Space weather at Mars, Venus and Titan

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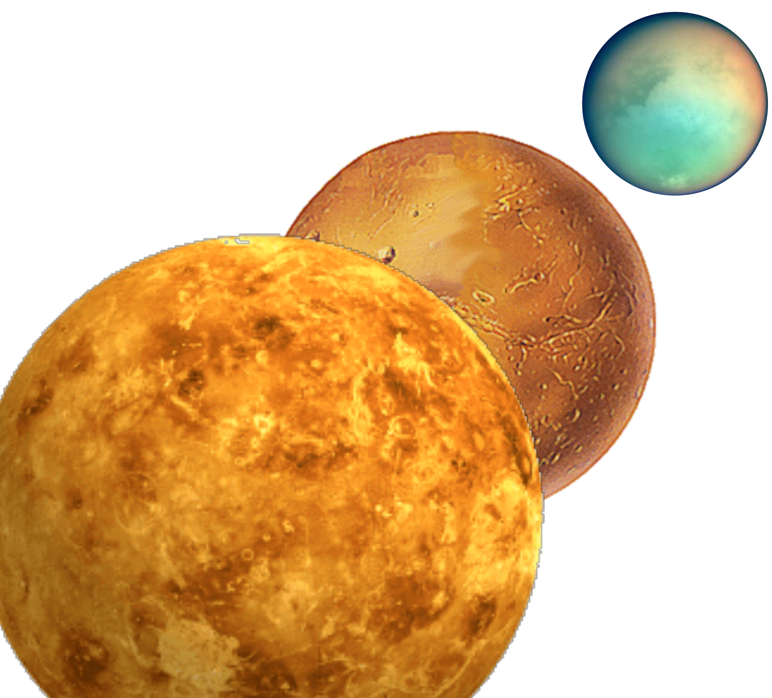
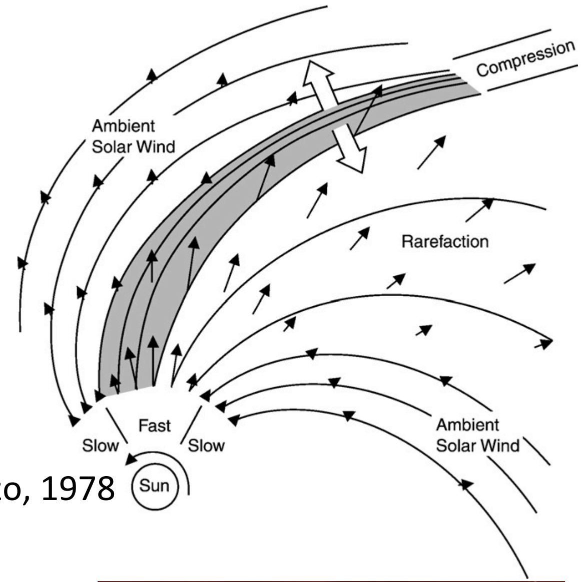


SIR/CIR/CME – a quick intro



Sketch from Pizzo, 1978

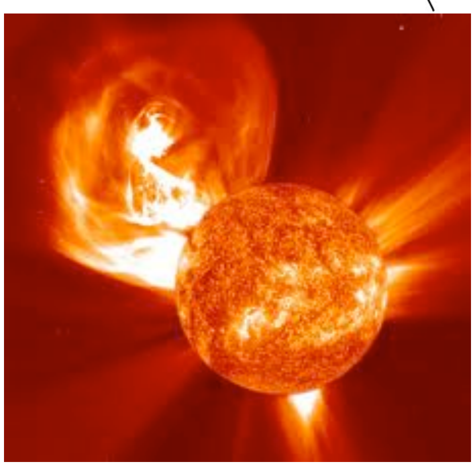


Image from SOHO

- SIR - fast solar wind catches up with slow solar wind and forms compression/rarefaction regions

- The interaction region forms a spiral arc in interplanetary space and rotates with the Sun.

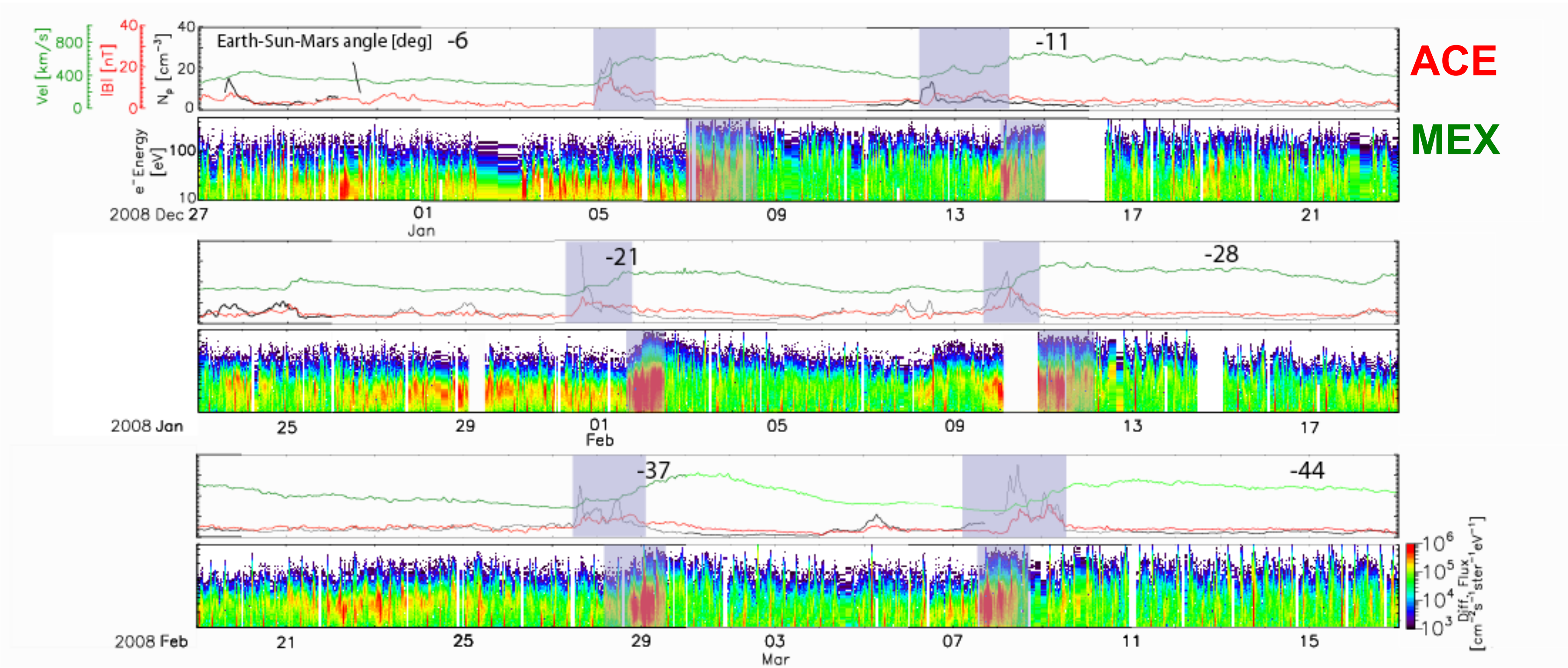
- CIR – if the SIR is a continuous over more than one solar rotation its called a CIR (I think, definitions seems to vary)

- Coronal mass ejections are more violent outburst of solar plasma, which propagate radialy outward and occasionally impact on planets and other solar system bodies

- Both types present major disturbances in the solar wind density, magnetic field, temperature etc, which causes disturbances to the solar wind-planet interaction

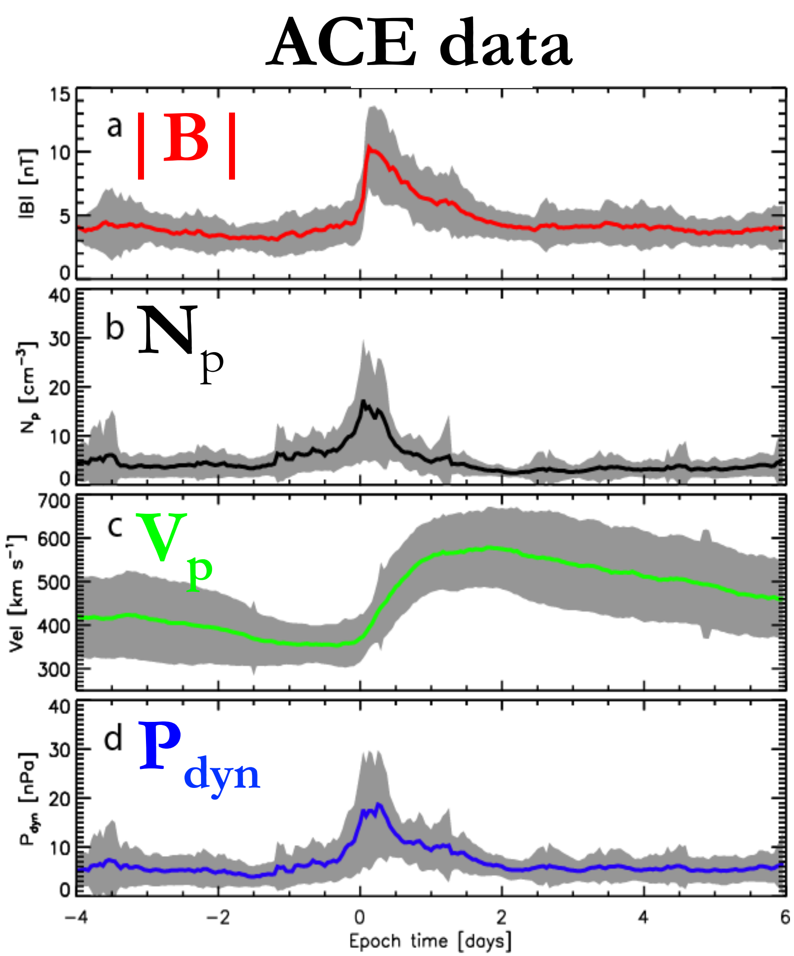
Observations of CIRs at Mars

- Each major CIR observed by ACE at Earth can also observed by MEX at Mars during 2007-2008



6 examples of CIRs in ACE and MEX data during 3 solar rotations.

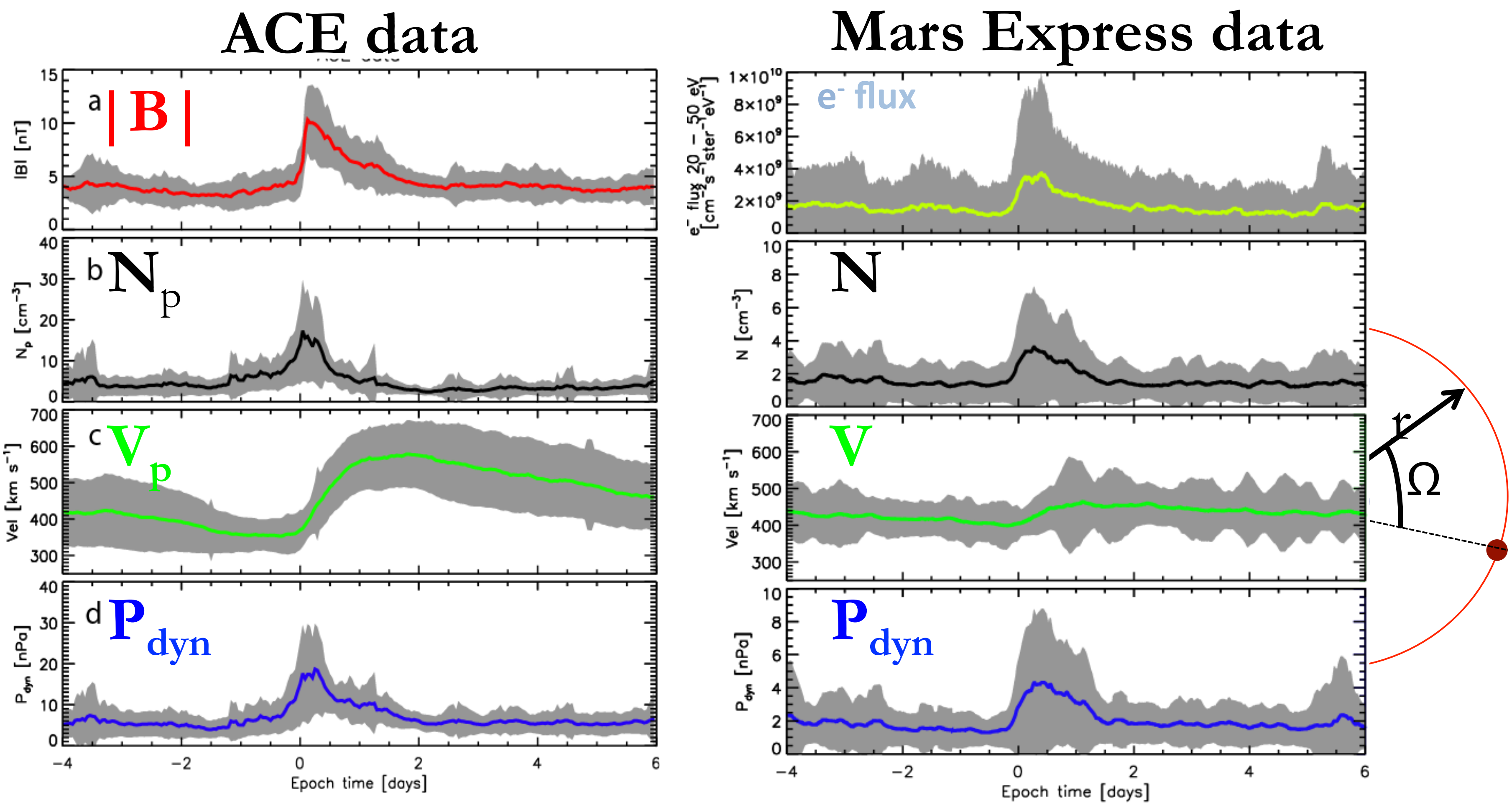
Superposed epoch analysis of 41 events



Automatic search for CIRs in ACE data:

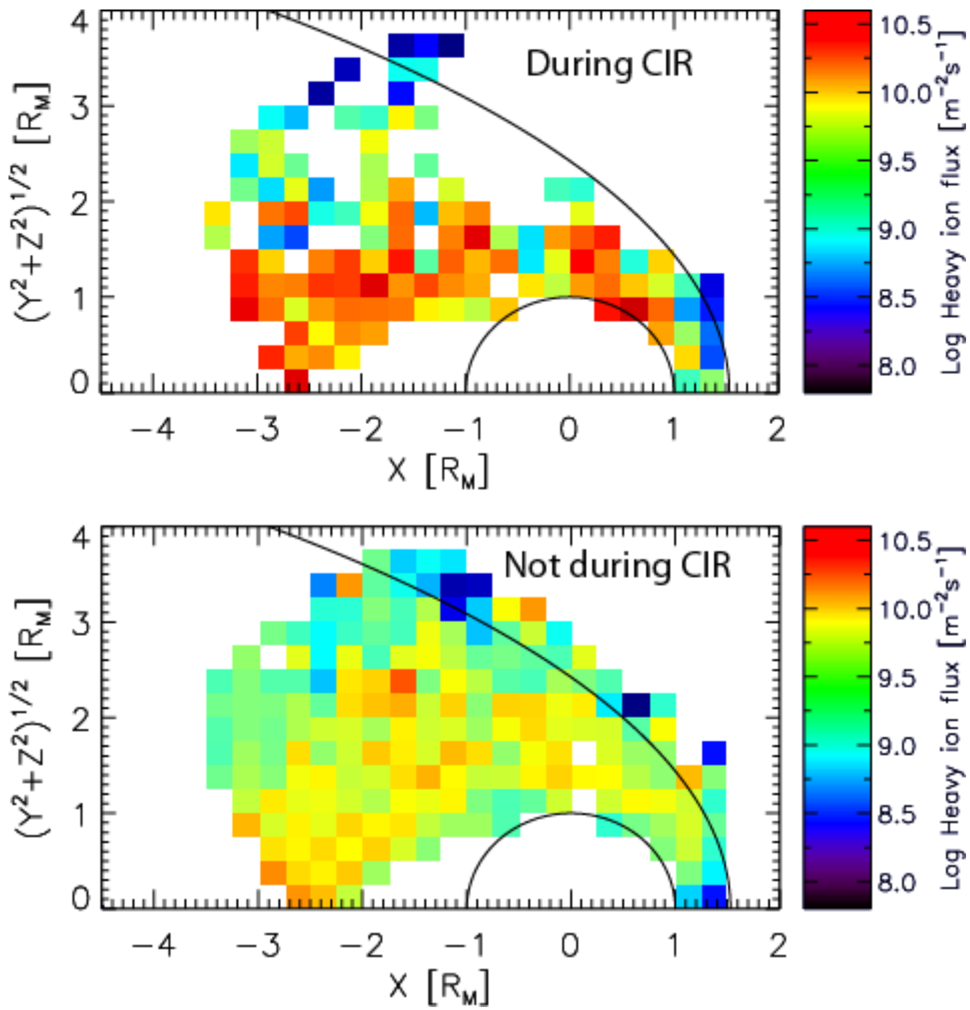
- Gradual increase in velocity over 24 hours
- Sudden increase in |B| of factor 1.5
- 41 CIRs/CMEs detected in 2007-08
- They appear as pressure pulses

Calculate arrival times at Mars



Ionospheric escape during CIR at Mars

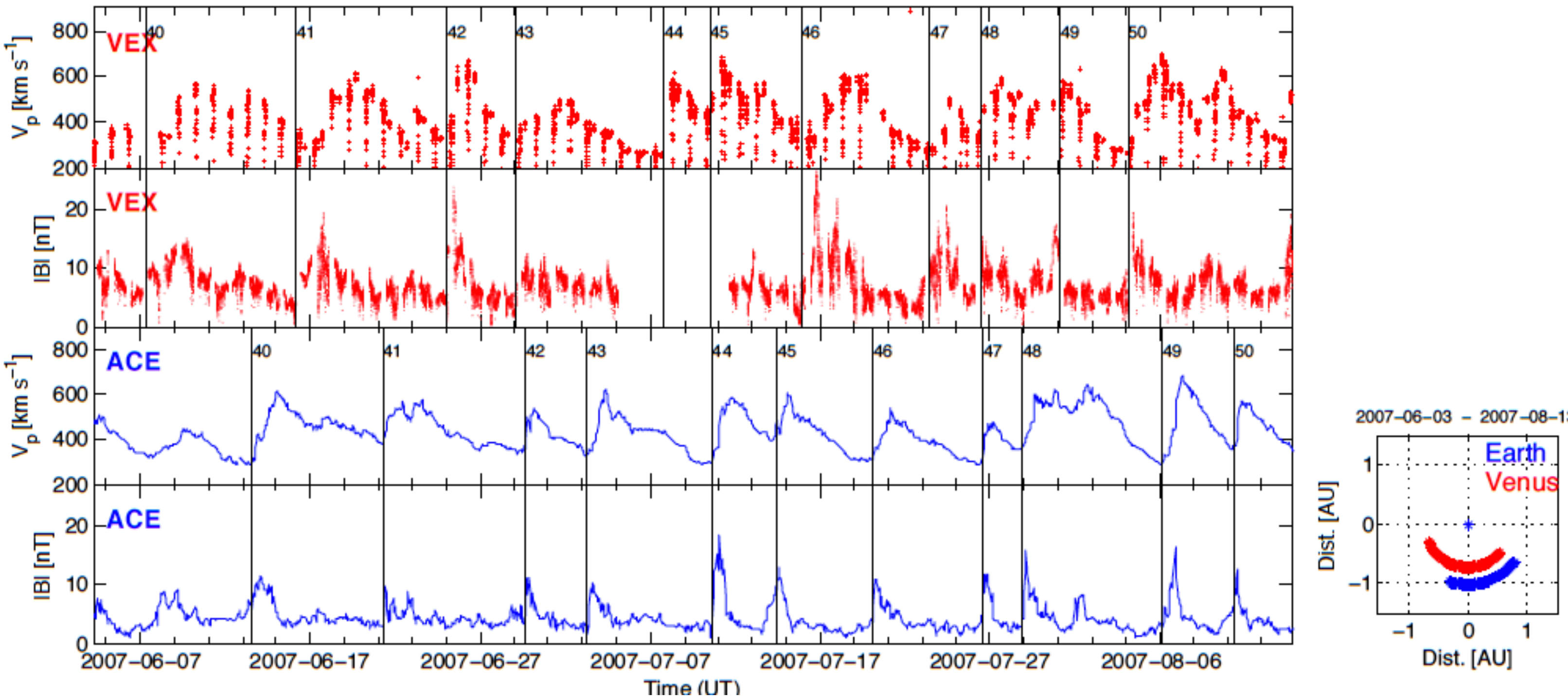
- The amount of outflowing heavy planetary ions increases by a factor of ~2.5 when a CIR passes by
- ~30% of the total outflow of heavy planetary ions occur during ~15% of the time, when pressure pulses impact.
- Important implications for atmospheric evolution at Mars.



Edberg et al., GRL, 2010

Observations of CIRs/CMEs at Venus

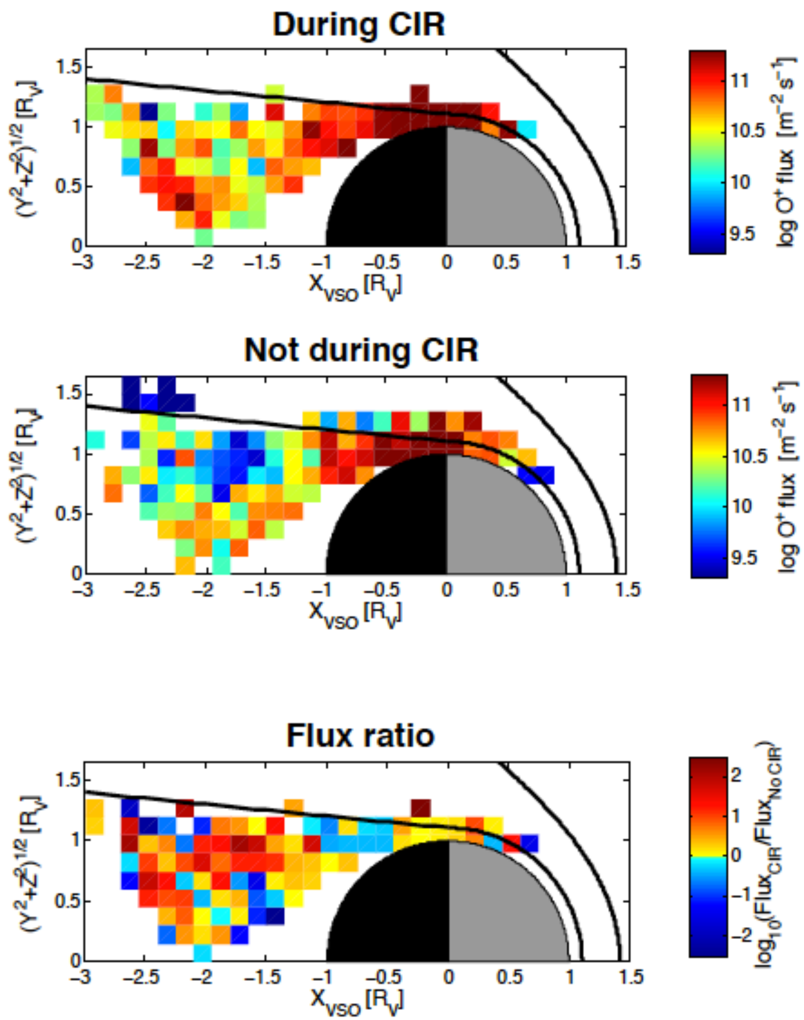
- CIRs/CMEs that are observed at ACE are also easily tracked to Venus.
- From May 2006- Jan 2010 we find 147 events.



10 examples of CIRs in ACE and VEX data during 3 solar rotations.

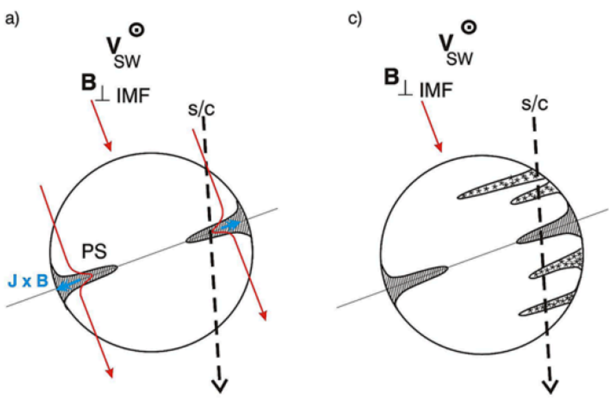
Ionospheric escape during CIRs at Venus

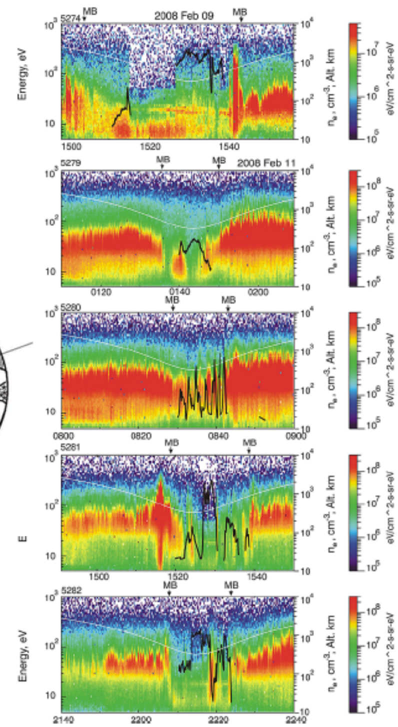
- The amount of outflowing heavy planetary ions (O^+) increases by a factor of ~1.9, on average over 147 CIRs/CMEs.
- The escape rate increase can occasionally be significantly higher.



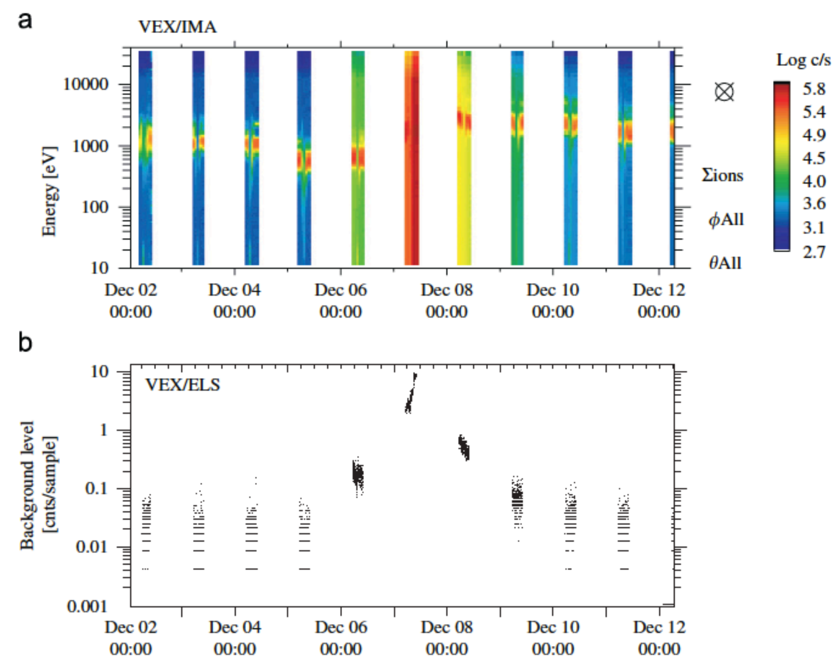
Edberg et al., JGR, 2011

Related work



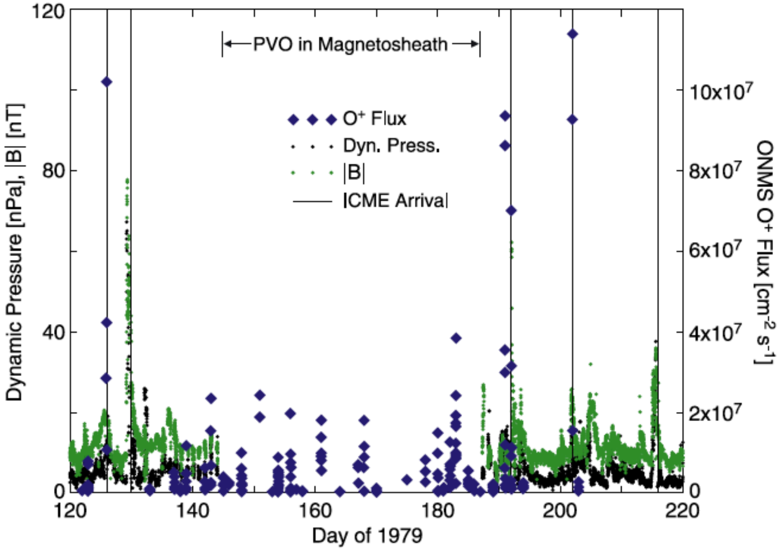


Futaana et al., 2008, estimated that heavy ion outflow from Mars and Venus increased by a factor of ~5-10, when a burst of solar energetic particles impacted

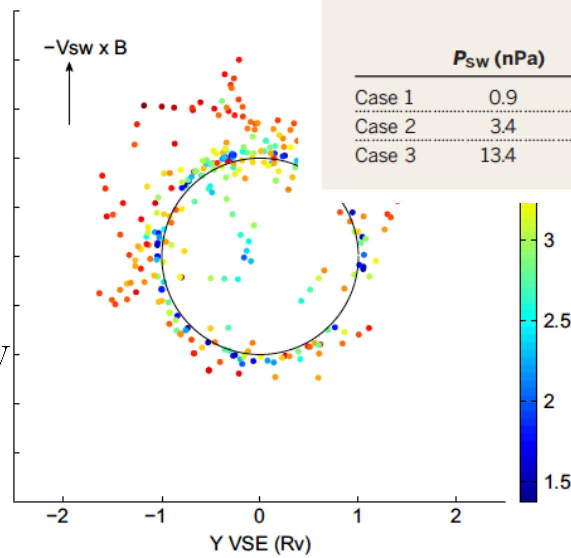


Dubinin et al., 2009, estimated that the atmospheric escape increased by a factor of ~10 when a CIR impacted on Mars due to the increased scavenging of the ionosphere.

Related work



Luhmann et al., 2008, showed that the flux of planetary ions from Venus increased by a factor 10 when CMEs impact the planet, but only in ¼ cases



McEnulty et al., 2010 showed that planetary ions from Venus are picked up and accelerated by the convective electric field to a greater extent when CMEs impact.

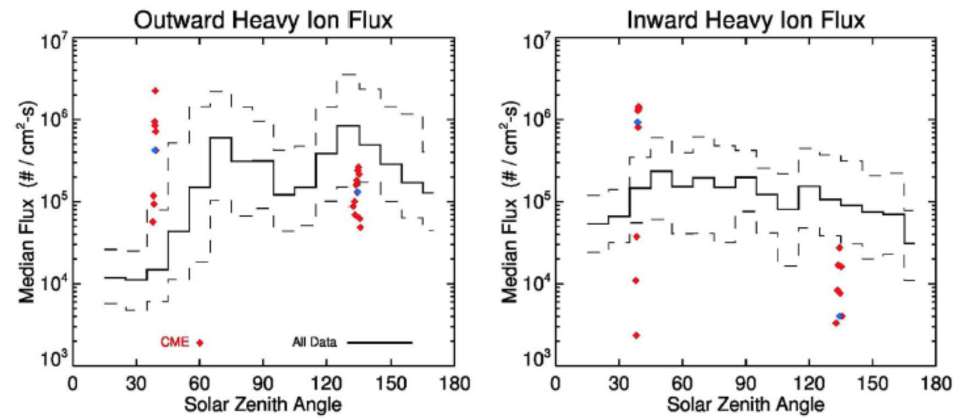


Fig. 4. Comparison of loss during ICME with integrated loss through the mission to date. Planetary heavy ion fluxes (>9 amu) measured by STATIC during the ICME event (red, with median value shown in blue) are shown in comparison to median and first/fourth quartile ion fluxes measured over a ~4 month period (gray traces). Fluxes are evaluated in a spherical shell around Mars from 1.25 to 1.45 R_M (radius of Mars), and the position of MAVEN is rotated into a coordinate system aligned with the solar wind electric field. During the ICME, strong outward flux is observed in regions of typically inward flow.

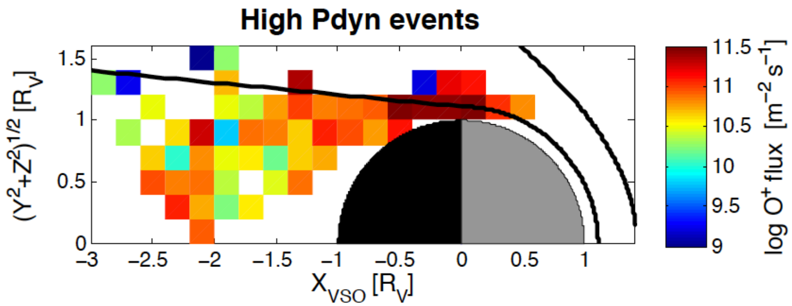
Table 1. Ion loss rates calculated by the MHD model for the three cases corresponding to three different stages of the ICME. *P*sw is the solar-wind pressure for the model run.

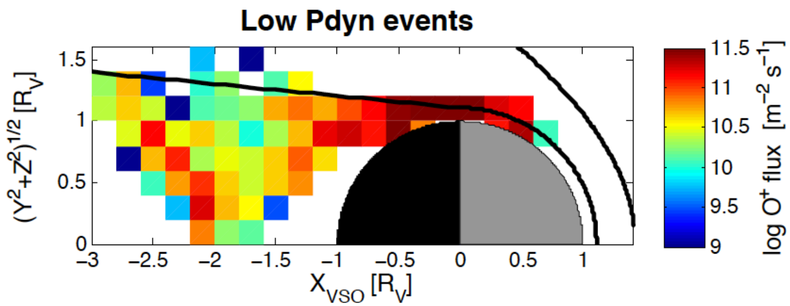
	P_{SW} (nPa)	O^+ (s^{-1})	O_2^+ (s^{-1})	CO_2^+ (s^{-1})	Total (s^{-1})	Total (kg/s)
Case 1	0.9	6.4×10^{23}	7.7×10^{23}	4.9×10^{22}	1.46×10^{24}	0.06
Case 2	3.4	2.6×10^{24}	7.6×10^{24}	3.3×10^{23}	1.06×10^{25}	0.50
Case 3	13.4	1.96×10^{25}	1.32×10^{25}	6.3×10^{23}	3.34×10^{25}	1.27

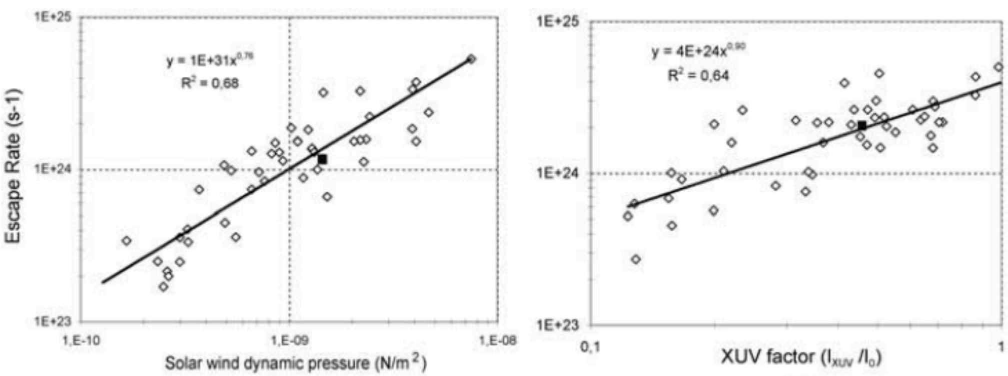
Jakosky et al., 2015 showed as a first results from the MAVEN mission that the escape rate increased during a CME impact

The influence of dynamic pressure increase

- For Venus, the CIR events with the highest mean dynamic pressure show a 30% higher outflow rate than the low pressure events
- The dynamic pressure is important.





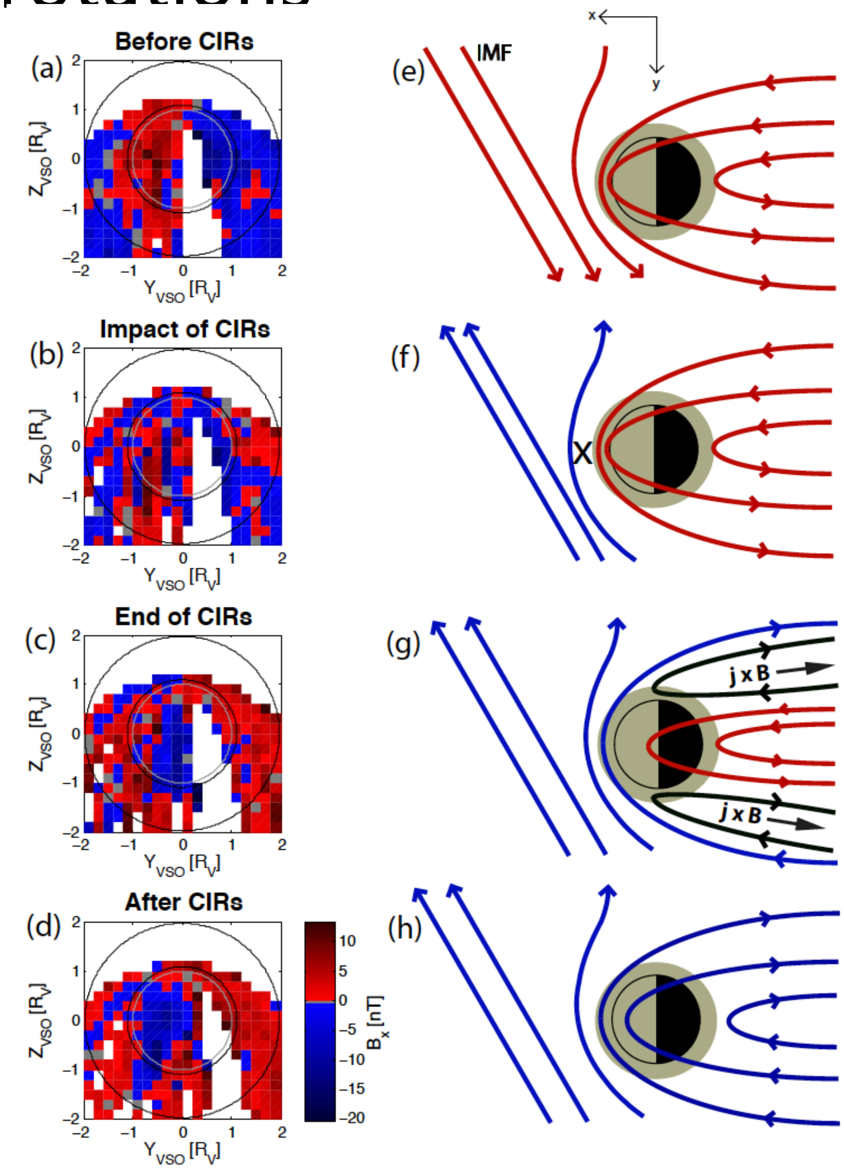


(a) (b)

The escape rate from Mars increased with increasing solar wind dynamic pressure [Lundin et al., 2008; Nilsson et al., 2010] and EUV flux [Lundin et al., 2008].

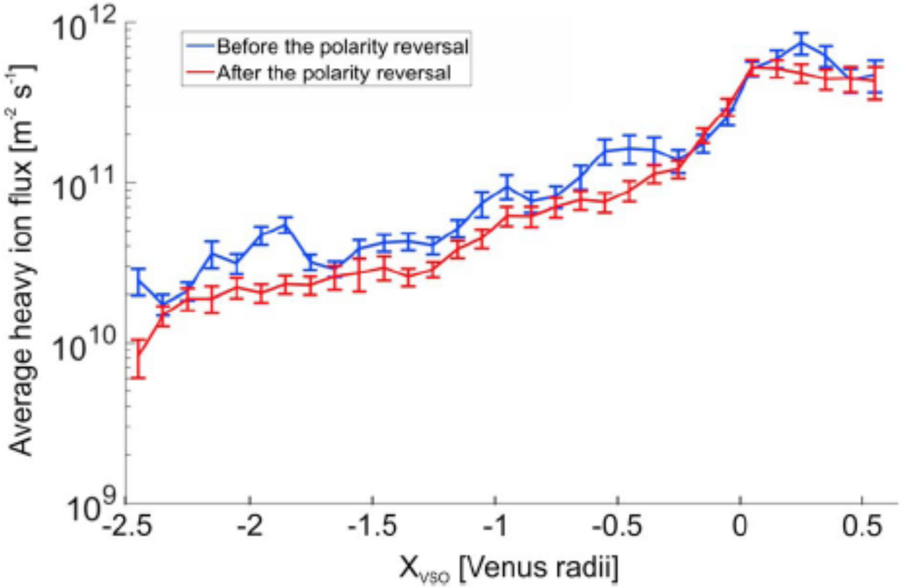
Another mechanism – magnetic reconnection during IMF rotations

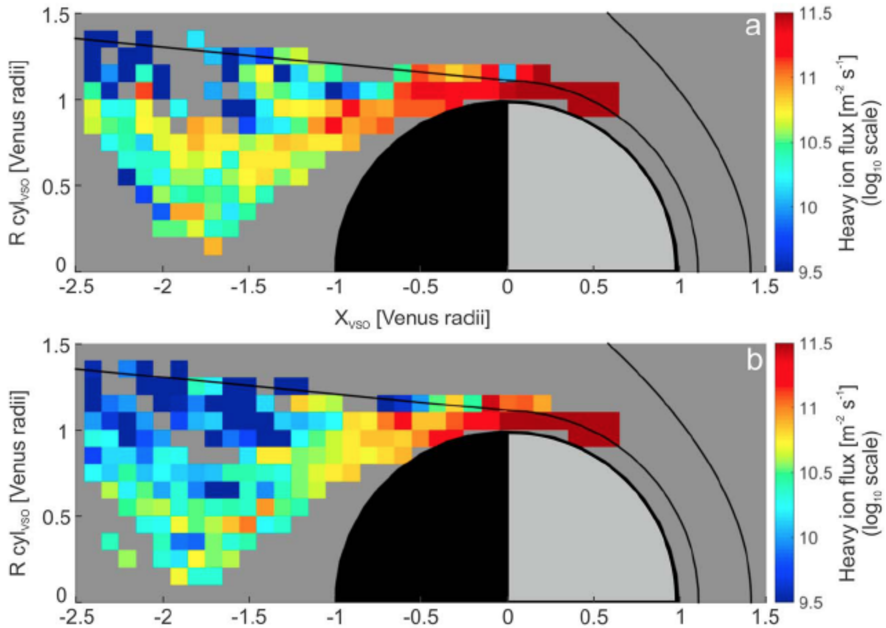
- Across each CIR the IMF changes polarity, and so will the induced magnetosphere of the planet.
- When anti-parallel magnetic fields from opposite sides of the CIRs meet magnetic reconnection events could be initiated on the dayside.
- Ong et al., 1993, related ionospheric clouds to IMF rotations.
- Similar to the comet-tail disconnection ideas by Brandt and Niedner, 1989.



Edberg et al., JGR, 2011

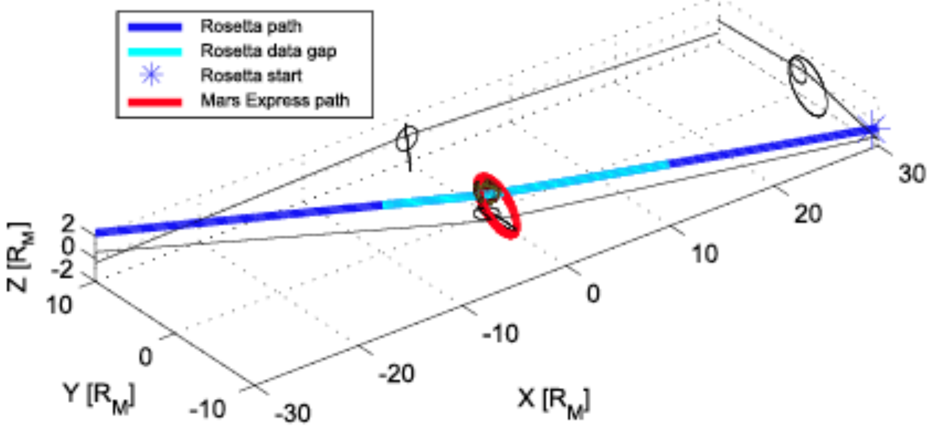
Effect of heliospheric current sheet crossings

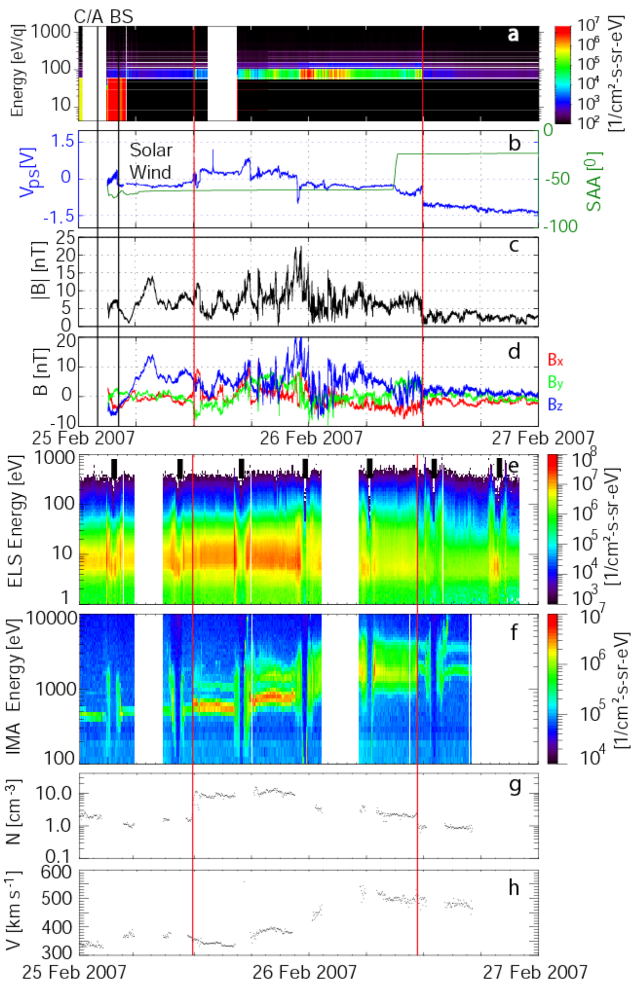




Vech et al., 2016 showed that the escape rate decreases by a factor of ~0.75 following a HCS crossing.

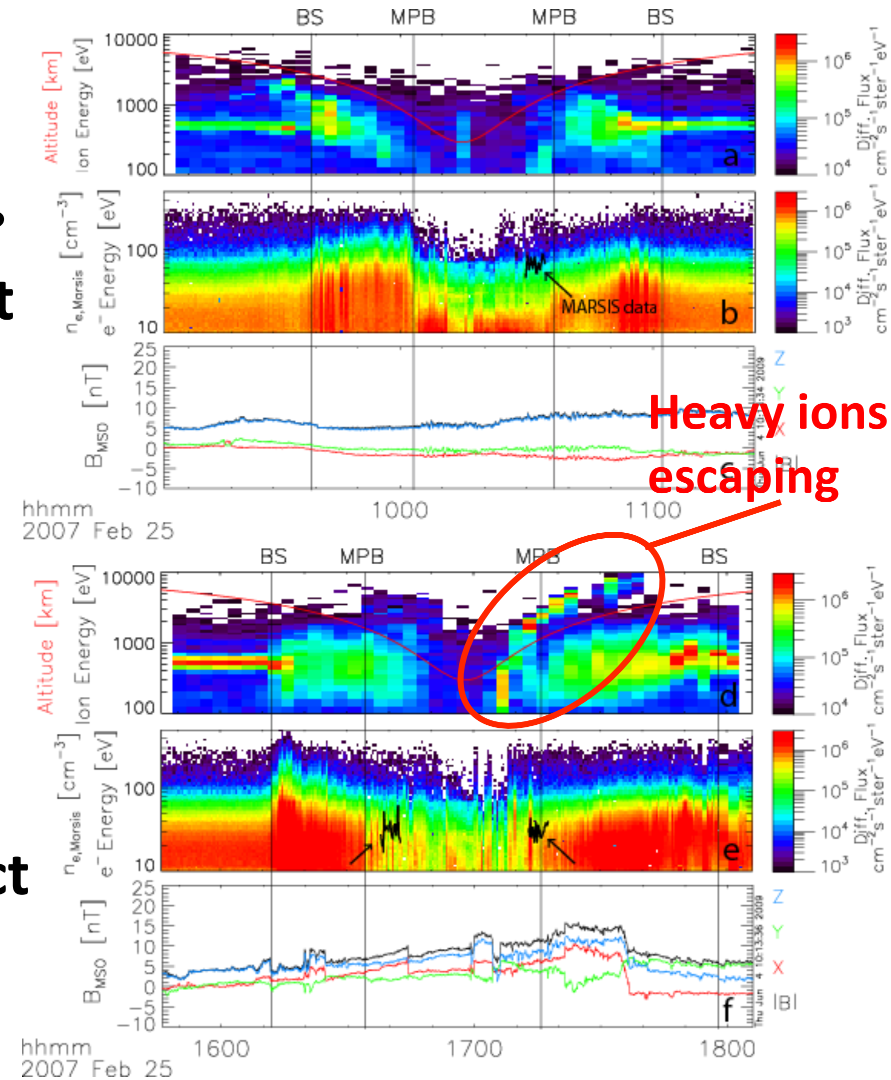
Rosetta Mars flyby





***before* impact**

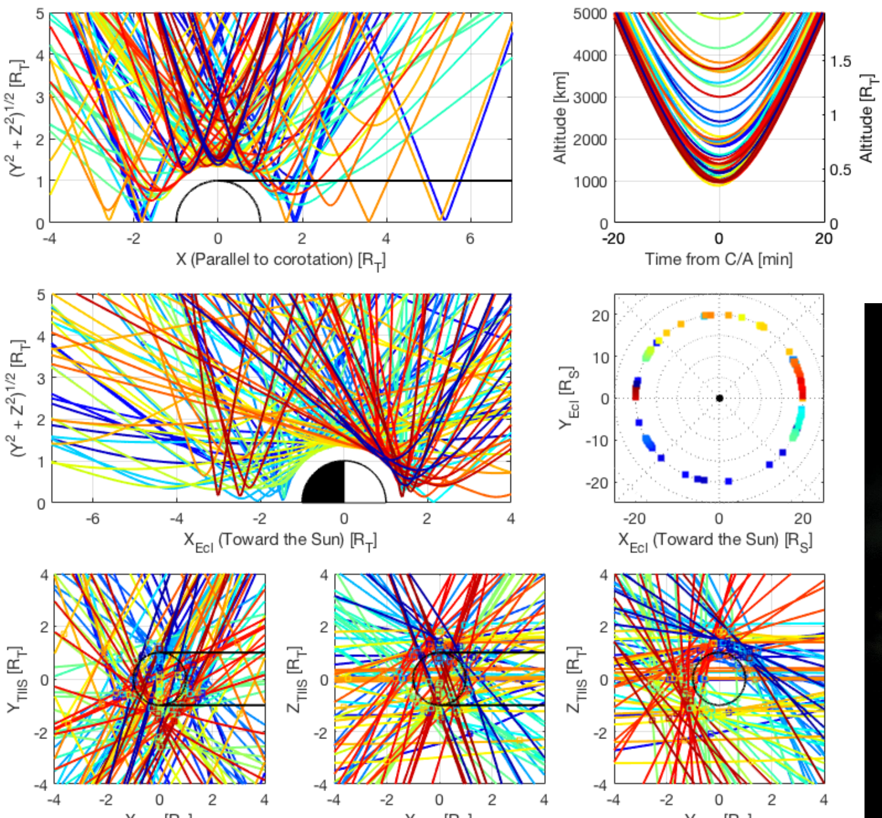
Orbit *after* impact

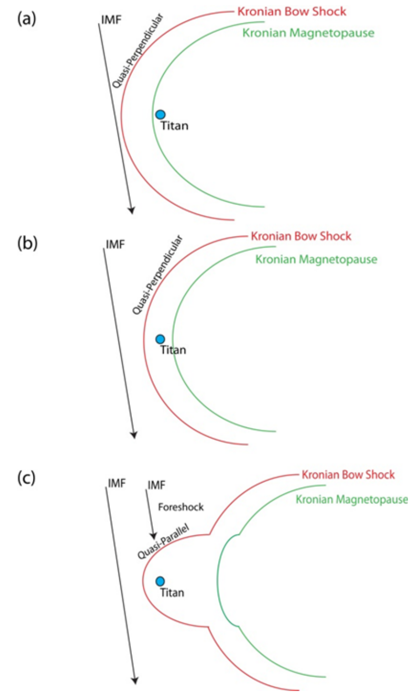


Edberg et al., 2010b

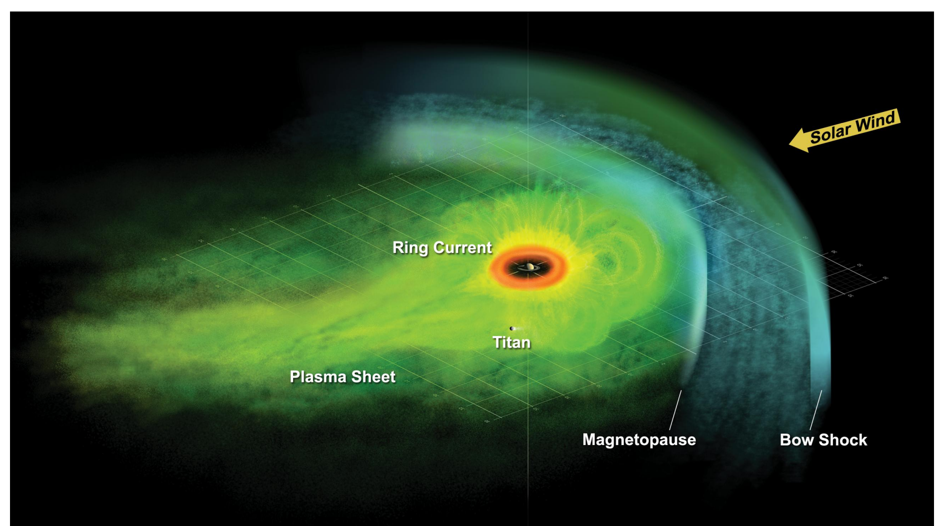
Titan

- 127 flybys by Cassini
- Titan mostly located within magneopause
- Observed in magnetosheath or solar wind during T32, T42, T85, T116 (T94, T97) (e.g. Simon et al., 2010,2013; Edberg et al., 2015, Kabnovic et al., 2017)



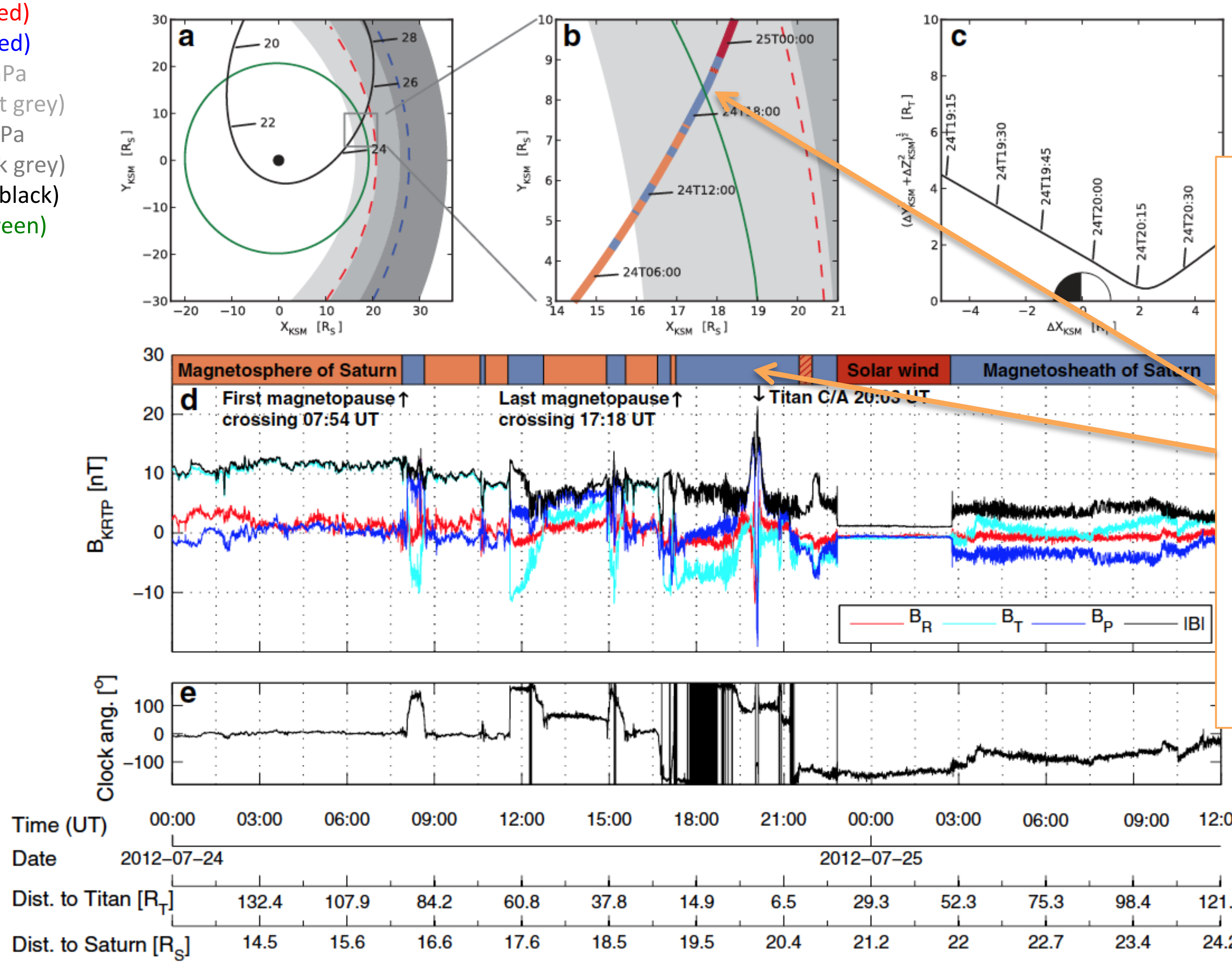


A deformed bowshock for the combined Titan/Saturn system observed and modelled (Bertucci et al., 2015, Omidi et al., submitted)



T85 magnetosheath excursion: result of a CME impact

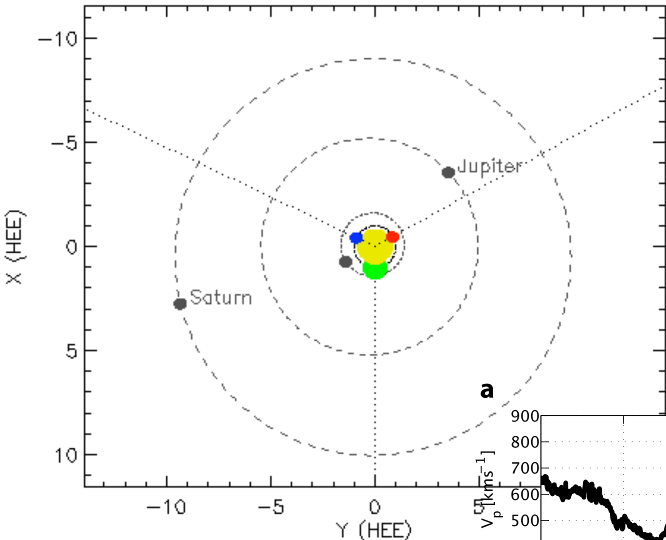
MP (red dashed)
BS (blue dashed)
MS 0.1-0.01 nPa pressure (light grey)
BS 0.1-0.01 nPa pressure (dark grey)
Cassini orbit (black)
Titan orbit (green)

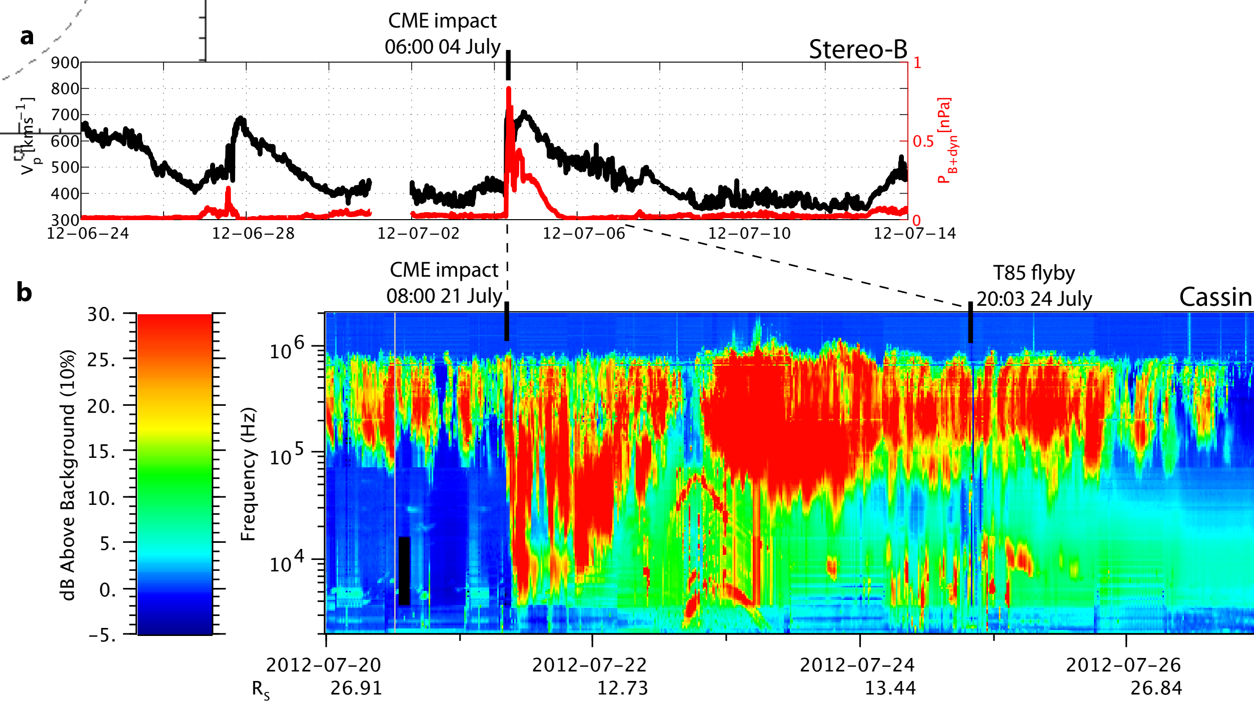


- MAG data: Titan in the magnetosheath during 2h45min prior to the flyby.
- No CAPS particle data
- Titan close to the bow shock.
- Long-term (1 day) rotation of IMF.

CME impact during the T85 flyby

- Stereo-B solar wind data indicate a coronal mass ejection (CME), 45 degrees off from Saturn direction.
- Simple radial propagation calculation: about 21±3 days to reach Saturn with a velocity of 700 ± 100 kms^{-1}.
- Significant broadening of SKR emission indicate a compression/relaxation of the Saturn's magnetosphere.

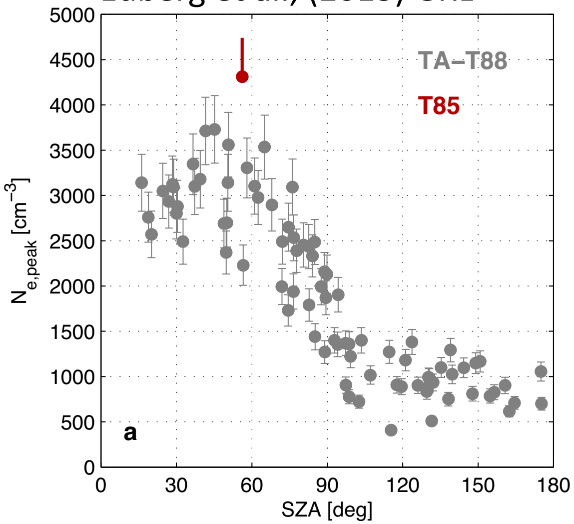


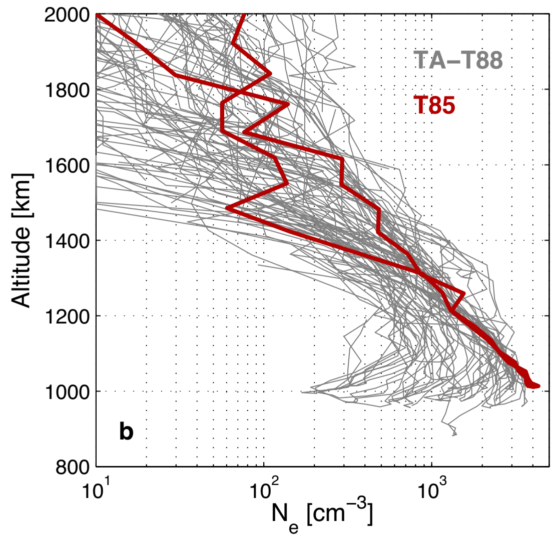


Extreme ionospheric peak densities

effect of increased particle precipitation?

Edberg et al., (2013) GRL

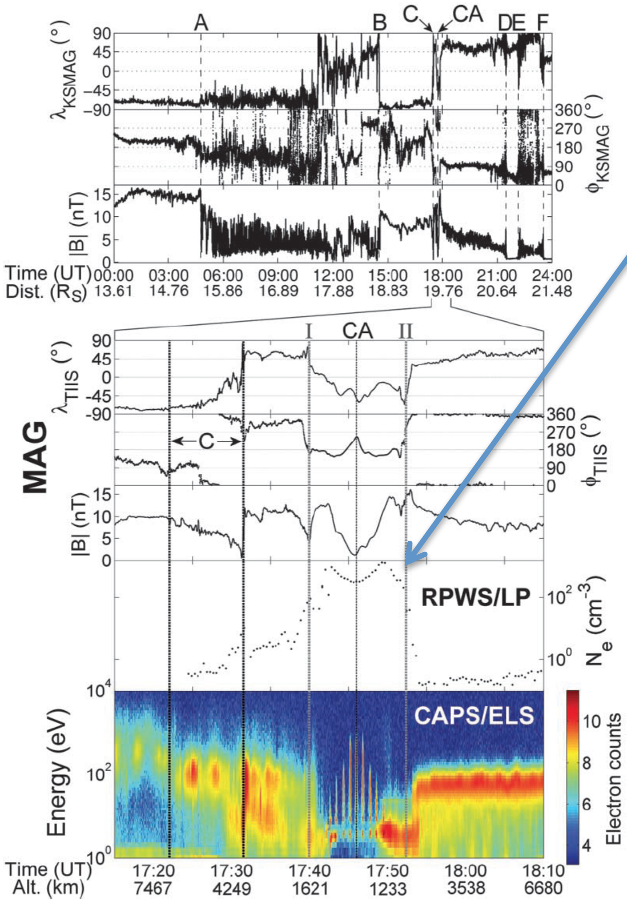




No observed increased solar X-rays or solar EUV flux during T85 (from GOES and NOAA) -> particle impact ionoisation a likely explanation. A back-of-the-envelope calculation of what fluxes are needed:

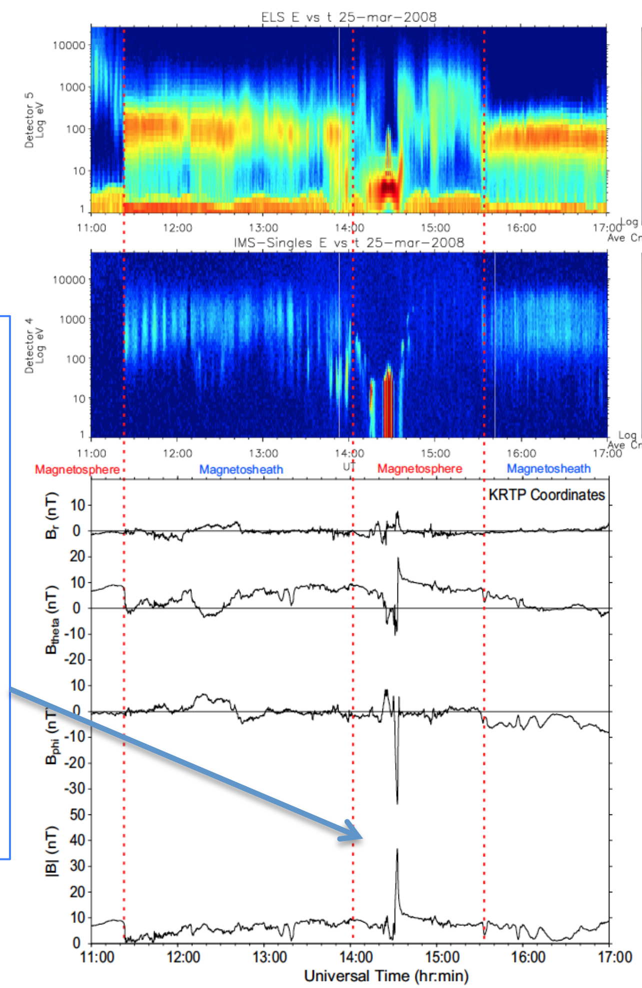
Effective dissociative recombination rate $\alpha = 6 \cdot 10^{-6}$ cm^3 s^{-1} (Vigren et al., 2012). Density of 4310 cm^{-3} at the peak implies an ionisation rate of $P \approx \alpha N_e^2 = 13$ $cm^{-3}s^{-1}$. Excess production rate to enhance the electron density by 500 cm^{-3} above the background is then 3 $cm^{-3}s^{-1}$.
1-3 keV protons required to reach 1000 km
Total column ion production rate is the scale height (50 km) times the excess production rate of 3 $cm^{-3}s^{-1}$, or $1.5 \cdot 10^7$ $cm^{-2}s^{-1}$. A 2 keV proton generates about 10-50 ions so a proton flux of $1 \cdot 10^6$ $cm^{-2}s^{-1}$ is needed, which is a reasonable number, especially taking into account a flux increase due to the CME and perhaps even the bow shock crossing (sorry for all the text!).

Previous Titan magnetosheath encounters

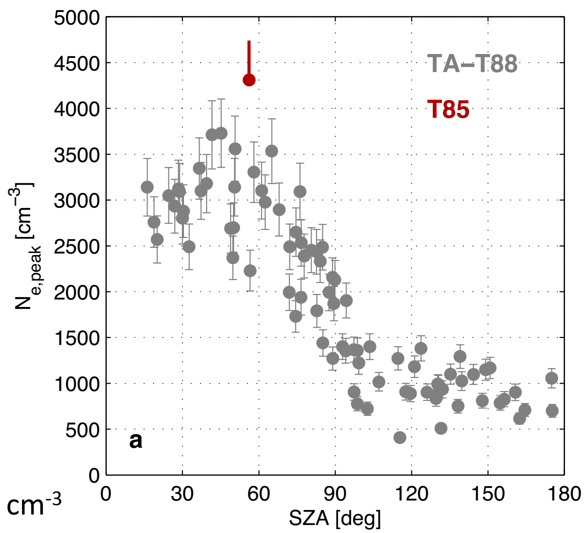


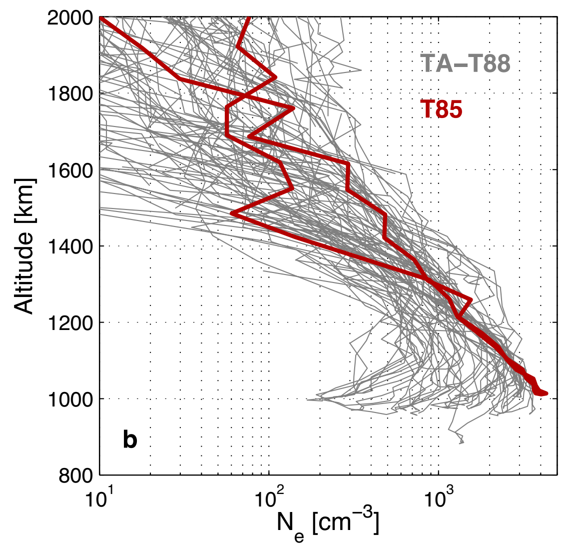
T32 – Bertucci et al., 2008, Garnier et al., 2009.
No enhanced electron densities reported.
Only in the MS for 10 min prior to the flyby.

T42 – Wei et al., 2011
Highest draped magnetic fields observed at Titan.
Increased solar wind dynamic pressure observed.
Not actually in the MS during the flyby.



Increased particle impact ionisation

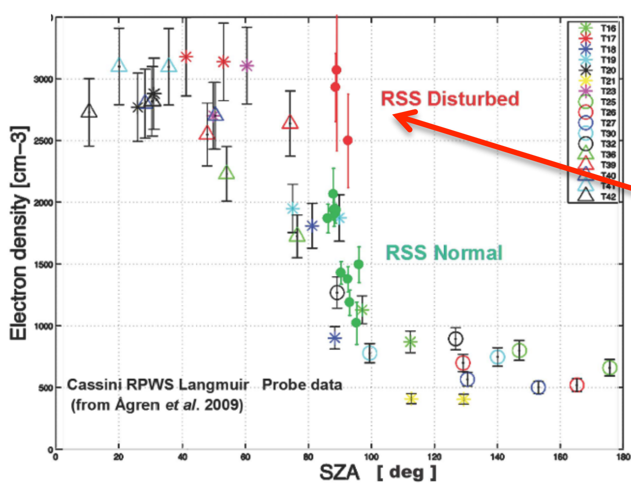




3500 cm^{-3}

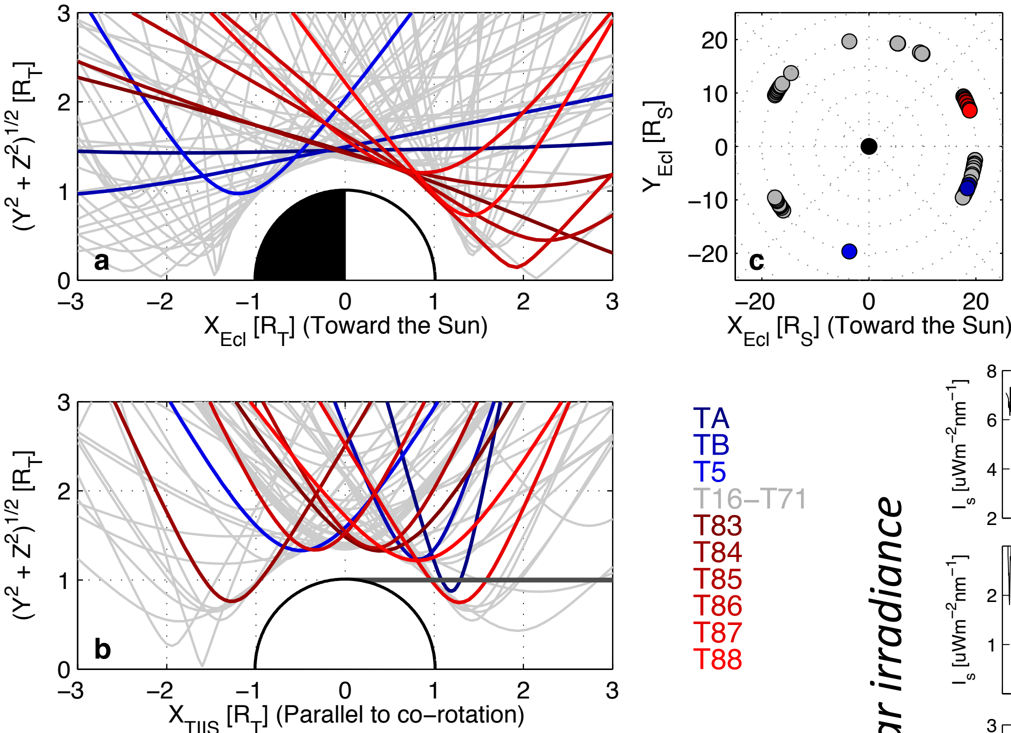
3000

2500

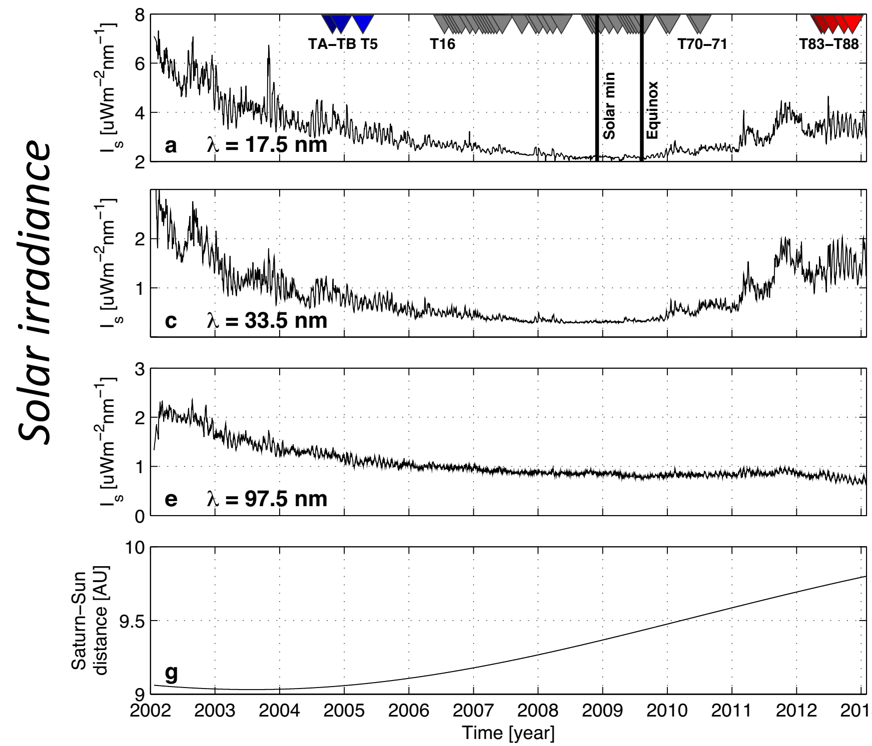


Kliore et al., 2011: high densities during a few radio occultation measurements. Increased particle impact ionisation suggested explanation.

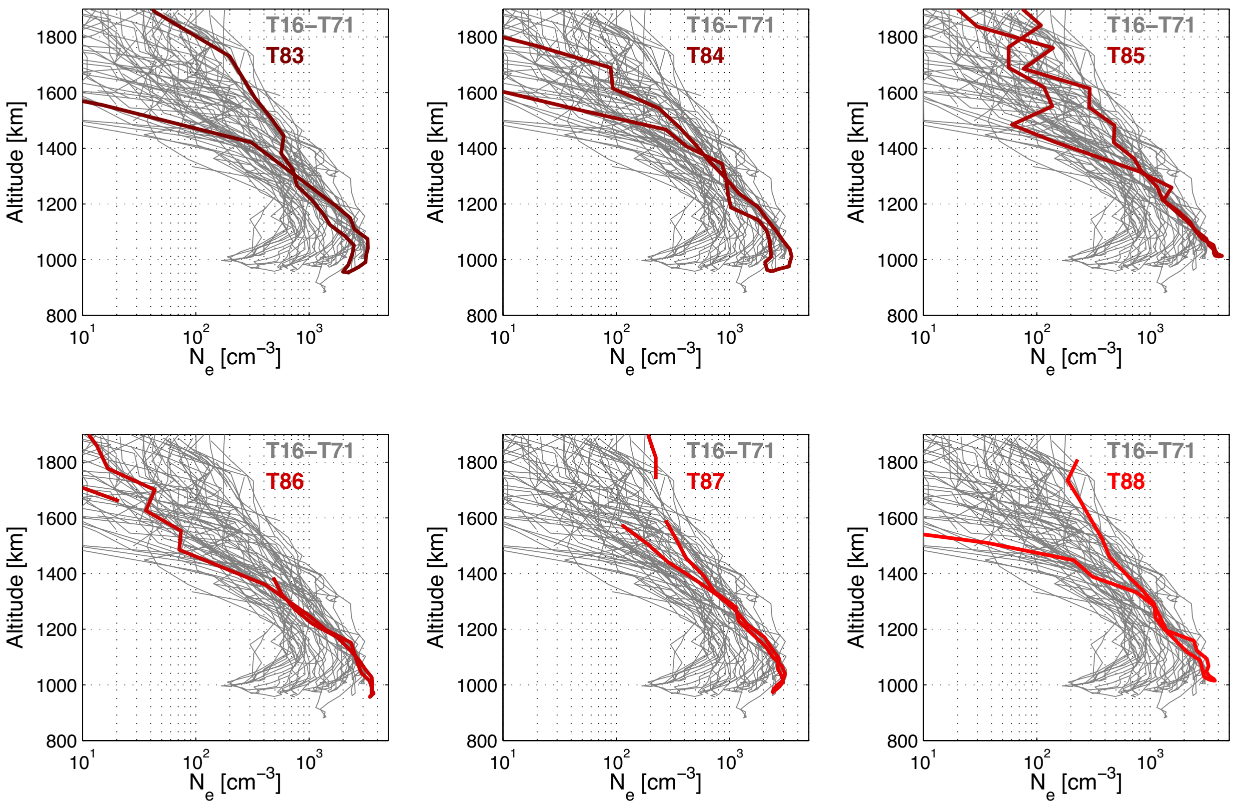
Solar cycle influence on the ionospheric peak density



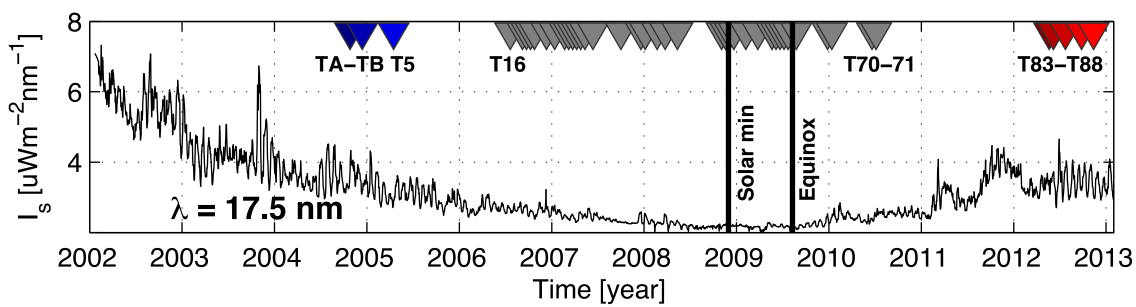
- 94 flybys over 9 years
- Measurements from a large fraction of a solar cycle.
- Fairly good coverage in space.
- Recently seen a variation in peak electron density with the solar cycle.

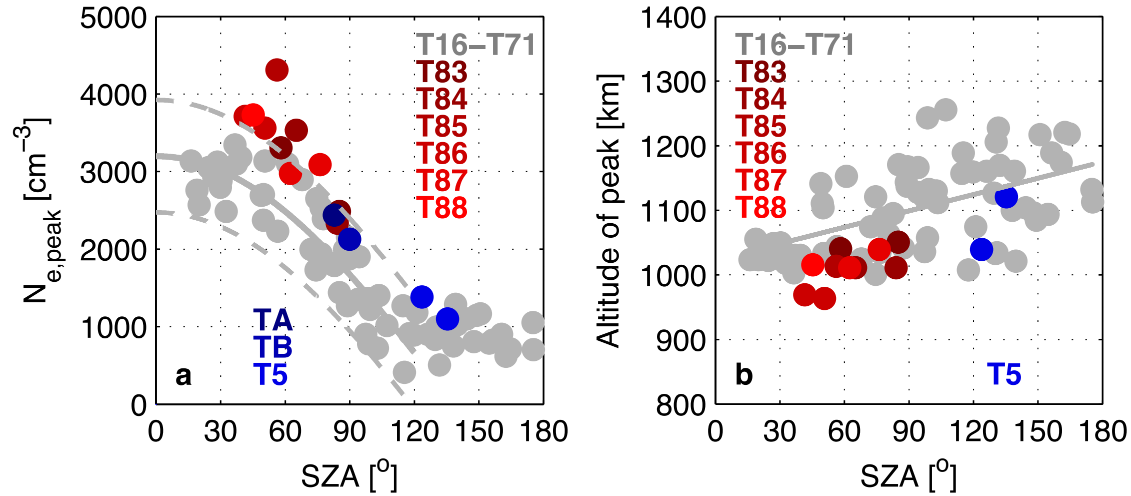


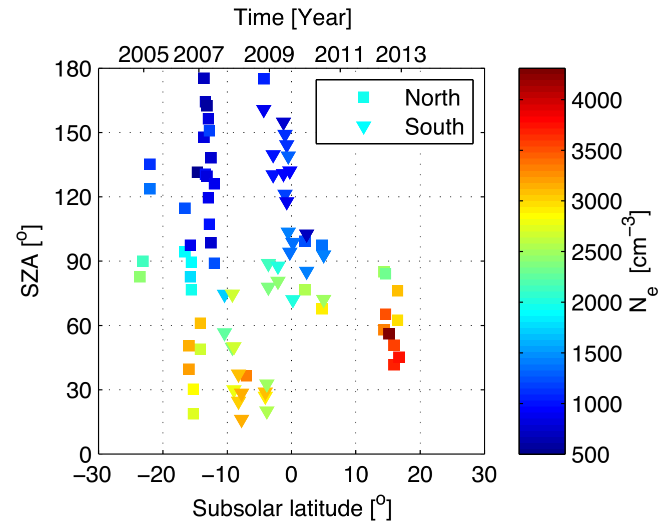
Solar max ionospheric profiles



- Large variations in the structure of the ionosphere.
- For a given altitude the density variation is about an order of magnitude below 1400 km.
- A large gap in "deep" flybys between T71 and T83.
- SZA is important (Ågren et al., 2009)



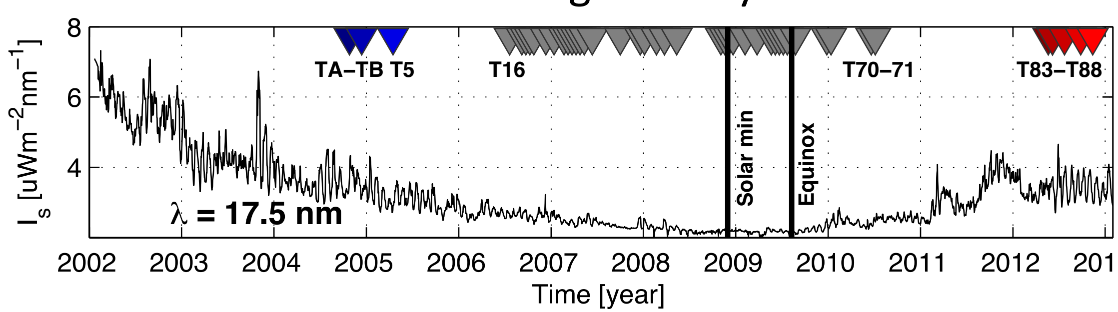




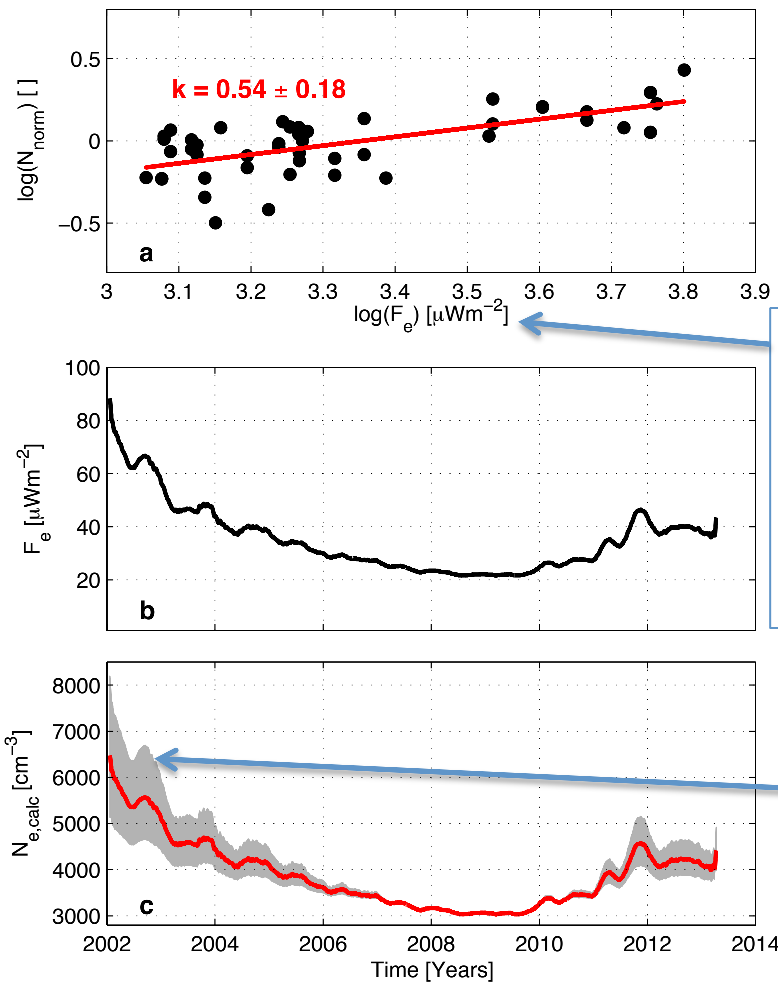
• The peak density during T83-T88 is clearly increased.
• TA, TB and T5 density are also higher than average.
• TA and TB, T85 and T88 did most likely not reach the peak altitude.

• The altitude of the peak has decreased with the solar activity.

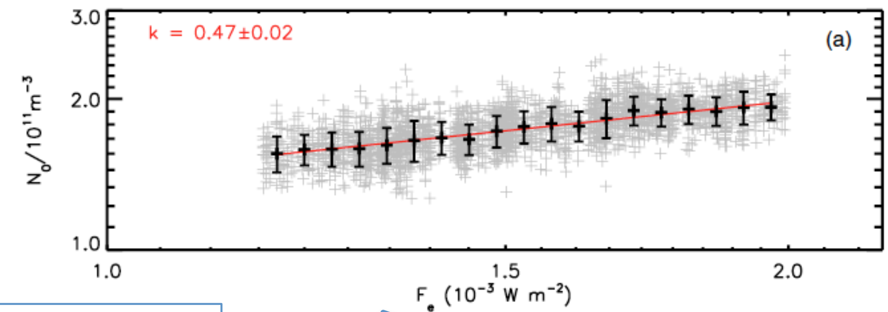
• T83-T88 all occurred in the northern hemisphere of Titan, so we cannot test for any effects of recent seasonal changes, but T93-T100 might provide the flyby geometry for that.



Titan: Edberg et al., 2013, JGR



Mars: Girazian and Withers, 2013, GRL



Integrated solar irradiance from TIMED/SEE used as proxy for the ionising flux (and not F10.7).

- 1-80 nm for Titan
- 1-90 nm for Mars

The subsolar peak density could have been > 6500 cm^{-3} during the previous solar max - 85-160% more than ever measured during the Cassini mission.

- According to Chapman theory the density $N_e \propto F_e^k$, where F_e is the ionising flux and k=0.5.

- Several assumptions violated: plane stratified ionosphere, monochromatic radiation, single neutral, a single ion species absorbing the flux, isothermal ionosphere.

- Still, our result of k=0.54 is very similar to theory, and very similar to results from the ionosphere of Mars (k=0.47) (Girazian and Withers, 2013)

Summary

- Mars and Venus loose more plasma during stormy space weather (CIR/CME impacts) – from case studies and statistical studies
- Heliospheric current sheet crossings seems to reduce the outflow (at Venus)
- Ionospheric density of Titan increases during a CME impact
- Solar cycle variations affect the ionosphere of Titan in agreement with theory