape of field-aligned electron beams.

They find that the ratio of the one-way travel time of the Alfvén wave from Io to Jupiter and the convection time of the plasma past Io controls the location of the beam.

Hence electron beams are expected to be found further into the wake than previously assumed, in good agreement with particle measurements from Galileo

Ganymede

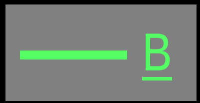


✓ *Induced* magnetic field → sub-surface (conducting) ocean?

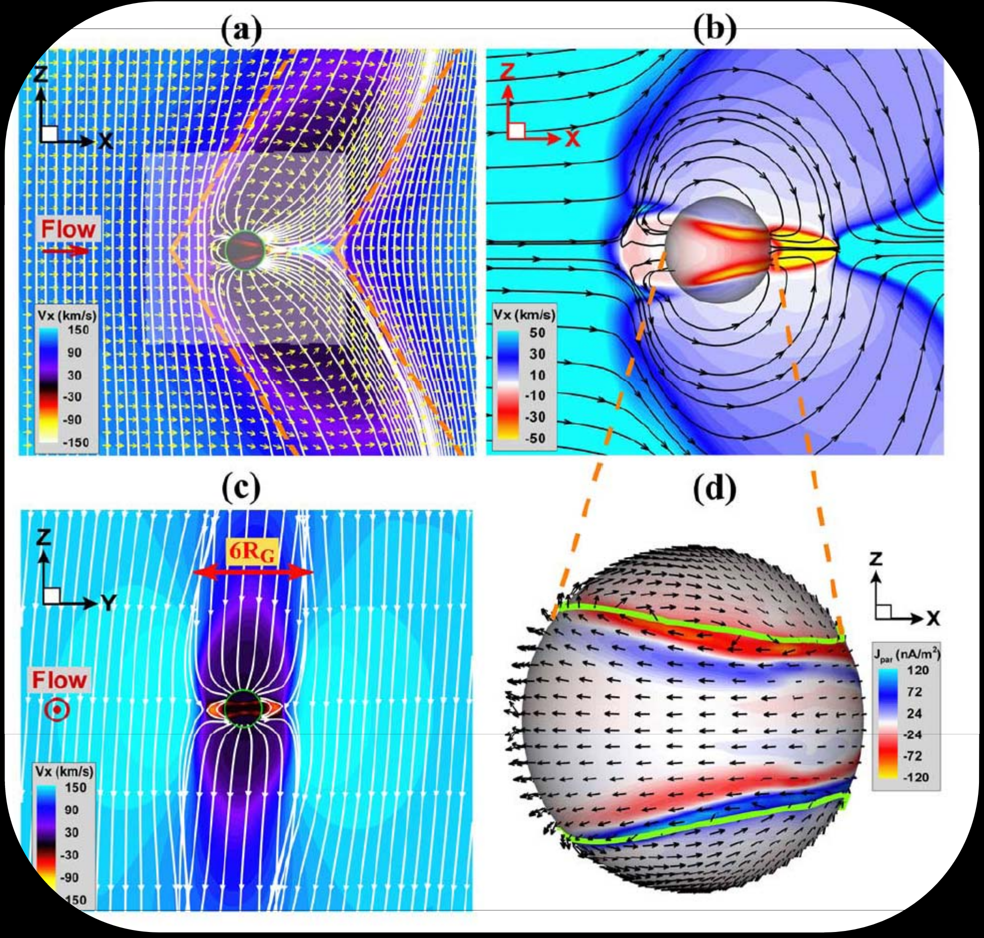
✓ *Intrinsic* dipole magnetic field

✓ *Mini-magnetosphere* is created

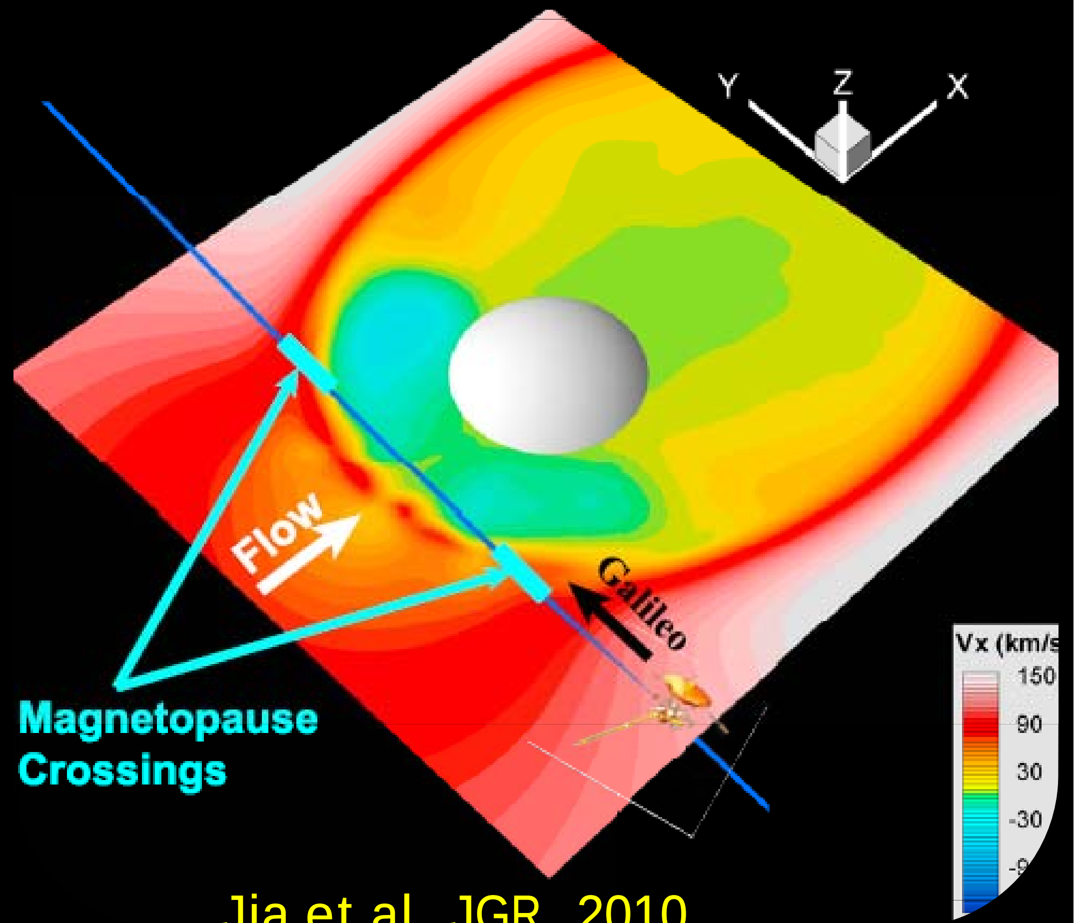
✓ Interaction is complex & highly variable



MHD simulations of Ganymede's miniature magnetosphere



Jia et al, JGR, 2009



Jia et al, JGR, 2010

- Model provides a realistic view of Ganymede's magnetosphere, which agrees well with field and particle data from Galileo
- New work show FTEs are intermittent on the dayside despite steady upstream conditions

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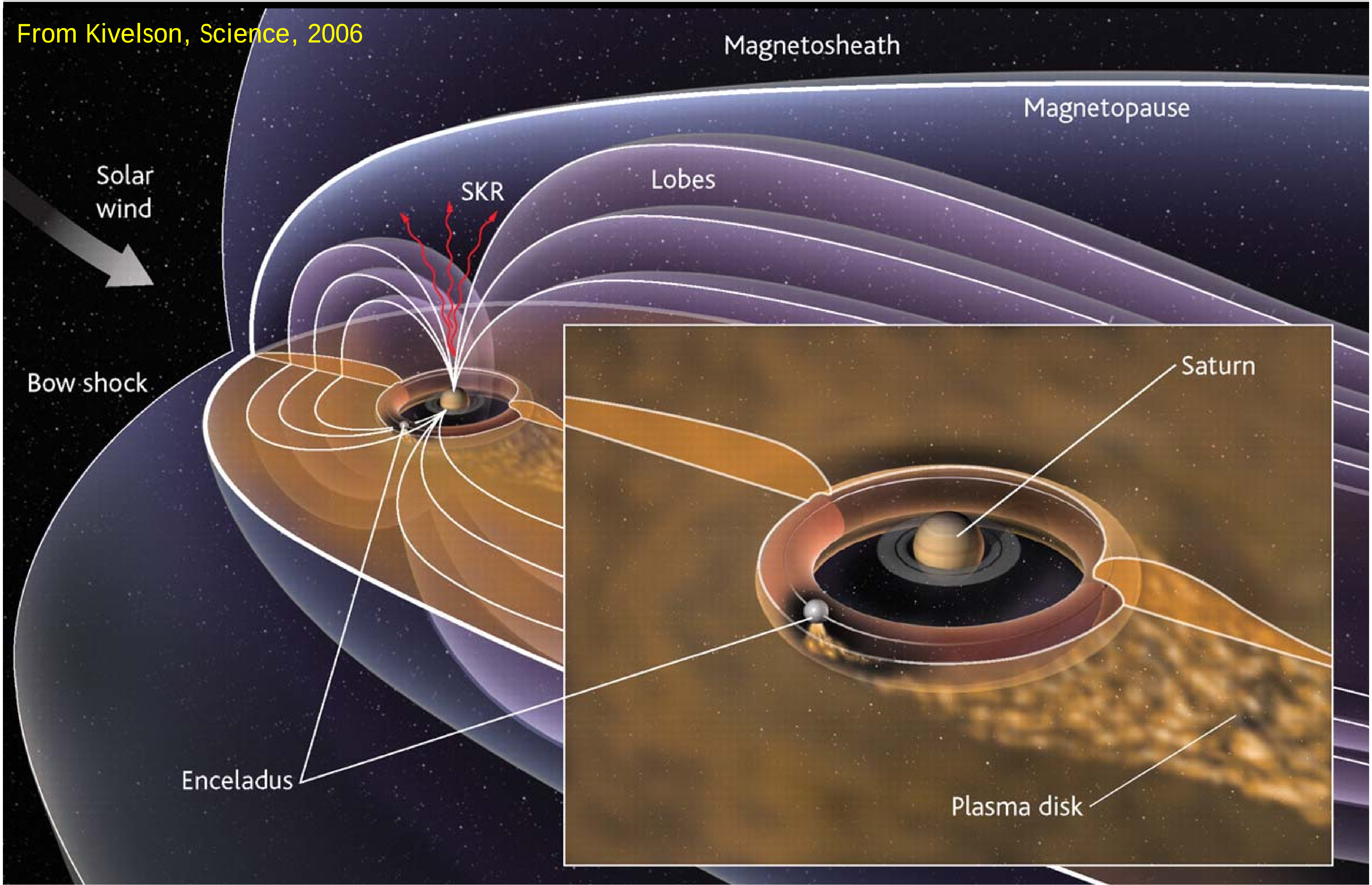
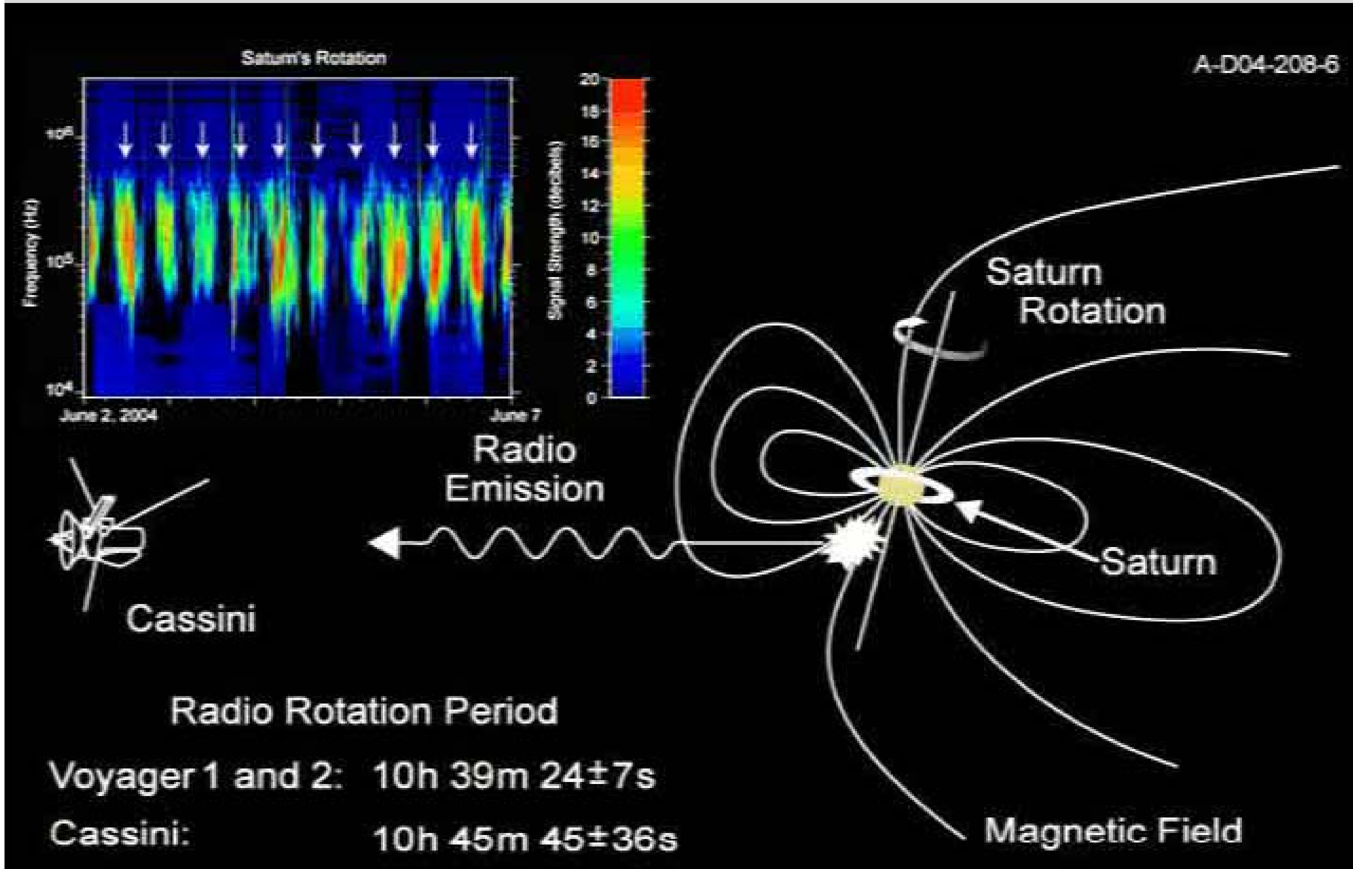
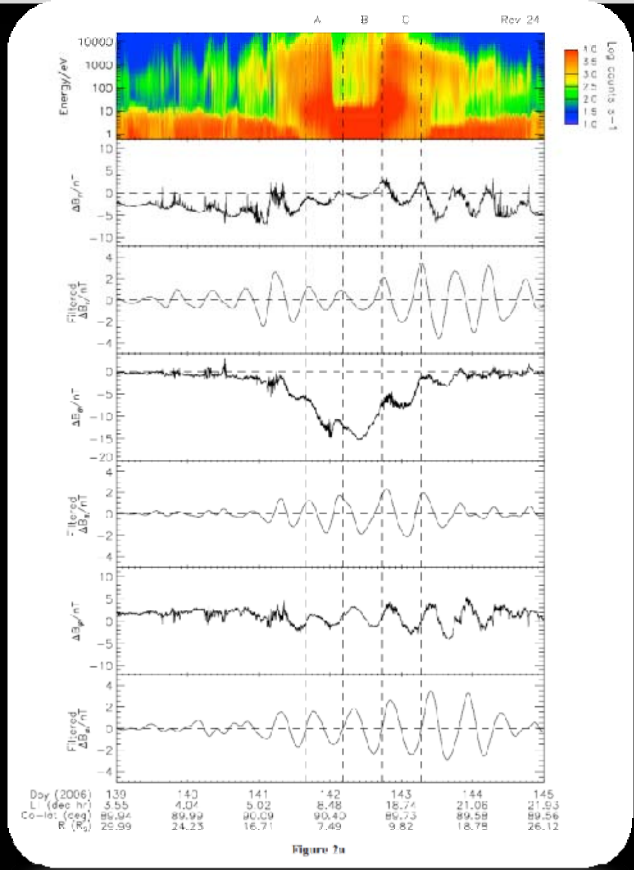
From Kivelson, Science, 2006



Saturn





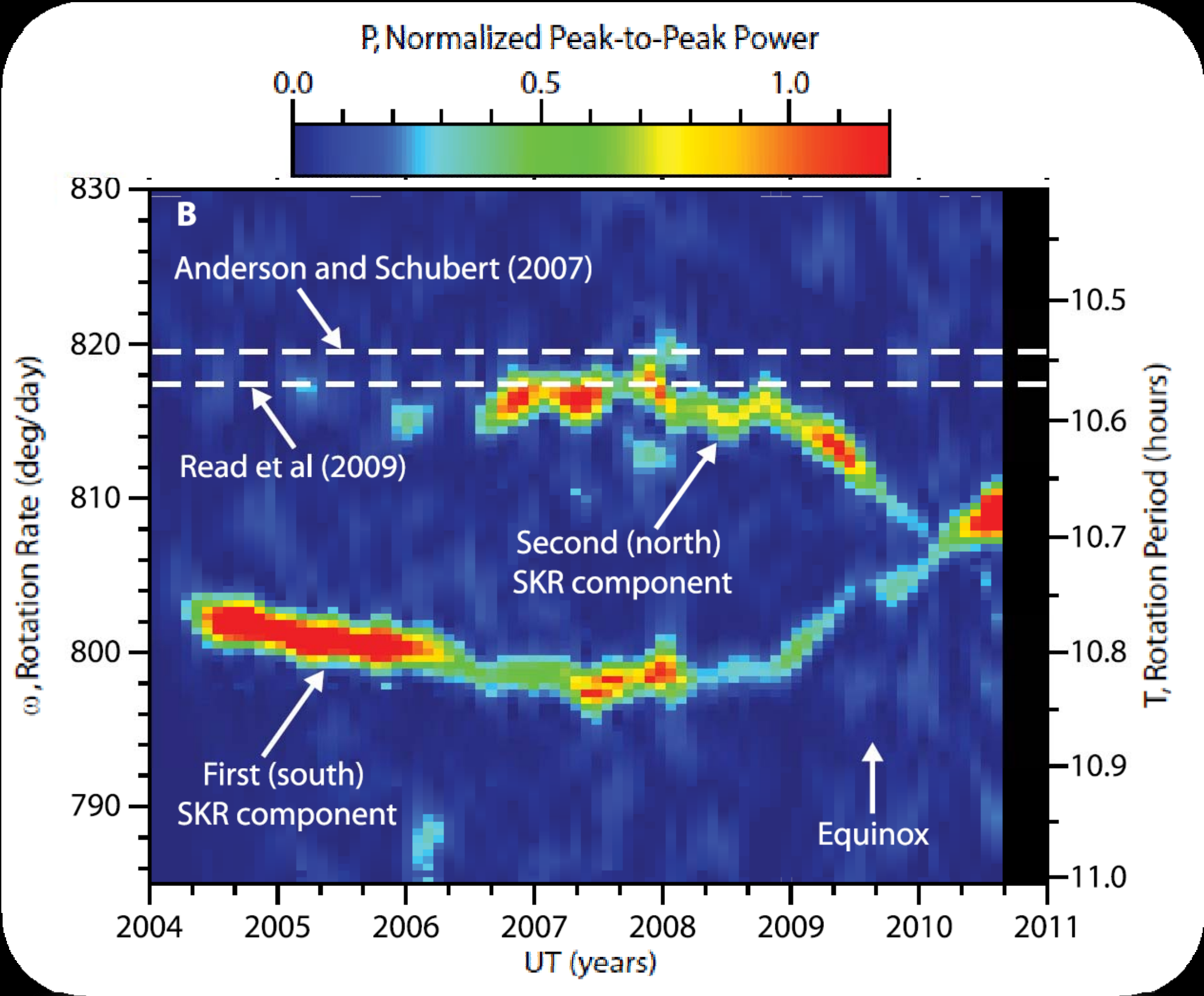
eg. from Provan et al., 2009

- A surprising and persistent feature of Saturn's magnetosphere is the presence of periodic signals – both in the Saturn Kilometric Radiation (SKR) and in the magnetosphere in situ data
- This is remarkable because Saturn's magnetic field is highly axi-symmetric
- More remarkable is the fact that these signals have a *variable* periodicity
- The periodic radio and magnetic signals have both been present continuously since 2004 and the periods of the two signals vary in the same manner (Gurnett et al., 2007; Kurth et al., 2008; Andrews et al., 2008).

Saturn Kilometric Radiation and the magnetosphere oscillations

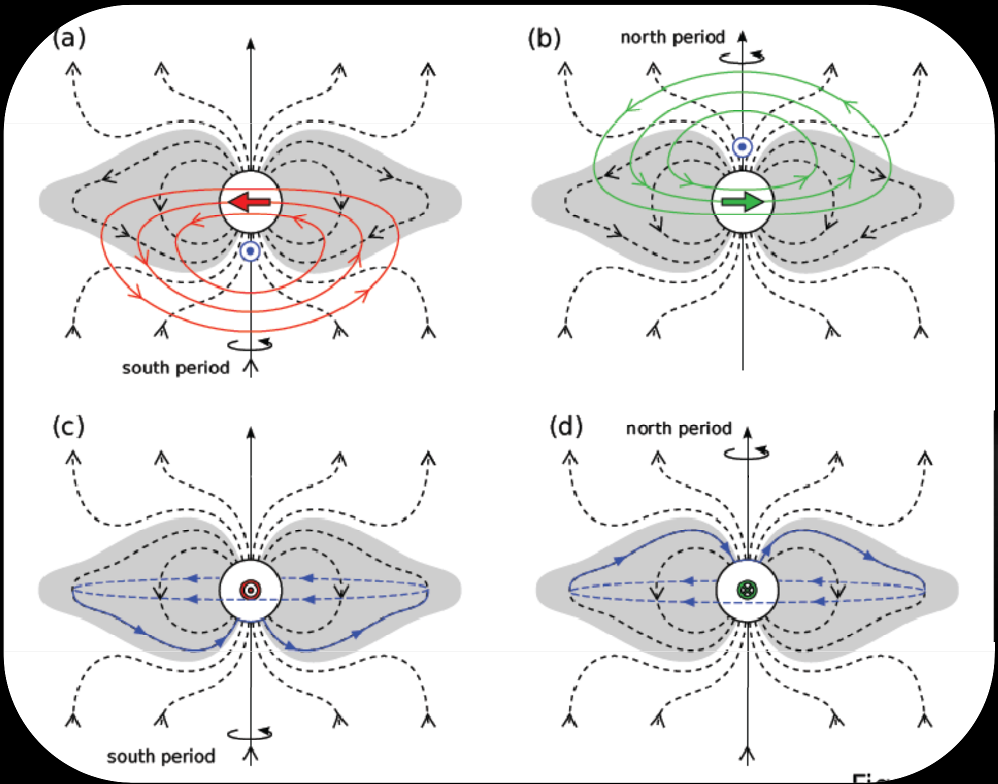
Gurnett et al., (GRL, 2009) Interestingly, they show that the shorter period emanates from the southern hemisphere high-latitude region, and the longer period emission is coming from the north.

Recently Gurnett et al., (GRL, 2010) have shown that the two periods have converged during 2010, following equinox



Saturn Kilometric Radiation and the magnetosphere oscillations

Magnetosphere oscillation studies (Andrews et al., 2010) indicate the presence of two current systems that rotate with different periods N and S, in agreement with the SKR observations.



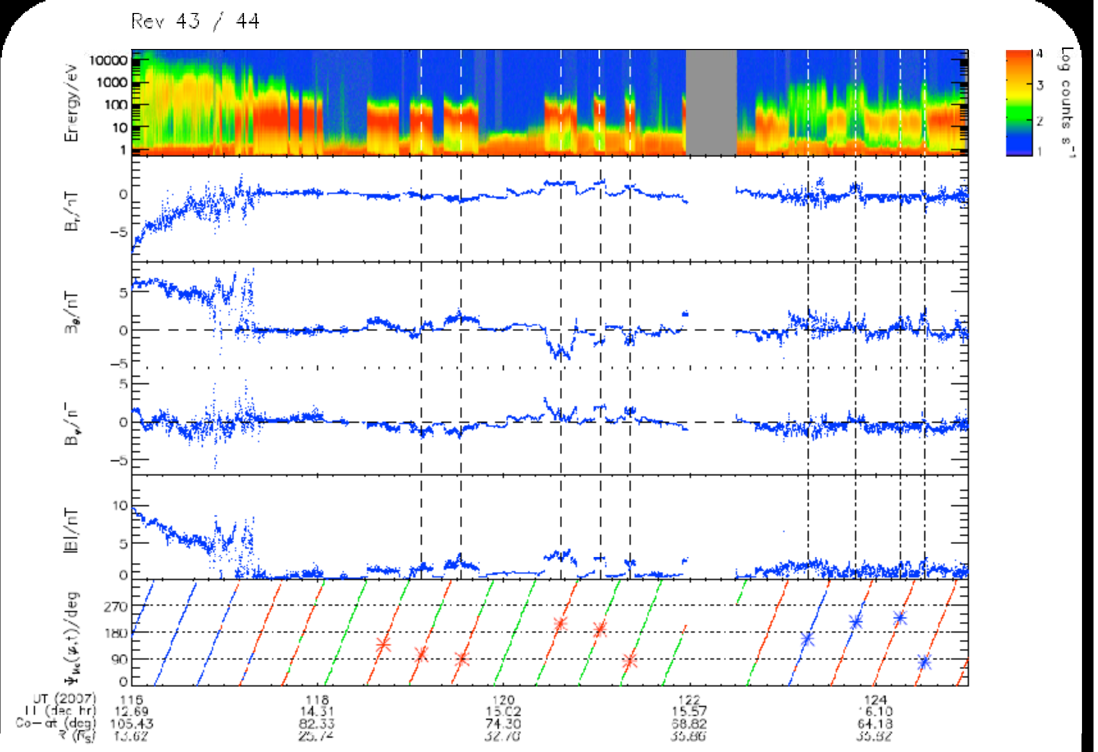


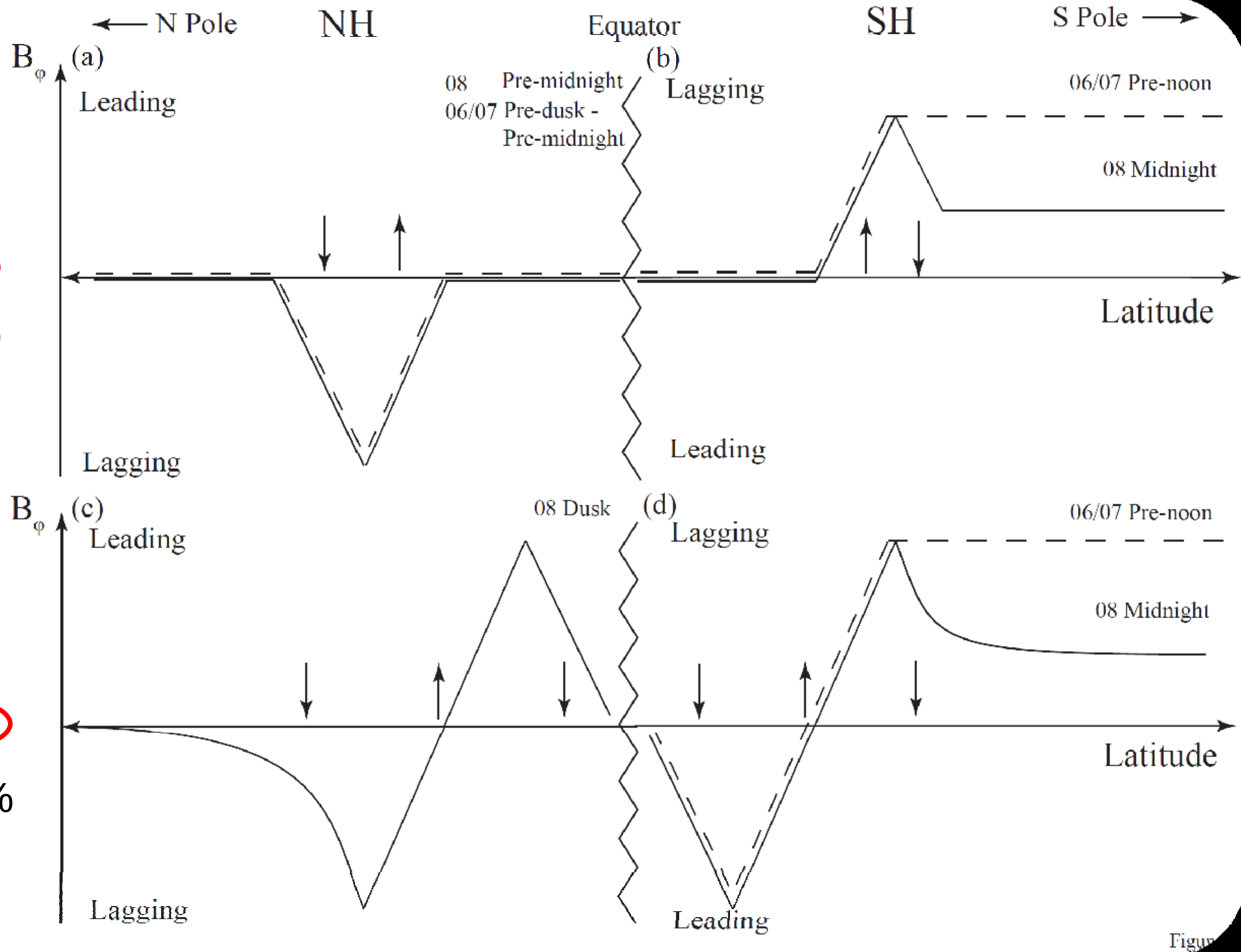
Figure 2. Electron count rate spectrogram, magnetic field data, and Provan phase (modulo 360°) for Cassini Rev 43 outbound and 44 inbound, days 116–124 of 2007.

Clarke et al. (2010) have shown the first evidence that both the magnetopause and the bow shock motions at Saturn are organised by the internal oscillation phase.

Auroral field-aligned currents in Saturn's magnetosphere

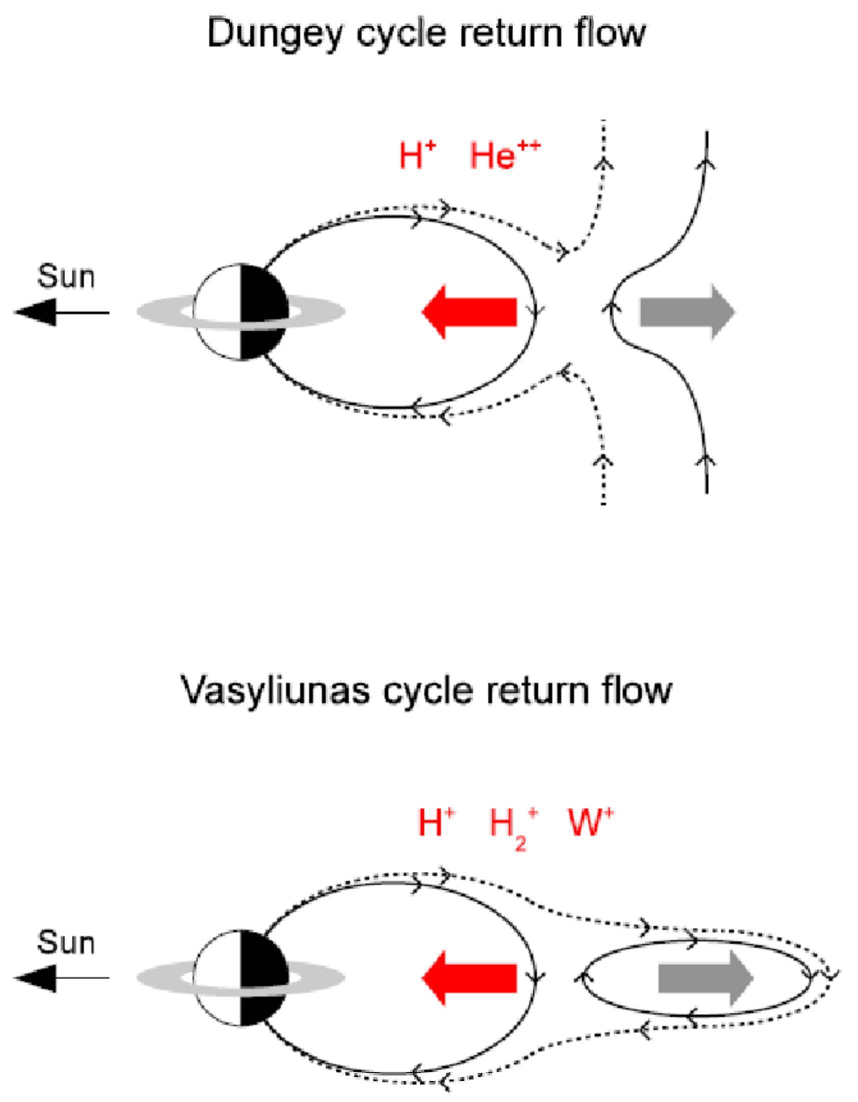
Type I
~60%

Type II
~25%



See Talboys et al., 2009a, 2009b & 2011, Field-aligned currents at Saturn, JGR & GRL

Supercorotating return flow at Saturn – evidence of tail reconnection



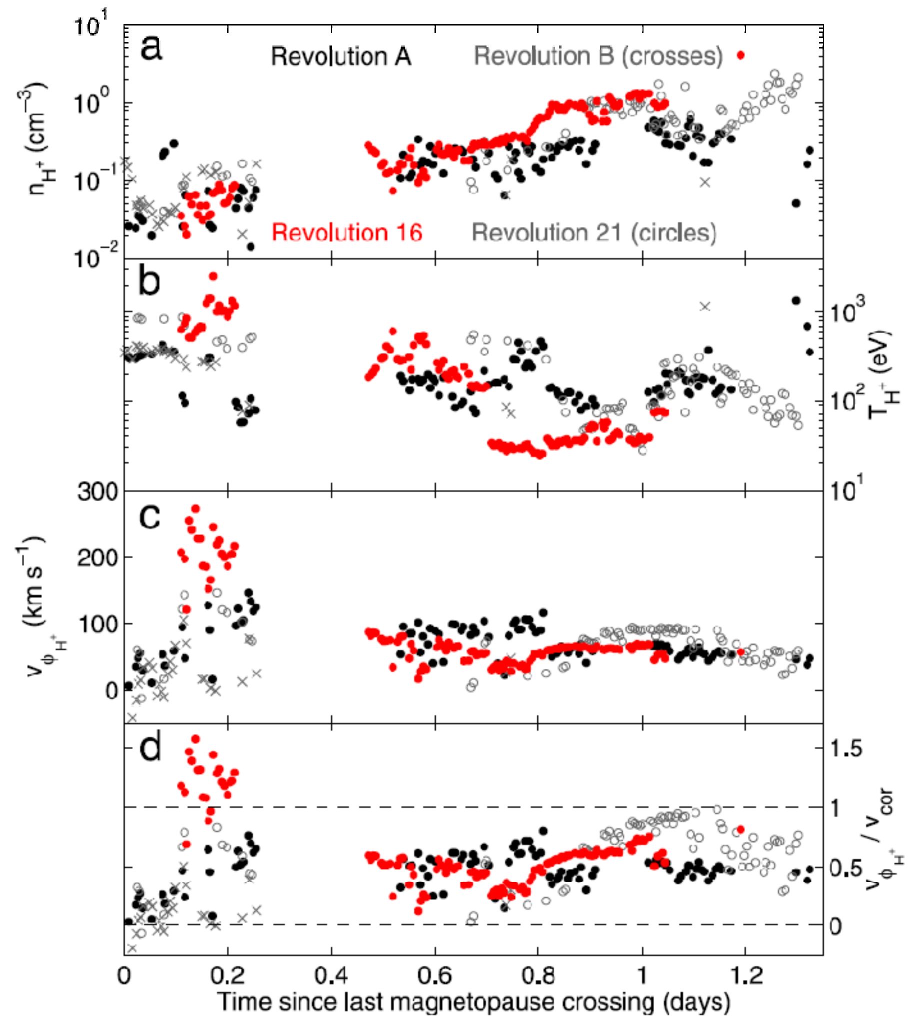
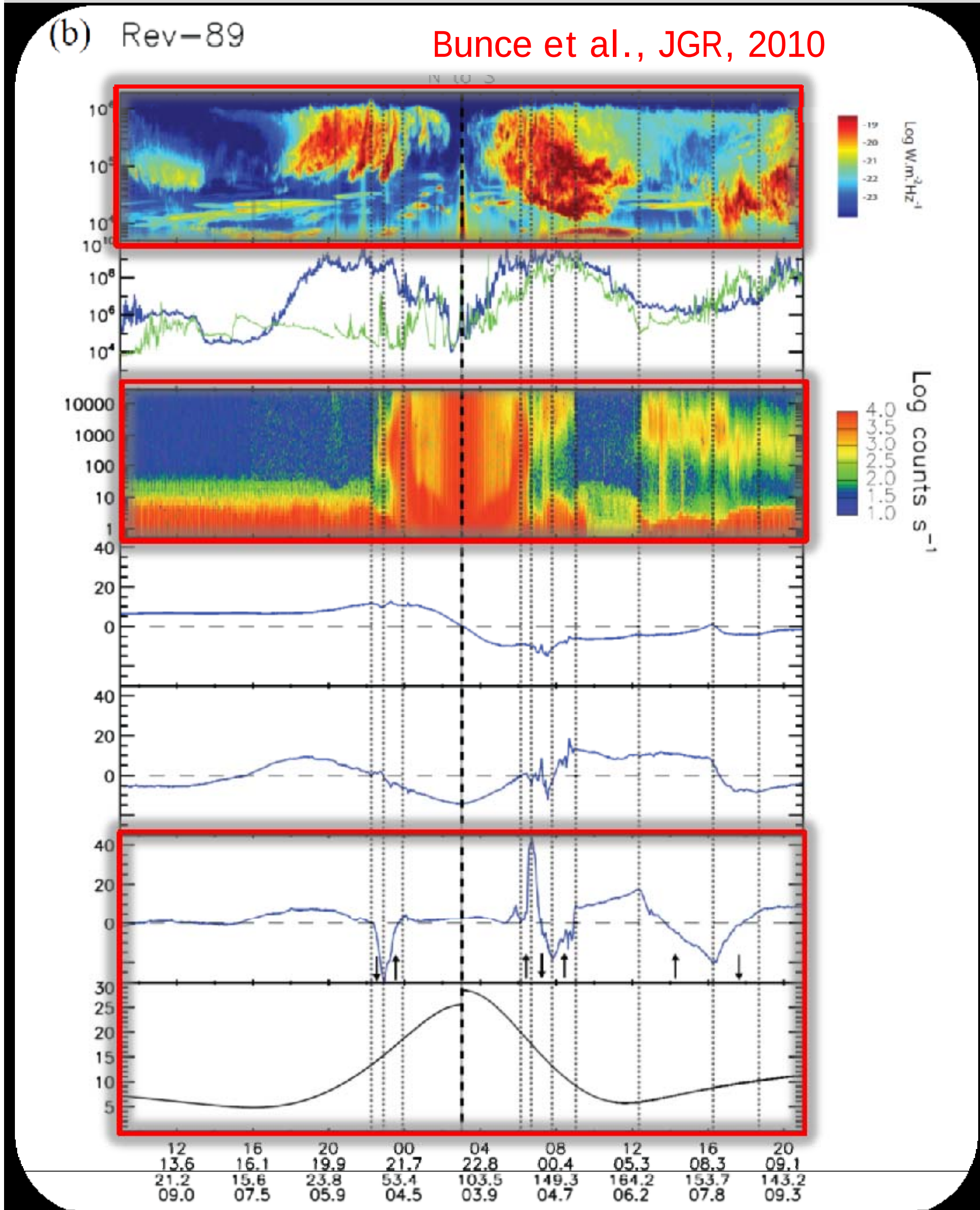


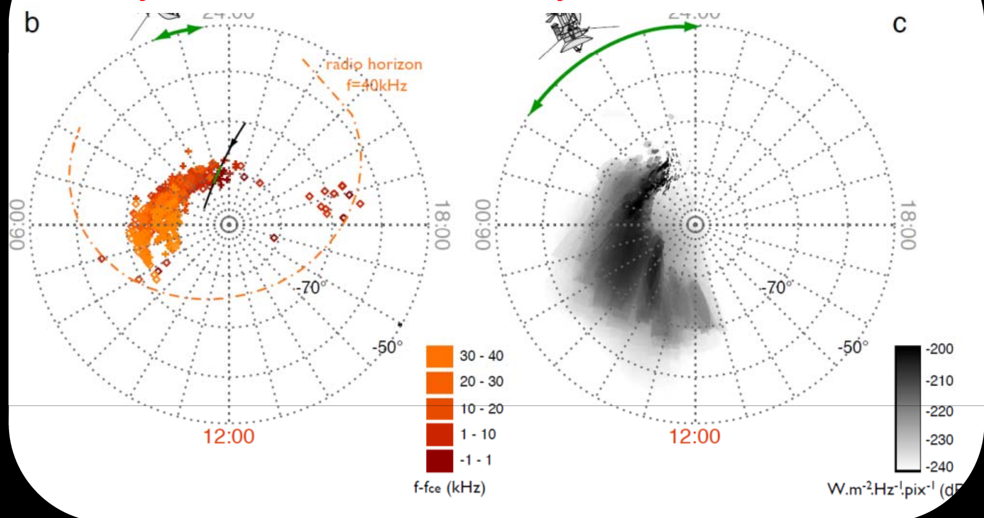
Figure 3. Ion moments derived from Cassini ion mass spectrometer data during the inbound passes of four orbits.

Masters et al., GRL, 2011

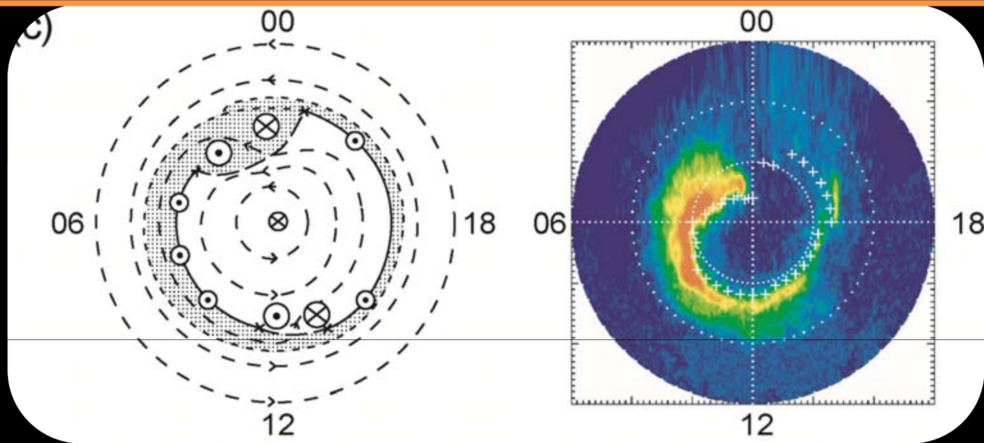
Bunce et al., JGR, 2010



Lamy et al., JGR, 2009; Lamy et al., GRL, 2010



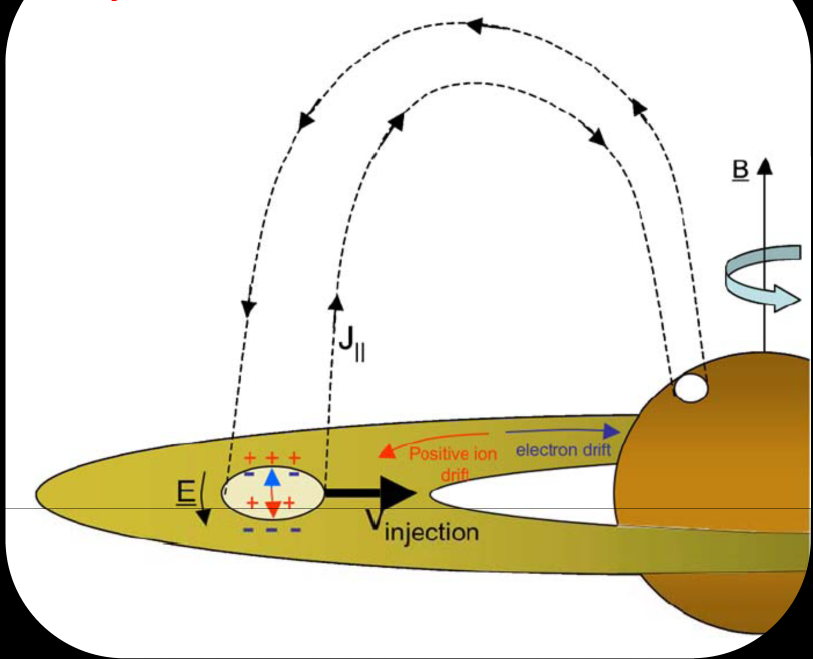
It is suggested that this event is produced by a solar wind compression of Saturn's magnetosphere. Occurs at the same time that Cassini enters the SKR source region – for the first (and only) time.

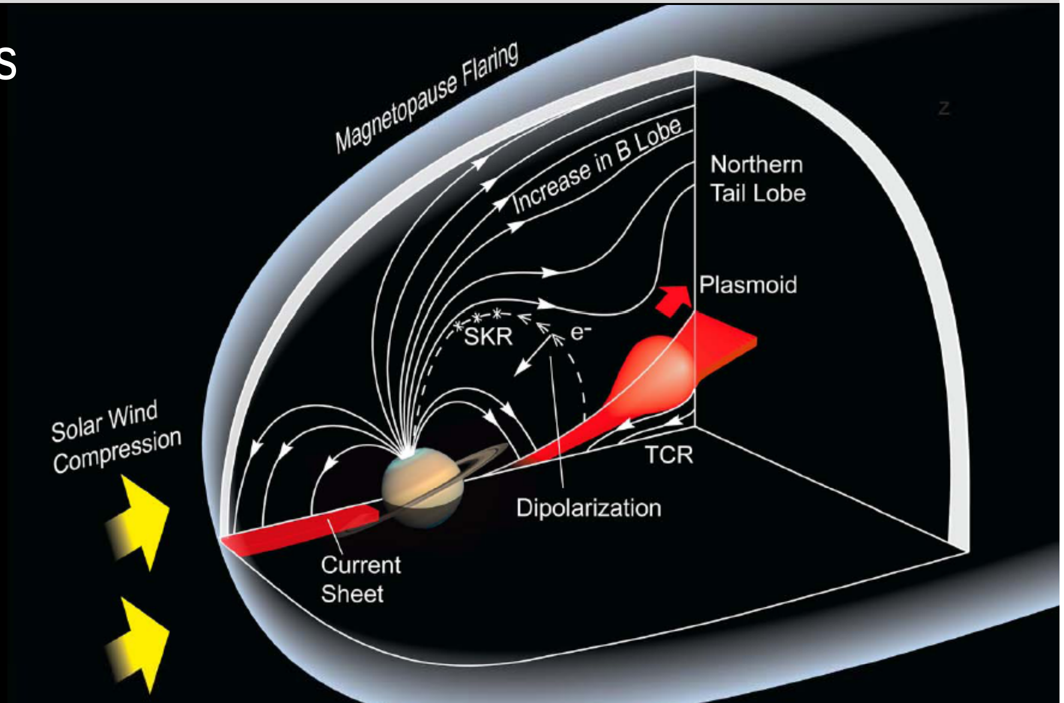


Cowley et al., JGR, 2005

Inner vs Outer magnetosphere dynamics

Rymer et al., P&SS 2009





Jackman et al., JGR, 2010

Inner magnetosphere:

Injection events are commonly observed, at all local times and over 6<L<11 RS. These are thought to be evidence of interchange motions.

Recent work shows electron density is lower within “bubble” and temperatures is 10x higher than surroundings. Bmag moderately increased.

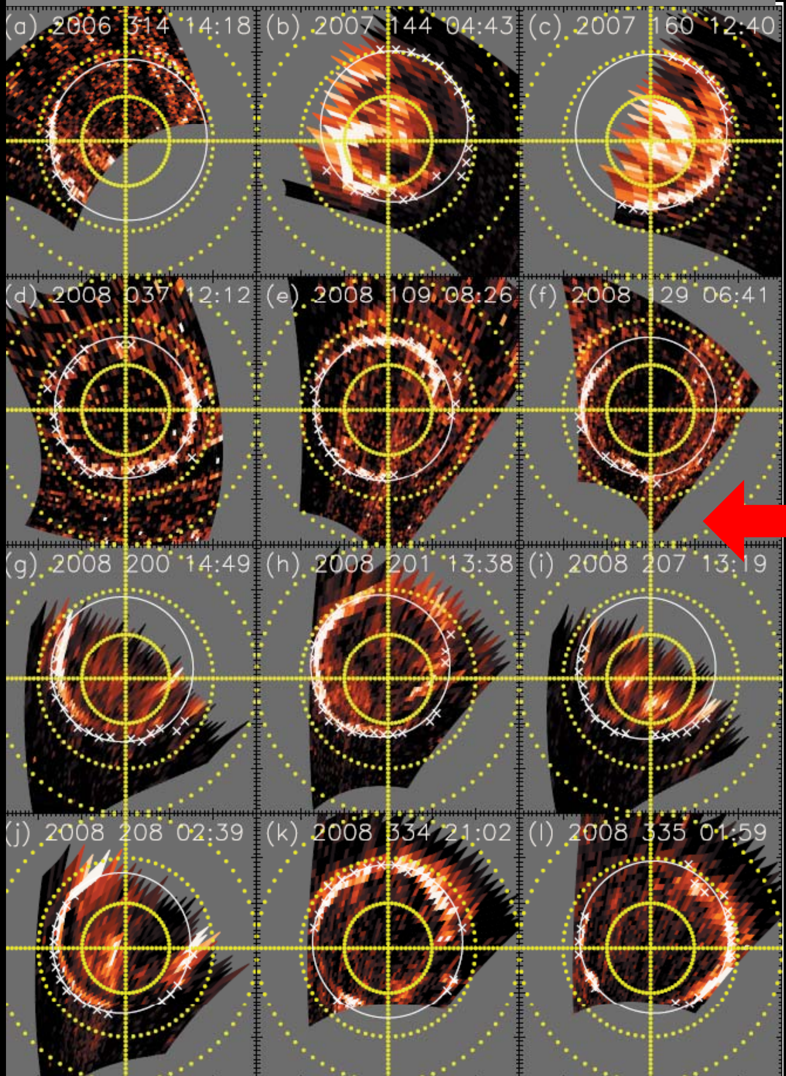
Outer magnetosphere:

Limited number of reconnection events have been observed in Saturn’s magnetotail, due to bowl shape of current sheet

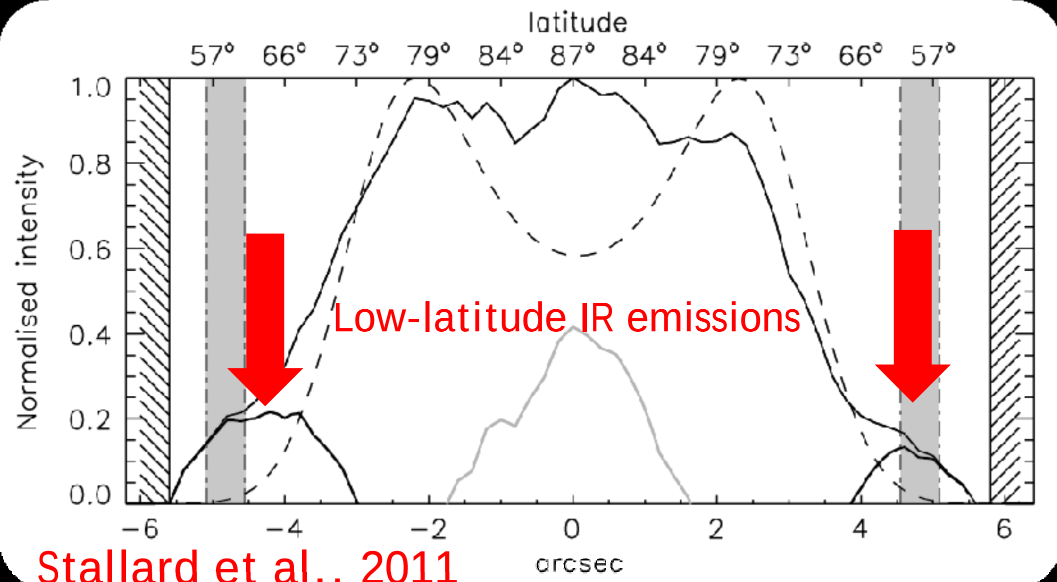
Recent works show the impact of a solar wind compression on the magnetosphere – first the magnetosphere compressed then the tail flared over subsequent days as flux accumulated. Finally signatures consistent with plasmoids were observed.

Studies of the ultraviolet & infrared auroral ovals at Saturn

Location of IR oval



Badman et al., GRL, 2011

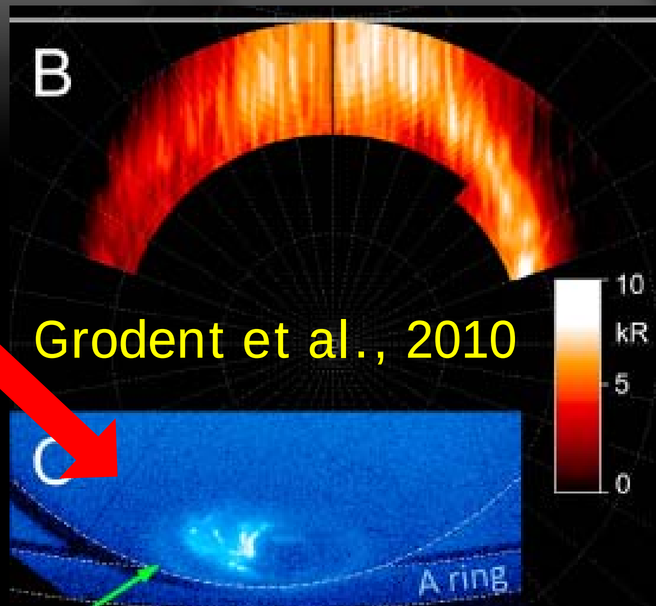


Stallard et al., 2011

The IR oval is located at very similar latitudes as the UV oval.

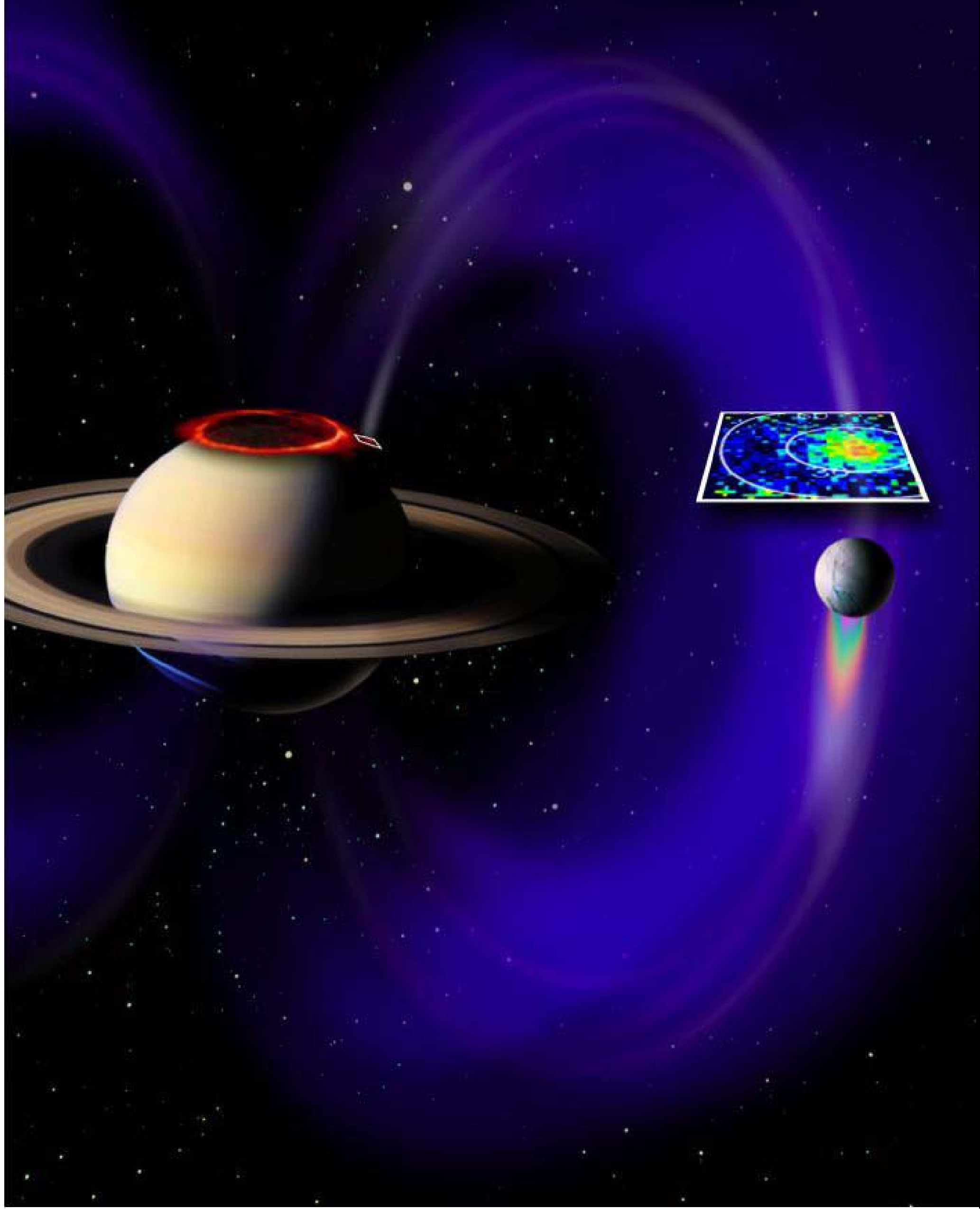
Evidence for a lower latitude band of (diffuse?) aurora exists on nightside in UV.

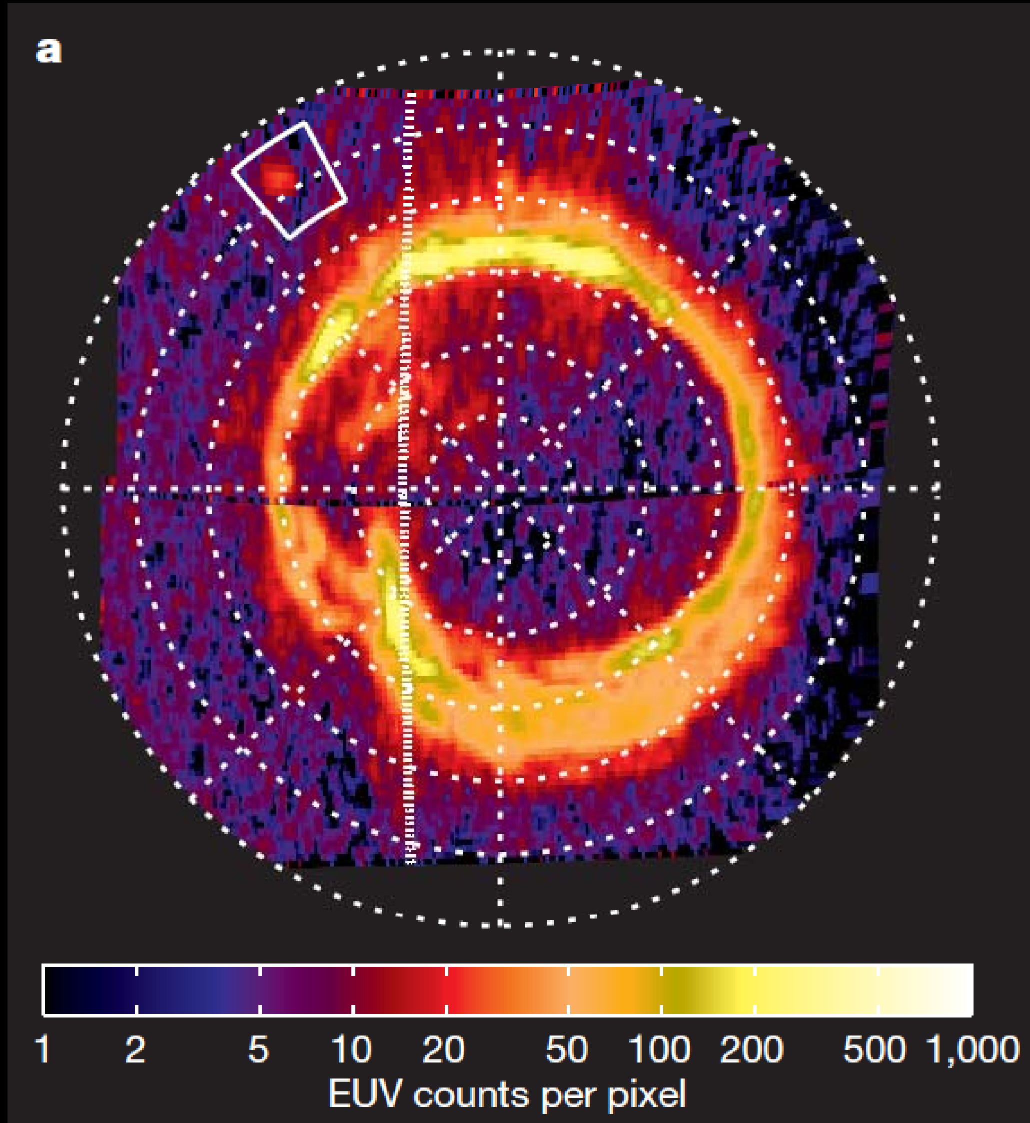
Low latitude IR emissions also seen at dawn/dusk from ground-based IR observations (above)



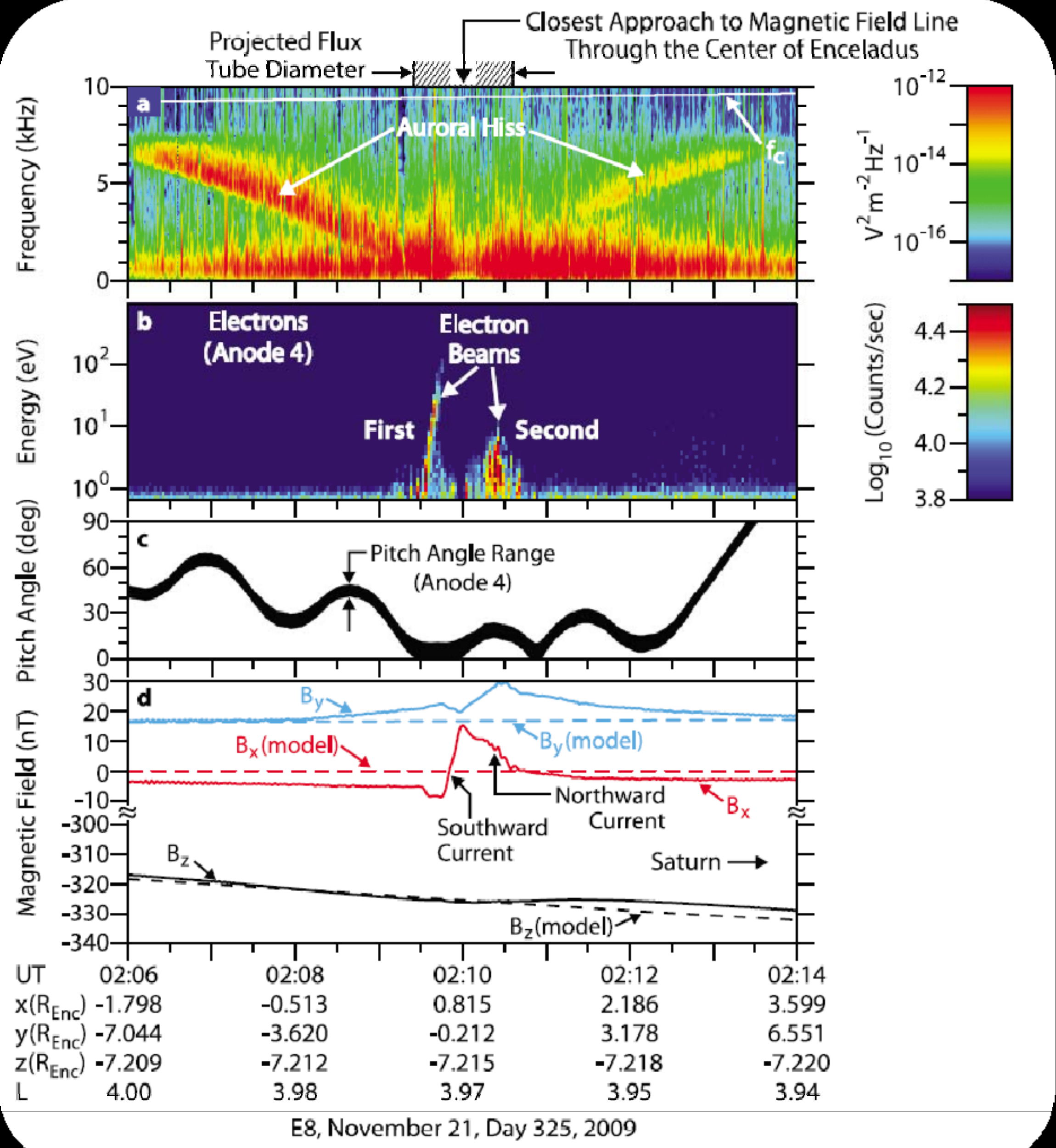
Grodent et al., 2010

Discovery of the Enceladus footprint in Saturn's atmosphere





Pryor, Rymer, et al., 2011, Nature



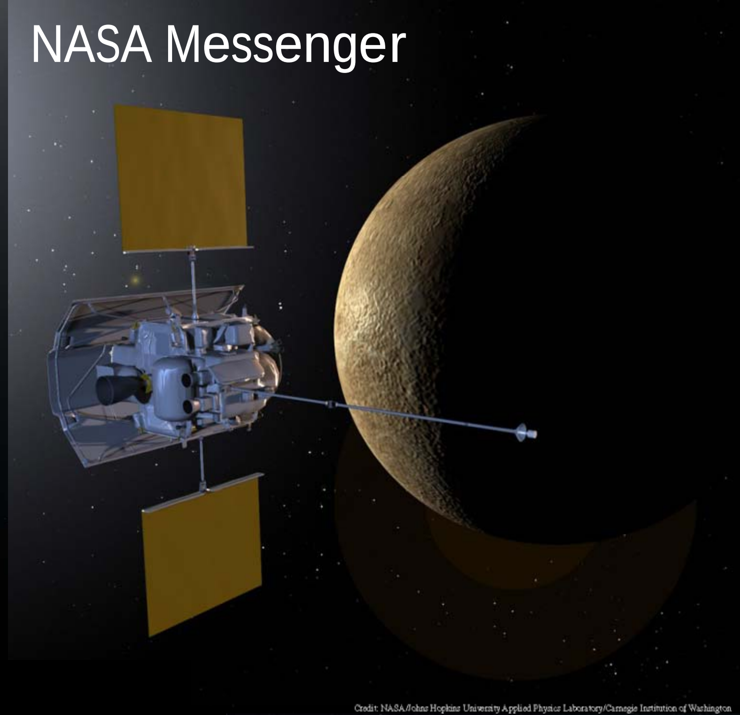
Gurnett et al. GRL, 2011

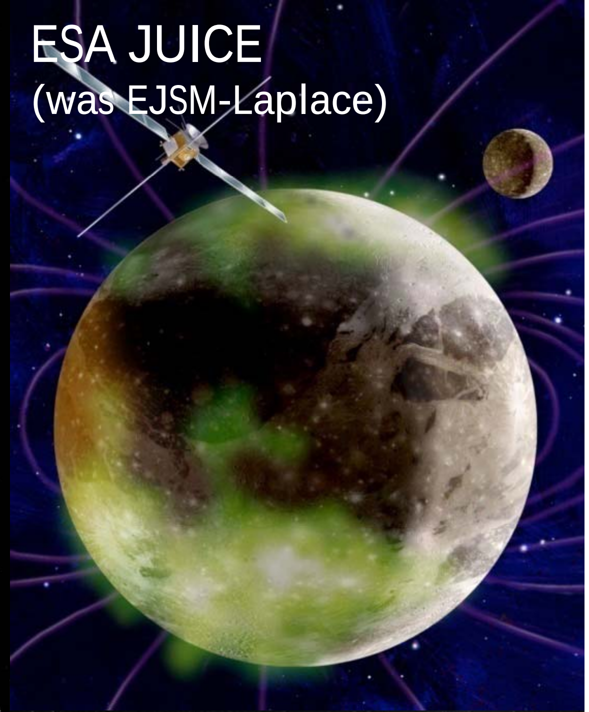
The interaction of Enceladus with Saturn's magnetospheric plasma produces a number of electrodynamics effects.

These include whistler-mode emissions similar to terrestrial auroral hiss, magnetic-field-aligned electron beams, and currents associated with a standing Alfvén wave excited by the moon.

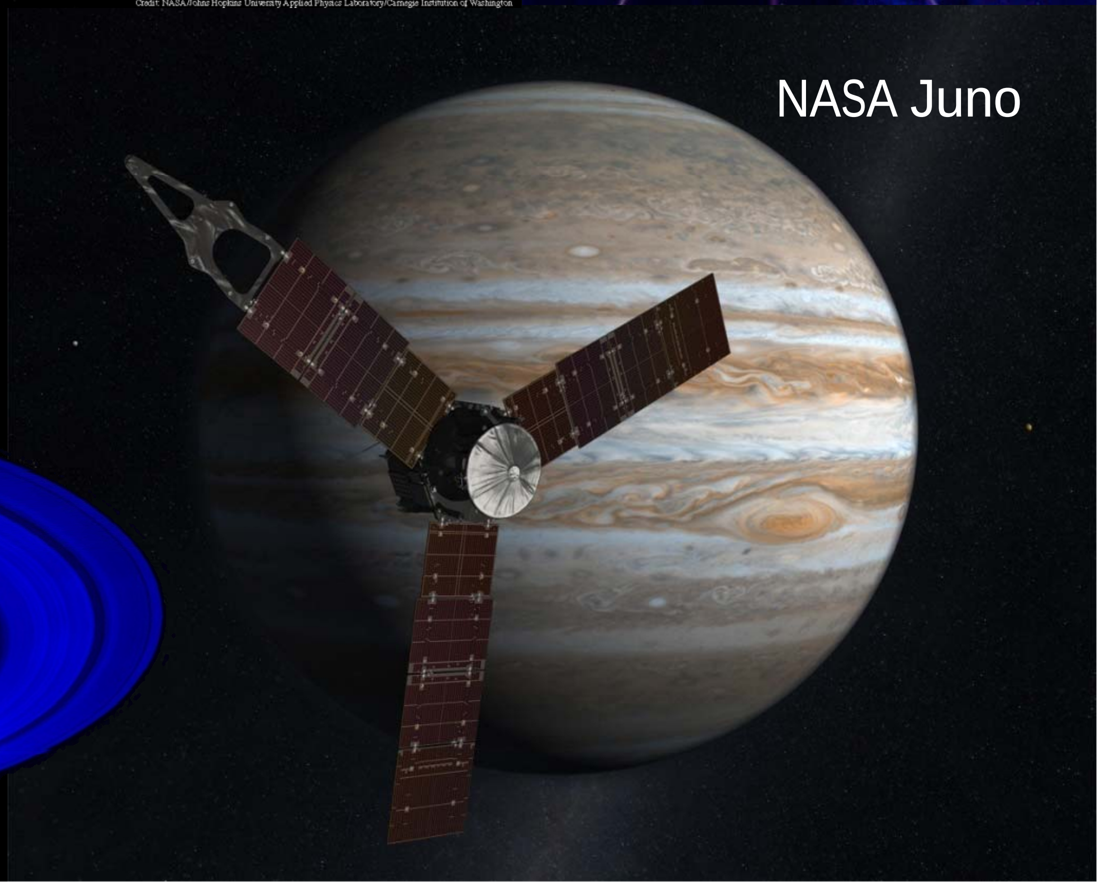
Electron beams responsible for the auroral hiss emissions are accelerated very close to the moon, most likely by parallel electric fields associated with the Alfvén wave.


ESA BepiColombo


NASA Messenger
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington


ESA JUICE
(was EJSM-Laplace)


solstice
MISSION
NASA/ESA Cassini-Huygens


NASA Juno