Narrowband Ion Cyclotron Waves at and near the Moon in the Earth’s Magnetotail

and the Association with the Plasma Environment

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Apollo Magnetic Field Experiments

Lunar Surface Magnetometer (LSM)

Sub-satellite Biaxial Magnetometer (SBM)

Lunar Portable Magnetometer

Apollo 15 & 16 subsatellites

Charles Sonnet & Palmer Dyal (NASA Ames)

Paul Coleman (UCLA)

LSM: A12, A15, A16

SBM: A15, A16

LPM: A14, A16
For many years the Apollo magnetic field data were not accessible due to their archaic format.

Recently a data restoration effort has made available all magnetic field data collected from Apollo sub-satellites and some data from Apollo Lunar Surface Magnetometers (LSM).
Apollo LSM Observation of Monochromatic Waves
Narrowband waves were frequently observed by Apollo LSMs when the Moon was in the Earth’s magnetotail.
Other Examples of 0.1-10 Hz Waves at the Moon

- Farrell et al. [1996]; WIND
- Nakagawa et al. [2003]; GEOTAIL
- Halekas et al. [2006]; LP
- Tsugawa et al. [2011]; Kaguya
- Nakagawa et al. [2011]; Kaguya
Solar wind $n_i \sim 7 \text{ cm}^{-3}$

Turbulent magnetosheath

Magnetotail $n_i \sim 0.3 \text{ cm}^{-3}$ (plasma sheet)

0.01 cm$^{-3}$ (lobes)

Narrowband waves observed by Apollo LSM
Wave Polarization (Apollo LSM)

- **Ellipticity**
  \[ f_{cp} = \frac{qB}{2} \]

- **Propagation Angle**

**Characteristics of ion cyclotron waves:**
- (1) Excited when \( T_{\perp} > T_{\parallel} \);
- (2) \( f \leq \) ion cyclotron frequency;
- (3) Left-hand polarized;
- (4) Propagation tends to be along magnetic field

Apollo LSM observations show consistency with all the magnetic field properties of ion cyclotron waves.
Why Ion Cyclotron Waves: (1) In the Earth’s Magnetosphere

Causes of thermal anisotropy:
• Substorm injection
• Drift-shell splitting
• Loss cone distribution
• (and more)

Major purpose:
Wave interaction with particles for assessment of particle loss or energization; Inference of ion composition.

Roux et al. [1982]
Why Ion Cyclotron Waves: (2) In the Solar System

Ion cyclotron waves associated with **pickup ions** have been observed in the vicinity of:

- Mars exosphere
- Venus exosphere
- Neutral torus of Io
- E-ring of Saturn

**Observation of wave amplitude** can be used to estimate the amount of the pick-up ions and atmospheric density.

(from Russell and Blanco-Cano, 2007)
In the Earth’s magnetotail the magnetic field is greatest in the lobes and weakens in the plasma sheet near the equatorial plane.

Many wave events occurred in the plasma sheet when the field was reduced, but waves could also occur near or in the lobes.
Observations of ICW at Two Apollo Sites

- Differences are found in both phase and wave vector ($k$).
- Wave amplitude observed at Apollo 16 LSM is persistently lower.
- Wavelength is expected to be at the order of a few hundred km or less.
- These clues suggest that the remnant crustal magnetic field is strong enough to make significant changes in wave properties.
ARTEMIS Observations
ARTEMIS Observations of ICW

• ARTEMIS has observed several events of ion cyclotron waves.
• All clear wave events were found close to the lunar dayside (highly location-dependent).
• $f \leq f_{cp}$
The wave properties observed by ARTEMIS are also consistent with the characteristics of ion cyclotron waves.

- Ellipticity: -0.71 (left-hand)
- Propagation angle $\theta_{Bk} = 56^\circ$

Poppe et al. [2011] also observed upward photoelectron beam during this wave event.
Ion Energy/Velocity Distribution during Wave Event

- Magnetic field line connected to the Moon
- Ion temperature ~3 keV (plasma sheet)
- Ion distribution function shows a clear shortage of particles in the sunward direction from the Moon.
- The anisotropy of ion temperature resulting from the “crab-shaped” velocity distribution could lead to ion cyclotron instability.
Ion Cyclotron Waves Farther From the Moon

**Associated with $H_2^+$?**

- ARTEMIS in SSE: (-2.61, -5.88, -1.13) $R_M$
- (1) $f$ at $f_{c,He^+}$; (2) Left-hand polarized; (3) field-aligned propagation
- Could be associated with $H^+$, $H_2^+$, or $He^+$
- Convection speed $\sim$ 100 km/s $\rightarrow$ PUI?
Possible Scenarios

1. Particle distribution, altered by the presence of the Moon, leads to ion cyclotron instability

2. Pickup ions from the lunar exosphere: ring-type distribution is noticeable only in the tenuous magnetotail.

- Reflected ions may become neutrals, such of which with sub-escape speeds
Narrowband waves with $f \sim f_{ci}$ have been observed at/near the Moon in the Earth’s magnetotail.

These narrowband waves can often be seen on the lunar surface and occasionally seen by orbiting satellites.

Surface and spacecraft observations of these waves suggest plasma sheet particles (with velocity distribution altered by surface absorption) and pickup ions from lunar atmosphere could be the sources.

These ion cyclotron waves at the Moon provide clues to the conditions of surrounding plasmas and the lunar exosphere.