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Existence of electrostatic solitary waves over the lunar magnetic anomaly region

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Abstract

The Moon lacks a global magnetic field, however regions of strong crustal magnetic field known as "Lunar magnetic anomaly" exists on the surface. Here, we report the generation of electrostatic solitary waves over the lunar magnetic anomaly region in the dayside by virtue of counter-streaming electron beam. The incoming solar wind electron counter streams with respect to the mirror-reflected electrons from the lunar magnetic anomaly. We observe bipolar parallel electric field structures with amplitude ~ (1 - 3) mV/m having a frequency ~ (20 Hz - 6 kHz). These waves could play a pertinent role in the acceleration and heating of the protons and electrons over the lunar magnetic anomaly region.

1. Introduction

The Moon is characterized by a thin surface-bound exosphere and lack of intrinsic magnetic field [1]. Nevertheless, regions of strong crustal magnetic field referred as "Lunar Magnetic Anomaly (LMA)" exists on the lunar surface [2, 3]. The solar wind interaction with the Moon was considered to be passive with the day side lunar surface absorbing the impinging solar wind plasma particles thereby generating a void in the night side known as "lunar wake" [4, 5]. However, spacecraft observations from recent lunar missions like Chandrayaan – 1 and 2, Kaguya, and ARTEMIS have corroborated the solar wind-Moon interaction to be highly dynamic [6]. Numerous processes such as back scattering of solar wind protons (~0.1 – 1 %) as ions [7] and energetic neutral atoms [8], sputtering of lunar surface [9], refilling of the lunar wake by Type-I (perpendicular entry of the solar wind protons) and Type-II (reflection from day side lunar surface) entries [10, 11] etc. has been shown to persist in the lunar plasma environment.

The solar wind interaction with the LMA is a topic of pertinent interest. The existence of mini-magnetosphere over the LMA was discovered by Chandrayaan-I [12]. The LMA deflects and heats the incoming solar wind protons, while the electrons are mirror-reflected [13, 14]. The counter-streaming of the incoming solar wind particle with the deflected and mirror reflected particles facilitates the generation of plasma instabilities and excitation of waves which consecutively affects the lunar plasma environment. A wave of relevance over the LMA is the electrostatic solitary waves (ESWs), which accounts for particle acceleration, heating and generation of broadband electrostatic noise (BEN) in the planetary magnetospheres [15].

Recent satellite observations have shown the existence of ESWs in wake boundary and over the LMA [16, 17]. Majority of the analysis of the generation mechanism and existence of the ESWs in the lunar plasma environment have focused mostly in the lunar wake region, with limited studies over the LMA. Over the LMA region also, a detailed analysis of the generation mechanism and properties of the ESWs is not available. In this paper, we have analyzed the generation mechanism for the ESWs over the LMA arising from counter-streaming electron beam utilizing the field and plasma measurements from the ARTEMIS Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with the Sun) satellite. The organization of the paper is as follows: Section 2 summarizes the instruments onboard the ARTEMIS used for the analysis and the observation, Section 3 summarizes the results.

2. Observations

ARTEMIS mission comprises of the two outermost satellites (P1 and P2) of the THEMIS (Time History of Events and Macroscale Interactions During Substorms) mission. Since 2011, ARTEMIS P1 and P2 are elliptically orbiting around the two Earth-Moon Lagrange points with a time period of ~25 hours. To investigate the ESWs occurring over the LMA we have used the measurements from ARTEMIS P1 instruments: Electric Field Instrument (EFI) [18], Fluxgate Magnetometer (FGM) [19], Search Coil Magnetometer (SCM) [20], and Electrostatic Analyzer (ESA) [21]. The EFI measures the three components of the ambient electric fields (frequencies ~ 10 Hz to 8 kHz). The FGM measures the low frequency fluctuations in the background magnetic field (~ 64 Hz). SCM measures the magnetic field fluctuations with frequency ~ 0.1 Hz – 8 kHz. ESA measures the ion and electron energies varying as ~ (1.6 eV – 25 keV) and (2 eV-32 keV), respectively.

In order to investigate the generation mechanism of the ESWs over the LMA, we have considered the event when the satellite was traversing at an altitude < 100 km over the LMA. ARTEMIS trajectory along with the global lunar magnetic field strength map derived from the Purucker model [2] at 30 km altitude above the lunar surface is depicted in Figure 1. The black dotted lines depict the trajectory, while the red dot is the periapsis of the satellite (~ 68 km). During the observation of the ESWs, the satellite was in the day side and in the pristine solar wind.

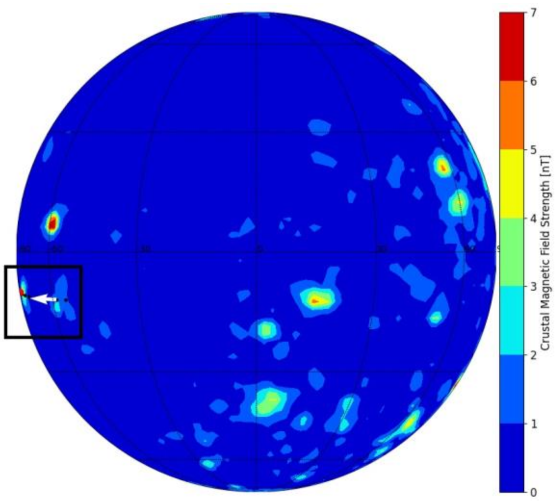

Figure 1: The trajectory of ARTEMIS P1 (black dots) plotted over the global magnetic field strength map derived from Purucker model at 30 km. The red dot depicts the periapsis of the flyby (~ 68 km) and the arrow indicates the satellite traversal direction.

The traversal of the satellite over the LMA is observed in the form of fluctuations in the magnetic field data from FGM. When the ESWs were observed two counter-streaming electron beams with energies around (10-100) eV was found to exist from the pitch angle distribution. The same can be observed from the parallel (0-15^{o} pitch angle) and anti-parallel (165-180^{o}) electron energy spectrograms as shown in Figure 2.

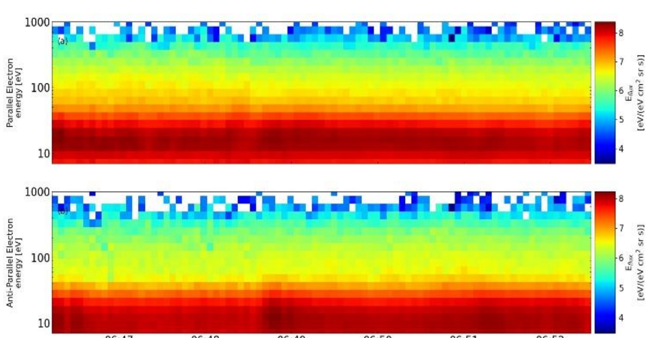

Figure 2: Electron spectrogram [eV/ (cm2 s sr eV)] for electrons propagating parallel (0-15^{0} pitch angle) and anti-parallel (165-180^{0} pitch angle).

The analysis of the plasma parameters was carried out in SSE coordinate system. The origin of the SSE system is at the center of the Moon and x-axis is along the Sun, z-axis is parallel to the ecliptic and y-axis completes the right-handed system. From, the FGM data, we observed the magnetic field in the positive x-direction (B_x) dominated. Thus, the electrons streaming with pitch angle ~ 180^{0} is the incoming solar wind. The electrons streaming with ~ 0^{0} pitch angle can be inferred to be mirror-reflected electrons over the LMA.

We observed isolated bipolar waveforms in the electric field parallel to the ambient magnetic field with amplitude ~ (1-3) mV/m as depicted in the Figure 3. As no significant fluctuations from the magnetic field data (SCM) was observed, we infer the waves to be electrostatic in nature. The electric field power spectrum obtained using the Fast Fourier Transform (FFT) of the electric field data, shows that the waves have frequency between ~ (20 Hz - 6 kHz).

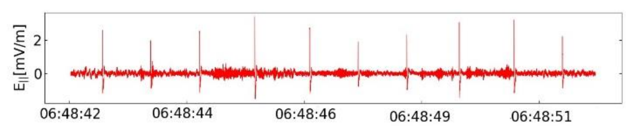

Figure3: Electrostatic solitary waves observed by the EFI instrument onboard the ARTEMIS P1.

3. Summary

We have observed electrostatic solitary waves generated over the lunar magnetic anomaly by virtue of counter streaming electrons beam. The solar wind electrons counter streams with respect to the mirror reflected electrons over the anomaly region. The parallel electric field amplitude of the ESWs varies from ~ (1-3) mV/m with frequencies ~ (10 Hz – 6 kHz). The interaction of these observed ESWs with the background plasma can play a pivotal role in acceleration and heating of the particles over the crustal magnetic anomaly regions.

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5. References

1. R. M. Killen and W. H. Ip, “The surface-bounded atmospheres of Mercury and the Moon”, *Reviews of Geophysics*, 37, 3, August 1999, pp. 361-406.

2. M. E. Purucker and J. B. Nicholas, “Global spherical harmonic models of the internal magnetic field of the Moon based on sequential and co-estimation approaches”, *Journal of Geophysical Research*, 115, E12007, 2010, doi:10.1029/2010JE003650.

3. H. Tsunakawa, F. Takahashi, H. Shimizu, H. Shibuya, and M. Matsushima, “Surface vector mapping of magnetic anomalies over the Moon using Kaguya and Lunar Prospector observations”, *Journal of Geophysical Research: Planets*, 120, June 2015, pp. 1160-1185, doi:10.1002/2014JE004785.

4. N. F. Ness, K. W. Behannon, H. E. Taylor, and Y. C. Whang, “Perturbations of the interplanetary magnetic field by the lunar wake”, *Journal of Geophysical Research*, 77, 11, June 1968, pp: 3421-3440.

5. K. W. Ogilvie, J. T. Steinberg, R. J. Fitzenreier et al., “Observations of the lunar plasma wake from the WIND spacecraft on December 27, 1994”, *Geophysical Research Letters*, 23, 10, May1996, pp. 1255-1258.

6. A. Bhardwaj, M. B. Dhanya, A. Alok, S. Barabash, M. Wieser, Y. Futaana et al., “A new view on the solar wind interaction with the Moon”, *Geoscience Letters*, 2, 10, 2015.

7. Y. Saito, S. Yokota, T. Tanaka, K. Asamura, M. N. Nishino, et al., “Solar wind proton reflection at the lunar surface: low energy ion-measurement by MAP-PACE onboard SELENE (KAGUYA)”, *Geophysical Research Letters*, 35, L24205, 2008.

8. D. J. McComas, F. Allegrini, P. Bochsler, P. Frisch, “Lunar backscatter and neutralization of the solar wind: First observations of neutral atoms from the Moon”, *Geophysical Research Letters*, 36, L12104, 2009, doi:10.1029/2009GL038794.

9. P. Wurz, U. Rohner, J. A. Whitby et al., “The lunar exosphere: the sputtering contribution”, *ICARUS*, 191, 2, 2007, pp: 486-496

10. M. N. Nishino, K. Maezawa, M. Fujimoto, Y. Saito et al., “Pairwise energy gain-loss feature of solar wind protons in the near-Moon wake”, *Geophysical Research Letters*, 36, L12108, 2009.

11. M. N. Nishino, M. Fujimoto, K. Maezawa, Y. Saito et al., “Solar-wind proton access deep into the near-Moon wake”, *Geophysical Research Letters*, 36, L16103, 2009.

12. M. Weiser, S. Barabash, Y. Futaana, et al., “First observation of a mini-magnetosphere above a lunar magnetic anomaly using energetic neutral atoms”, *Geophysical Research Letters*, 37, L05103, 2010.

13. C. Lue, Y. Futaana, S. Barabash, M. Wieser et al., “Strong influence of lunar crustal fields on the solar wind flow”, *Geophysical Research Letters*, 38, L03202, 2011.

14. Y. Saito, M. N. Nishino, M. Fujimoto, et al., “Simultaneous observation of the electron acceleration and ion deceleration over the lunar magnetic anomalies”, *Earth, Planets, Space*, 64, 2012, pp: 83-92.

15. G. S. Lakhina, S. V. Singh, R. Rubia, and T. Sreeraj, “A review of nonlinear fluid models for ion-and electron-acoustic solitons and double layers”, *Physics of Plasmas*, 25, 080501, 2018.

16. K. Hashimoto, M. Hashitani, Y. Kasahara, Y. Omura et al., “Electrostatic solitary waves associated with magnetic anomalies and wake boundary of the Moon observed by KAGUYA”, *Geophysical Research Letters*, 37, L19204, 2010.

17. D. M. Malaspina and I. H. Hutchinson, “Properties of electron phase space holes in the lunar plasma environment”, *Journal of Geophysical Research: Space Physics*, 124, 2019.

18. J. W. Bonnell, F. S. Mozer, G. T. Delory et al., “The Electric Field Instrument for THEMIS”, *Space Science Reviews*, 141, 2008, pp:303-341.

19. H. U. Auster, K. H. Glassmeier, W. Magnes, et al., “The THEMIS Fluxgate Magnetometer”, *Space Science Reviews*, 141, 2008, pp: 235-264

20. A. Roux, O. L. Contel, C. Coillot, et al., “The search coil magnetometer for THEMIS”, *Space Science Reviews*, 141, 2008, pp:265-275.

21.J. M. McFadden, C. W. Carlson, D. Larson et al., “The THEMIS ESA Plasma instrument and in-flight calibration”, *Space Science Reviews*, 141, 2008, pp. 277-302.