SELENOGENIC ION CYCLOTRON WAVES: ARTEMIS OBSERVATIONS AND IMPLICATIONS FOR THE LUNAR EXOSPHERE. P. J. Chi[1], H. Y. Wei[1], W. M. Farrell[2], J. S. Halekas[3]. [1]UCLA, Earth, Planetary, and Space Sciences, Box 951567, Los Angeles, California, pchi@igpp.ucla.edu, hwei@igpp.ucla.edu [2]NASA Goddard Space Flight Center, Greenbelt, Maryland, William.M.Farrell@nasa.gov [3]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, jasper-halekas@uiowa.edu.

Introduction: The recent restoration of the Apollo Lunar Surface Magnetometer (LSM) data has revealed a type of electromagnetic waves that was previously overlooked [1]. These waves are narrowband in nature, and they are seen only when the Moon was in the Earth's magnetotail. The waves have frequencies that are close to the proton gyrofrequency ($f_{c,p}$), which is of the order of 0.1 Hz at the lunar distance in the magnetotail, and they are predominantly left-handed polarized. These two features are the main characteristics of of ion cyclotron waves (ICW's).

The generation of these narrowband ICW's at the Moon is still an open question, but existing observations at the Moon and in other regions of the magnetotail strongly suggest that these waves occur because of the existence of the Moon. Several mechanisms have been proposed to explain the presence of ICW's at the Moon [1]: (a) At the time when the electric field is present, the ionized particles in the lunar exosphere will become pickup ions moving away from the Moon, forming a ring or a ring-beam velocity distribution that is highly unstable to the growth of ICW's. This process has been identified for the generation of ICW's at comets [2], Venus [3], and Mars [4], or in the Io torus [5] and the Saturn E-ring [6]. (b) In the regions near and magnetically connected to the Moon, the majority of ions that flow into the Moon will be absorbed by the surface, resulting in an asymmetry in ion velocity distribution and hence temperature anisotropy. (c) The presence of multiple ion species and the cold phtoelectron beam can generate electromagnetic ICW's [7,8].

The objective of this study is to understand the generation of selenogenic ICW's at the Moon through the detailed wave and particle observations by the two ARTEMIS probes near the Moon. As pickup ions are one of the major loss mechanisms of the lunar exospehre, the connection between selenogenic ICW's and pickup ions is a part of the larger problem related to the loss of volatiles from the Moon (Figure 1).

ARTEMIS Observations: ARTEMIS consists of two identical spacecraft orbiting around the L1 and L2 Lagrangian points in the Earth-Moon system. The two spacecraft, P1 and P2, were inserted into lunar orbits in June and July 2011. Since then they have been in stable equatorial, high-eccentricity orbits, of ~100 km × 19,000 km altitude. Each of the two ARTEMIS spacecraft is equipped with a comprehensive set of field and particle instruments. With orbit periods of about 26 hours, the two probes are separated by distances between 500 km and 5 R_E.

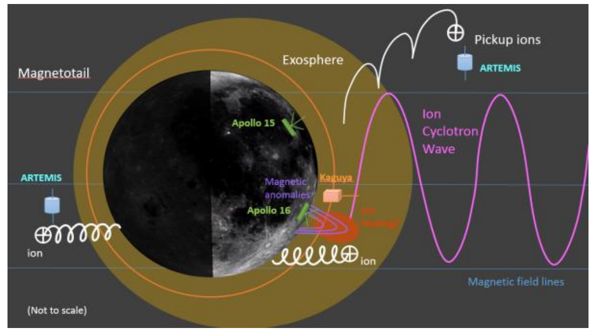

Fig. 1. Connection between ion cyclotron waves and the lunar exosphere.

Two examples of ICW's observed by ARTEMIS are displayed in Figure 2. The first example was also shown in the study of the lunar photoelectron sheath in the Earth's magnetotail [7]. ARTEMIS P1 was at an altitude of 1200 km and on the sunward side of the Moon, and was connected to the Moon by magnetic field lines. Unlike the more continuous trains of ICW's typicall found in the Apollo LSM data, this ICW event is much shorter in duration (Figure 2a), a result likely due to spacecraft motion. The wave frequency is close to $f_{c,p}$, and the hodogram analysis shows clear left-handed, almost circular polarization. The ESA instrument on board ARTEMIS P1 detected keV ions that are typical of the Earth's plasma sheet. More importantly, the velocity distribution of ions shows a half-sphere geometry, except for ions with higher energies that can come over from the other side of the Moon through gyration motion (Figure 2b).

The second ICW example was also observed by ARTEMIS P1, but at a time when the spacecraft was located about 5.5 lunar radii from the Moon (in the SSE $-Y$ direction) and was not connected to the Moon by magnetic field lines. The wave frequency in this case was approximately $f_{c,He+}$, the gyrofrequency of He^+ (Figure 2c). The ESA instrument detected ions at energies of around 100 eV, and the ion velocity distribution was mostly symmetric, with a net flow velocity at around 150 km/s in the anti-sunward direction (Figure 2d).

(a)

(b)

(c)

(d)

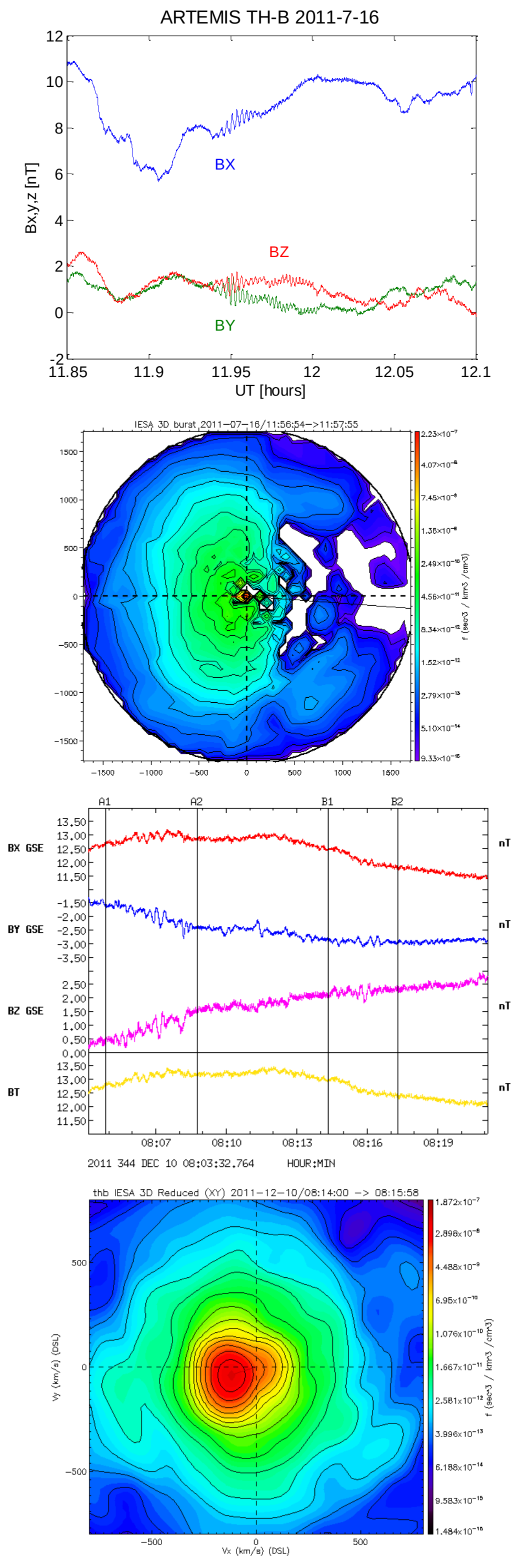

Fig. 2. Two examples of ion cyclotron waves near the Moon observed by ARTEMIS. (a,b) Magnetic field and ion velocity distribution for the 16 July 2011 event. (c,b) Observations by the same ARTEMIS instruments for the 10 December 2011 event.

We have seen other ARTEMIS events with wave frequencies close to $f_{c,He+}$, suggesting a possible association with the relatively abundant Helium constituent in the lunar exosphere.

Generation of Selenogenic ICW and Implications for the Lunar Exosphere: The ARTEMIS observations of ICW's that we have examined suggest that ICW's can be generated by more than one mechanism. The ICW events at locations near and magnetically connected to the Moon strongly hint the generation through the absorption of ions by the Moon. This process is similar to the loss-cone-induced ion cyclotron instability in the inner magnetosphere [9], and it implies that the presence of the Moon can modify the local plasma condition in the Earth's magnetotail.

The ICW's located at several lunar radii from the Moon are likely caused by a different mechanism, such as through the pickup ions (PUI) originating from the lunar exosphere. The amplitude of the PUI-induced ICW is known to relate to the PUI density [10,11]. If selenogenic ICWs can be excited by pickup ions from the lunar exosphere, the measurements of ICWs can provide an additional way to estimate the amount of exospheric constituents that participate in the wave excitation process.

References: [1] Chi P. J. et al. (2013) *Planet. Space Sci.*, *89*, 21-28. [2] Smith E. J. et al. (1986) *Science*, *232*, 382-385. [3] Delva M. et al. (2008) *GRL*, *35*, L03103. [4] Russell C. T. et al. (1990) *GRL*, *17*, 897-900. [5] Kivelson M. G. et al. (1996) *Science*, *274*, 396-398. [6] Russell C. T. (2006), *JGR*, *111*, A12205. [7] Poppe A. R. et al. (2012) *GRL*, *39*, L17104. [8] Temerin M. and Lysak R. L. (1984) *JGR*, *89*(A5), 2849-2859. [9] Denton R. E. et al. (1992) *JGR*, *97*, 12093-12103. [10] Huddleston D. E. and Johnstone A. D. (1992) *JGR*, *97*, 12217-12230. [11] Cowee M. M. et al. (2009) *JGR*, *114*, A04219.