Mirror Mode Storms in Solar Wind and ULF Waves in the Solar Wind

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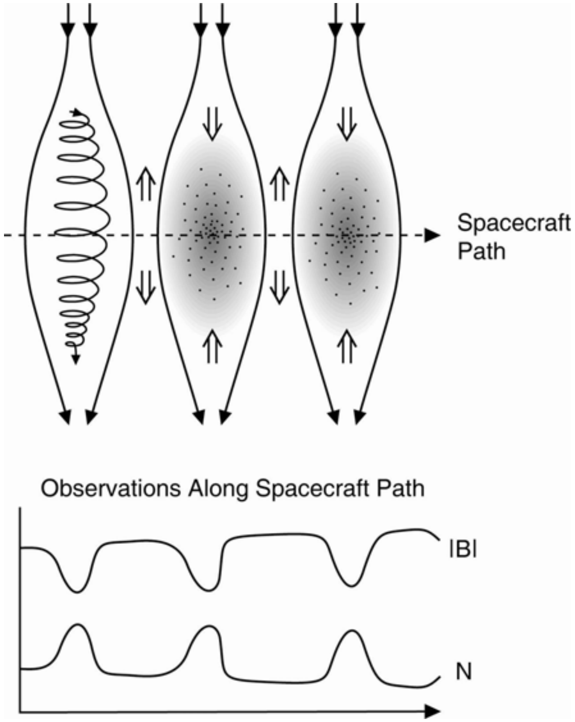
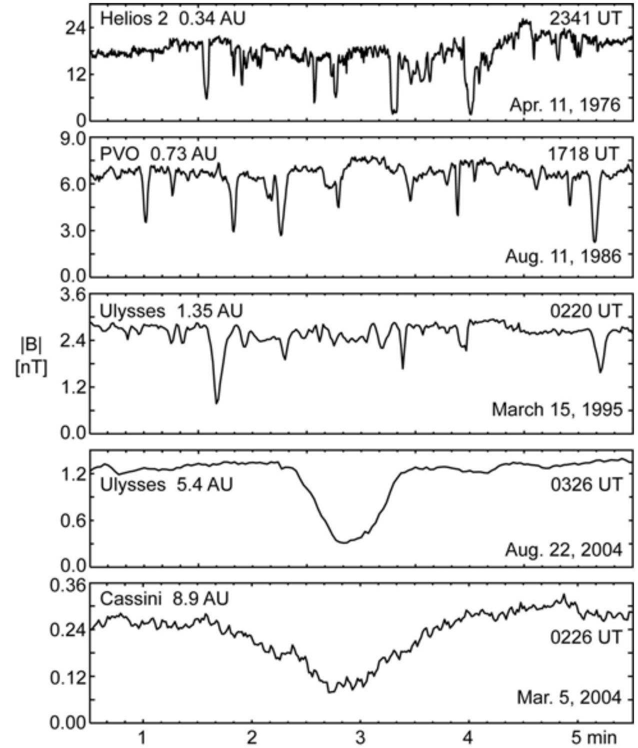
Mirror Mode Waves

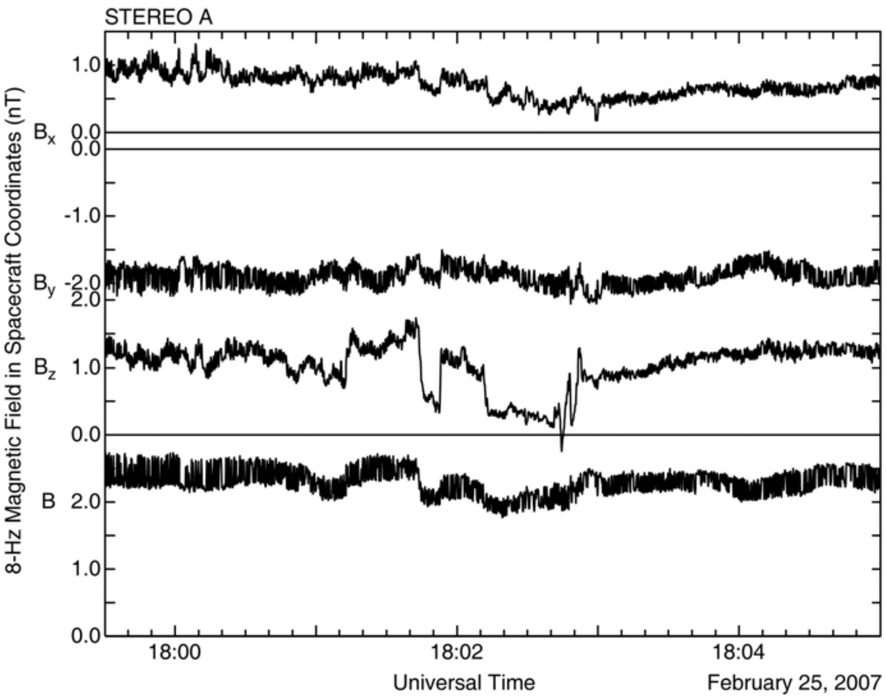


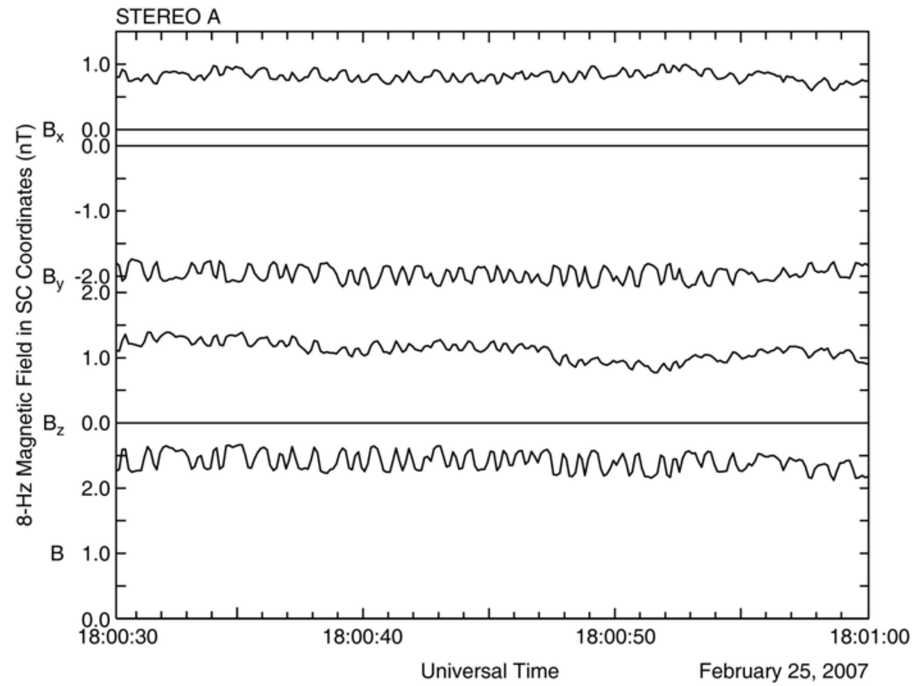


- Mirror-mode waves arise from a velocity space anisotropy in which the perpendicular pressure exceeds the parallel pressure.
- Shocks and ion pickup produce such anisotropies.
- The free energy in the ring is isotropized by the creation of coordinate space irregularities.

- In the solar wind these waves are most often isolated and quite often deep.
- Here we show the evolution of their appearance with distance from the Sun.

Mirror Mode Wave Storms

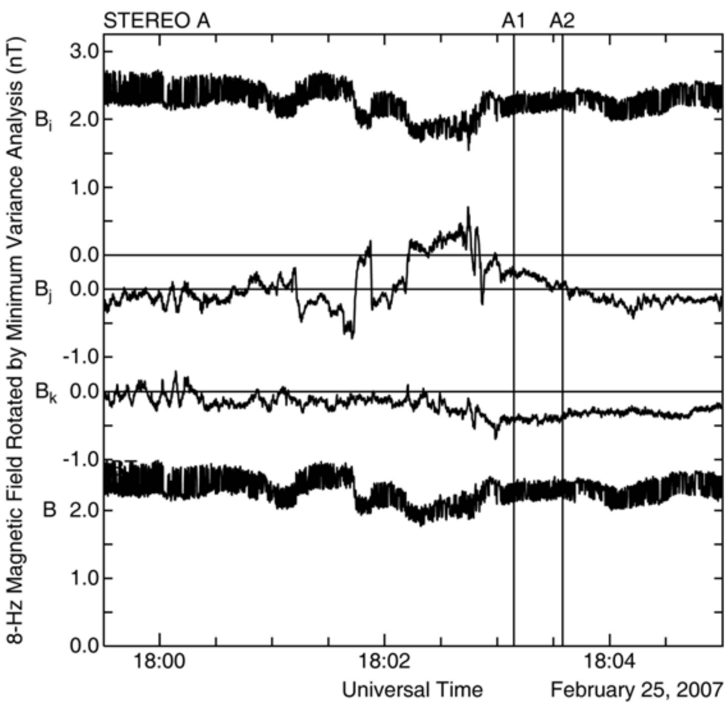


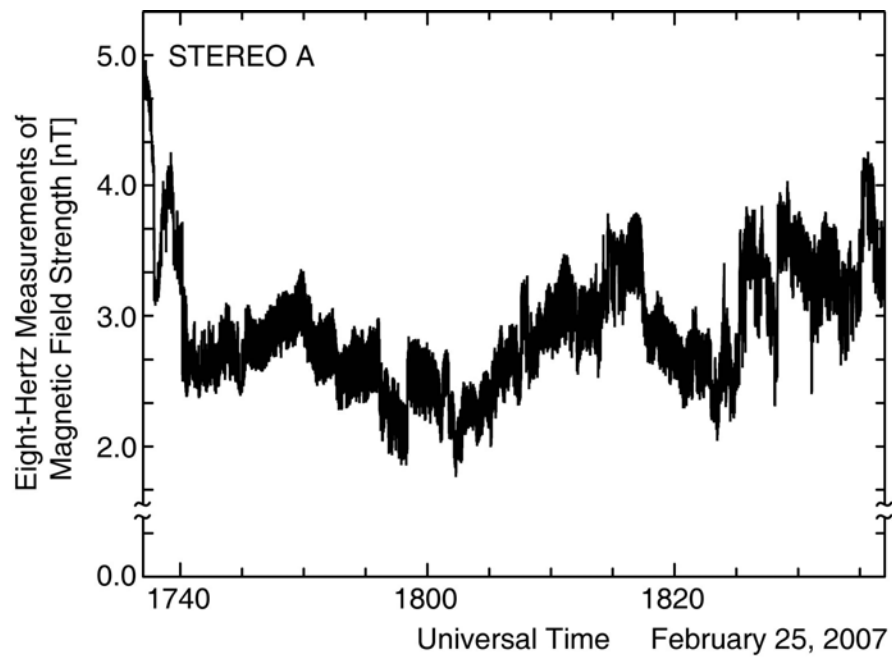


- On rare occasions, mirror mode waves occur continuously for long periods for hours on occasion.
- These are real events and not magnetometer malfunctions.

- The waves are individually quite weak.
- The waves can appear as “holes” in a steady background or peaks above a steady background.

Mirror Mode Storm: Continued

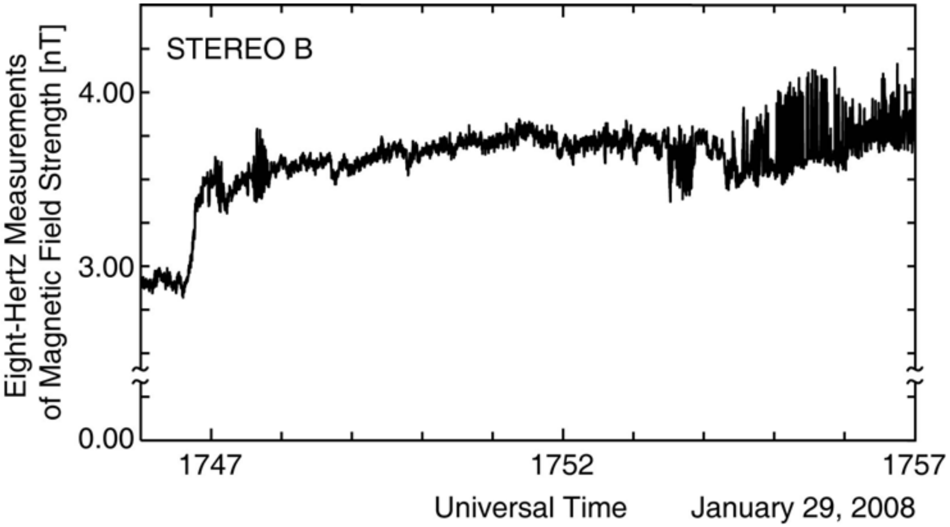


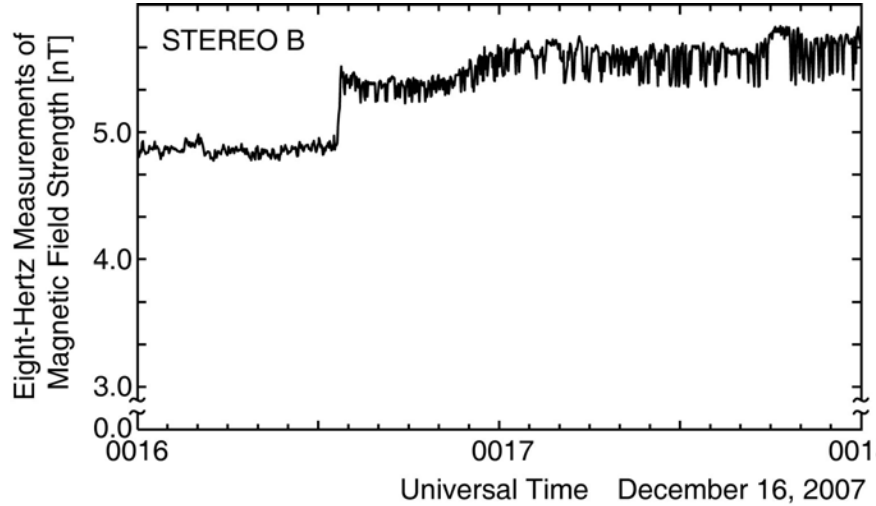


- These waves are solely compressional.
- A principal axis analysis shows that the maximum variance is along the magnetic field.

- These waves began when the magnetic field strength suddenly dropped suggesting that the waves growth is controlled by plasma beta.

Shock Generation of Mirror Mode Waves

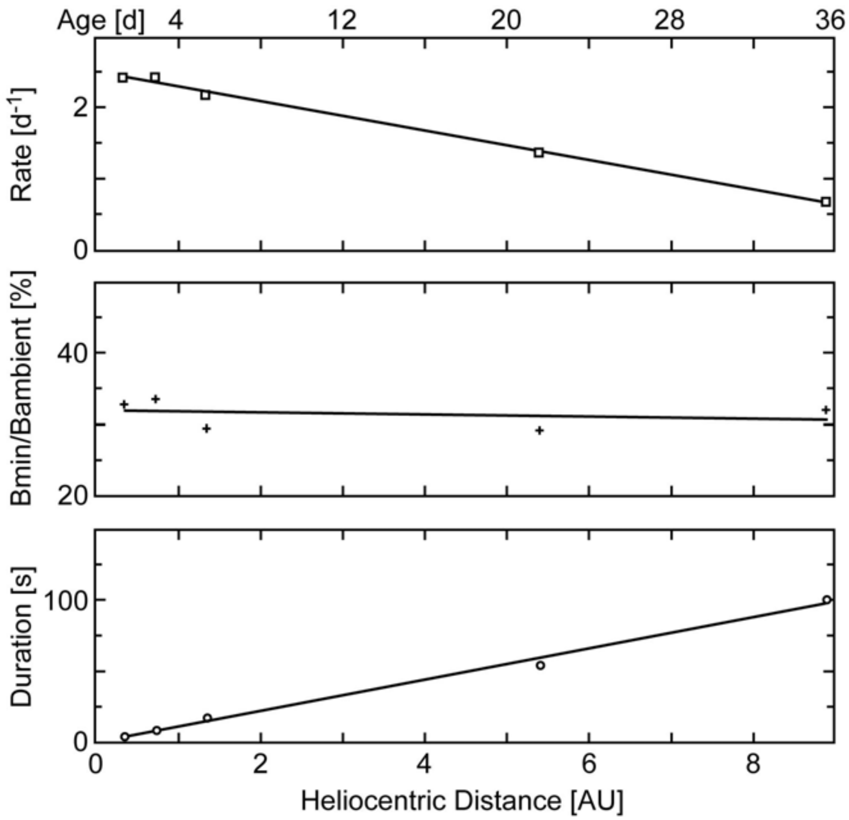




- These two examples illustrate generation by weak shocks, that created a pressure anisotropy.
- These events stimulate many questions, one of which is--how do these waves evolve with time? Do they coalesce? Do they deepen?
- This mechanism cannot provide the mirror-mode waves seen at Helios and at Venus because shocks are very rare well inside 1 AU.

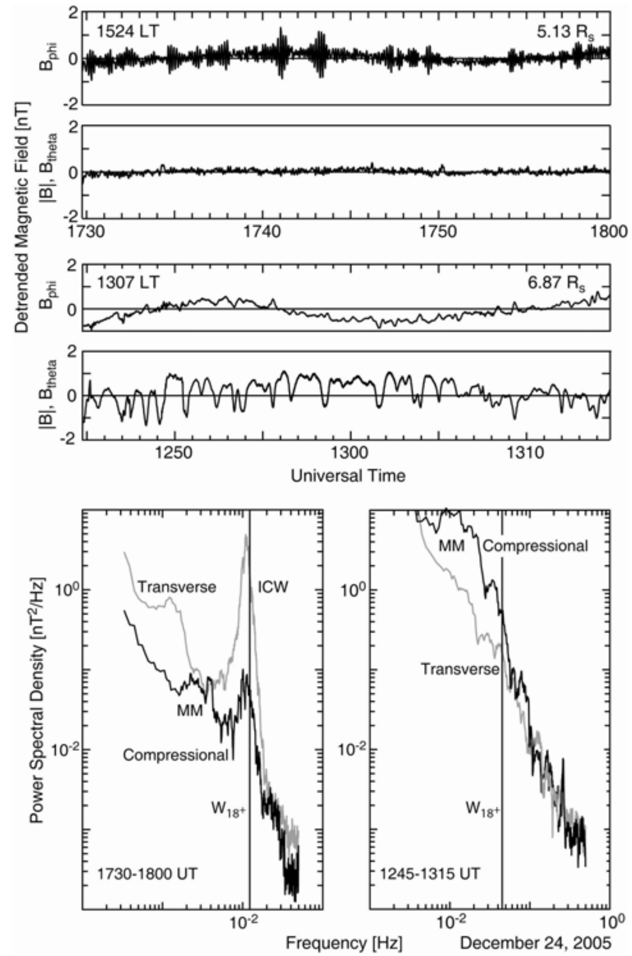
Radial Variation of Solar Wind Mirror-Mode Waves

- Mirror mode waves usually are highly evolved when detected. Most often they appear as isolated waves as in the first slide.
- If we examine these mirror-mode waves as a function of distance, we see that their occurrence rate drops with heliocentric distance.
- Their depth or amplitude remains constant.
- Their width grows as the field weakens and the density drops.
- The simplest explanation for the observed distribution is that they are created deep in the corona and are carried outward with little damping but with a change in geometry (length and width).



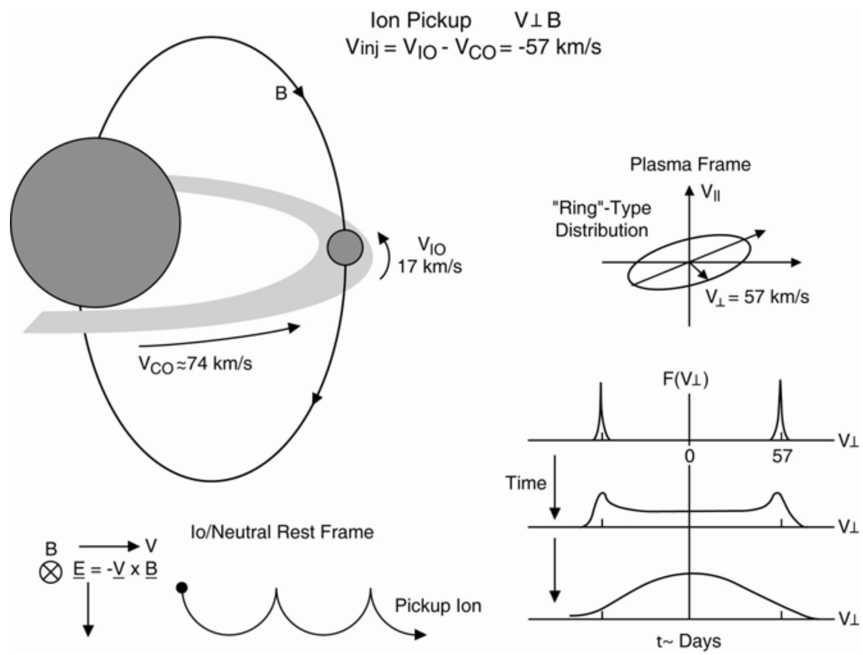
Cogeneration of ICWs and Mirror-Mode Waves

- In the Saturn magnetosphere, ion cyclotron waves are co-generated with mirror mode waves where they grow from ring beams.
  - Both modes grow simultaneously
  - Not one mode at the expense of the other
- The energy from the pickup process is efficiently transferred from the ring beam into heating the plasma.
- The ion-cyclotron waves move along the field line and damp.
- The co-generated mirror-mode waves do not leave the equator and are convected outward by the flow.
- The mirror-mode waves can act as messengers from the ion-cyclotron generation region.



Heating by Ion Cyclotron Waves

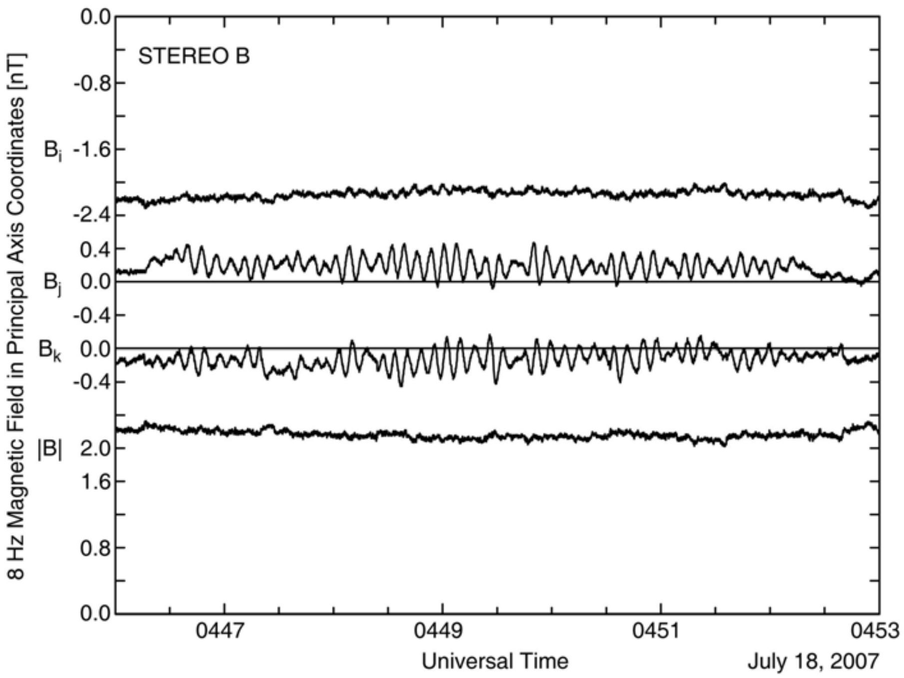
- Ion cyclotron waves are efficient heaters of the core plasma.
- Waves propagate along the field line and damp rapidly.
- Much evidence that ion cyclotron waves are present
  - UV spectrometer
- Solar wind heating requires a strong, sustained anisotropy such as provided by ion pickup in a strong perpendicular electric field.
- Pick-up ion production in planetary magnetosphere is easy but not so in solar wind.
  - Interstellars – unlikely too weak?
  - Atmosphere neutrals?
  - Vaporized dust?
- Shocks produce anisotropies in the solar wind plasma but we expect them to be weak and intermittent.
- We may have to wait for solar probe to get direct evidence for ion-cyclotron waves in the corona, but STEREO gives us evidence of some very strong ion-cyclotron waves activity closer to the sun.

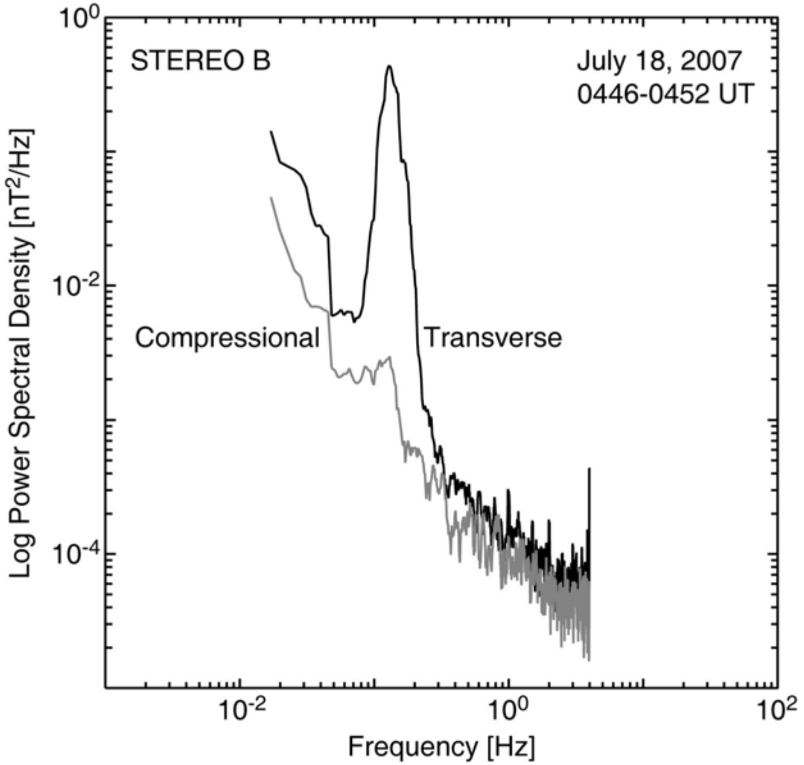


Detection of Ion Cyclotron Waves Generated in the Corona

- The solar wind convects Alfven and mirror-mode waves outward from the corona. Why do we not see these putative ion-cyclotron waves convected out to 1 AU? Or even to Venus?
- Ion-cyclotron waves damp rapidly. This makes them efficient heat sources for the plasma but also makes them poor messengers.
- As ion-cyclotron waves are carried outward in the solar wind, the proton gyro frequency decreases. When it reaches the frequency of any ion-cyclotron waves generated closer to the Sun by heavier ions, the waves are absorbed.

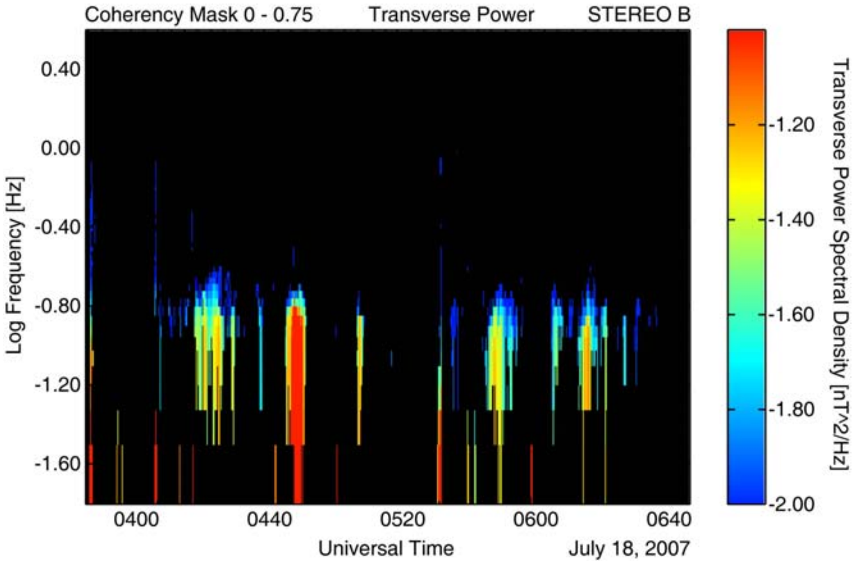
Ion Cyclotron Waves at 1 AU

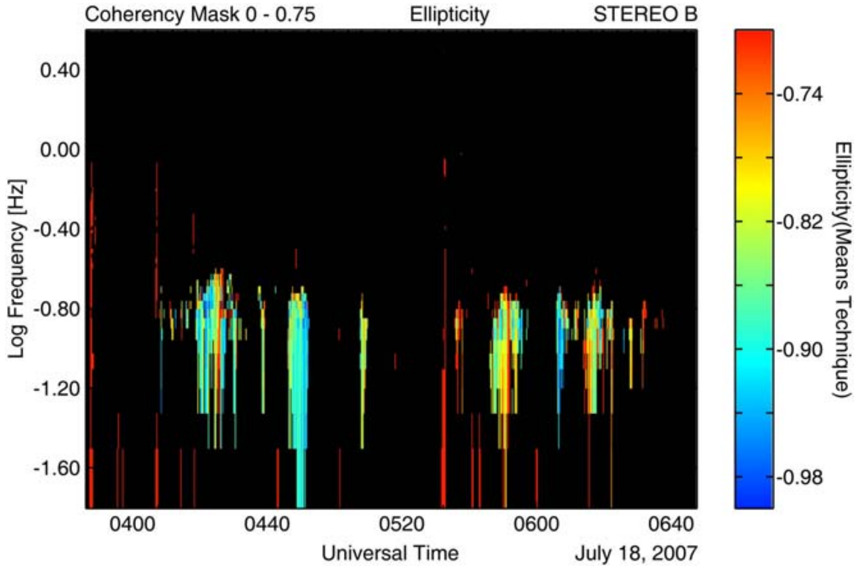




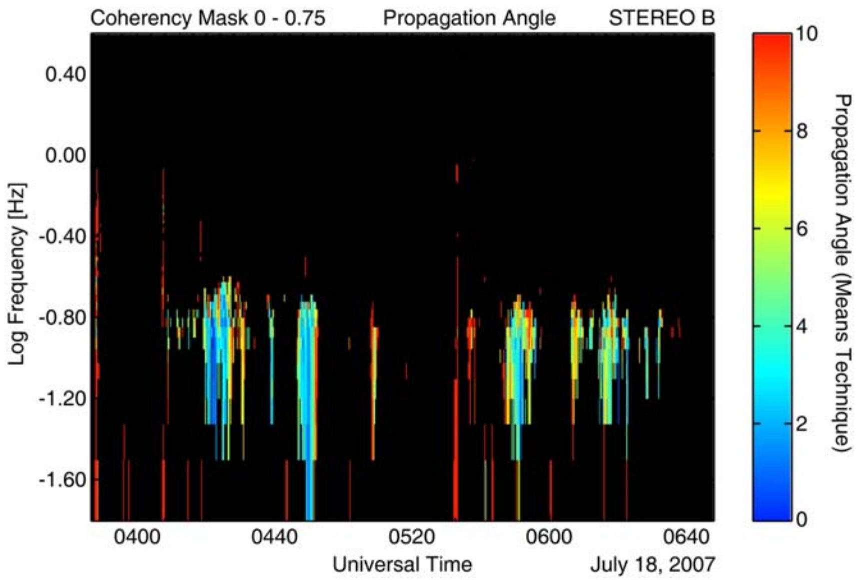
- The STEREO mission provides some insight into the corona, even at 1 AU.
- Sometimes when the IMF is radial, we see what appears to be Doppler-shifted ion-cyclotron waves of surprising large amplitude.
- These are left-handed polarized waves in the spacecraft frame that could be upshifted to the observed frequency by a factor of possibly 20 or more. The plasma frame frequency could be well below the local proton gyro frequency.

Dynamic Spectra





- The waves are strong, left-hand circularly polarized and propagating along the magnetic field.
- Parallel propagation would allow these waves to persist a long time.
- If produced at the local ion gyro-frequency, these waves could be produced by He^+ at 50 R_S, by O^+ at 25 R_S and Fe^+ at about 13 R_S.



Summary

- Mirror-mode waves occur throughout the solar wind.
- Mirror-mode waves usually occur as isolated dips in the field, but sometimes occur in continuous "storms."
- Mirror-mode storms can be triggered by drops in the field strength (increase in beta) or by even weak shocks.
- Mirror-mode waves may be messengers from the inner corona telling us that ICWs are co-generated there.
- Ion-cyclotron waves do have some direct observations at 1 AU on occasion.
    - When the magnetic field is radial
    - When the local magnetic field is weak.
- The ion-cyclotron waves propagate very close to the IMF direction, are left-handed and very coherent.
- Since under these conditions the Doppler shift is large, the waves may be produced deep in the corona close to the Sun.