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Localized Heating of the Martian Topside Ionosphere Through the Combined Effects of Magnetic Pumping by Large-Scale Magnetosonic Waves and Pitch Angle Diffusion by Whistler Waves

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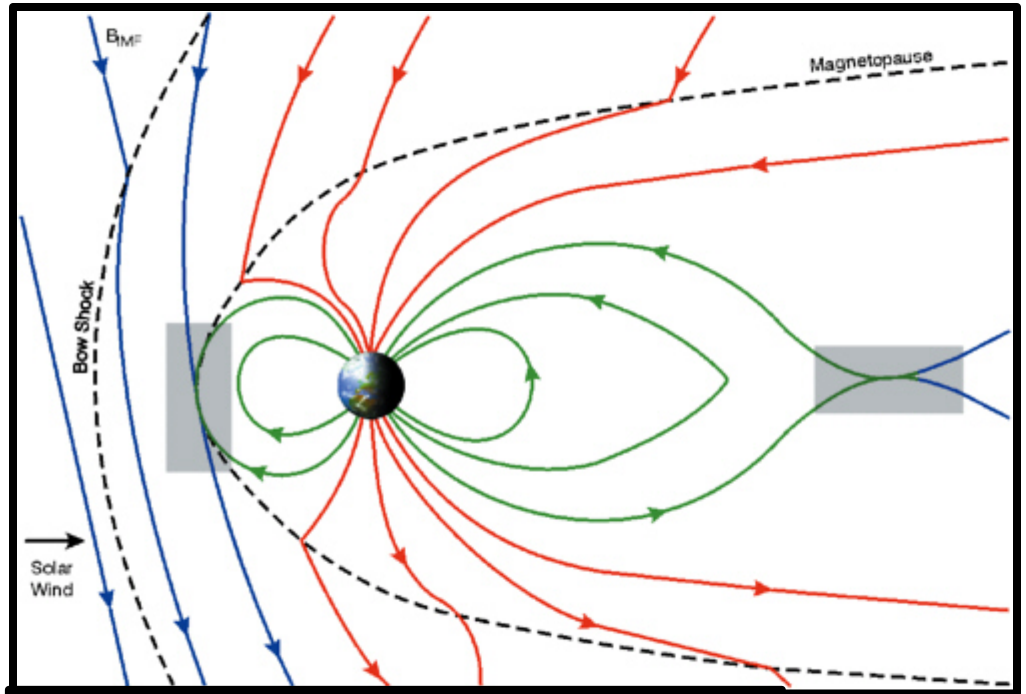
EGU 2020, Session: Space environments of unmagnetized or weakly magnetized solar system bodies and the effects of space weather on these systems.

Magnetospheres: magnetized vs unmagnetized

The solar wind interaction with unmagnetized bodies is very different to that with magnetized counterparts.

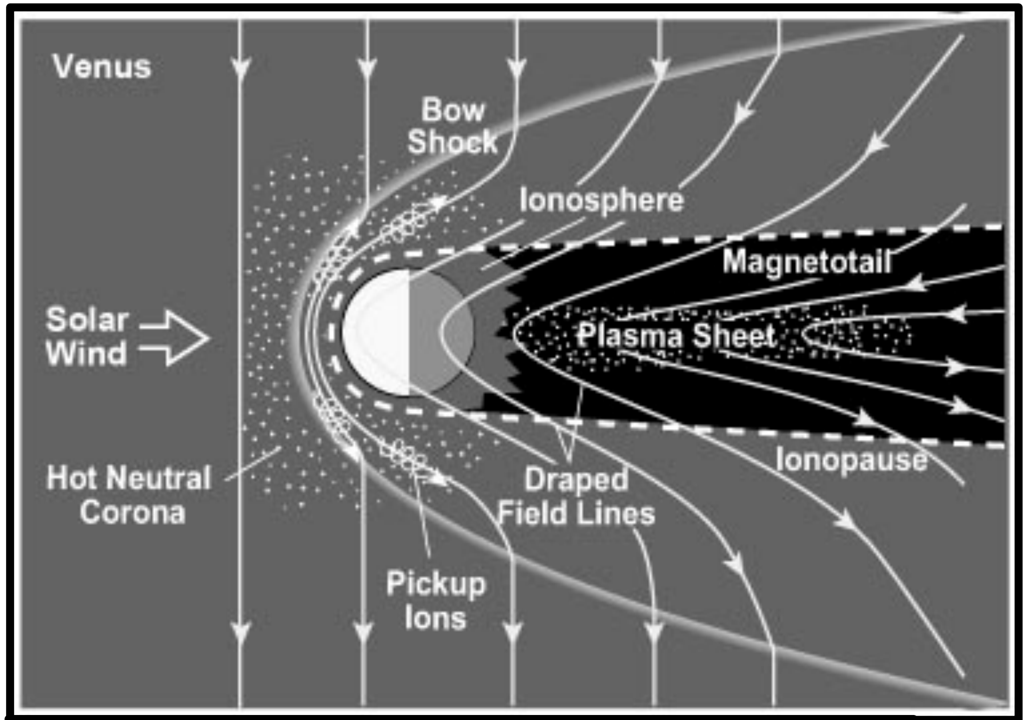
Magnetized – e.g. Earth



https://www.nap.edu/read/10993/chapter/4

- Magnetic pressure of dipole stands off solar wind flow.
- Energy and particle deposition in polar cusp regions.

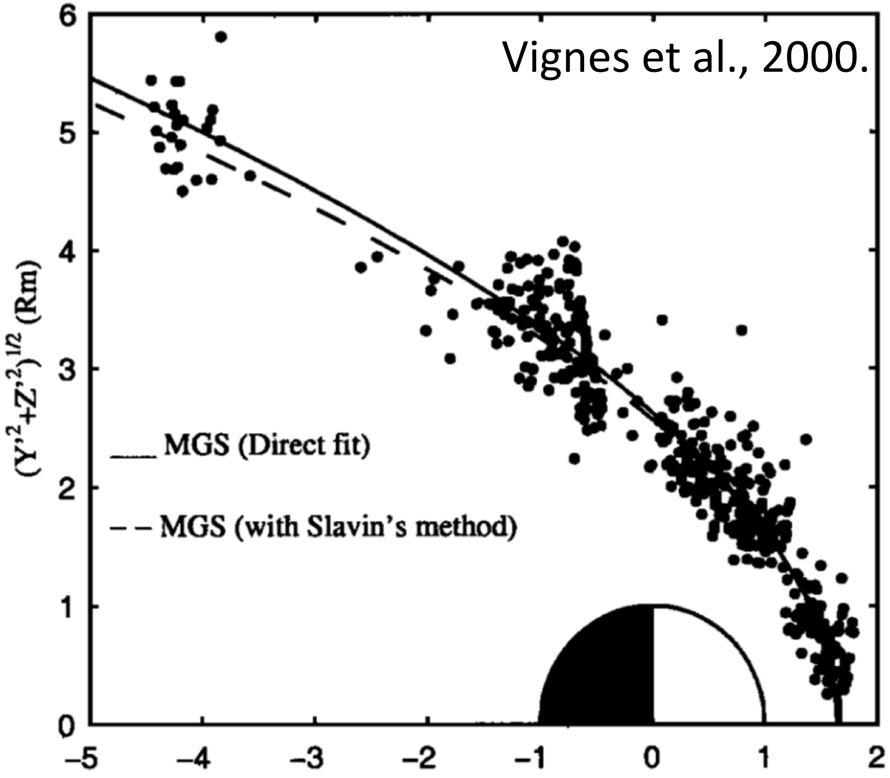
Unmagnetized – e.g. Venus, Mars, comets



http://ase.tufts.edu/cosmos/print_images.asp?id=7

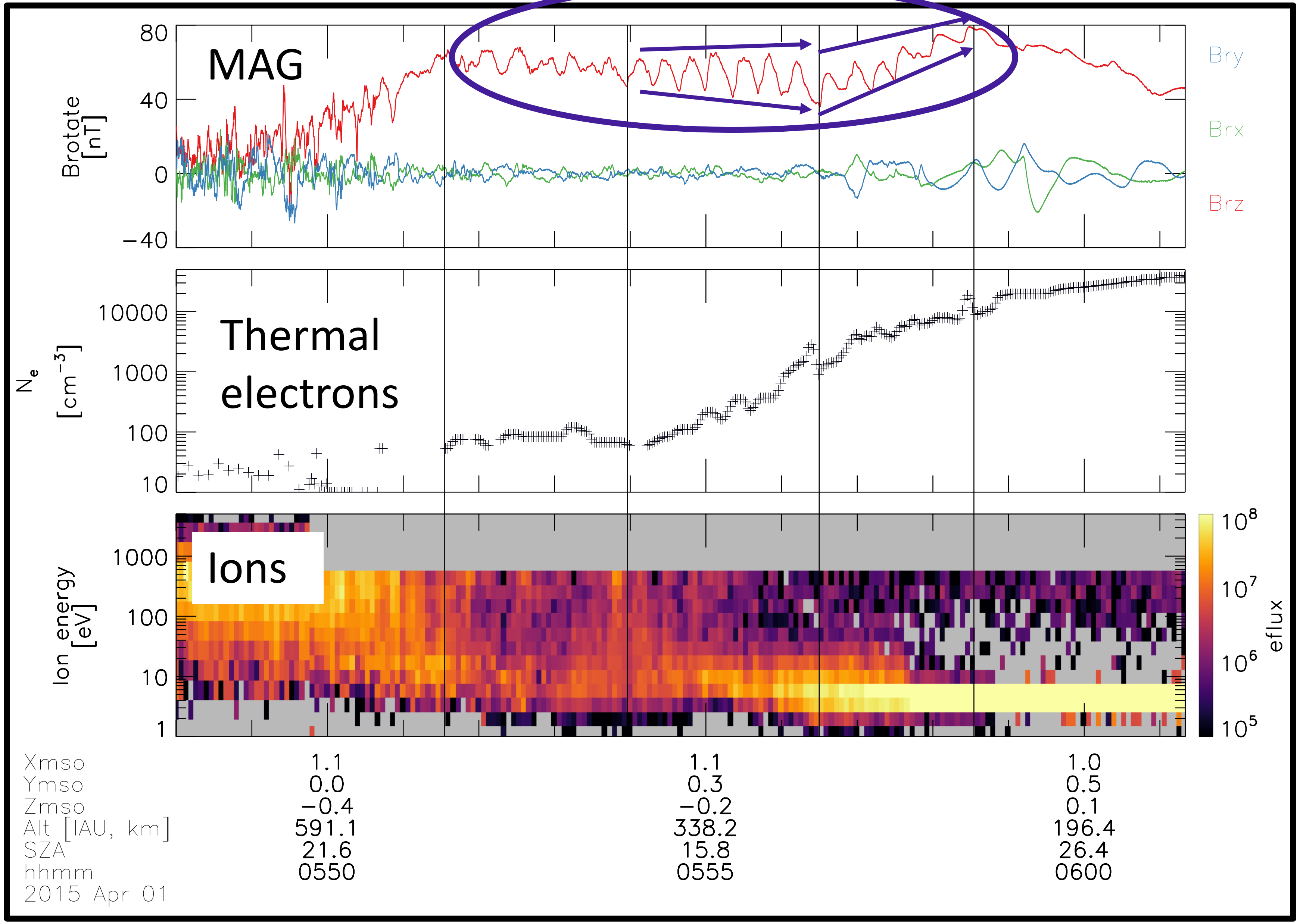
- Combination of ion pick up and ionospheric currents stand off solar wind.
- No large scale magnetic field to guide particles into ionosphere.

Mars' magnetosphere



- Solar wind proton gyro radius comparable to solar wind stand off distance.
- Waves generated at ~proton gyro-length scale at bow shock.
- Wave-particle interactions expected to facilitate energy deposition from solar wind to ionosphere.
- We observe these wave particle interactions with orbiters at Mars, e.g. MGS, MEX, MAVEN…

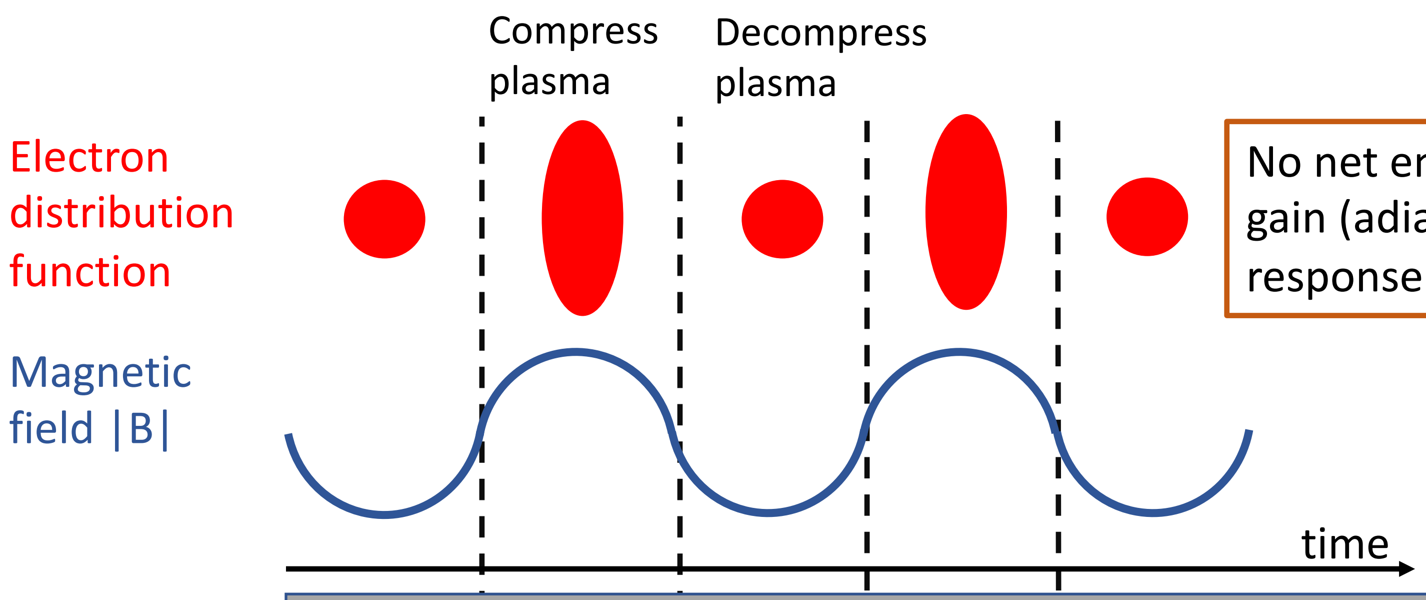
Previous observations at Mars



- MAVEN observations demonstrate that magnetosonic (MS) waves can heat dayside planetary ions and drive significant ionospheric erosion (Fowler et al., 2018, MAVEN observations of solar wind-driven magnetosonic waves heating the Martian dayside ionosphere. *Journal of Geophysical Research: Space Physics*, *123*(5), 4129-4149).

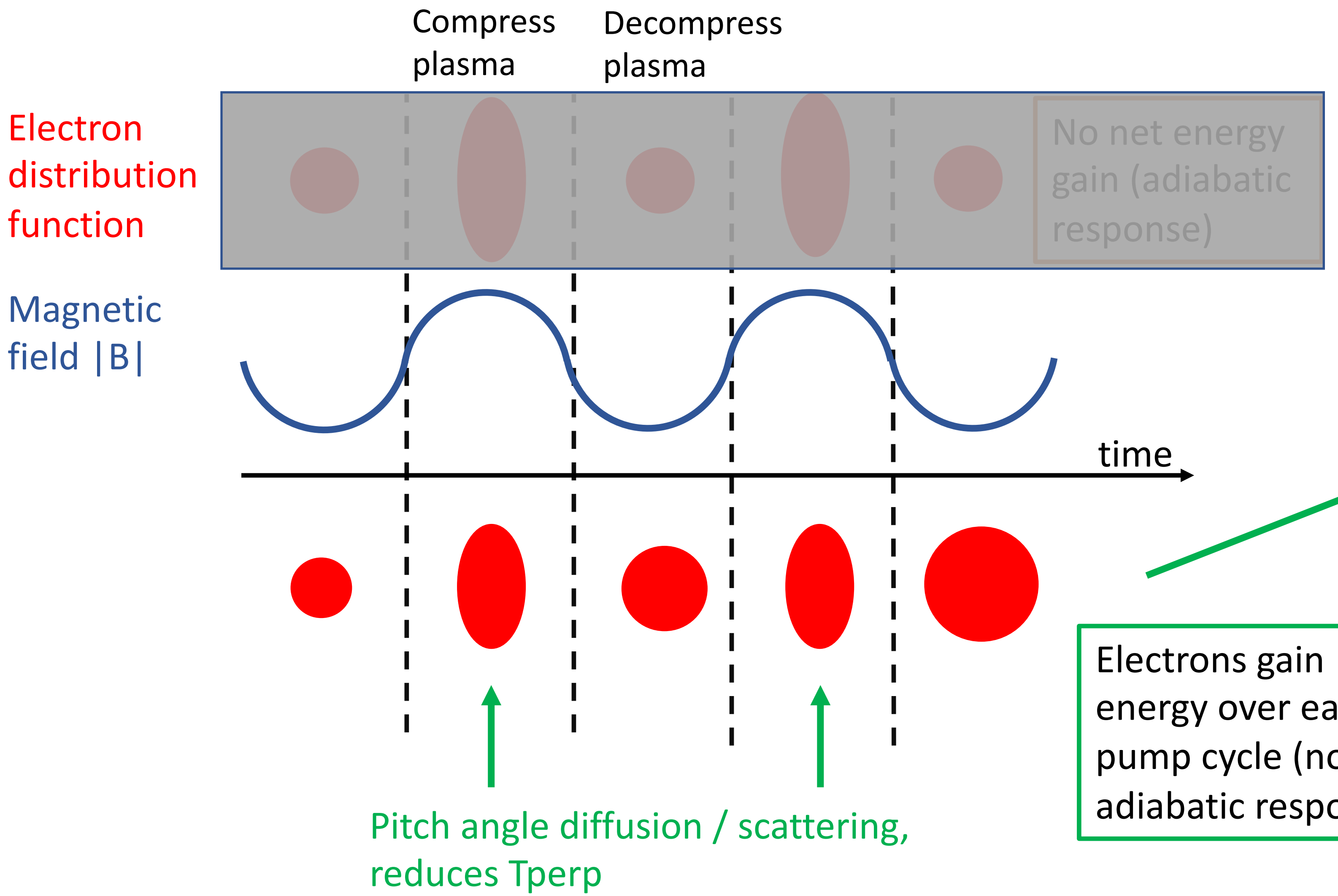
- **<u>This presentation:</u>** study of same event, demonstrating that MS waves also heat ionospheric electrons via magnetic pumping and pitch angle scattering.

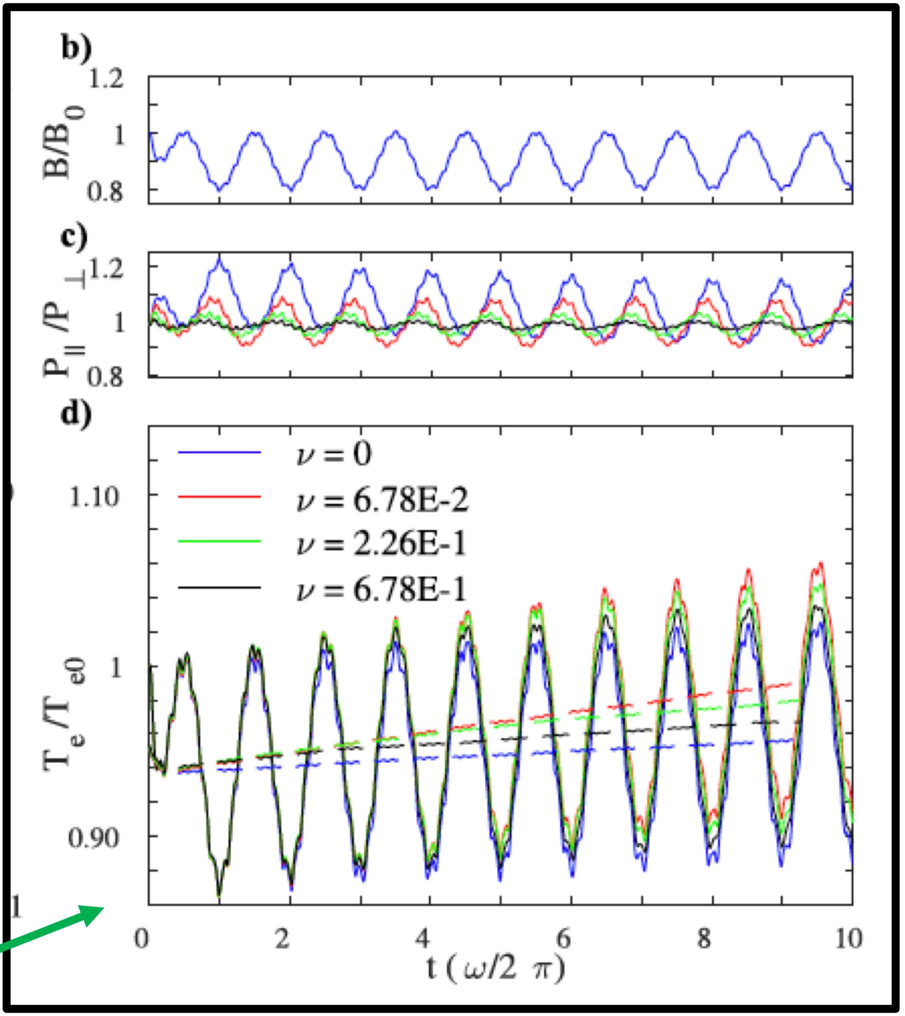
Electron heating mechanism – magnetic pumping and pitch angle scattering of the plasma



No net energy gain (adiabatic response)

Electron heating mechanism – magnetic pumping and pitch angle scattering of the plasma

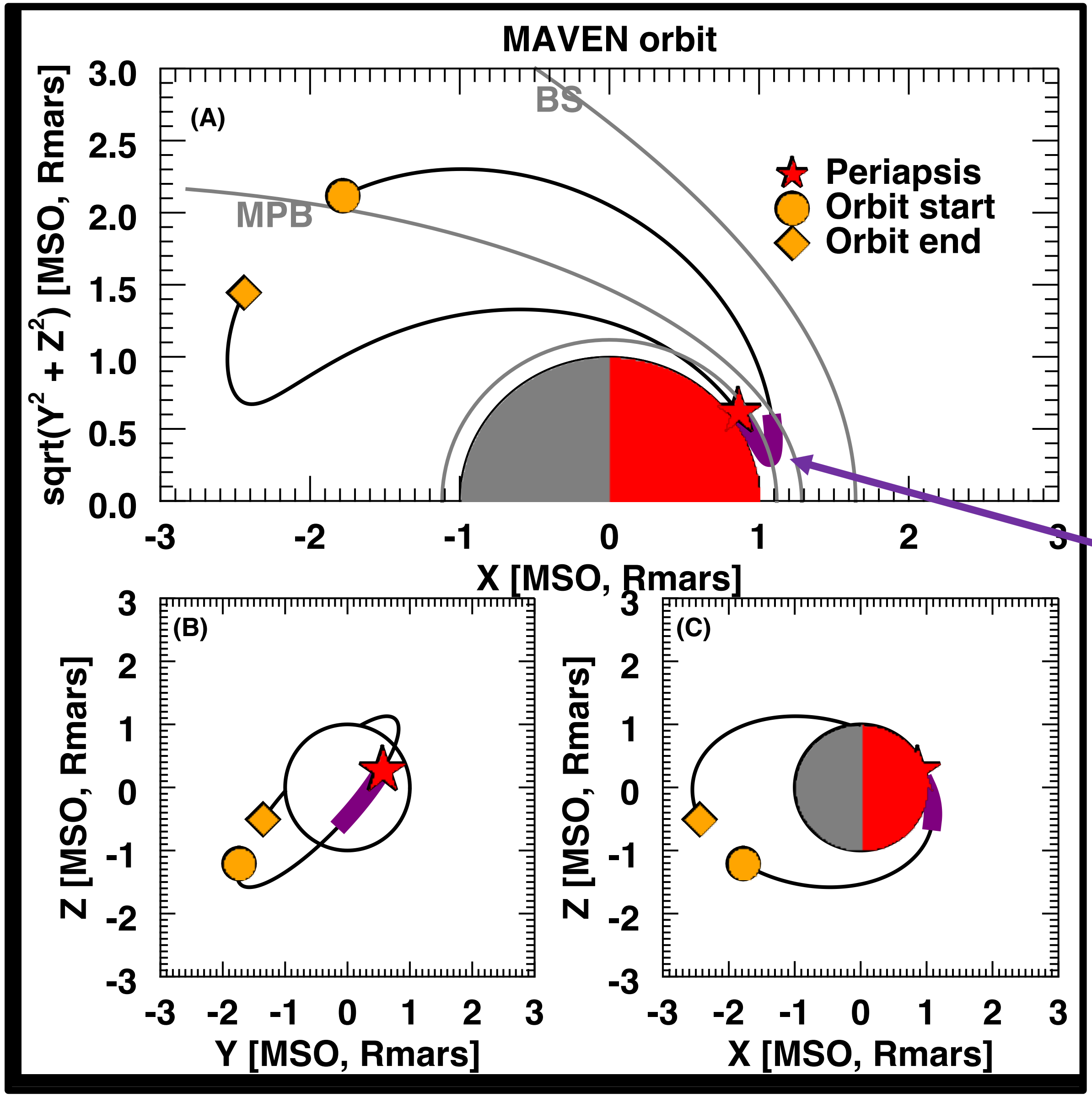




Electrons gain energy over each pump cycle (non-adiabatic response)

Lichko et al., 2017, Magnetic pumping as a source of particle heating and power-law distributions in the solar wind.

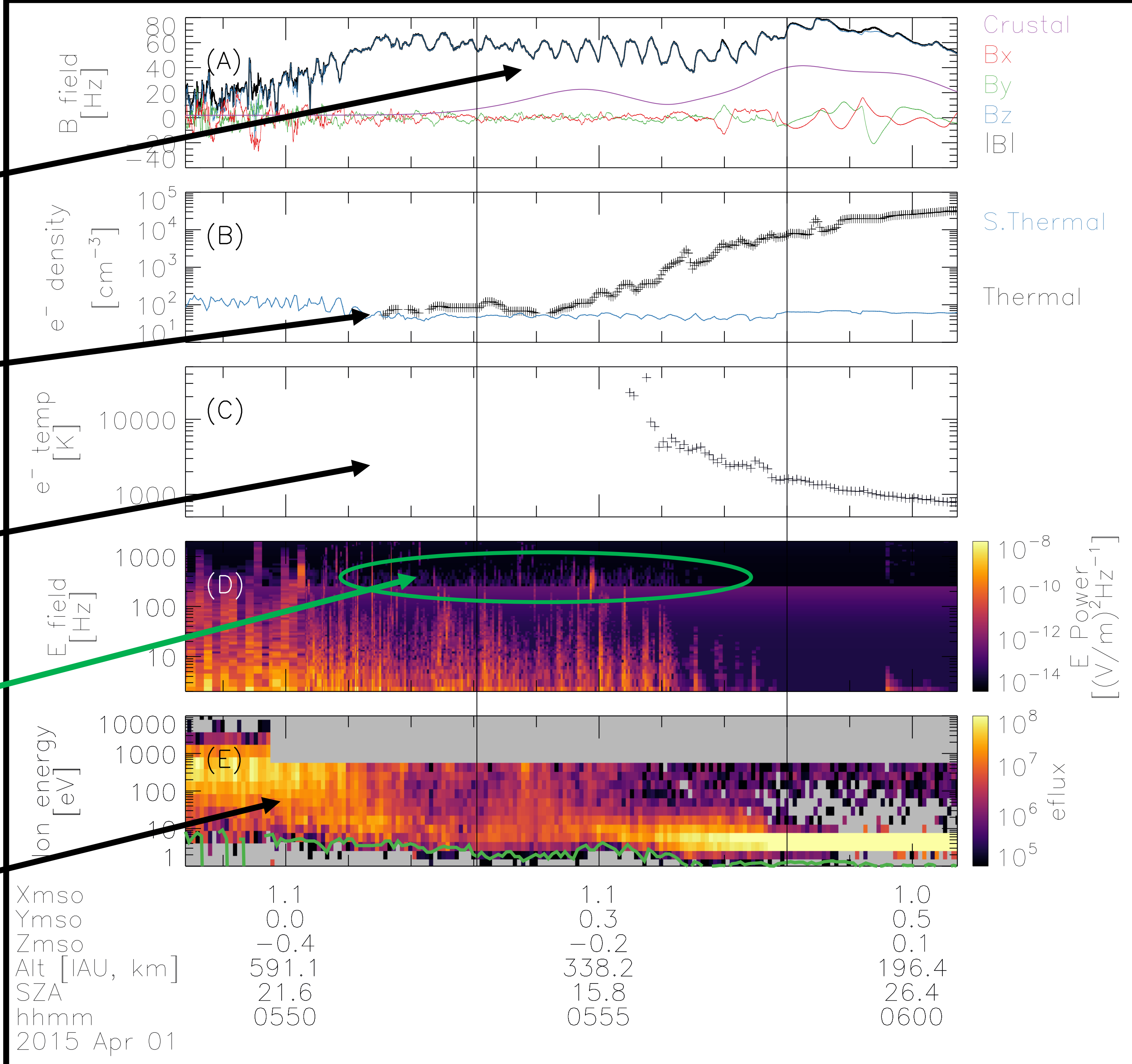
The MAVEN observations



- The event is during a time when MAVENs orbit samples the dayside ionosphere and upstream magnetosheath, close to the sub-solar point.
- Following time series data are from the purple region highlighted here.

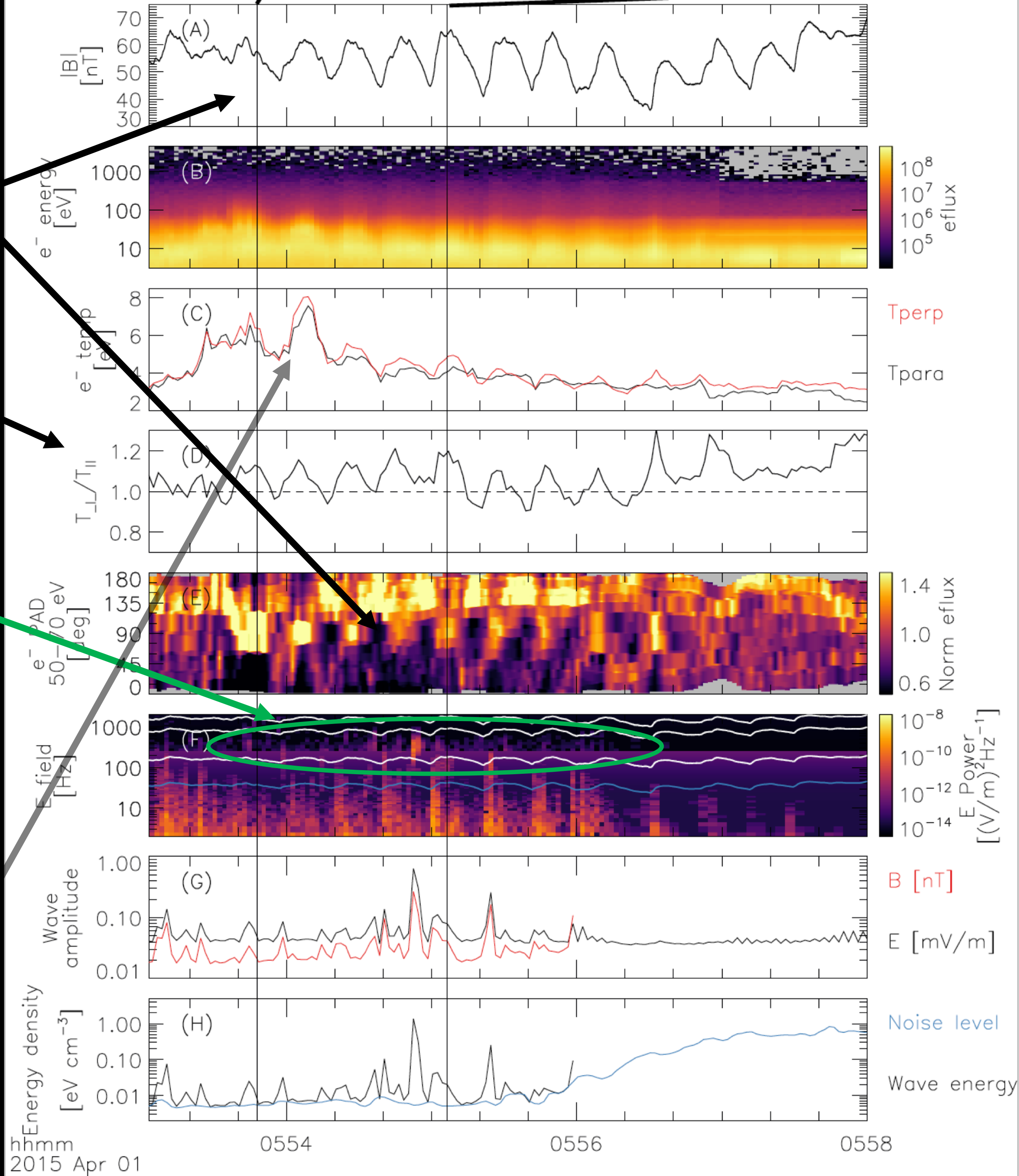
Overview of event

- Magnetic field: compressive MS waves propagate into ionosphere.
- Thermal and suprathermal electron densities – MAVEN samples the topside ionosphere.
- Thermal electron temperature.
- Electric field wave spectra – whistlers observed coincident with compressive waves.
- Ion energy spectrum – MAVEN transitions from magnetosheath to topside ionosphere.



More detailed plasma observations

- Magnetic compressions produce a pitch angle response in the suprathermal electrons due to conservation of the magnetic invariant.
- Suprathermal electron Tperp > Tpara during magnetic compression.
- Whistlers generated (white lines = 0.1, 0.5, 1* f_{ce}, blue line = lower hybrid).
- Whistlers act back on the suprathermal electrons to isotropize the distribution.
  - Drives phase shift between (Tperp/Tpara) and compressive wave fronts.
  - Breaks adiabaticity of large scale magnetic pumping, leading to heating of electrons.
- Surpathermal electron temperatures are enhanced by a few eV.



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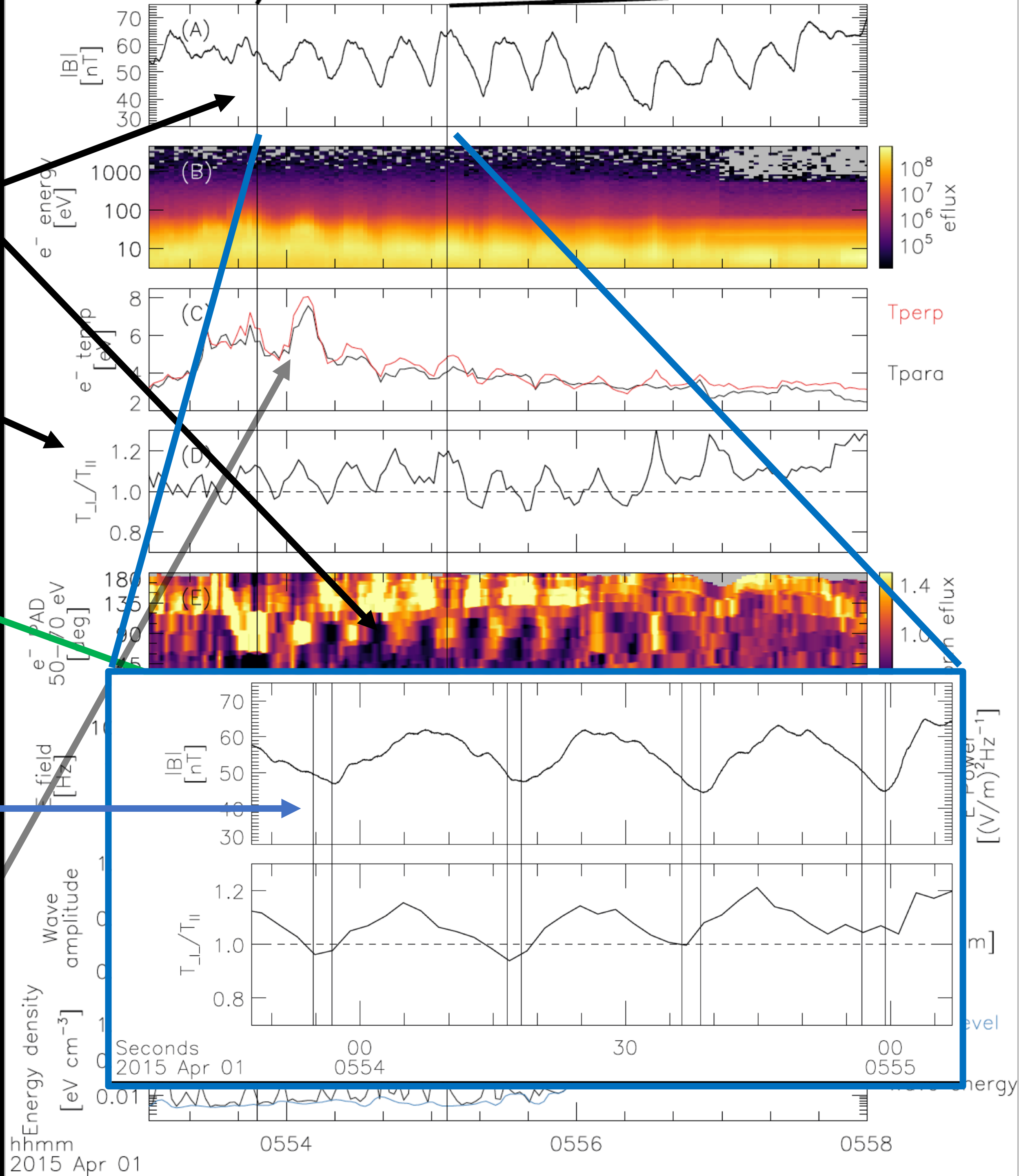
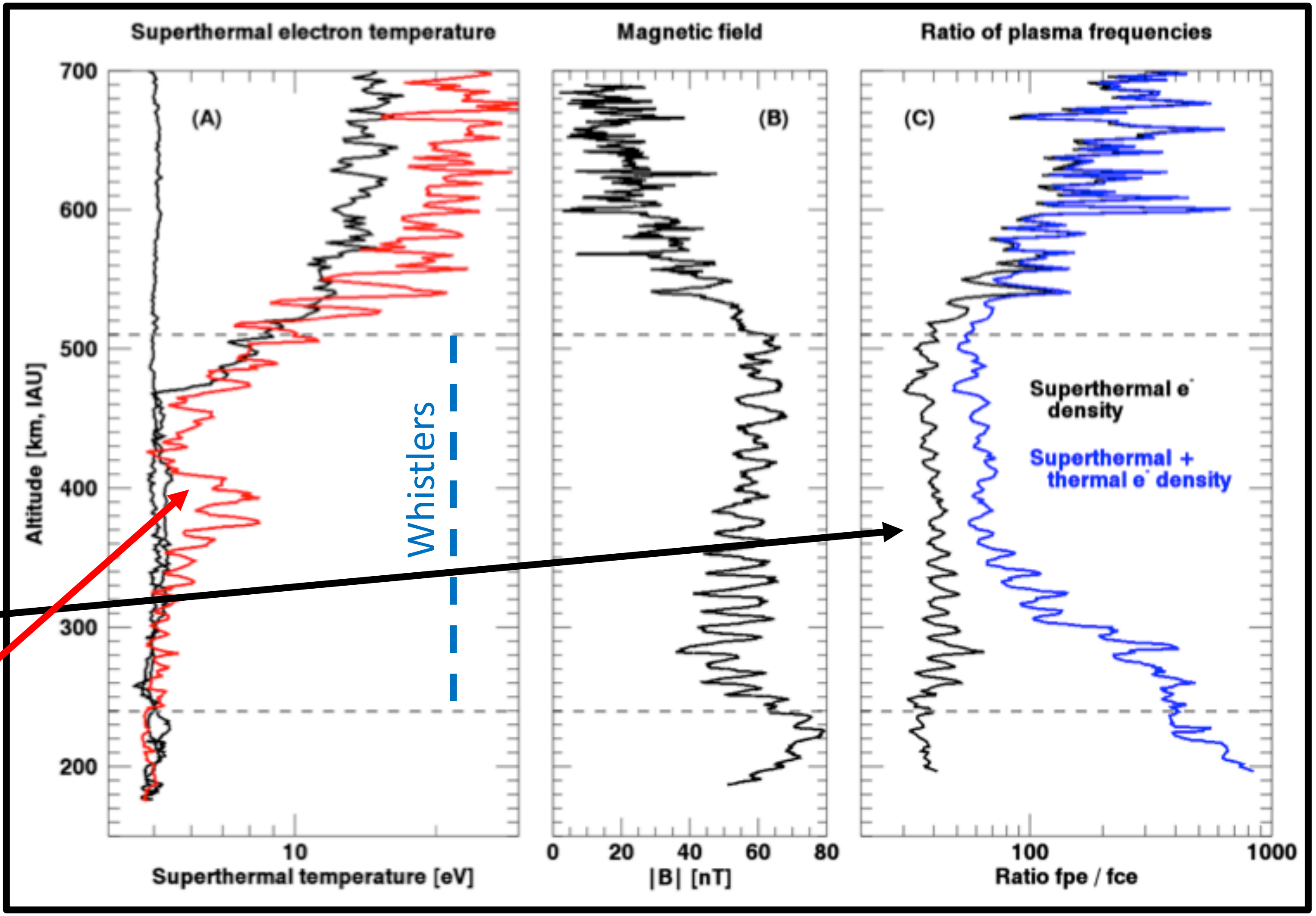


Are plasma conditions ripe for wave-particle interactions? (yes)

- f_{pe} / f_{ce} important for:
  - Efficiency of wave-particle interactions.
  - Whistler wave growth rate.
  - Pitch angle diffusion rate.

f_{pe} = electron plasma frequency
f_{ce} = electron cyclotron frequency

- Electron distribution functions (next) demonstrate efficient pitch angle diffusion.
- Whistlers observed by MAVEN.
- Minimum in f_{pe} / f_{ce} means larger pitch angle diffusion rate.
  - Pitch angle diffusion rate about ~10x greater for f_{pe} / f_{ce} = 50 vs 120.
- Electron heating observed.

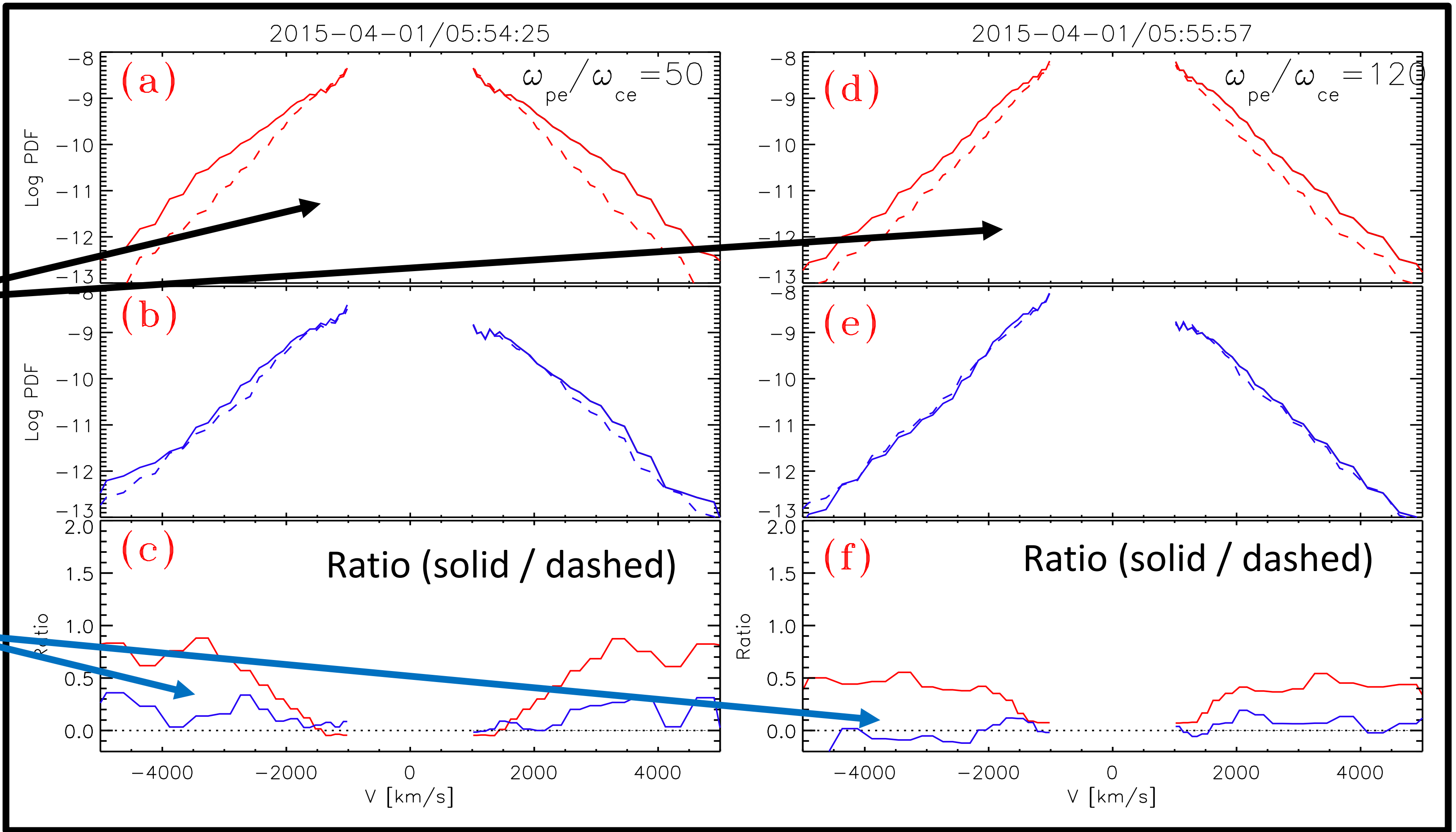


Superthermal electron distribution functions (DF)

- Distributions Transverse and parallel to **B**.
- Solid = maximum in |B|.
- Dashed = minimum in |B|.
- Transverse response of DF similar for each column.
    - (Conservation of magnetic invariant).
- Parallel DF enhanced <u>over all velocities</u> (ie not a single resonant velocity as occurs for Landau damping) for first column.
    - **<u>Pitch angle diffusion present!</u>**

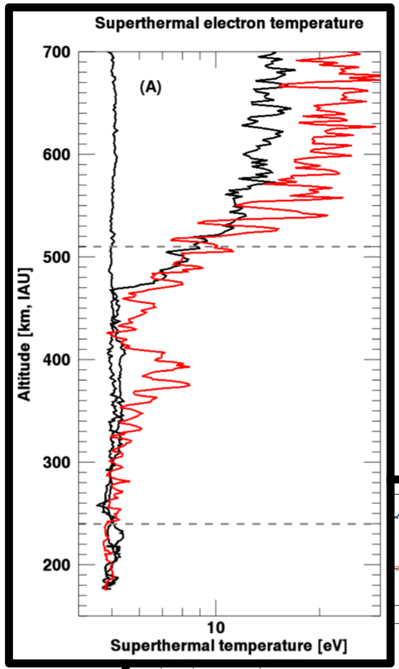
Efficient pitch angle diffusion

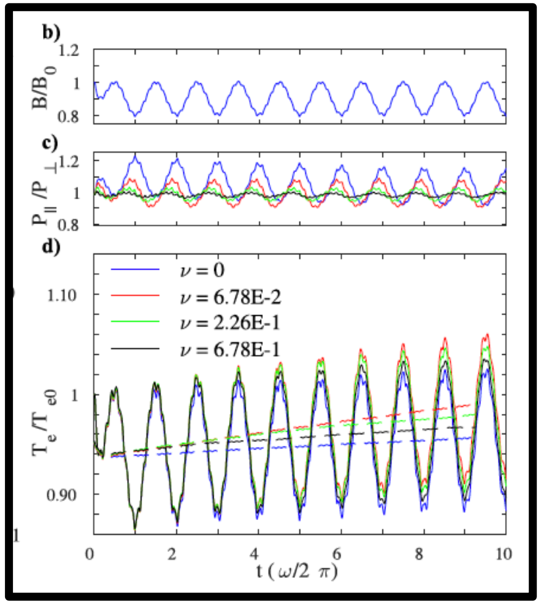
~10x less efficient pitch angle diffusion

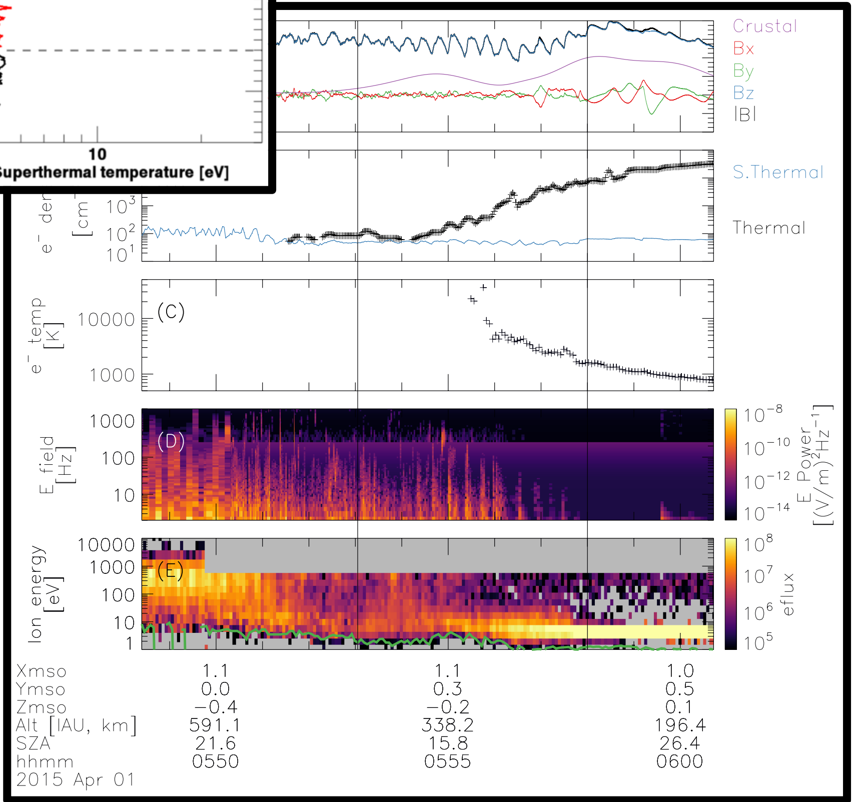


A summary of the heating process at Mars

- Mars – solar wind interaction generates compressive magnetosonic waves that propagate into the dayside ionosphere.
- Conservation of first magnetic invariant leads to Tperp > Tpara for suprathermal electrons during compressive waves fronts.
    - Leads to generation of whistler waves.
- Whistlers act back on electrons to isotropize distribution.
    - Generates phase shift between (Tperp / Tpara) and compressive wave fronts.
    - Breaks adiabaticity of magnetic pumping.
- Electrons gain energy over a pumping cycle.
- MAVEN observations show localized enhancements of a few eV in suprathermal electron temperature.





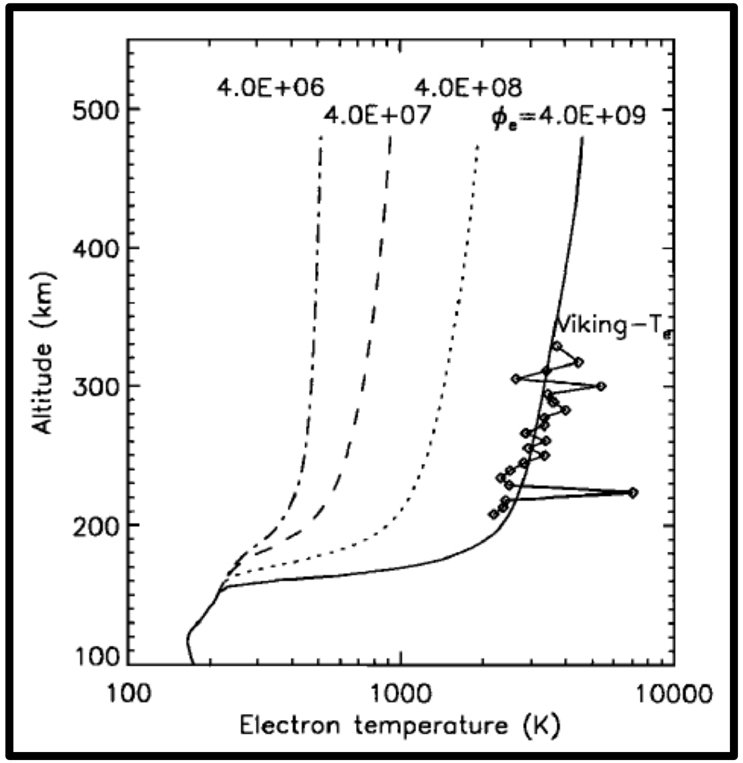


Implications of this heating

- Ionospheric structure and composition:
  - Suprathermal electrons provide energy to thermal population.
  - Thermal electrons important in ionospheric chemistry.

- Mars' ionospheric energy budget:
  - Models of temperature do not match observations in upper ionosphere.
  - Topside heating long thought to be a possible heating source.
  - Magnetic pumping one such heating mechanism.

- Atmospheric escape to space:
  - $O_2^+ + e^- \Rightarrow O + O$ (DR)
  - Exothermic reaction: O can have close to or greater than escape energy.
  - DR rate $\propto Te^{-0.7}$



Choi et al., 1998