The nightside Martian ionosphere observed by MARSIS depending on solar wind and IMF

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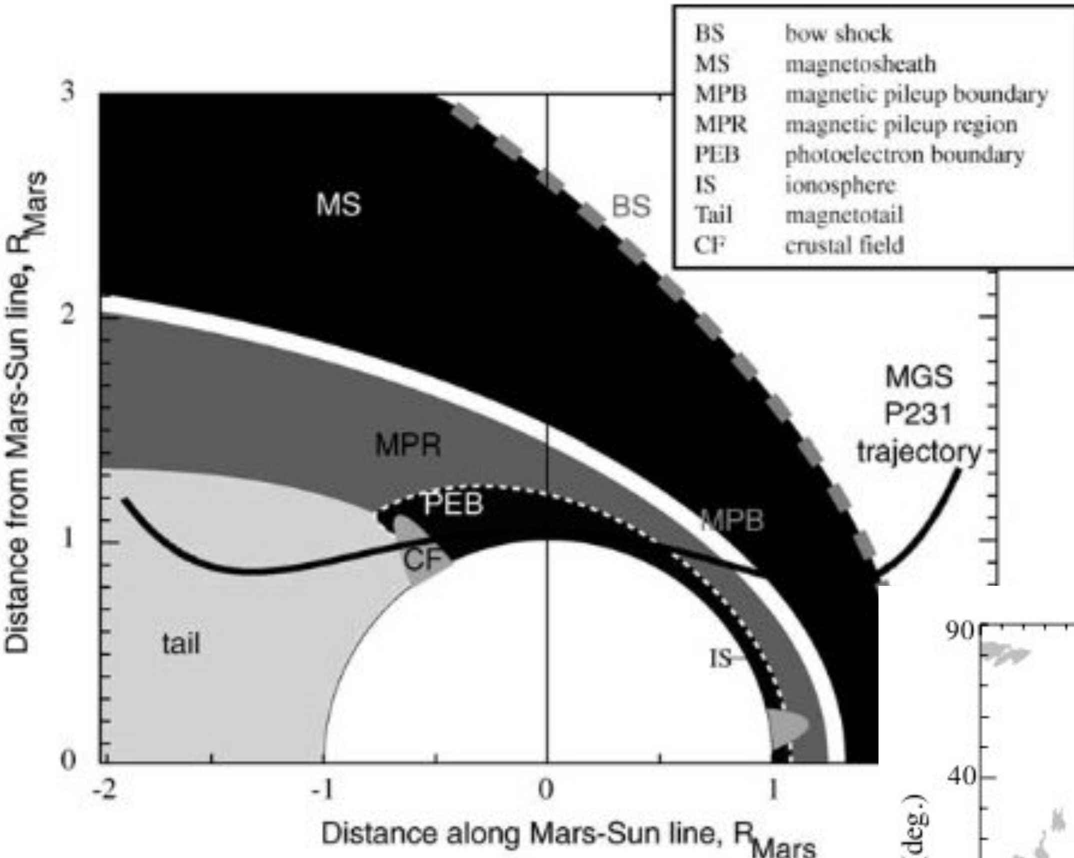
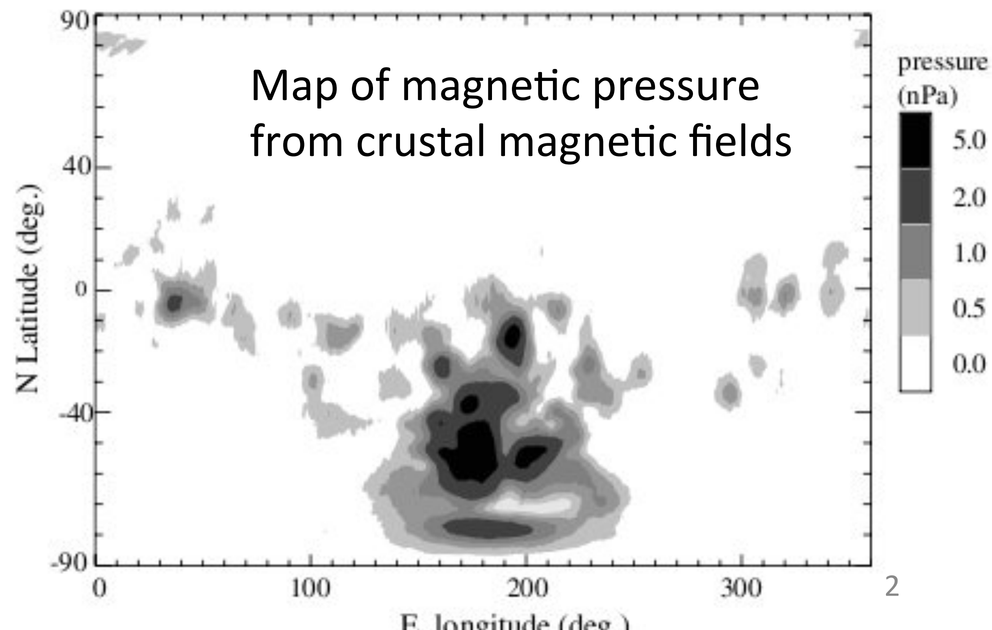
Plasma regions near Mars

- Mars has no significant magnetic dipole.
- Upper atmosphere exposed to solar wind erosion.
- Ionosphere provides conductive obstacle → induced magnetosphere is formed.
- Planetary crustal magnetic fields add to the picture.

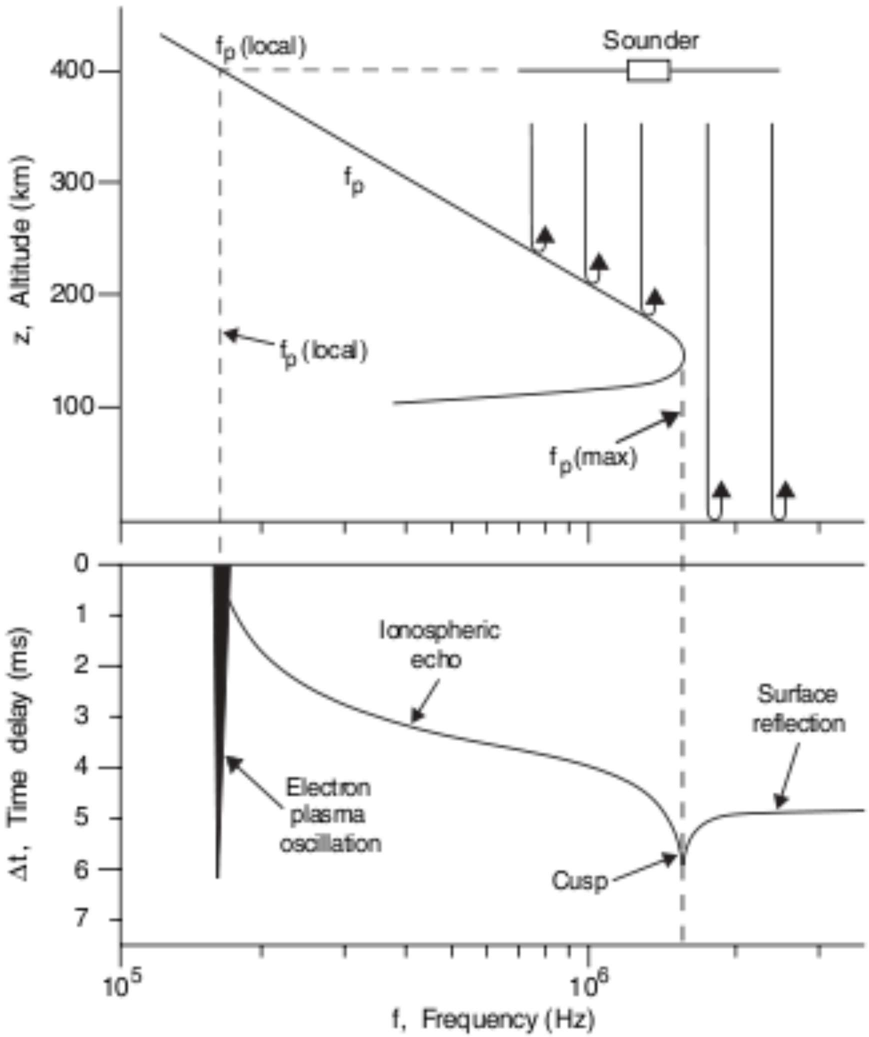


Crider et al., 2004



Map of magnetic pressure from crustal magnetic fields

MARSIS



Gurnett et al., 2005

Mars Express MEX: polar elliptical orbit, periapsis ~280 km, apoapsis ~10500 km.

MARSIS: Mars Advanced Radar for Subsurface and Ionospheric Sounding [*Picardi et al., 2004*].

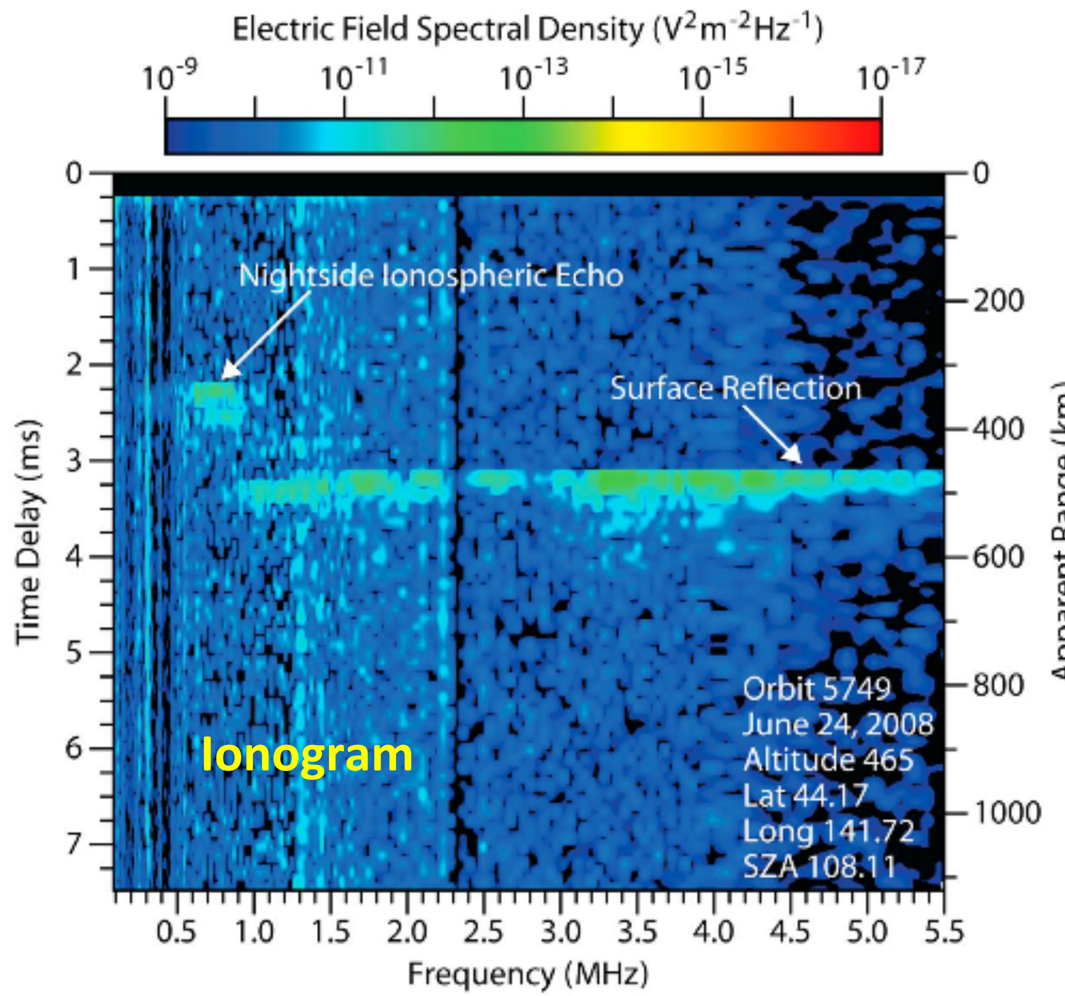
Ionospheric mode:
The radar sweeps through a series of frequencies between 0.5 and 5.5 MHz, where it transmits a pulse at a frequency f, which is reflected at a given altitude by plasmas of corresponding plasma frequency. The radar measures the time delay to receive the reflection.

The ionosphere is detected for frequencies from the local plasma frequency to the peak plasma frequency. The ground is detected at higher frequencies.

The Martian nightside ionosphere

Low peak electron densities, measured values are typically near 5000 cm^{-3} [*Němec et al., 2010; Zhang et al., 1990*] one order of magnitude lower than on the dayside.

The densities are **often too low to be detected** by MARSIS: detection rate of ~11%.



Němec et al., 2010

The Martian nightside ionosphere

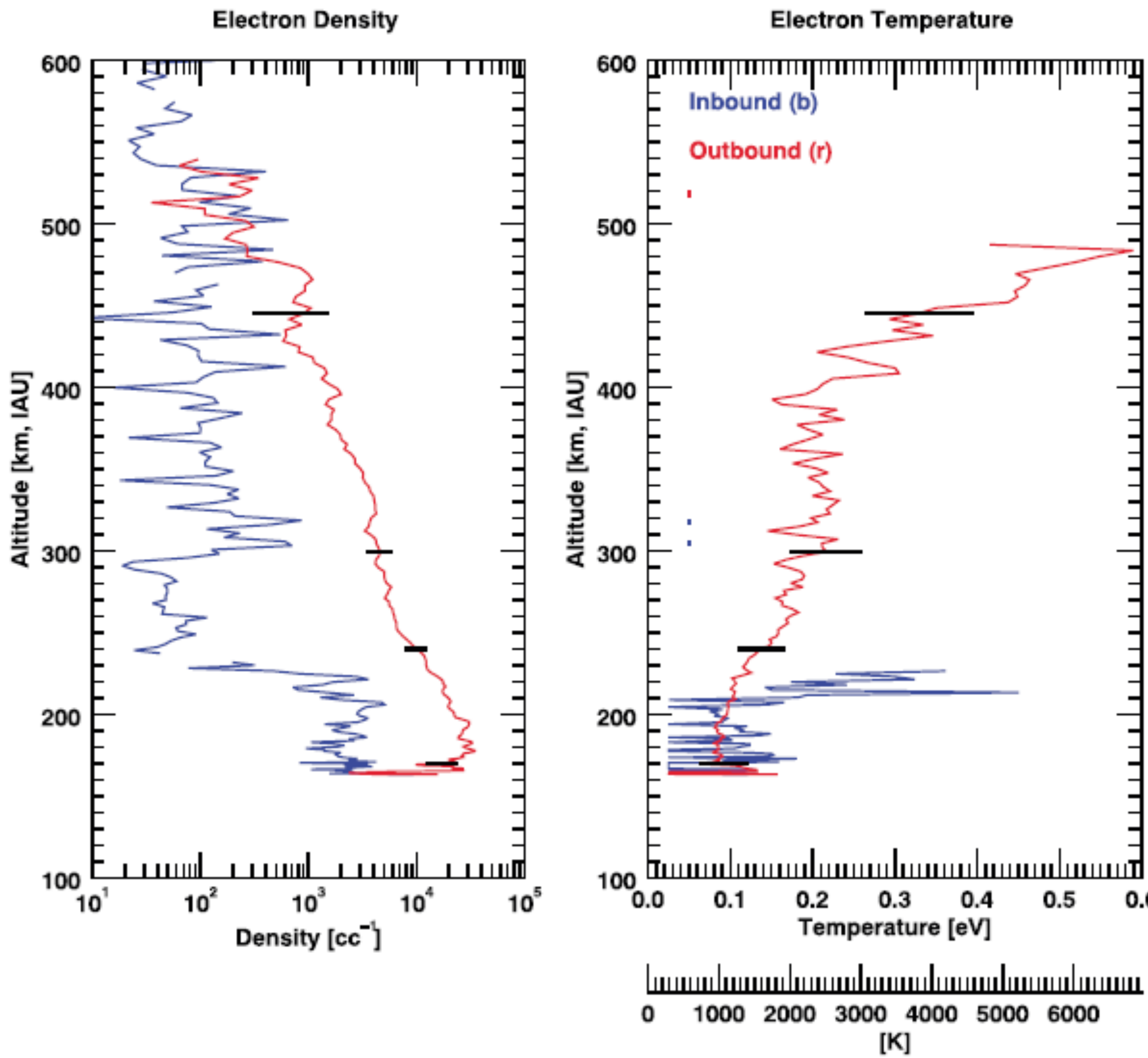
The Langmuir Probe and Wave LPW instrument onboard MAVEN made possible the first in situ nightside electron density and temperature profiles on the nightside of Mars [*Fowler et al.*, 2015].

The lowest temperatures were observed below 180 km and approach the neutral atmospheric temperature.

LPW is able to measure densities as low as ~100 cm^{-3}.

Above 200 km, densities of a few hundred cm^{-3} were observed for almost all nightside LT.

Below 200 km, density peaks of a few thousand cm^{-3} were observed at all nightside LT.



Fowler et al., 2015

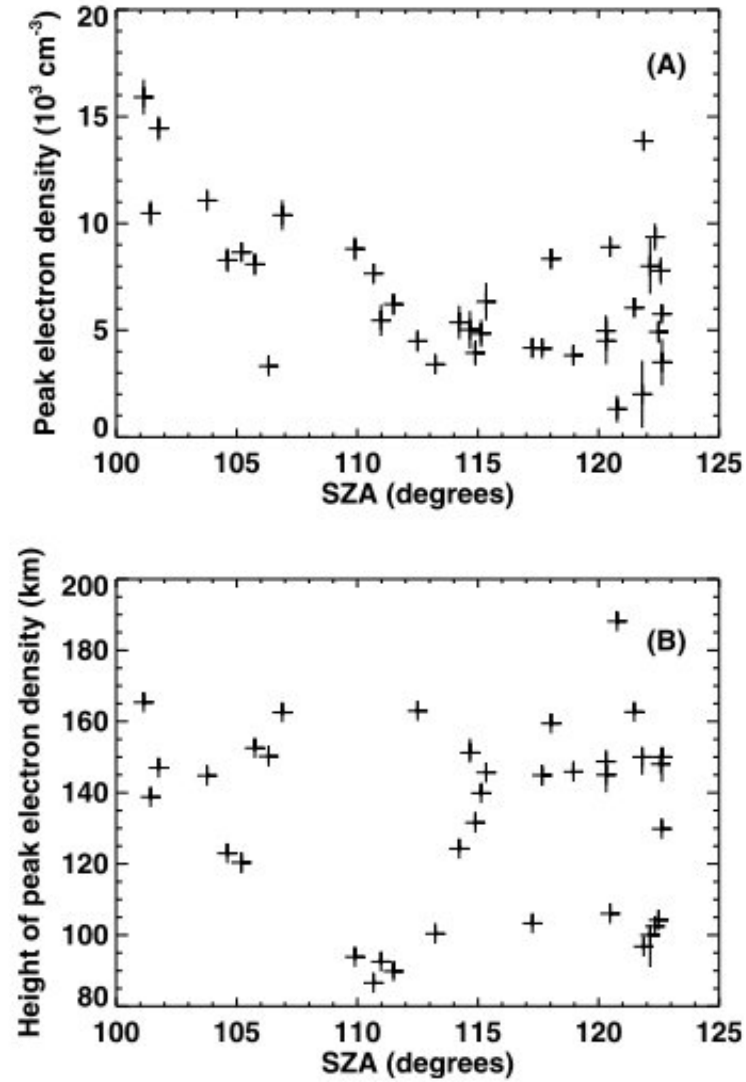
The Martian nightside ionosphere

Main sources of plasma for the nightside ionosphere, predicted by models:

- plasma transport from dayside [*e.g. Fox et al., 1993]*
- solar wind electron precipitation [e.g. *Lillis et al., 2009*]

Radio occultation measurements on MEX [*Withers et al., 2012*]:

- **Peak densities decrease as solar zenith angle SZA increases from ~107 to 115° → plasma transport** from dayside is important.
- **At SZA > 115°,** the peak densities show scatter and the peak altitudes stay near 150-160 km → consistent with **solar wind electron precipitation as a plasma source**.



Withers et al., 2012

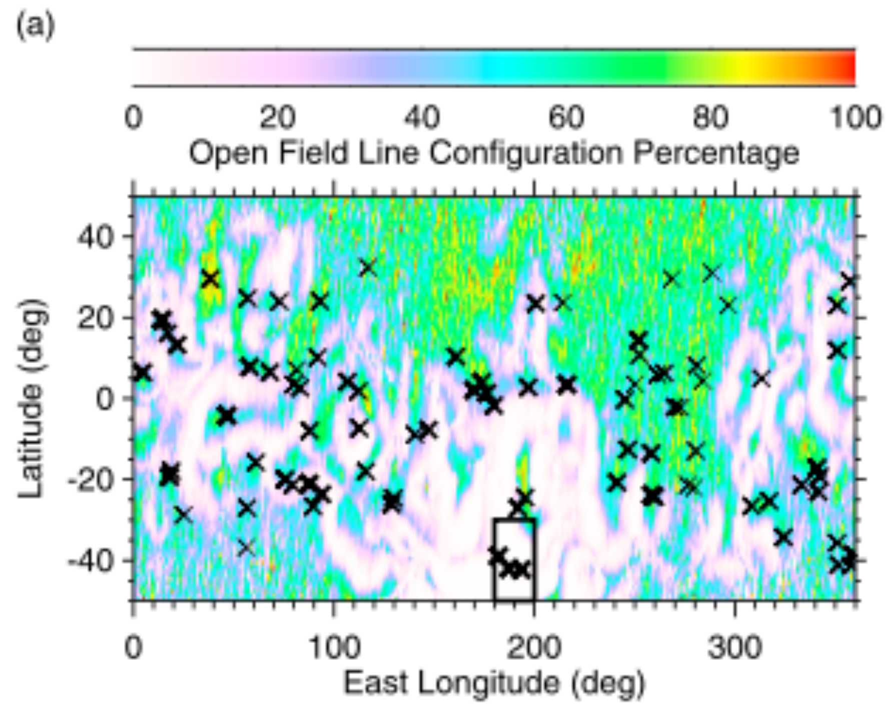
The Martian nightside ionosphere

Vertical crustal magnetic fields:

- hinder the horizontal plasma transport from dayside [*e.g. Němec et al., 2010*].
- allow electron precipitation when magnetic reconnection occurs between the interplanetary magnetic field IMF and the crustal fields [*e.g. Lillis and Brain, 2013*].

Irregular ionosphere, with patches of plasma, with high peak densities ~10^4 cm^{-3} found in areas of vertical crustal magnetic field [*e.g. Němec et al., 2011*]

→ ionization by electron precipitation through the magnetic cusps.



Němec et al., 2011

This work

Statistical study of nightside ionospheric echoes: SZA from 107° to 130°, MEX altitude < 1100 km.
Period: November 2005 – May 2006.

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Key Points:
- Observations of the nightside Martian ionosphere by the fix spacing MARSIS radar sounder
- The ionospheric peak densities increase

MARSIS observations of the Martian nightside ionosphere dependence on solar wind conditions

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Motivation: The solar wind conditions influence the main sources of the nightside ionosphere, at unmagnetized Mars and Venus: horizontal plasma transport and solar wind electron precipitation [*e.g. Lillis and Brain, 2013; Fraenz et al., 2006; Zhang et al., 1990*].

Question: What are the **effects of the IMF orientation and the upstream dynamic pressure** on the nightside ionosphere?

This work

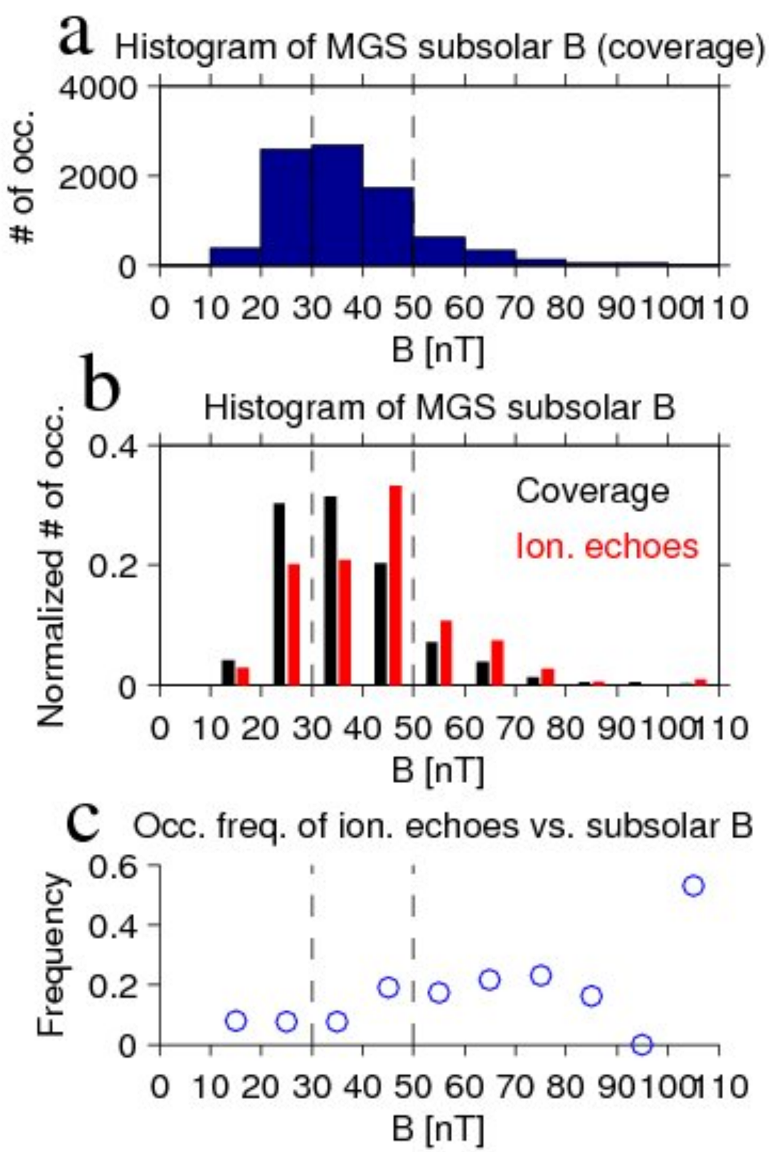
MEX does not have a magnetometer: we use instead two **solar wind proxies** developed from the magnetometer data from Mars Global Surveyor.

- the **IMF direction proxy** [*Brain et al., 2006*], taken in the dayside magnetic pileup region, far from crustal fields (the external draped field is expected to dominate). It is assumed to roughly represent the upstream IMF direction.
- the **dynamic pressure proxy** [*Brain et al., 2005*], taken as the magnetic pressure in the dayside magnetic pileup region, far from crustal fields. Magnetic field measurements are fitted to SZA to get a value at SZA = 0°. The corresponding magnetic pressure is assumed equal to the dynamic pressure [*Crider et al., 2003*].

For each ionogram, MGS proxy values are selected between 2h before and after the ionogram time if they exist. The dynamic pressure proxy is taken as the median of these values. The IMF clock angle is taken as the first of these values.

This way, the proxies are determined for the times of 8535 ionograms of the data coverage, including 985 ionograms having an ionospheric echo (occurrence frequency of having an ionospheric echo 11%).

Effect of dynamic pressure



3 groups of dynamic pressure:

- **Low**: B < 30 nT
- **Moderate:** 30 ≤ B ≤ 50 nT
- **High:** B > 50 nT

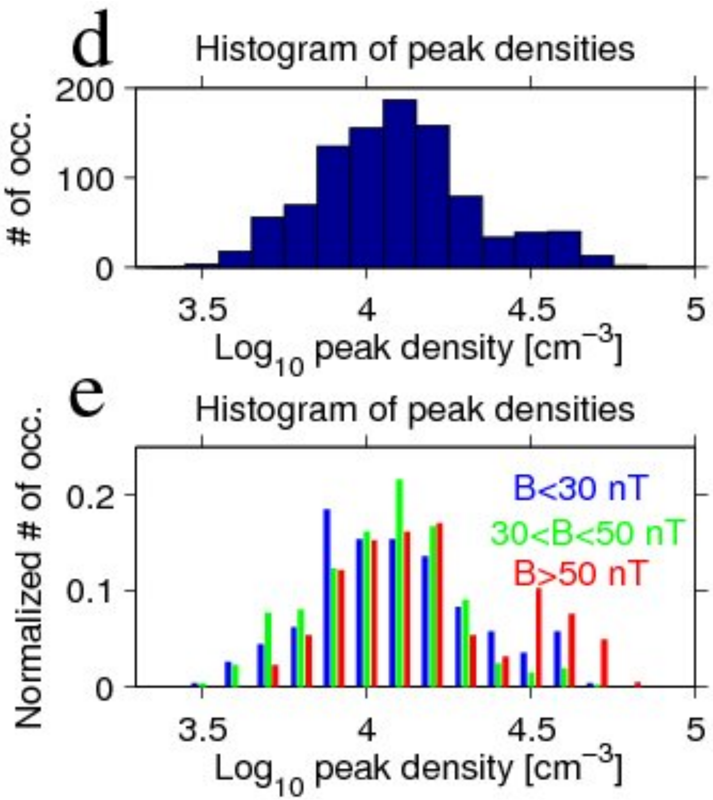
The distribution of subsolar B values for the data coverage has a median of 35 nT and a tail up to 110 nT.

The **occurrence frequency** of ionograms with peak densities large enough to be detected **increases** when the **dynamic pressure increases**.

What about the ionization sources?

- Ionization by electron impact should increase during stormy space weather (CIRs, CMEs) because the inflow of solar wind plasma increases [*e.g. Lillis and Brain, 2013; Edberg et al., 2010*].
- Plasma transport from the dayside may decrease when high dynamic pressure conditions compress the ionosphere to lower altitudes. A similar situation is observed at Venus during high dynamic pressure, causing a decrease in nightside peak densities [*e.g. Knudsen et al., 1987*].

Effect of dynamic pressure



The **measured peak densities are relatively high** (median 12000 cm^{-3}) because we cannot access the bulk of peak densities (typically below 5000 cm^{-3}).

The distribution of **peak densities** for **low subsolar B is shifted to lower values** (median 11000 cm^{-3}) than the distribution for high subsolar B (median 14000 cm^{-3}).

A secondary populations of **very high peak densities** ($Ne_{max} > 10^{4.5} \sim 32000$ cm^{-3}) is visible in the **low and high subsolar B** groups. The corresponding orbit numbers are written in the plot next slide.

Effect of IMF sector

The **IMF clock angle** is measured counterclockwise from the local East direction at Mars Global Surveyor (orbit is ~circular at ~400 km altitude, fixed at 02h00-14h00 local time).

The draped IMF clock angle varies as much as 25° with the Martian year. The period of study covers an equivalent of one season.

We are interested in the **Eastward-Westward component of the clock angle** of the draped IMF, which we assume to be representative of the Eastward-Westward component of the upstream IMF.

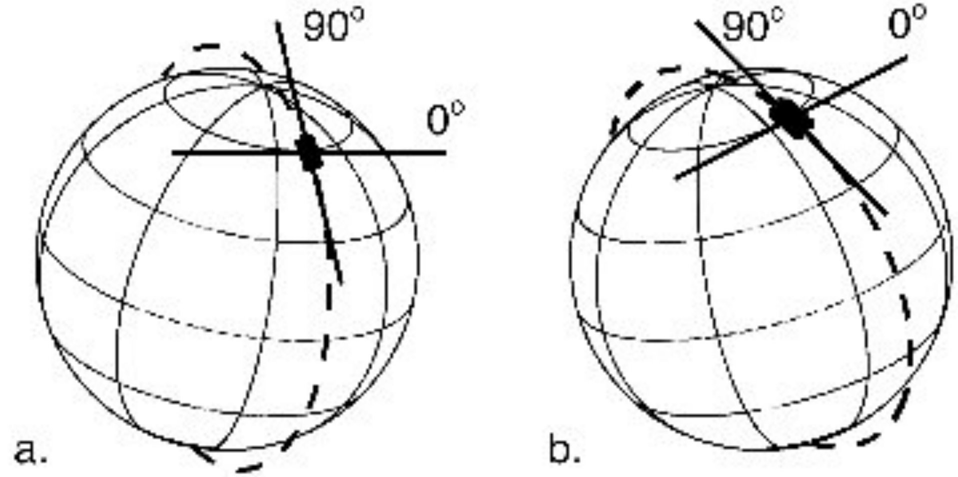


Fig. 1. MGS orbit geometry and definition of draping direction azimuth angle for (a) $L_S = 63°$ and (b) $L_S = 125°$. L_S is the solar longitude, and corresponds to martian season. The MGS orbit is shown as a dashed line. A rectangular box covers the portion of the orbit from 50°–60° North latitude. The horizontal components from MAG measurements in this region are used to derive the draping azimuth angle, which we define as 0° locally eastward and 90° locally northward. Elevation angle is defined with respect to the local horizontal.

Brain et al., 2006

Effect of IMF sector

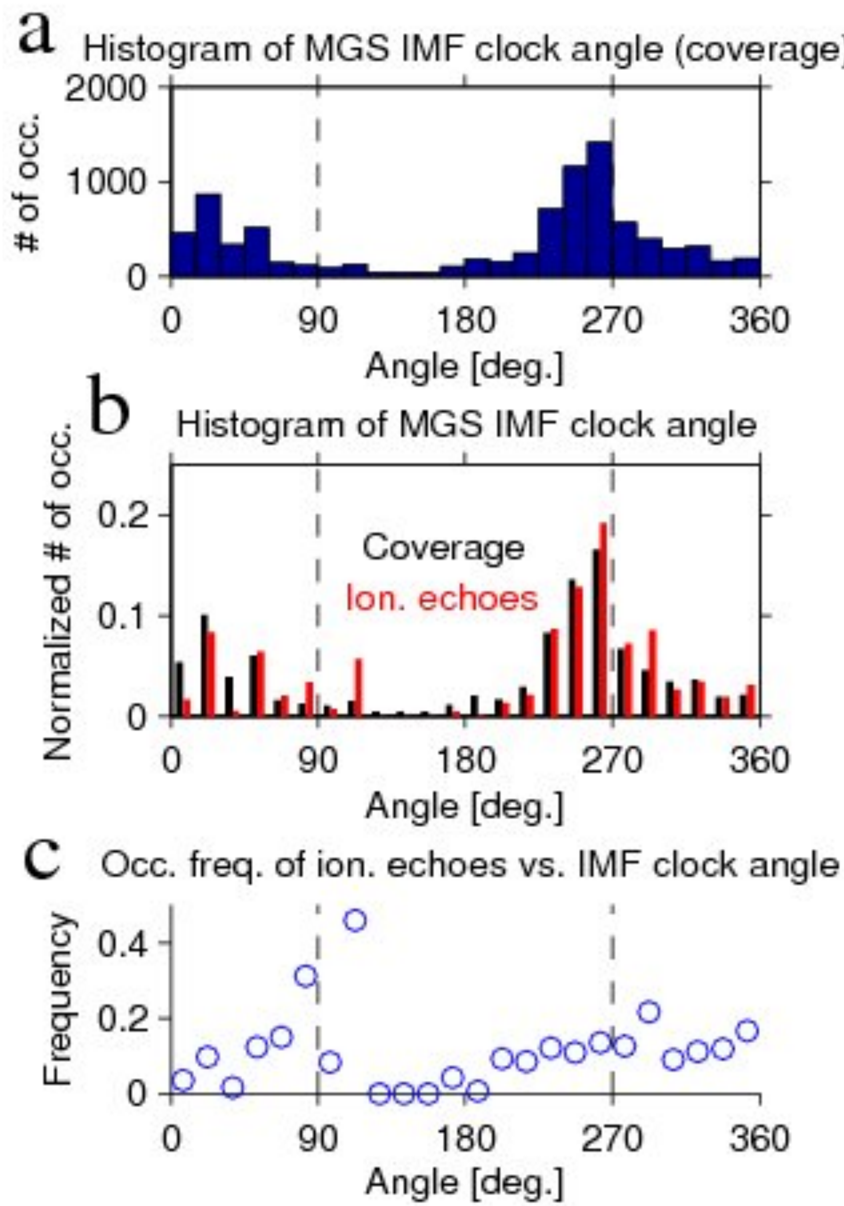
We define two **IMF sectors**:

- **Eastward**: angle < 90° or angle > 270° (IMF away from Sun).
- **Westward**: 90° < angle < 270° (IMF toward Sun).

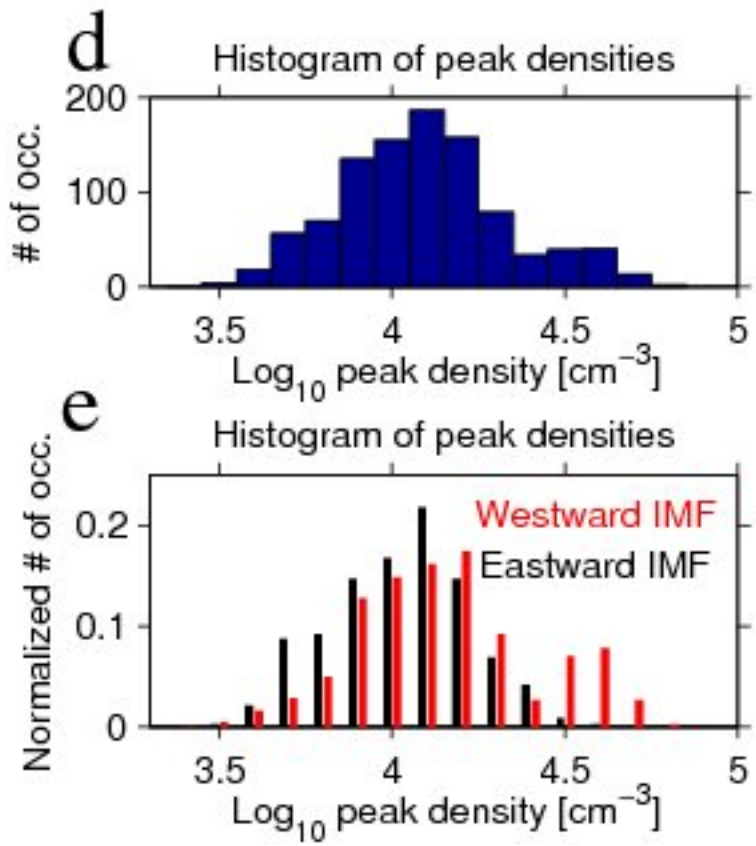
The **occurrence frequency** of ionograms with peak densities large enough to be detected **does not depend** on the **IMF clock angle**.

What about the ionization sources?

- It is not known if the plasma transport from dayside depends on the IMF sector.
- The access of solar wind electrons to the low altitude nightside in low crustal field regions does not depend on the IMF sector [*e.g. Lillis and Brain, 2013*].



Effect of IMF sector



The distribution of measured peak densities presents a secondary population at **very high peak densities** ($Ne_{max} > 10^{4.5}$ cm^{-3}) in the **Westward IMF group**, compared to the Eastward IMF group.

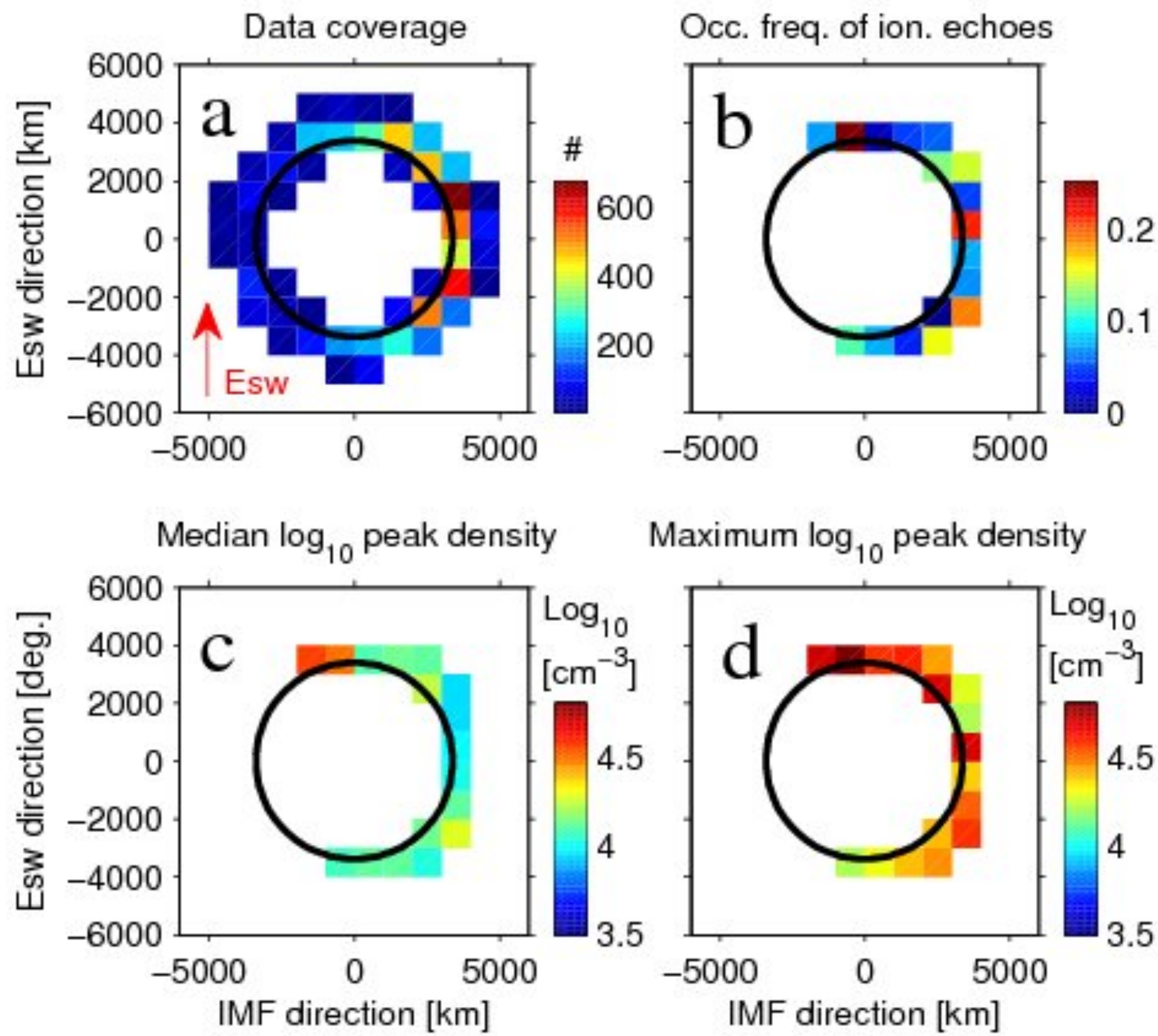
Very high peak densities are thus favored by a **particular IMF sector**.

Effect of IMF sector

When the data are rotated into the Mars Solar Electric frame, we see the **highest peak densities in the hemisphere where the convective electric field points outward (+Esw hemisphere)**. Indeed these densities are found mostly for Westward IMF, while the data coverage is in the South.

We make the hypothesis that the source of the highest peak densities may be accelerated electrons, which are often found in the +Esw hemisphere [*e.g. Brain et al., 2006; Dubinin et al., 2008*].

Let's check with **ASPERA3 ELS**.



Case study of clusters of very high peak density

1st panel: MEX altitude and SZA.

2nd panel: B field and magnetic zenith angle of crustal field Cain model at 150 km altitude.

3rd panel: electron energy time spectrogram.

4th panel: electron particle flux integrated over 40-80 eV and all anodes.

5th panel: MARSIS echogram averaged over 0.5-2 MHz.

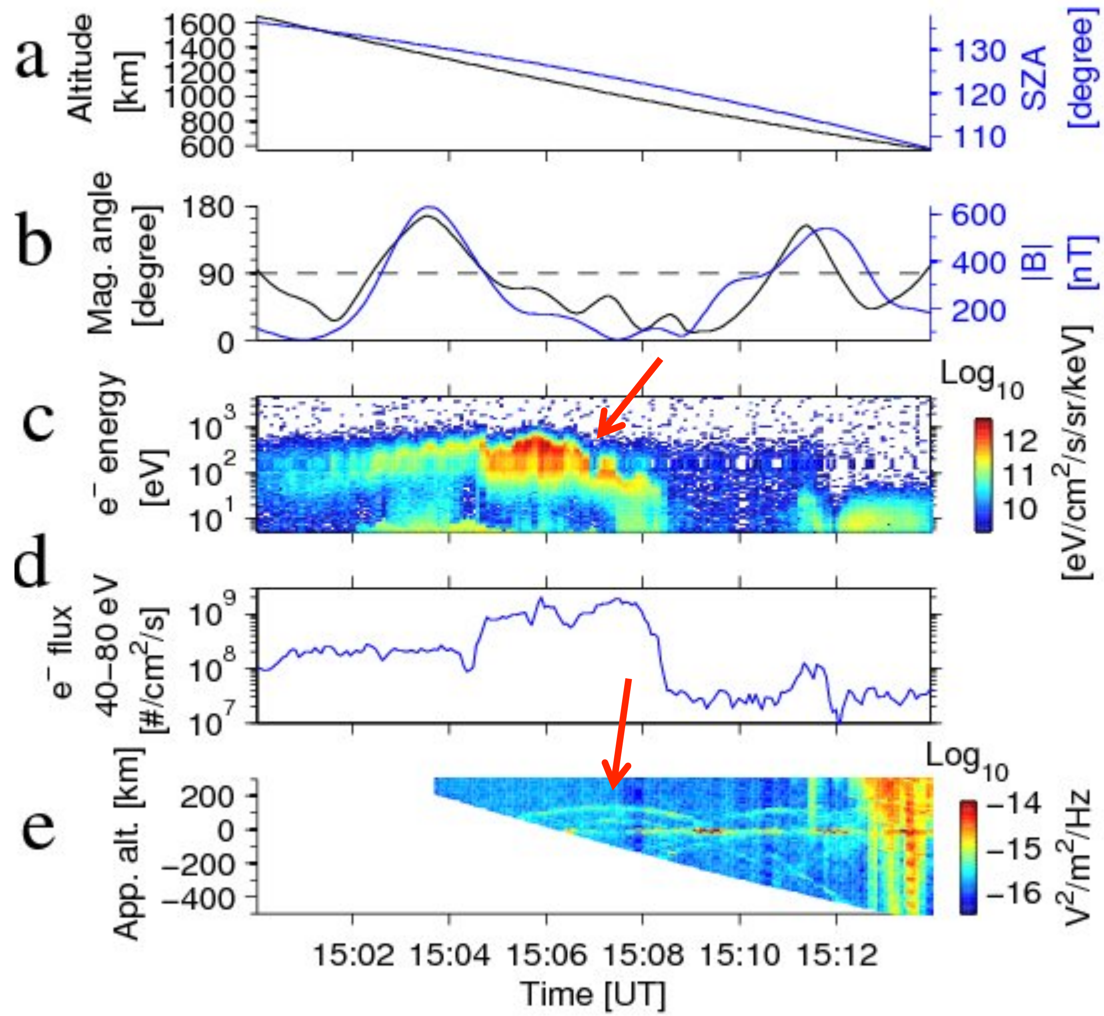
We have 9 **clusters of very high peak densities** having simultaneous measurements by ASPERA3 ELS. The example here shows accelerated electrons.

Summary:

7 clusters present **accelerated electron** spectra.

2 other clusters present **magnetic pileup region** spectra.

Orbit 2489

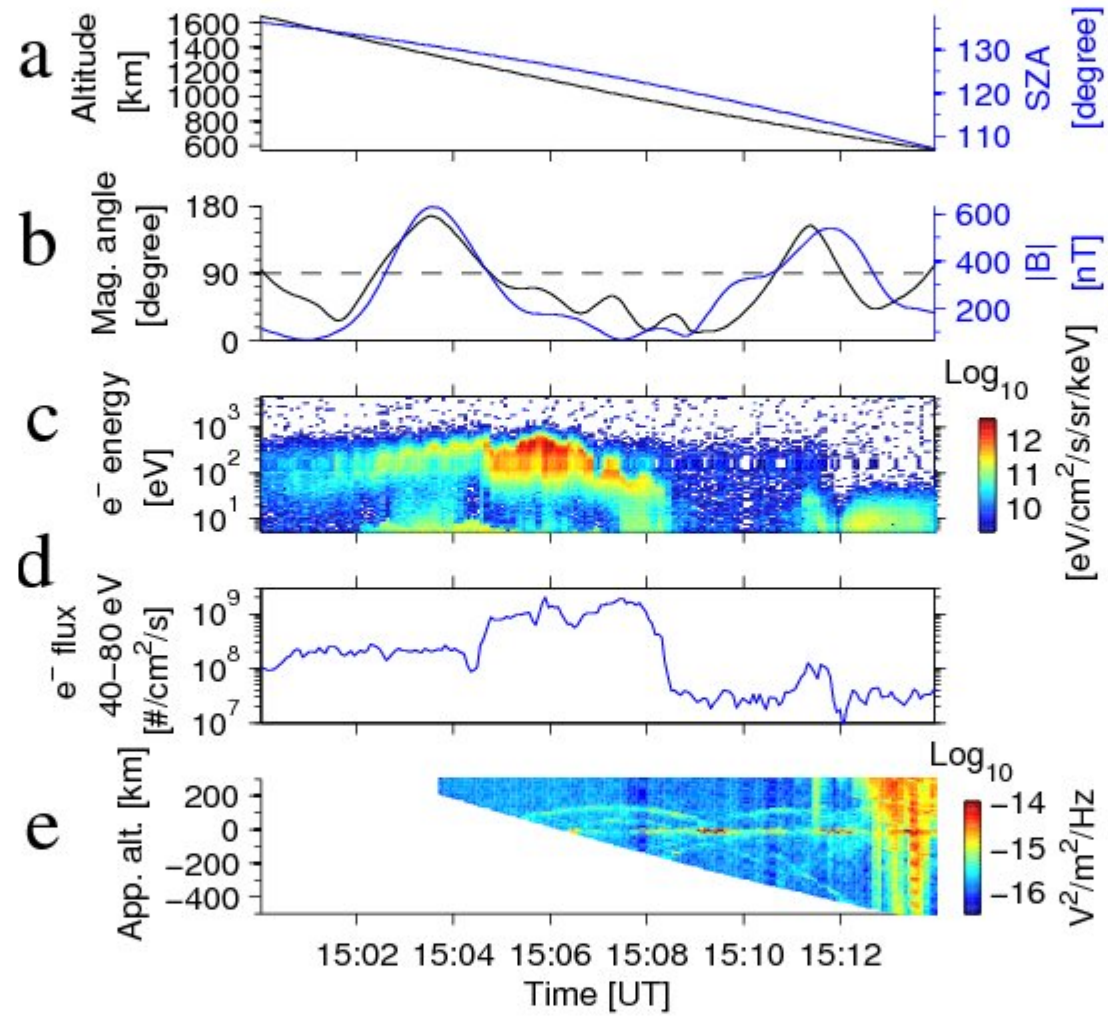


Case study of clusters of very high peak density

Modelling of ionization by precipitating electrons obtains **higher peak densities** when **accelerated spectra** are used, compared to magnetotail electrons [*e.g. Fillingim et al., 2007*].

→ consistent with the frequent observation of accelerated spectra during the times of the clusters.

Orbit 2489



Conclusion

Statistical observations of the Martian nightside ionosphere by MARSIS.

Effects of solar wind conditions?

Dynamic pressure:

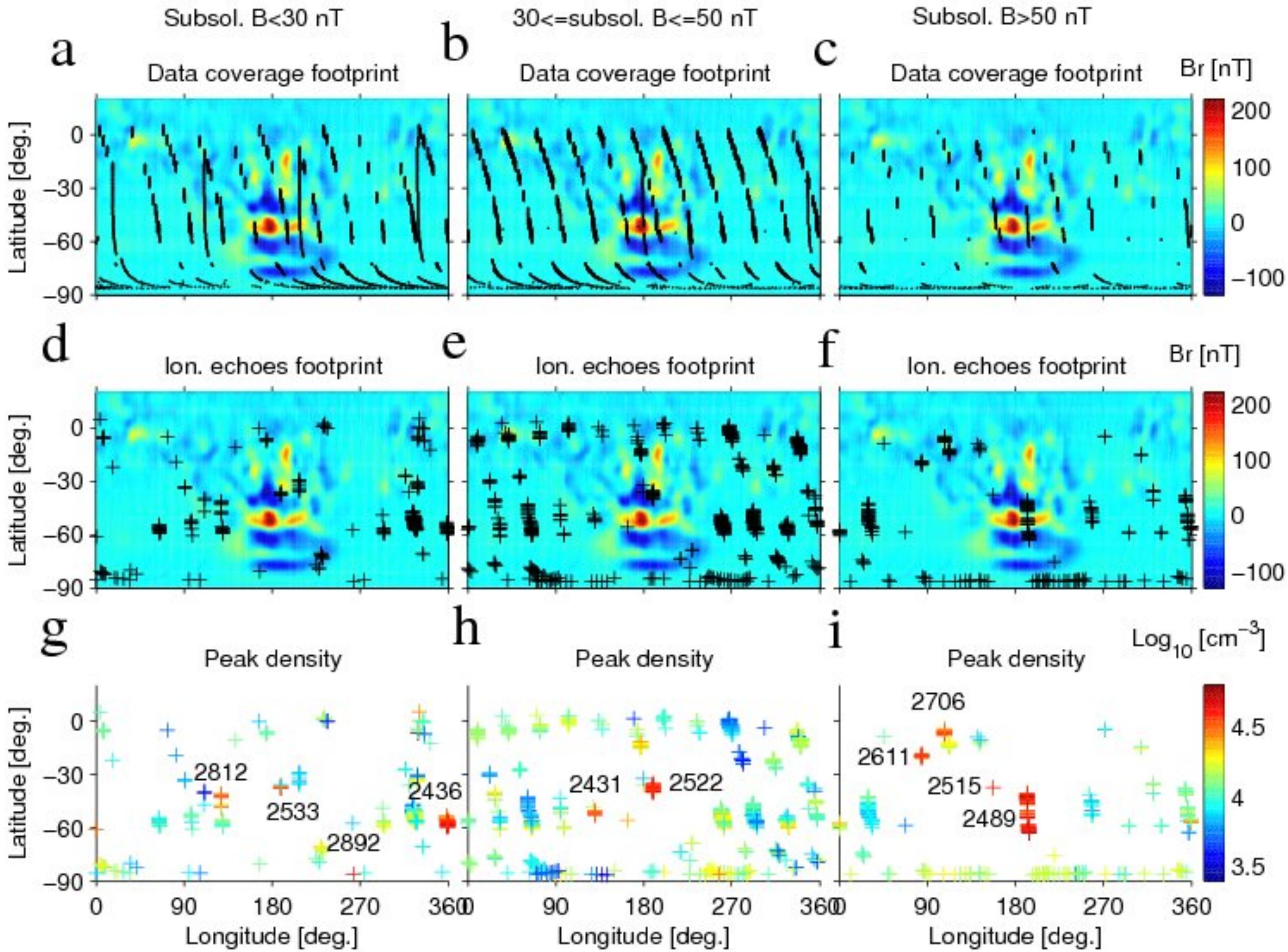
- The **ionosphere is detected more often during high dynamic pressure**: the peak densities reach more often above the MARSIS measurement threshold of 5000 cm^{-3}.
- **In this case electron precipitation may be an important plasma source**, as solar wind electron fluxes become stronger and reach lower altitudes.

IMF direction:

- The **detection rate of the ionosphere does not change with the IMF sector**.
- **Very high peak densities** are measured preferably when the **IMF points Westward**. These cases are found for various dynamic pressure conditions, in regions of low and large crustal field and **often associated** with measurements of **accelerated electrons** by ASPERA-3. These observations are good indications for **precipitating electrons** as a ionization source.

Future studies on the role of **varying solar wind conditions on the dayside-nightside transport** are needed to better understand its role as a plasma **source for the nightside** ionosphere.

Effect of dynamic pressure



Effect of IMF sector