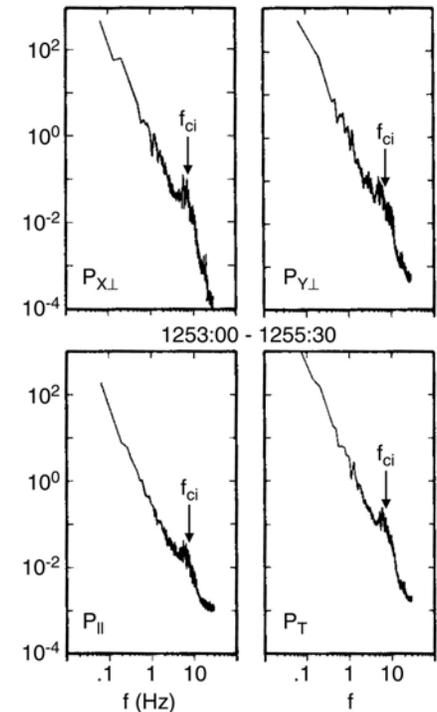
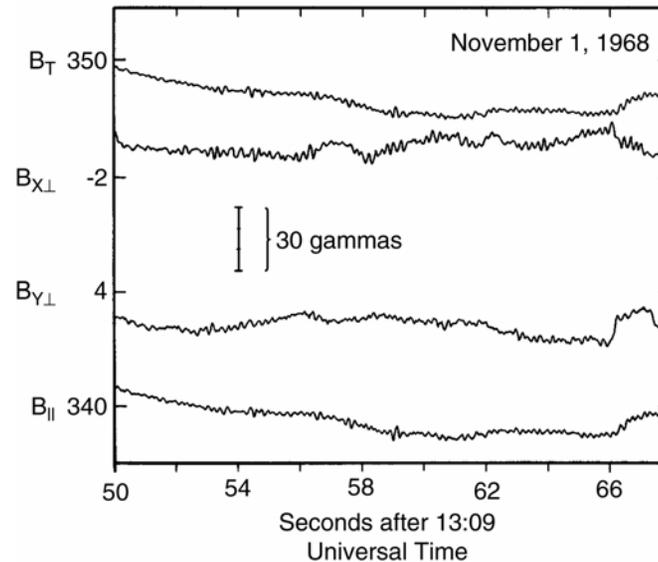
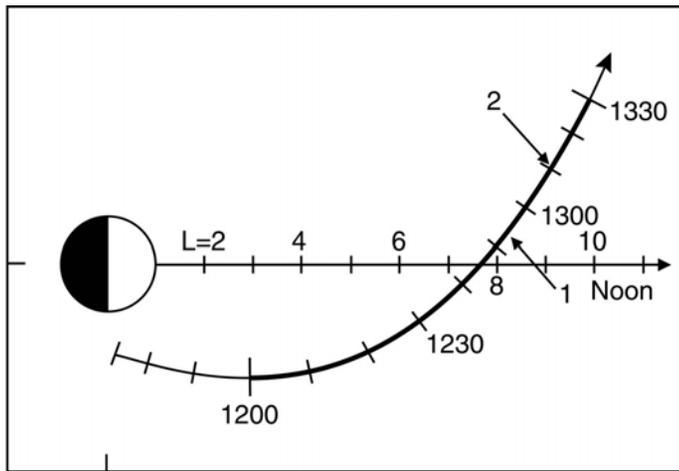


# Origin of Ion Cyclotron Waves in the Polar Cusp: Insights from Comparative Planetology

- Discovery by OGO-5
- Ion cyclotron waves in other planetary magnetospheres
  - Jupiter
  - Saturn
- Theory
- Ion cyclotron waves at Mars and Venus
- Ion cyclotron waves observed by Polar
- Origin of ICWs in polar cusp?

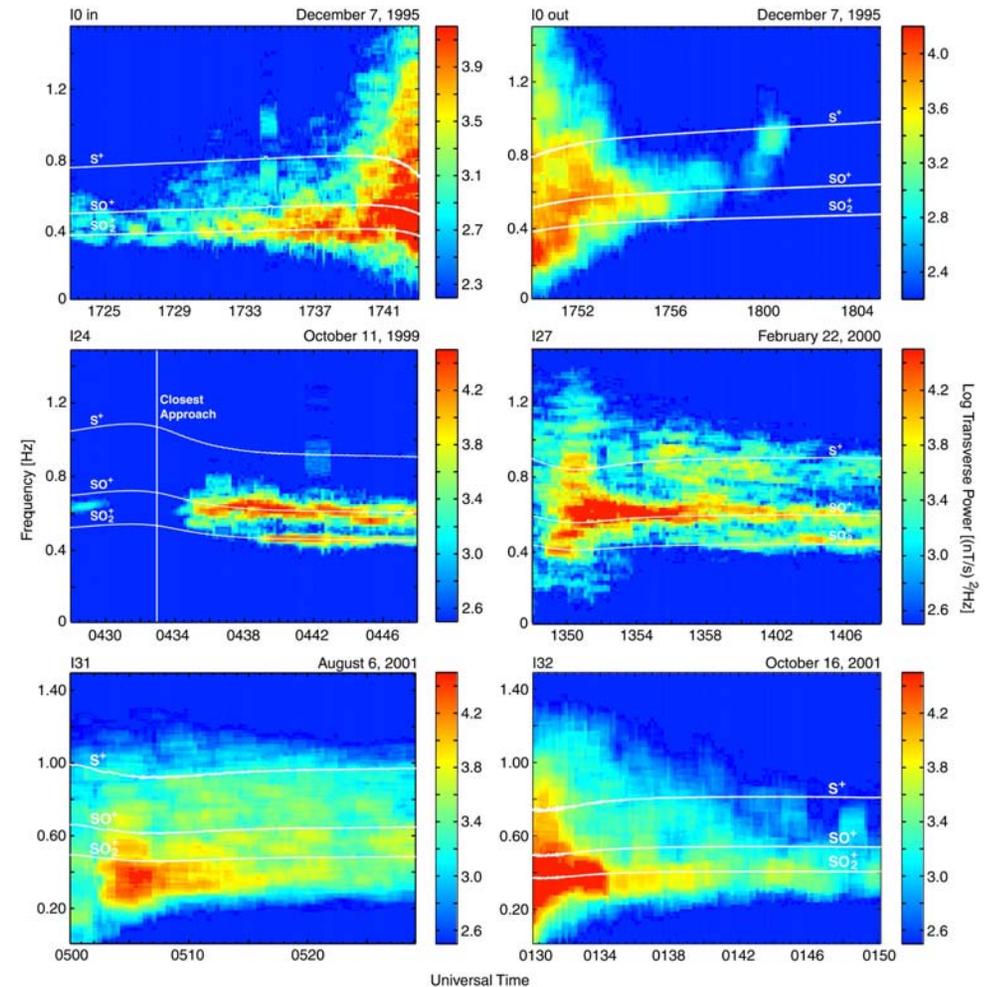
# Discovery by OGO-5



- On Nov 1, 1968 during a large geomagnetic storm (ICME induced?) the polar cusp crossed OGO-5's moderately inclined orbit near noon
- Proton cyclotron waves near the local ion cyclotron frequency were seen deep in the magnetosphere
- Puzzling observation: What is the free energy source? Why so close to the proton gyro frequency? Why the local gyro frequency?

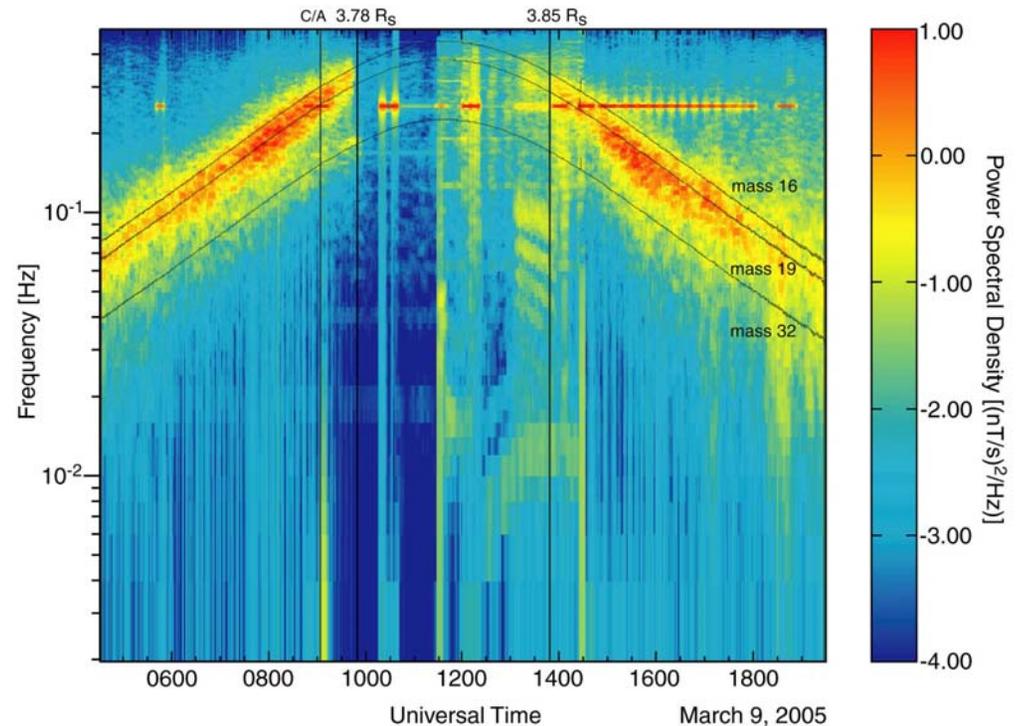
# Ion Cyclotron Waves at Jupiter

- When Galileo flew by Io it observed  $\text{SO}_2^+$ ,  $\text{SO}^+$  and  $\text{S}^+$  ion cyclotron waves, downstream and to either side of Io
- Again the puzzle was : what is the free energy source? Why the local ion cyclotron frequency?
- Another puzzle was the large distance from Io at which the waves were seen



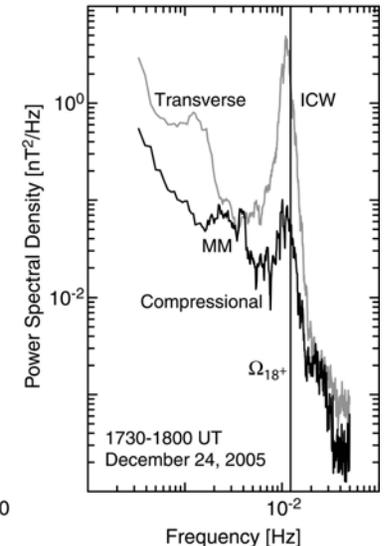
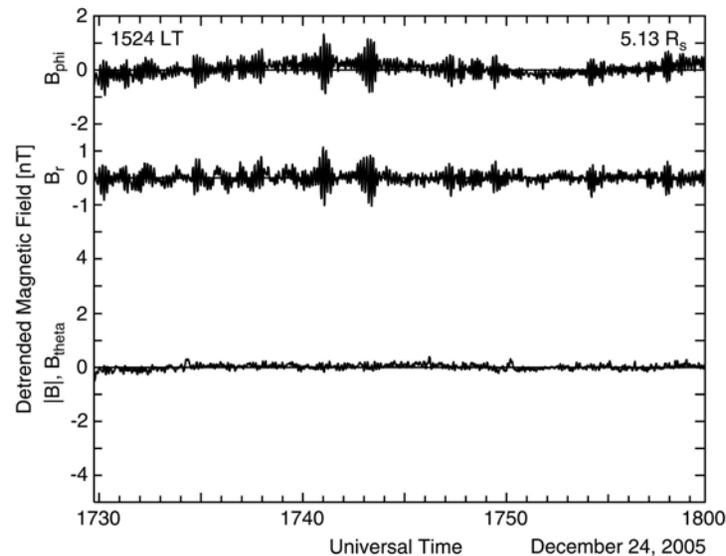
# Ion Cyclotron Waves at Saturn 1

- When Cassini reached Saturn it found ion cyclotron waves essentially everywhere from 4 to 6  $R_s$
- Ions must be being produced at Enceladus at 3.9  $R_s$  and the E-ring neutral torus
- How does the free energy arise? Why the local ion cyclotron frequency?
- Why such a broad generation region?



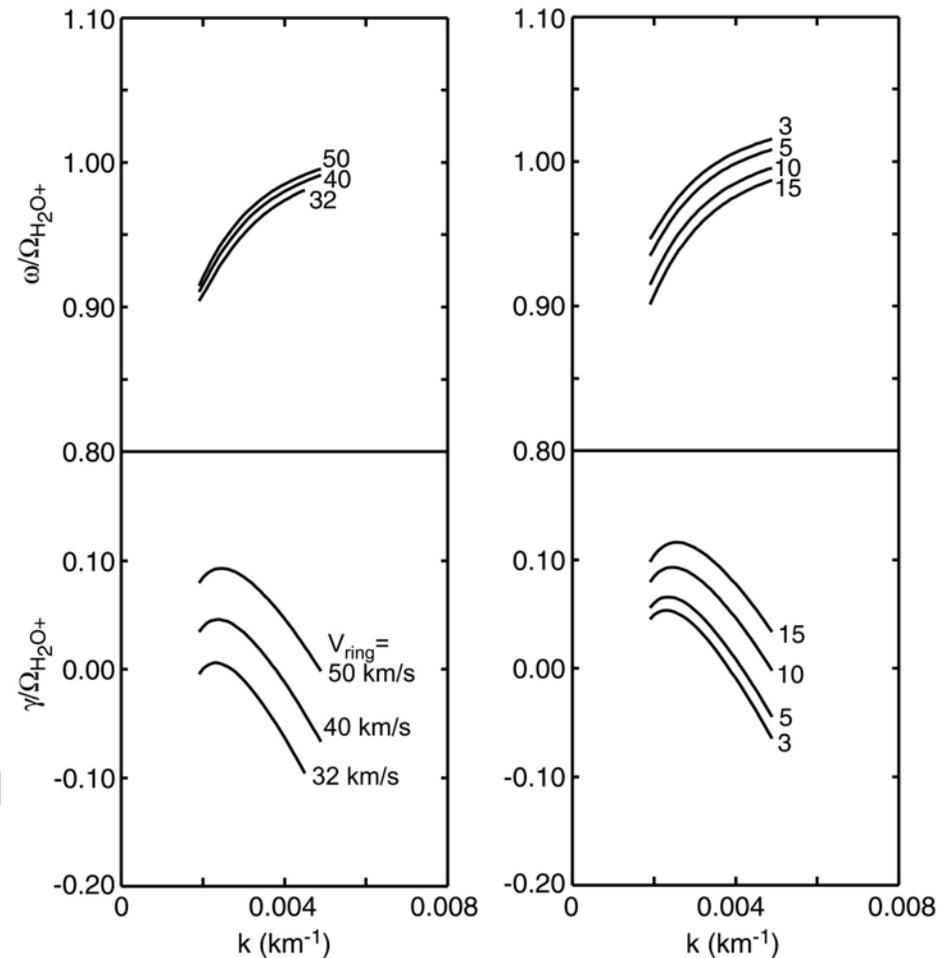
# Ion Cyclotron Waves at Saturn 2

- The wave forms of ICWs at Saturn are similar to ICWs in the Earth's magnetosphere and at Jupiter
- The wave forms are amplitude modulated and narrow band
- They propagate nearly parallel to the magnetic field
- The growth rate is strongest below the ion cyclotron frequency but close to it

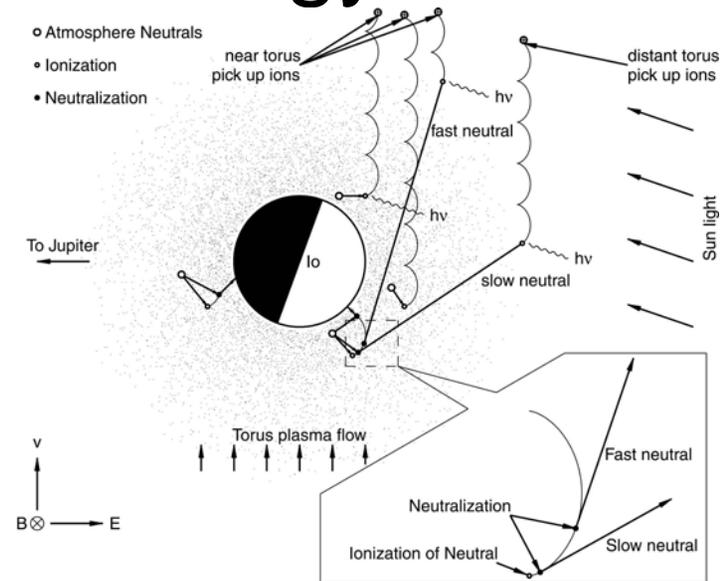
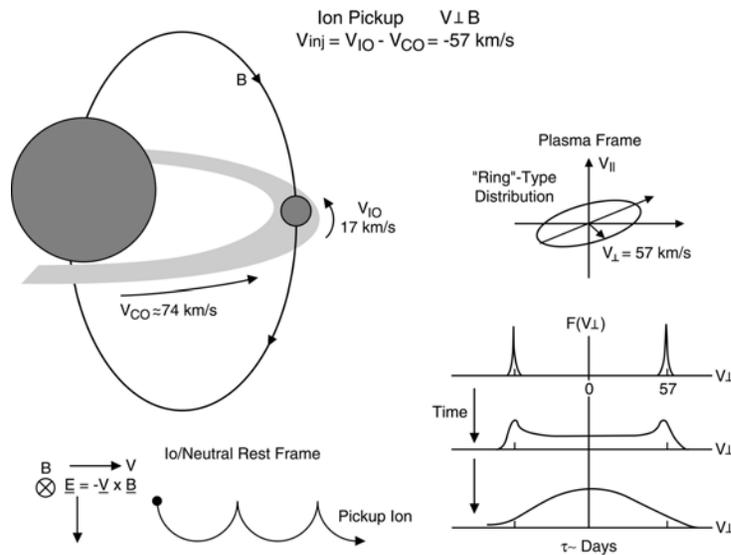


# Theory: Warm, Homogeneous, Anisotropic, Multicomponent Plasma

- In 1982 K G Ronnmark developed WHAMP, a computer program for determining the growth rate and dispersion of waves in a warm plasma
- Today we can duplicate these results with hybrid (ion-following) codes but Ronnmark's code provides a quick path to a useful solution
- For example we can produce the waves seen at Jupiter and Saturn with ring beams, with delta-function, perpendicular-velocity distributions arising from the ionization of neutral particles in an electric field associated with the relative motion of the magnetospheric plasma (corotating) and the Keplerian neutrals (orbiting)
- Growth rate and frequency are sensitive to the pickup speed and the density of the ring beam

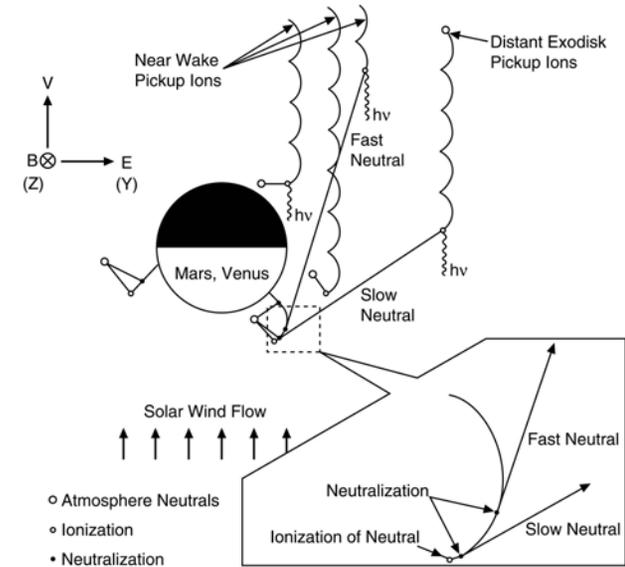
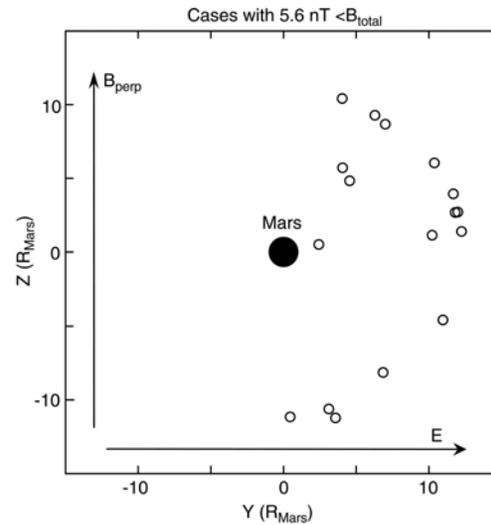
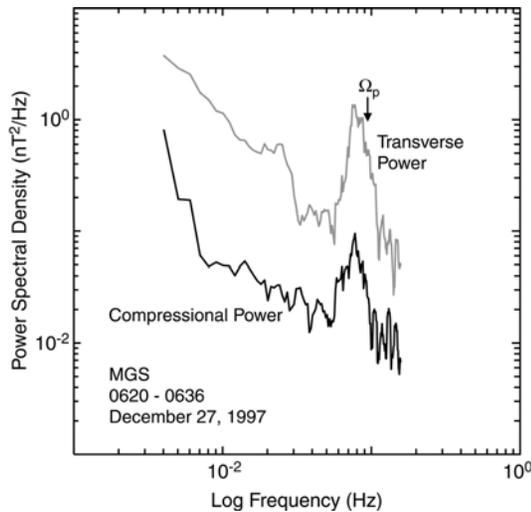


# Model for Energization of Ions, Dispersal of Free Energy



- The relative velocity of the plasma and the neutral particle sources and their source strength (Io at Jupiter and Enceladus and the E-ring at Saturn) are large enough to produce large waves
- To spread the free energy to large distances from the moon producing the particles, fast neutrals must be involved. When they reionize they can produce a ring beam that produces waves near the local gyro frequency

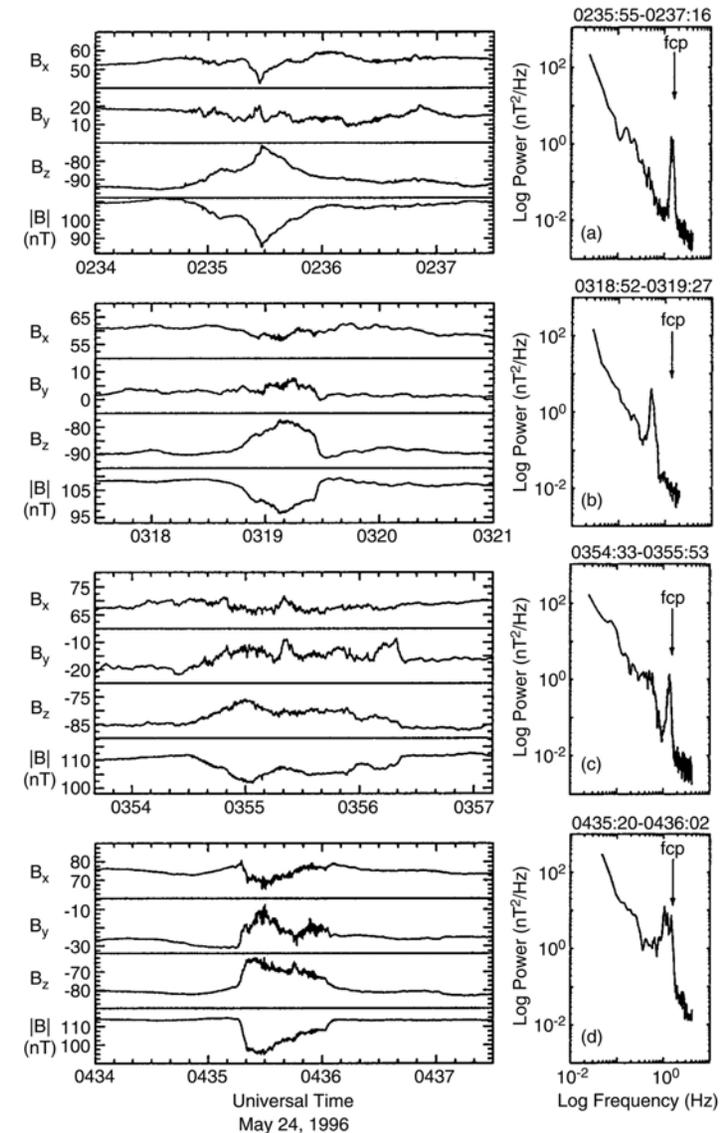
# Ion Cyclotron Waves Produced in the Solar Wind



- Proton cyclotron waves have been found in the solar wind near Mars (Phobos, MGS) and near Venus (PVO, Venus Express)
- When the locations of the wave observations are displayed in a magnetic-electric coordinate system, the waves appear on one side of the planet displaced in the direction of the electric field
- Again we believe that fast neutrals are created and transport the free energy to one side of the planet creating an exodisk rather than an exosphere

# Polar Observations of Proton cyclotron Waves

- Polar is ideally suited to study the proton cyclotron waves in the cusp region
- Guan Le undertook an excellent study of these waves with Polar magnetometer data (Le et al 2001)
- The waves are seen in and close to the polar cusp
- They are generally close to but just below the local proton gyro frequency
- However, they can keep their same spectral shapes and move away from the local gyro frequency unlike the planetary waves
- Where does the free energy arise?
  - Near the cusp the plasma is in constant motion and the cusp moves back and forth penetrating the Earth's exosphere. The electric field of the moving plasma will accelerate any newly created protons
- Why are waves seen outside the cusp proper?
  - Charge exchange with the exospheric hydrogen will produce fast neutrals that spread the free energy away from the cusp



# Concluding Remarks

- By examining the same process in different settings we can learn more about that process
- Ring beam generation of ion cyclotron waves produces a very characteristic signature
- We can learn much from ion cyclotron waves both at the magnetized and unmagnetized planets
- Energy ultimately is provided by plasma flowing relative to a neutral population. Spreading of the energy can occur by the formation of fast neutrals
- Lesson for the Earth's magnetosphere and interpreting the Polar observations
  - flows in and around the cusp can energize the magnetosphere plasma by creating fast neutrals and fast plasma out of the interaction of the solar wind and the exosphere
  - fast neutrals are important in transporting particles and energy in magnetospheres. They are more than just diagnostic
  - waves created by the low energy plasma could be damped by the high energy particles thus heating them and explaining perhaps the energetic particles proposed to be produced therein