Selenogenic Ion Cyclotron Waves:

ARTEMIS Observations and Implications for the Lunar Exosphere

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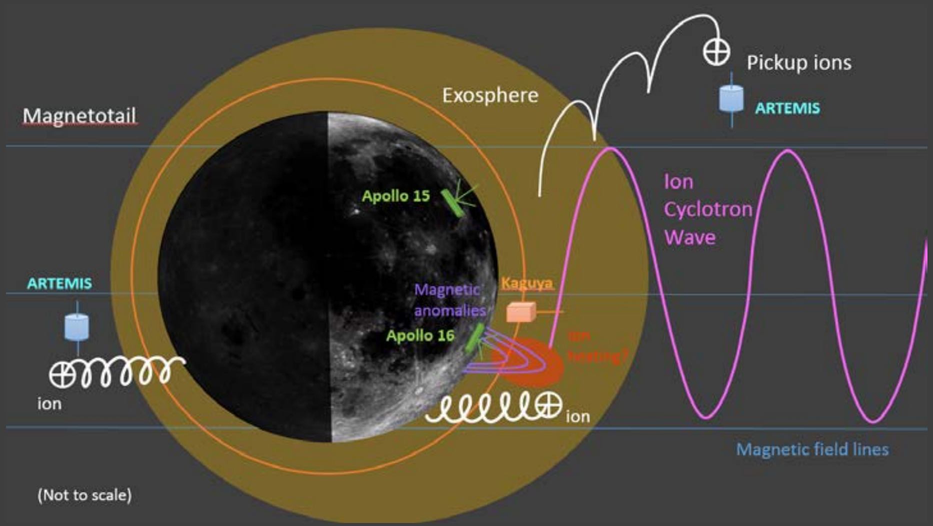
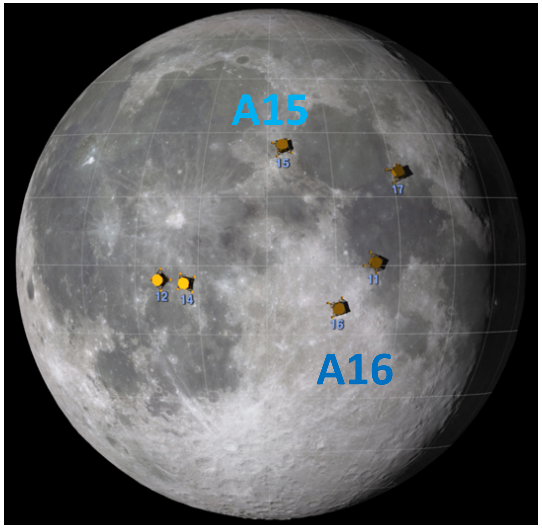


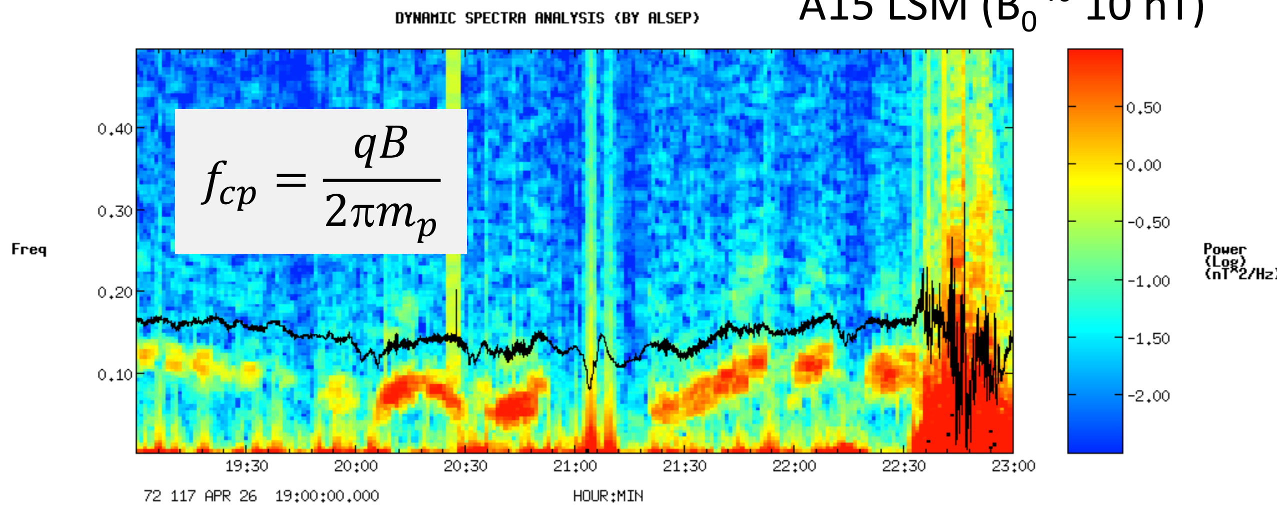
Lunar Exploration Analysis Group (LEAG) Meeting

Columbia, Maryland, October 20-22, 2015

Detection of Ion Cyclotron Waves (ICW) by Apollo

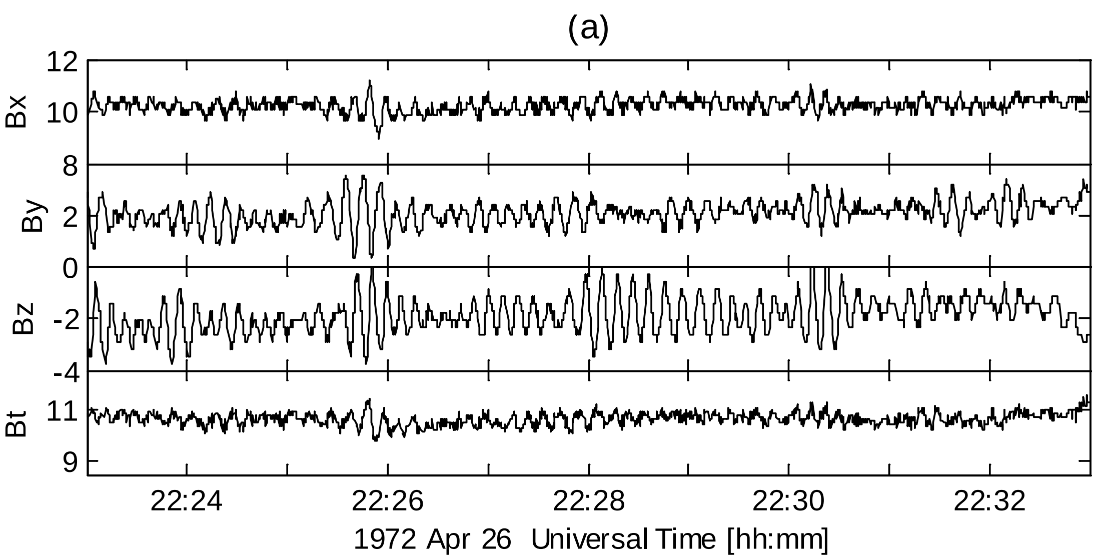


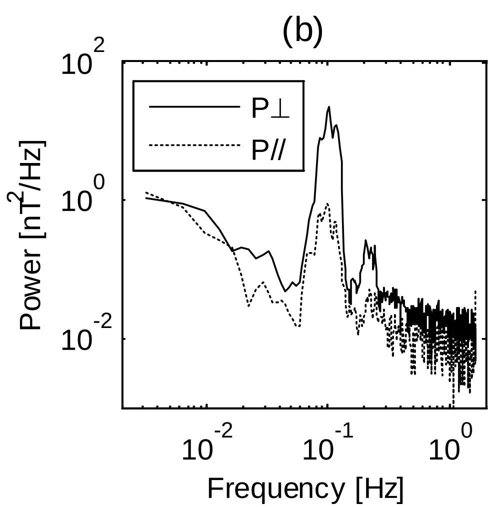
A15 LSM (B_0 ~ 10 nT)



$$f_{cp} = \frac{qB}{2\pi m_p}$$

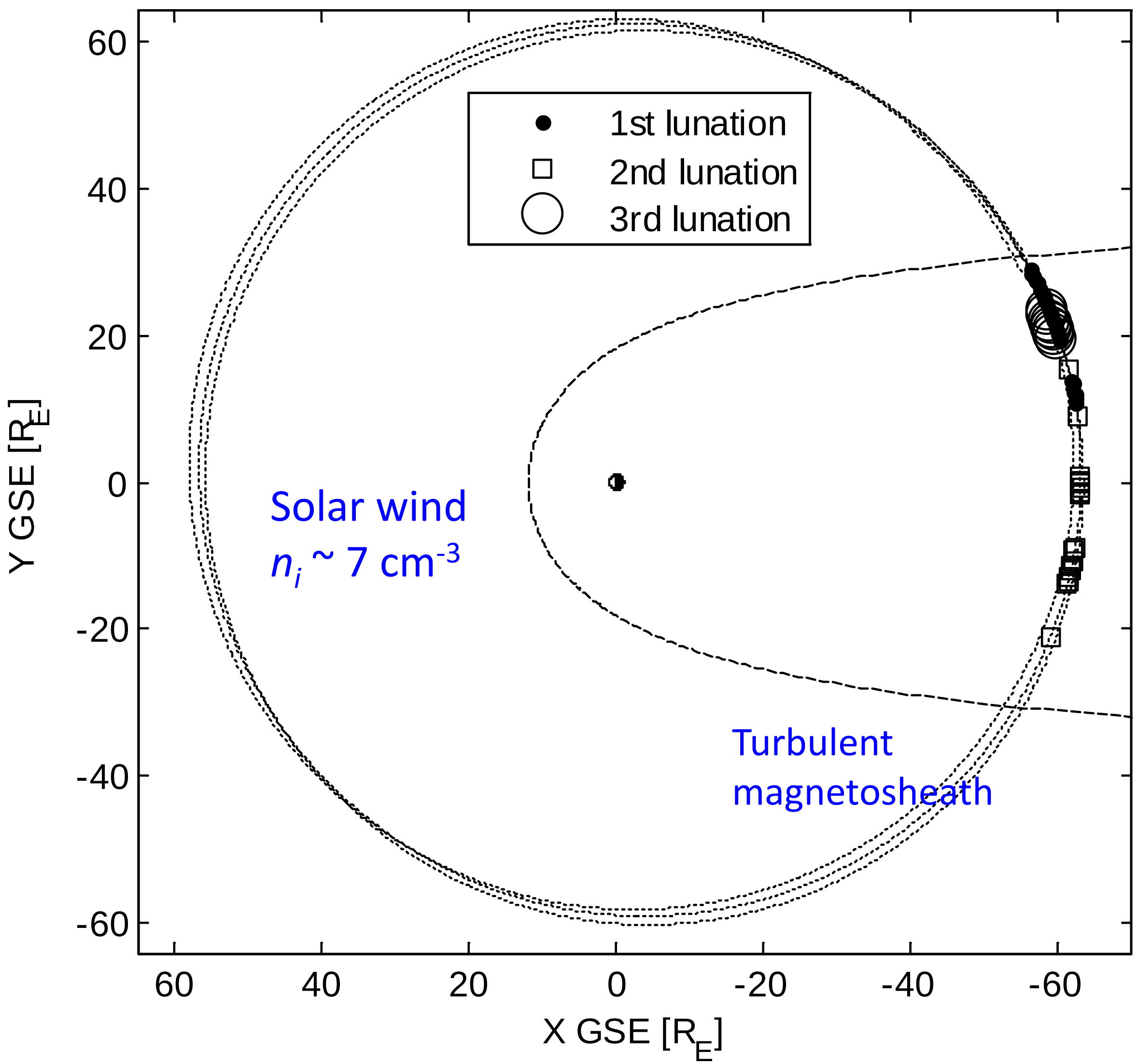
Magnetotail





Chi et al. (2013), *PSS.*

Locations of Waves Observed by Apollo



Magnetotail

n_i ~ 0.3 cm^{-3} (plasma sheet)

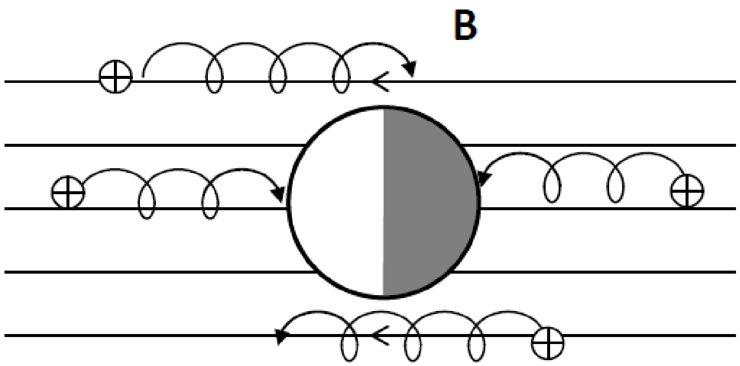
0.01 cm^{-3} (lobes)

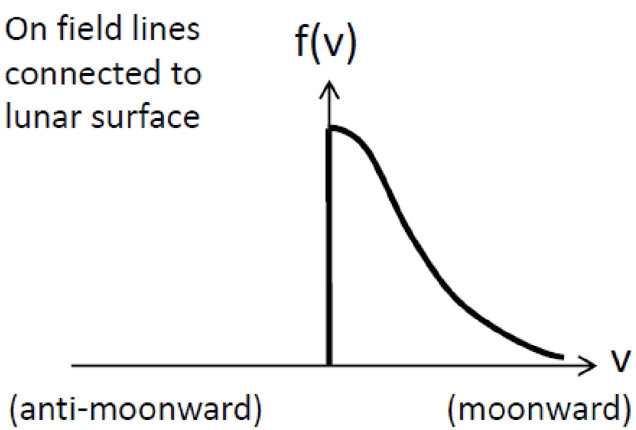
Narrowband waves were frequently observed by Apollo LSMs when the Moon was in the Earth's magnetotail.

Possible Mechanisms of ICW Excitation at the Moon

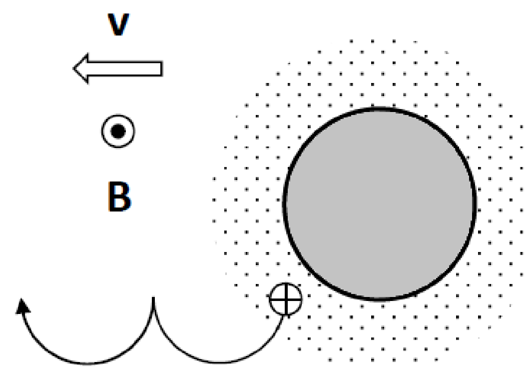
Chi et al. (2013), *PSS.*

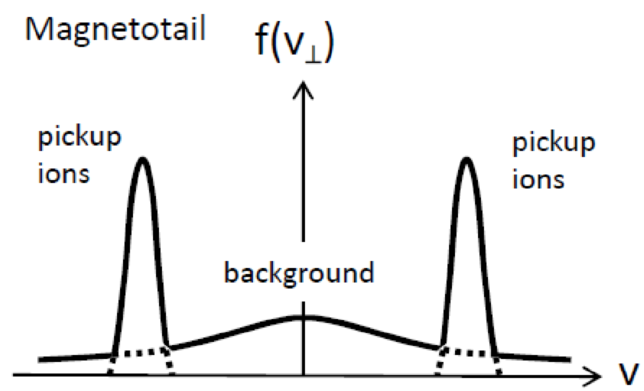
(a) Ion Absorption at the Moon





(b) Pickup Ions

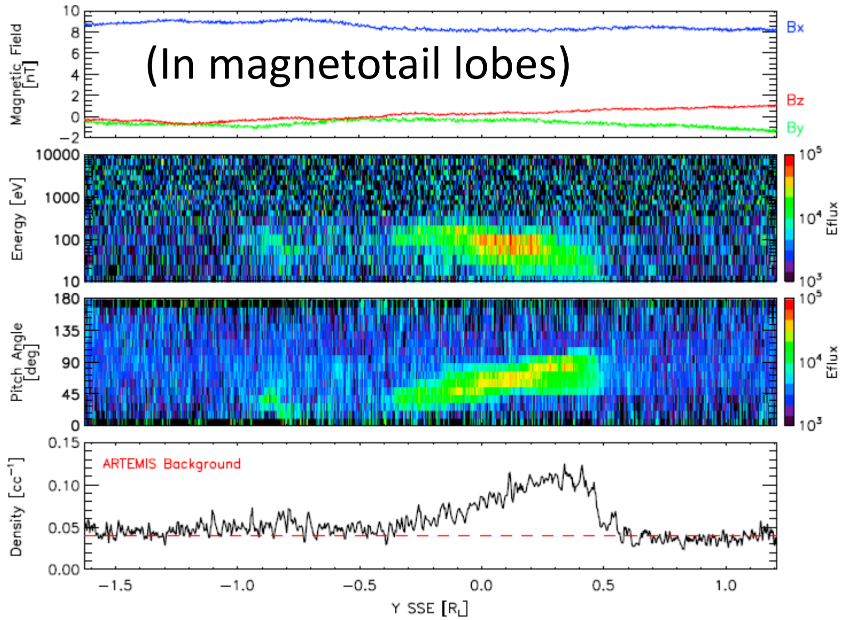


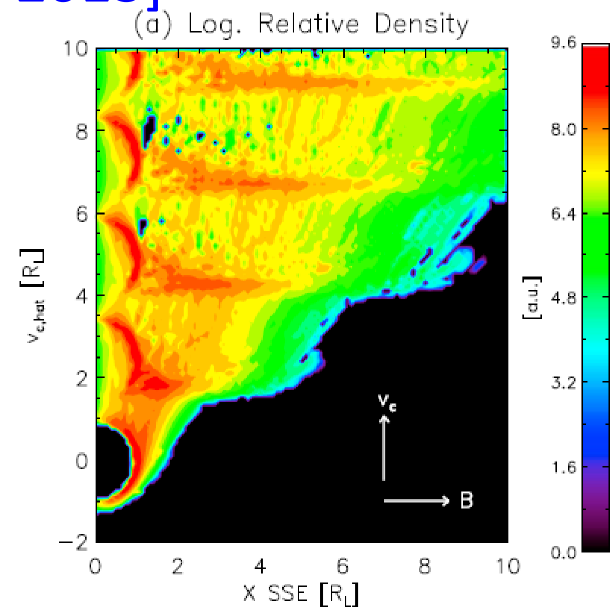


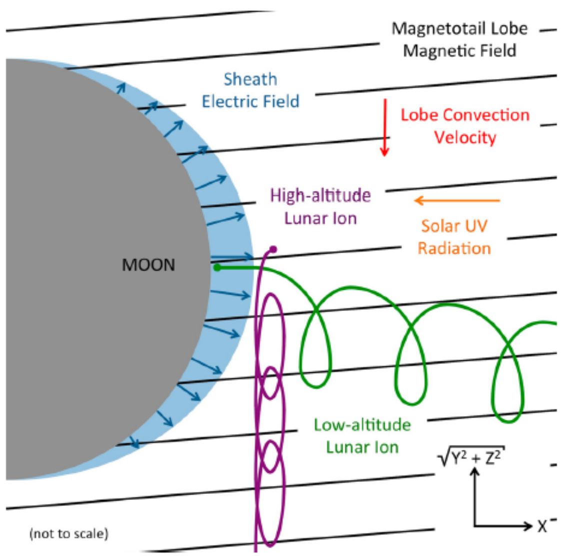
Pick-up Ions (PUI): ARTEMIS Observations and Modeling

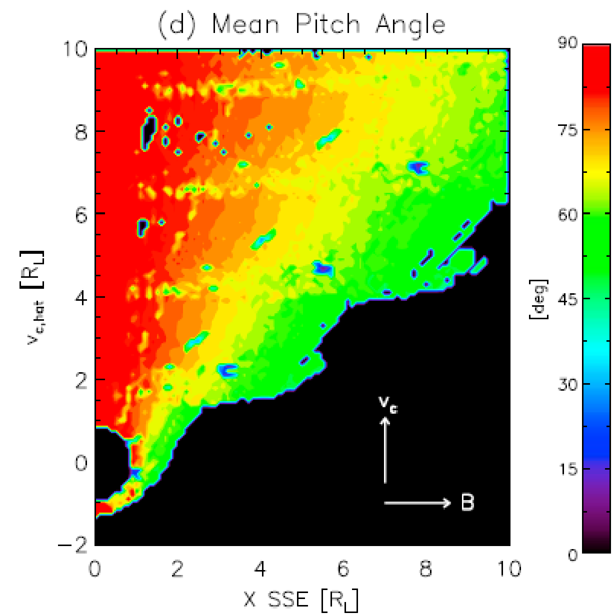
Poppe et al. [2012; 2013]

ARTEMIS P2 – November 11, 2011



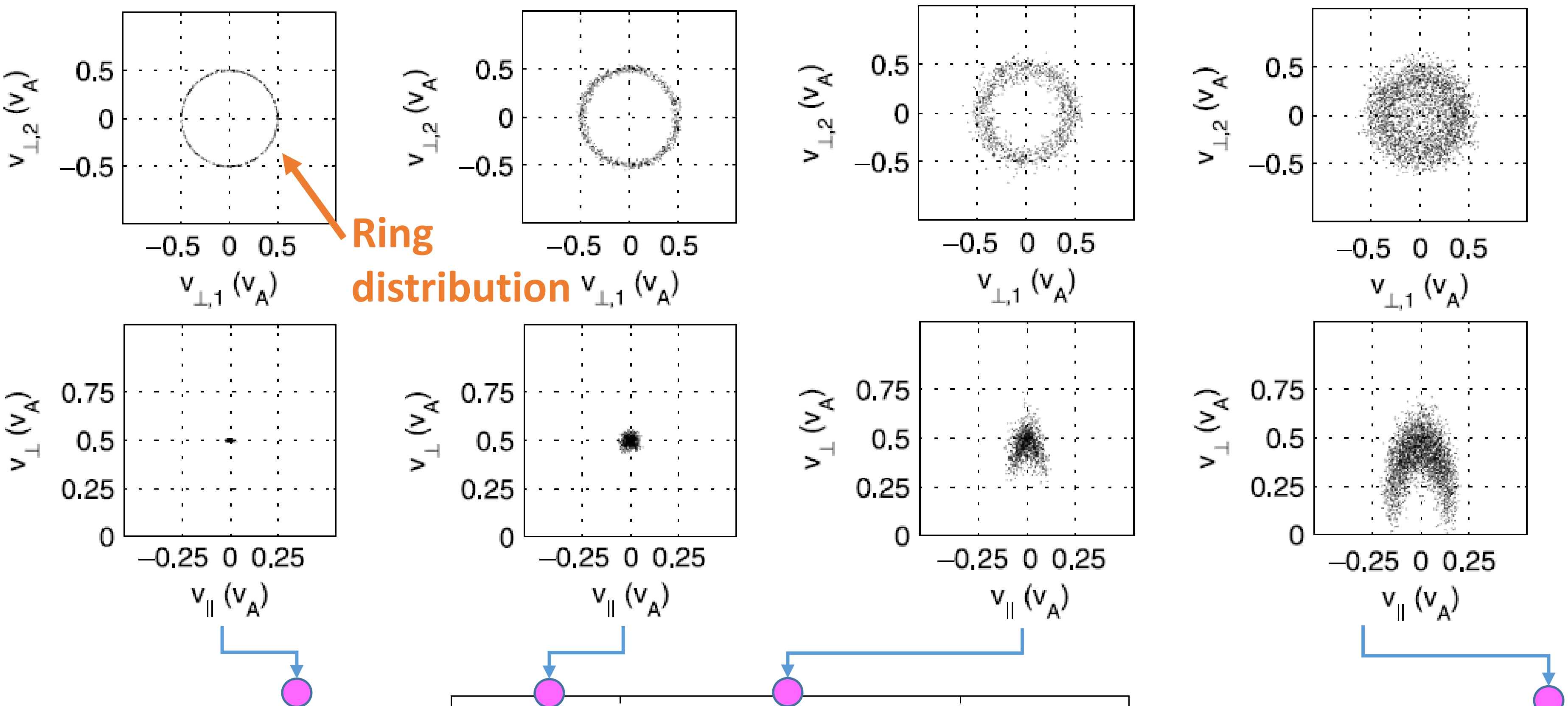




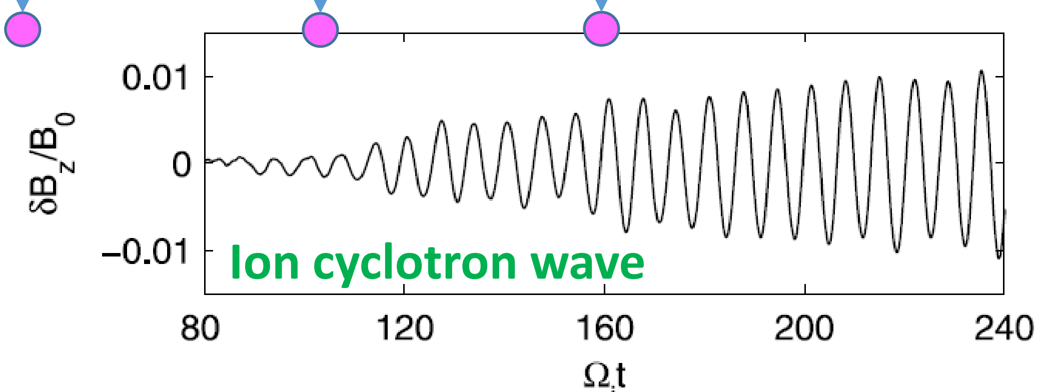


Excitation of ICW by PUI

Hybrid simulation by *Cowee and Gary* (2012)



Ion cyclotron instability reduces free particle energy by electromagnetic fluctuations .



Fluctuations scatter pickup and background ions toward a more isotropic distribution.

Estimating PUI Density from ICW Observations

(Venus, Mars, Io torus, Saturn E-ring, etc.)

$$\langle \delta B^2 \rangle = \frac{1}{2}\mu_0 m_i N_i {V_{inj}}^2 \left[\frac{R}{\left((1+R^2)^{1/2} - R\right)} - 2R^2 \right]$$

(Assuming all ring particle energy is converted into wave energy)

Huddleston et al. (1998)

Typical parameters in magnetotail lobes:

V_{inj} = 50 km/s

|B| = 10 nT

$N_{tail\ lobe}$ = 0.01 cm^{-3}

$R \equiv V_A/V_{inj}$

[•] ~ ½

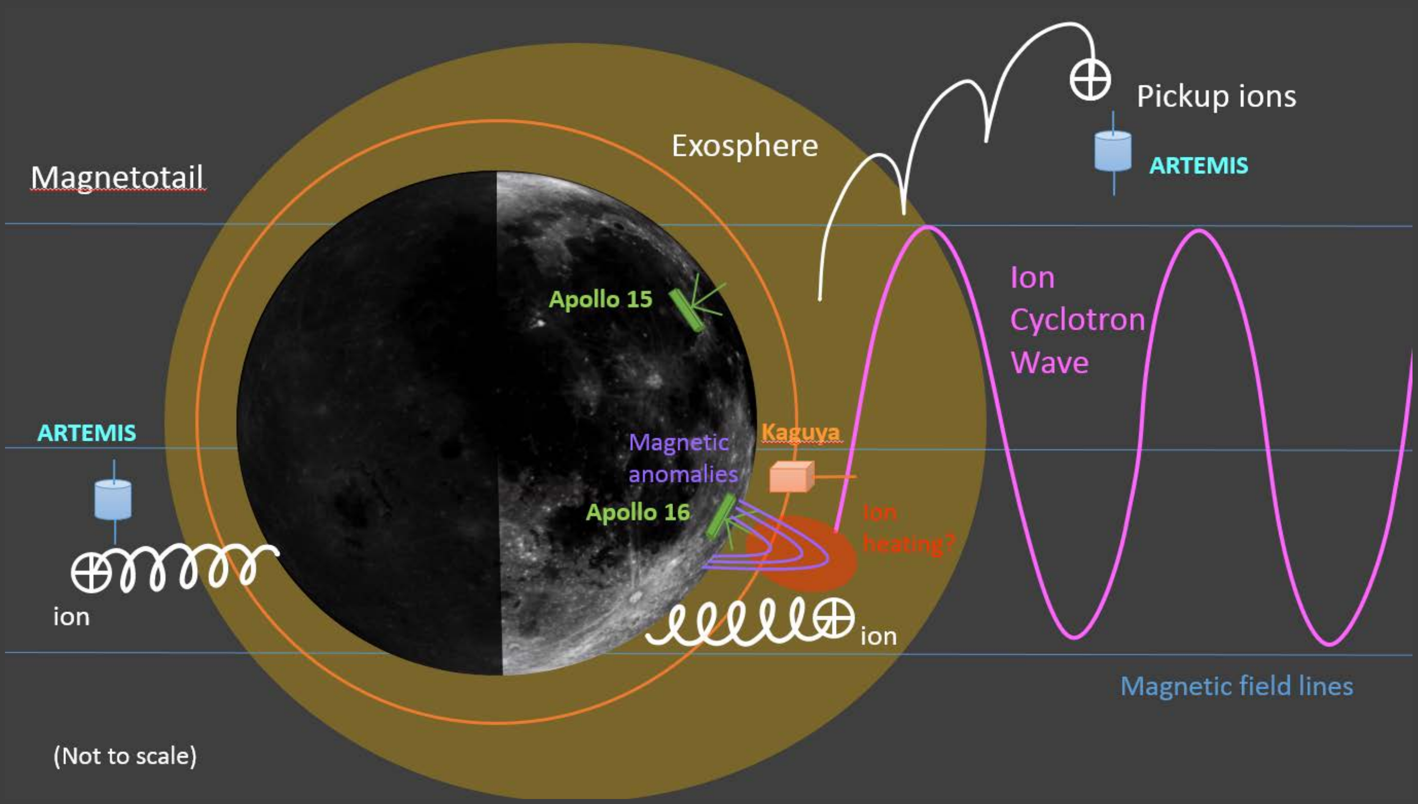
PUI density (conjectural):

$N_i \sim 0.8\ (\delta B[nT])^2\ (m_i[amu])^{-1}\ cm^{-3}$

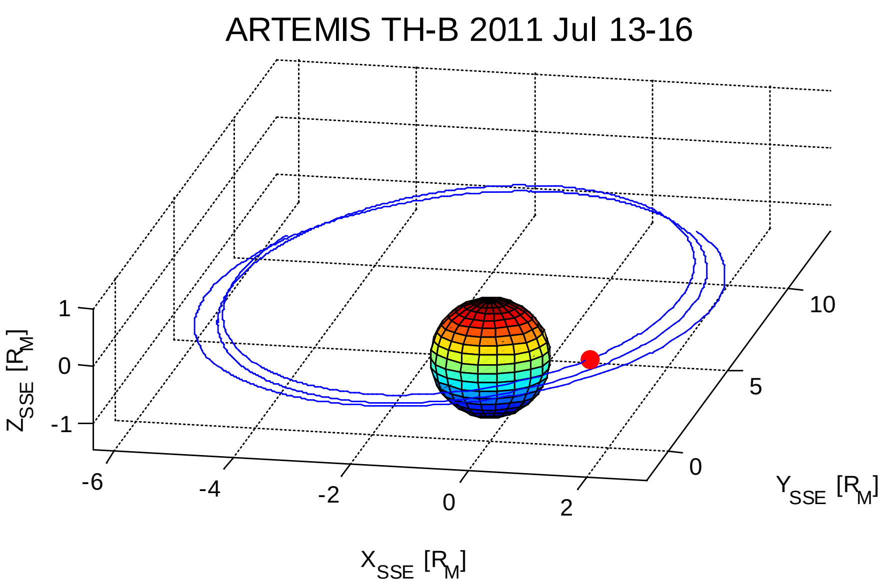
- However, not all ring particle energy will be converted to waves energy.
- The velocity distribution for lunar pickup ions is unlikely to be the same as a ring. An unstable distribution is still expected.

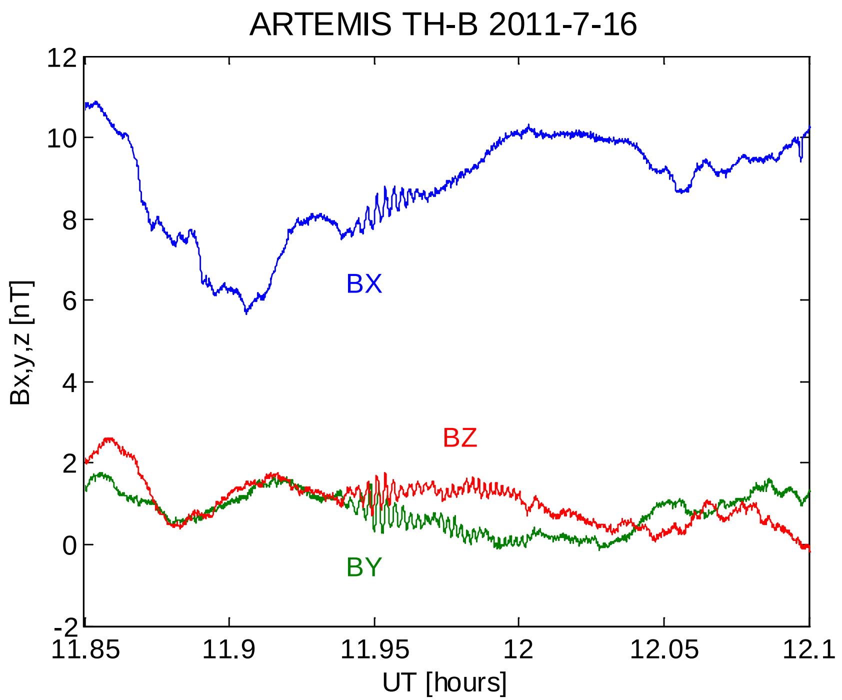
Relevance to LEAG

- **Ion cyclotron waves can provide a new way to infer the <u>mass numbers</u> and possibly the <u>amount</u> of pickup ions from the lunar exosphere.**
- Here we use observations by ARTEMIS probes, whose orbits and field/particle instruments are well suited for understanding the nature of ICW at the Moon.

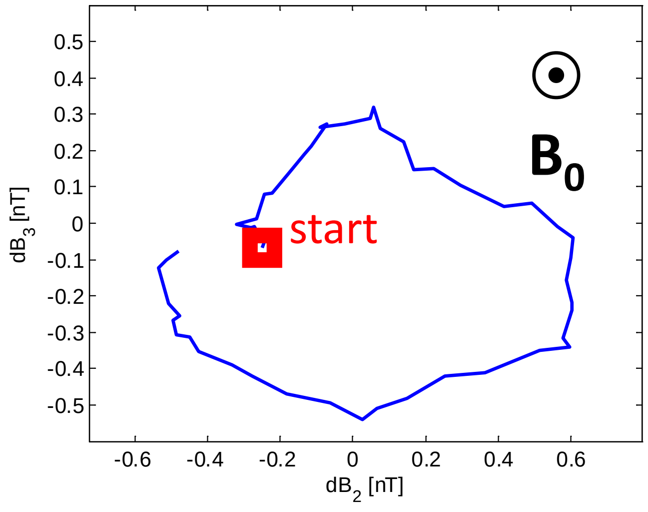


ARTEMIS Observations of ICW: Type 1

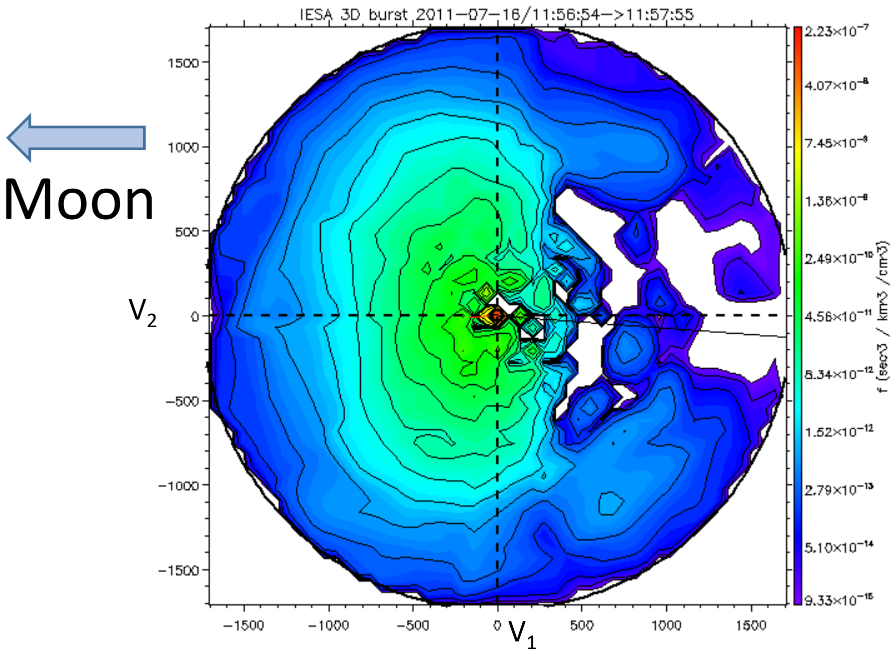


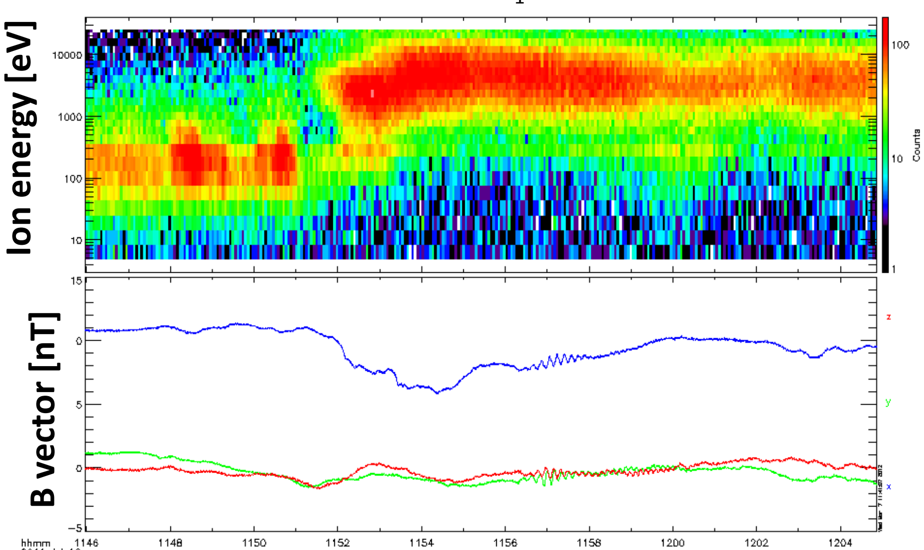


- Several clear wave events were found close to the lunar dayside (highly location-dependent).
- f <= $f$cp
- Left-handed, elliptically polarized

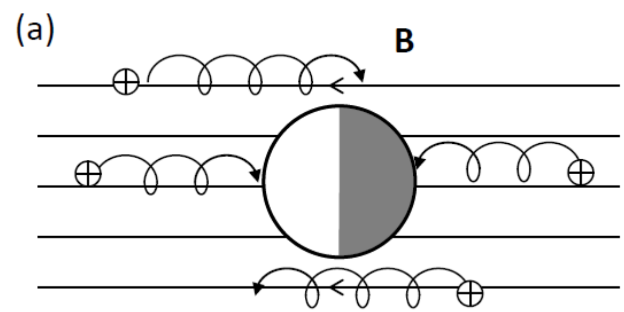


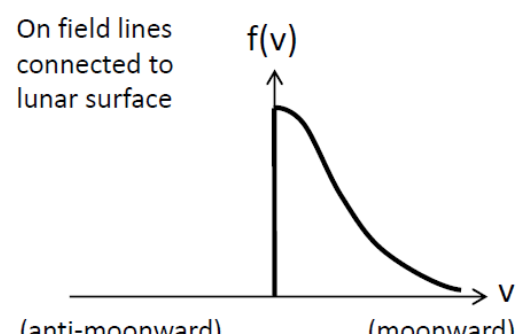
Ion Energy/Velocity Distribution: Type 1





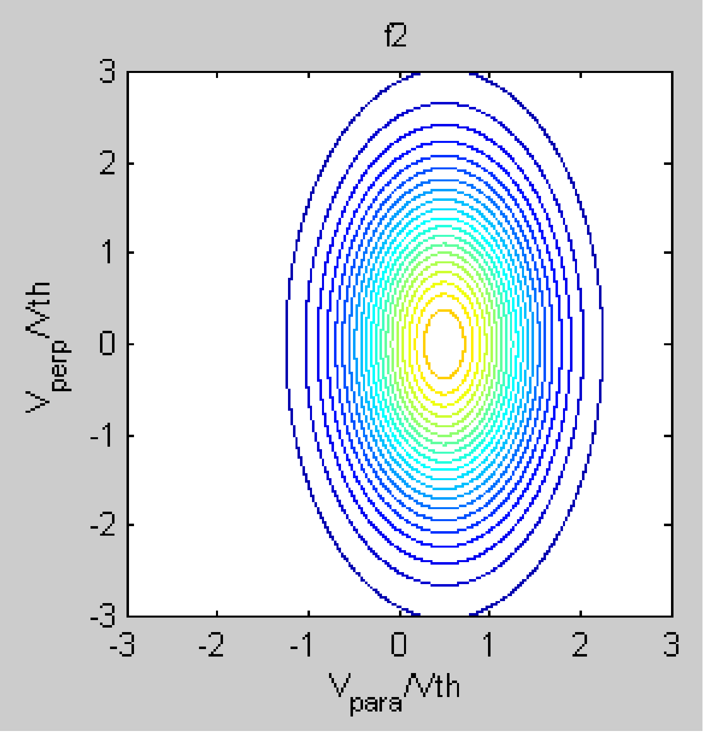
- Magnetic field line connected to the Moon
- Ion temperature ~3 keV (plasma sheet)
- “Crab-shaped” velocity distribution (a half sphere plus high-energy particles from the other side of the Moon)
- The ICW is likely associated with the temperature anisotropy due to particle absorption at the Moon.

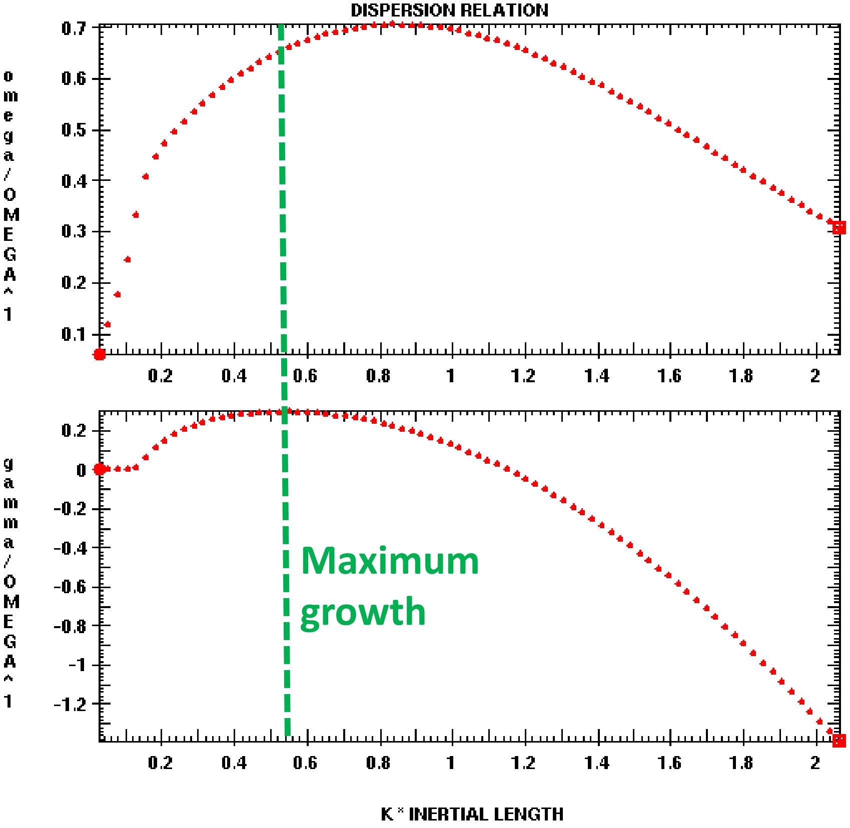




Model Prediction of Wave Excitation: Type 1

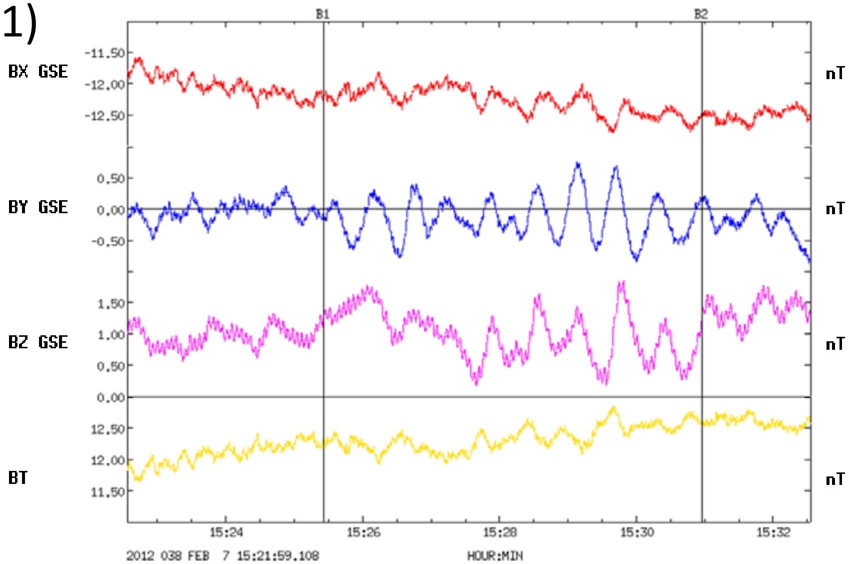
- Theoretical wave growth can be modeled by the *Waves in Homogeneous Anisotropic Magnetized Plasma* (WHAMP) code.
- Here we model (1) a drifted anisotropic distribution to emulate the asymmetric distribution observed; (2) field-aligned propagation
- Wave growth at frequencies below proton cyclotron frequency



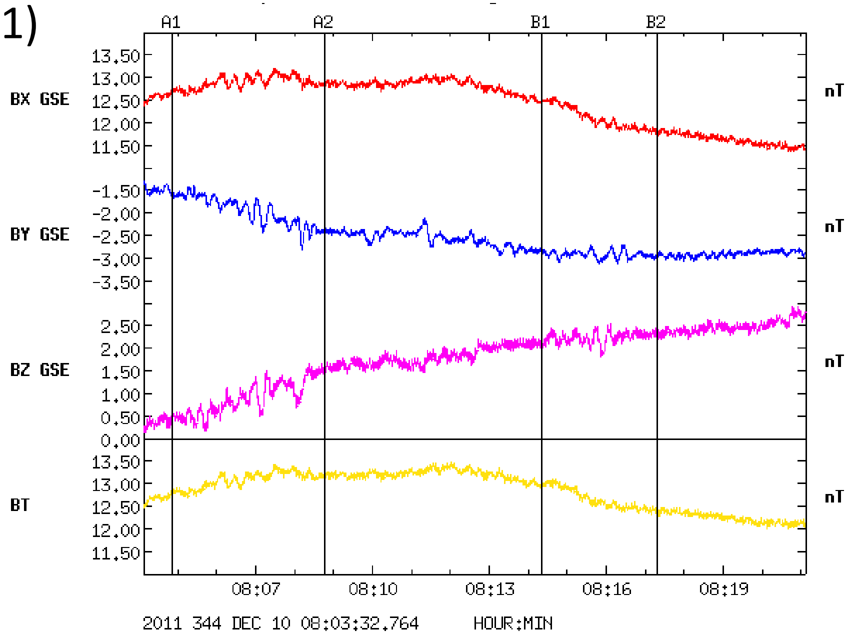


ARTEMIS Observations of ICW: Type 2

THB(P1)

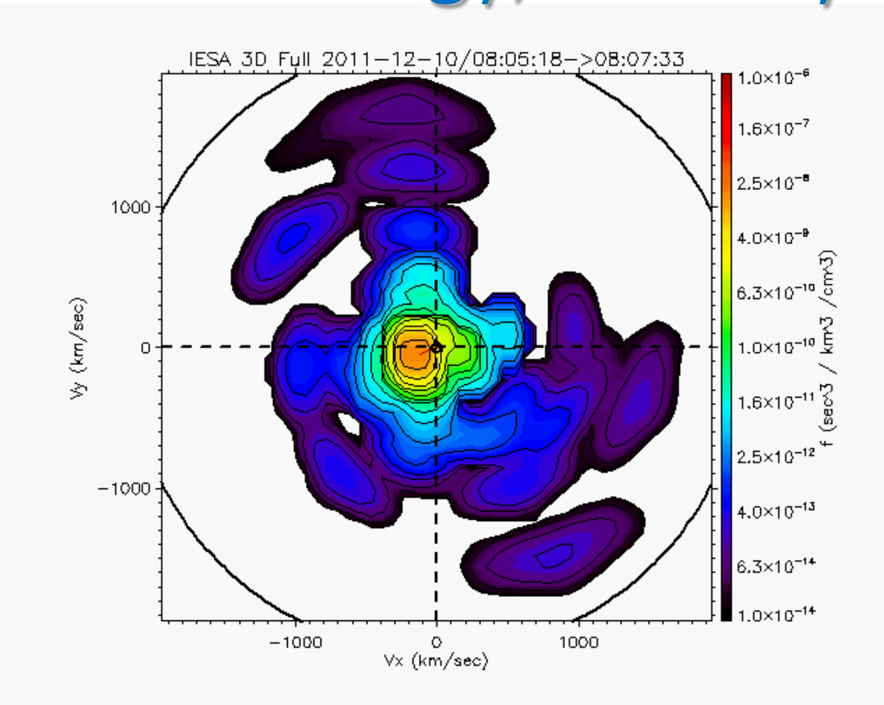


THB(P1)

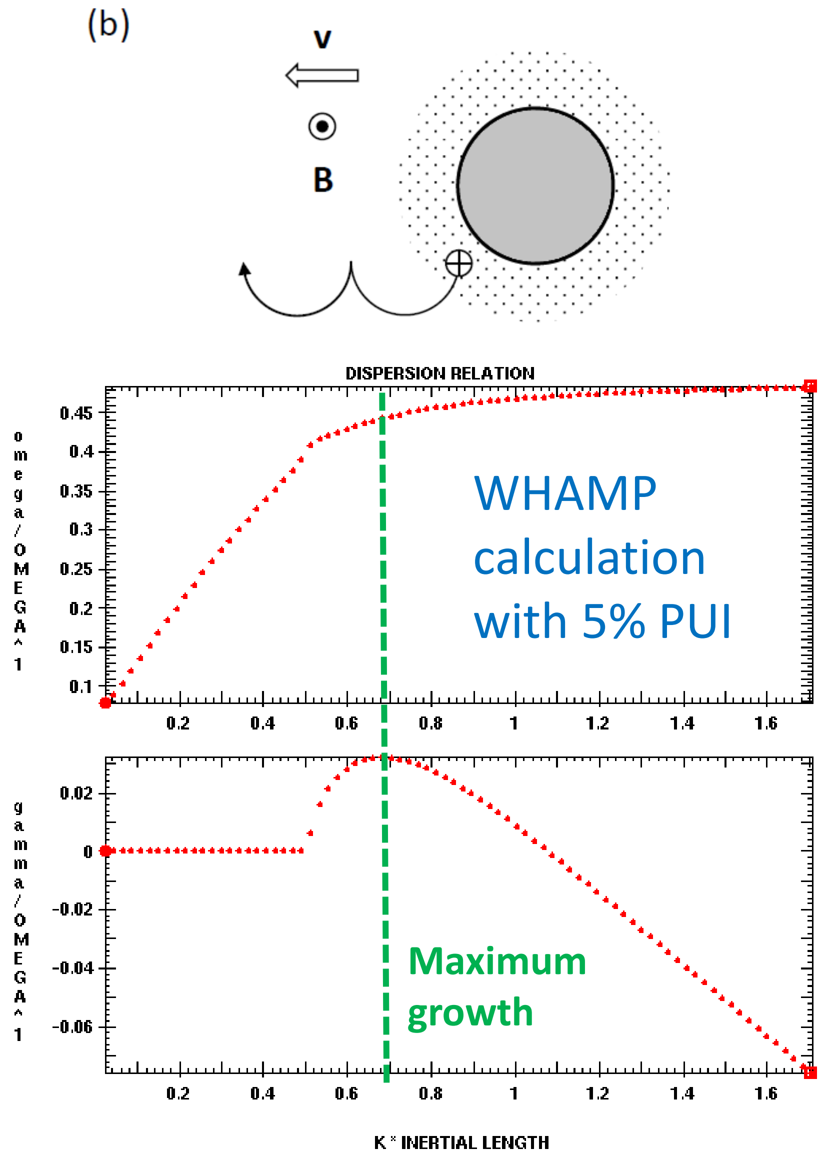


- Observation was made by ARTEMIS in the magnetotail lobes and several lunar radii from the Moon.
- Spacecraft and the Moon are not connected by magnetic field lines.
- Wave properties:
  - $f \leq f_{c,H2+}$ or $f_{c,He+}$
  - Left-handed polarized
  - Field-aligned propagation

Ion Energy/Velocity Distribution: Type 2

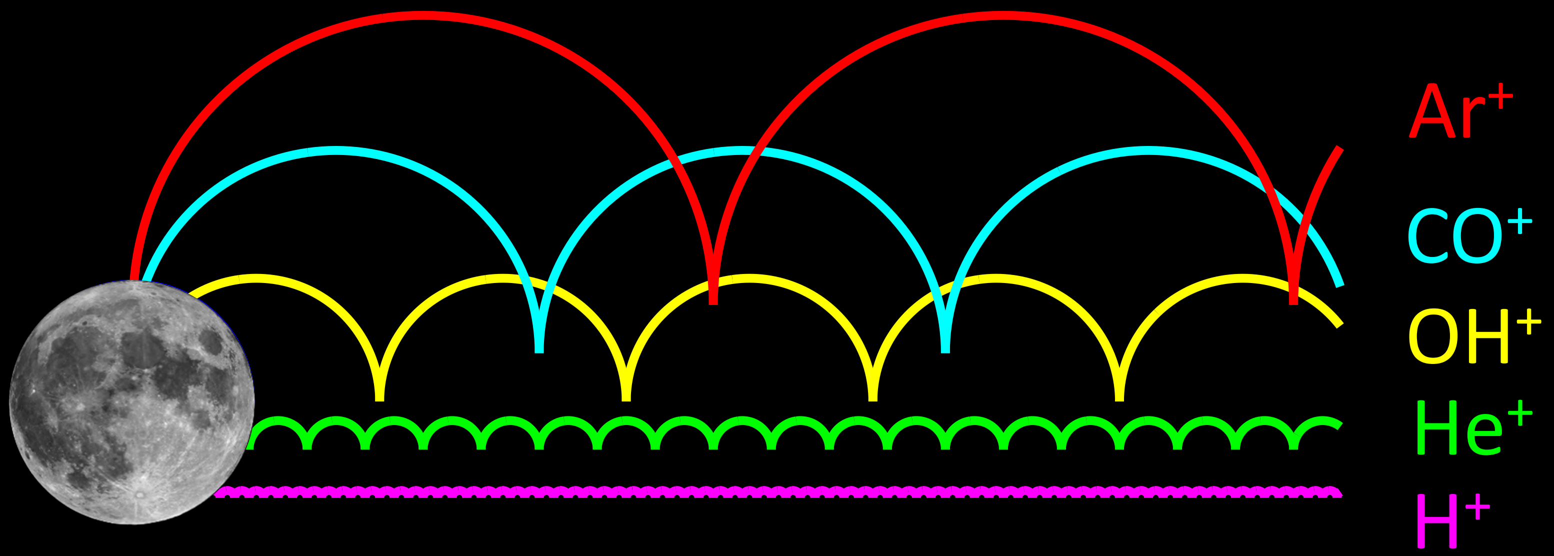


- Ion energy at ~100 eV (i.e. not plasmasheet)
- Drift velocity at ~150 km/s (i.e. net flow present)
- The ICW is likely associated with pickup He^+ (although light ions may be repelled by spacecraft potential and are more difficult to observe).



Searching for ion cyclotron waves associated with heavy ions

- ICWs found in ARTEMIS (and Apollo) data are associated with H^+, He^+ and possibly H_2^+.
- ICW associated with heavy ions are not apparent in data:
  a. These waves have much longer periods (minutes), and are less discernible if the background field is varying.
  b. Larger gyroradii associated with heavy ions are less likely to form ring distributions within the range of ARTEMIS.



(in scale for typical conditions)

Summary

- Narrowband ion cyclotron waves at the Moon in the Earth's magnetotail can provide information about the escape of pickup ions from the Moon.
- ARTEMIS observations of ion cyclotron waves suggest that these waves are generated by (1) absorption of plasmasheet ions by the Moon, and (2) pickup ions.
- ARTEMIS observed ICWs associated with H^+, He^+ and possibly H_2^+. The ICWs associated with heavy ions are not apparent in data.
- We are conducting a statistical survey of PUI-related ICWs observed by ARTEMIS to investigate the ion escape rates.