Effect of the Earth's Magnetosphere on the Lunar Wake

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Abstract

The main goal of this research is to investigate the physical structure of space plasma around the Moon. The moon, which is an obstacle in front of the solar wind, surrounds by solar wind plasma and this plasma displays different physical characteristics on the day and night sides of the Moon. The properties of this plasma surrounding the Moon, the behavior of the lunar wake, and how it depends on the solar wind parameters have not been revealed yet. For this purpose, ARTEMIS spacecraft have been placed in orbits to provide a more precise understanding of the physical structure of the plasma around the moon. In this study, we examined the similarities and differences of the lunar wake behavior when the Moon is inside and outside of the magnetosphere via ARTEMIS spacecraft, when one of the spacecraft takes measurements in the lunar wake while the other directly takes solar wind data.

1 Introduction

The space near the Moon displays different physical properties on the day and night sides. On the night side of the Moon, the flow of the solar wind creates a plasma cavity which is called lunar wake (LW) [1]. Y.C. Wang developed a theory to explain the observational values of the magnetic field and plasma behavior that surrounds the Moon [2] using Maxwell equations and determined that the magnetic field perturbations are limited to the region within the Mach cone.

The formation of the plasma surrounds the moon was previously thought from a magnetohydrodynamic (MHD) perspective. With WIND observations, the idea of LW forming by kinetic processes is emerged. Owen et al. and Bosqued et al. analyzed data from WIND spacecraft in plasma region. Their observations revealed that the of kinetic processes are important in the plasma region surrounding the Moon [3,4,5]. It was suggested by Farell et al that particle dynamics play an active role in the physics of the LW and ion sonic velocity may have more effective role in defining the LW rather than magneto sonic velocity [6]. In 2012 Nishino et al. and Holmstrom et al. reported that solar wind plasma density at night side is less frequent than the day side, as the Moon blocks the solar wind plasma. They also stated that the plasma environment in the LW can be negatively charged in the wake region, as the high energy solar wind electrons can easily reach the night side of the Moon. Halekas et al. see the Moon's plasma environment as a natural plasma physics laboratory. There are many kinetic processes in solar wind-Moon interaction that cannot be defined by fluid models [3, 7 and in references].

Observations made with the WIND spacecraft emphasized that the plasma kinetic effects should be taken into account in solar wind-Moon interaction. With the launch of ARTEMIS spacecraft, properties of the plasma environment around the Moon can be observed with more and precise data [8].

In this study, we compared the properties of the LW when the Moon is inside and outside of Earth's magnetosphere, using the ARTEMIS B and ARTEMIS C spacecraft which orbiting the Moon, we specifically showed the difference in the Mach cone angle.

2 Data and Methodology

ARTEMIS spacecraft THEMIS B (THB) and THEMIS C (THC) orbit the moon, around 60 Earth radii (R_E) far from the Earth. They spend about four days each on the Earth's magnetotail and magnetosheath as these spacecraft spin in their orbits. These spacecraft pass through the shadow of the Moon in about an hour and stay in solar wind plasma for about 20 days [9,10]. For this reason, ARTEMIS data are used to understand the physical structure of space plasma that encounters the lunar barrier around the moon.

We analyzed the solar wind parameters (Velocity Components (v_x,v_y,v_z), Density, Average Temperature, and Magnetic Field Components (B_x,B_y,B_z)) from the Electrostatic Analyzer (ESA) and Mission Operations Manager (MOM) device by using Space Physics Environment Data Analysis Software (SPEDAS) V3.1. This IDL based software is accessible at the following link: http://themis.igpp.ucla.edu/software.shtml. We analyzed parameters 40 minutes before and after the spacecraft crossing over the LW area. Also, we took the locations of the THEMIS spacecraft on those times from following link: http://themis.ssl.berkeley.edu.

ARTEMIS spacecraft were inside in magnetosphere in one of our observations and outside in the other. In both observations, one of the spacecraft is mostly in LW while the other is mostly not. The reason for this is to provide the conditions suitable for calculating the sonic Mach number, which is a dimensionless quantity in representing the ratio of the velocity of the flow passed a boundary to the speed of sound in that medium [11]. Ion Thermal Mach Number, which denoted by S, can be calculated as follows [12].

$$S = \frac{v_0}{v_{ti}} \quad (1)$$

In this equation v_0 is velocity of the plasma in the environment observed by a spacecraft inside the LW and v_{ti} is ion thermal velocity. We can easily calculate the speed of sound (v_s) in the investigated environment:

$$v_s = \sqrt{\frac{5k_B(T_i+T_e)}{3(m_i+m_e)}} \quad (2)$$

Respectively k_B , T_i , T_e , m_i , m_e *is* Boltzmann constant, ion temperature, electron temperature, ion mass, electron mass. The sonic Mach number can be calculated as function of v_s:

$$M_s = \frac{v_0}{v_s} \quad (3)$$

As Landau and Lifshitz showed; steady, supersonic flows can be described easily as a simple wave function [13]. We calculate the angle that LW makes with the solar wind, from now on we will call this calculation the Mach cone angle, in order to change Wolf's approach. Assuming that the region where the LW begins is located close to supersonic flow characteristic, the Mach Cone angle for sonic velocities is as follows:

$$\theta = \arcsin\left(\frac{1}{M_s}\right) \quad (4)$$

The angle θ could be seen in the Figure 1, the angle between undisturbed solar wind and the LW is 5°.

3 ARTEMIS Observations

In our research, we used two different dates, one inside the Earth's magnetosphere and one outside. While the Moon is inside of the magnetosphere, the date is December 14, 2019, while outside the date is December 26, 2019, in the Figure 1.

3.1 December 14th, 2019

In Figure 2a, the positions of the THB and THC spacecraft in the Selenocentric Solar Ecliptic coordinate system (SSE), THB passes from the night side of the Moon to the day side of the Moon, with no more than 3 moon radii from the Moon while in LW and THC starts from the dayside of the Moon and reaches approximately the terminator in the +y direction in the SSE coordinate system. In Figure 2b, the positions of THB and THC in the Earth centered coordinate system are given between 02:00 to 04:00 UTC on 14 December 2019. In Figure 2b, for the same dates and times as in Figure 2a, the Moon, the THB and THC, the Earth, the Earth's magnetopause, and the Bowshock are shown in the Geocentric Solar Magnetospheric coordinate system (GSM). The Moon, and therefore the THB and THC are in the magnetosphere.

In Figure 2c, we see the data of THB and THC spacecraft from 01:35:04 to 04:00. Until 02.15, when THC enters the LW; since THC and THB spacecraft are out of the LW, their data are similar, as expected. We see the similarity of the data received by the spacecraft from 03:07 until the end of the graph. When the values seen in the graphs between 02:14 to 03:08 UTC are written in their places in the above equations, it will be seen that the M_S and S numbers are close to each other. Besides, the data of THB in this range are the data we expect to see when THB is in LW during the measurement, especially the decrease of the ion density. Besides, the data of THB in this range are the data we expect to see when THB is in LW during the observation, especially the decrease in the ion density.

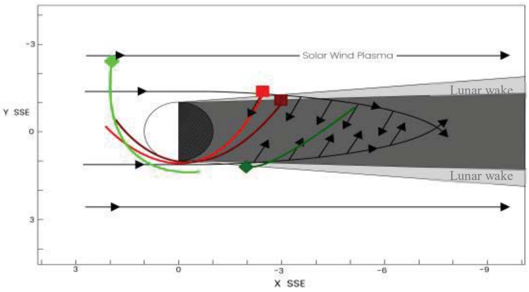

Figure 1. Illustration of the orbits of THEMIS spacecraft and distributions of the magnetic field in the LW projected on x-y plane in SSE coordinate system. The light red line represents THB and the light green line represents THC at 02.00-04.00 UTC interval on 14 December 2019, while the dark red line represents THB and the dark green line represent THC at 14.00-16.00 UTC interval on 26 December 2019. Light grey area represents LW and dark grey area represents the light shadow of the Moon.

The spikes in electron density between 02:15 and 02:22 and between 03:07 and 03:12 exactly coincide with the wake limits, which can cause increases in the electric field. Component B_y drew a complete wave graph that went from positive to negative, back to positive, with a sudden change, it turned to positive for the last time and returned to its normal state, the B_x component reached positive values and turned negative, while the B_z remains approximately constant since there was no acceleration.

3.2 December 26th, 2019

In Figure 3a the positions of the THB and THC in the SSE, and in Figure 3b the positions THB, THC, the Moon, the Earth, the Earth's magnetopause, and the Bowshock are shown in the GSM are given between 14:00 to 16:00 UTC on 26 December 2019. As seen in Figure 3a, THB moves through the LW while moving from the night side of the Moon to the day side, while THC moves from the day to the night side. The authors recommend examining other axes to avoid misunderstanding the trajectory of the THC.

In Figure 3b, it could be seen that the Moon, and therefore the THB and THC spacecraft are outside of the magnetosphere, even there was a Lunar Eclipse early on that day. When we examine Figure 3c, we see the data of THB and THC spacecraft between 13:35:04 and 16:00. All data in Figure 3c of the THC, which is not affected by LW, and THB, which will enter LW, are pretty much similar as

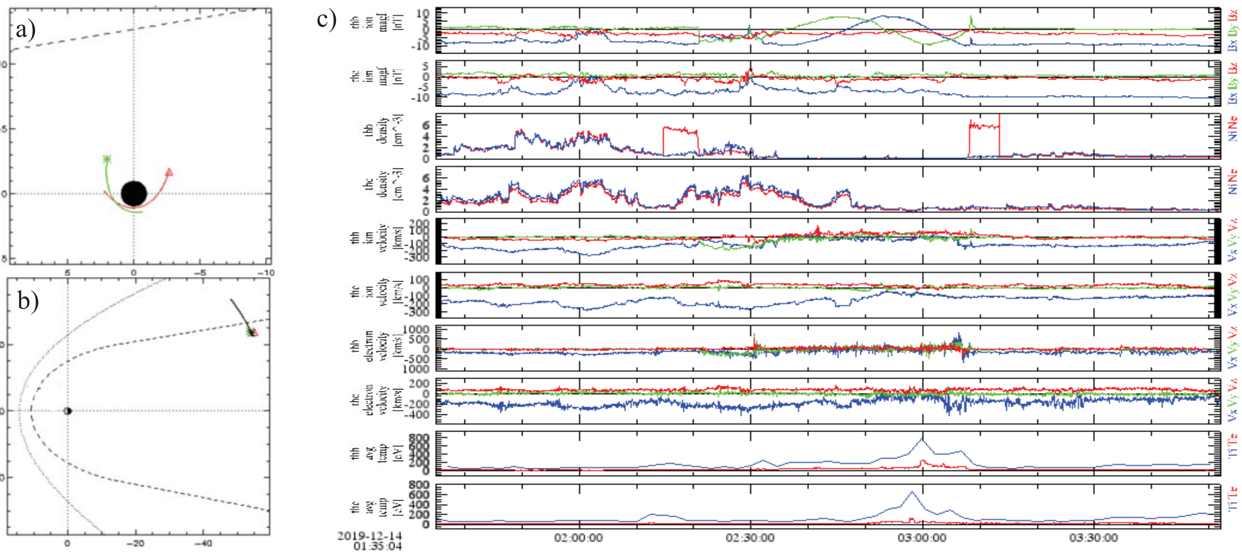

Figure 2. a) The orbits of THB and THC projected 02.00-04.00 UTC interval on 14 December 2019, where the object in the origin in the figures on the top line is representing the Moon, the red triangle is representing THB, the green asterisk THC on the x-y plane in SSE. b) Where object in the origin in the figures on the second is representing the Earth, asterisk is Moon, dotted lines are Bow Shock, dashes are Earth's magnetopause on x-y plane in GSM. c) An overview plot of THB and THC observations of the solar wind flow and magnetic fields measured in 14.12.2019 between 01:35:04 to 04:00 UTC while Moon's inside of the Earth's Magnetopause. From the top to bottom panels show the following respectively: ion B_x,B_y,B_z, (nT) for THB and THC in DSL coordinate system, ion and electron densities(cm^{-3}) for THB and THC, ion v_x, v_y and v_z, (km/s) for THB and THC in DSL coordinate system, electron v_x, $v_{y,}$ and v_{z},(km/s) for THB and THC in DSL coordinate system, average temperature (eV) of ion and electron for THB and THC.

expected up to 14:12 because both spacecraft are outside of the LW. We see the similarity of the data received by the spacecraft from 15:09 until the end of the graph. When the values seen in the graphs between 14:12 to 15:09 UTC are written in their places in the above equations, although Thermal Mach Number and Mach Number are slightly different than the value which we calculated in the first date, it will be seen that the Mach number and the Thermal Mach number are still quite close to each other.

Even values such as the number density of both electrons and ions, magnetic fields, and velocities are different than the first date, the behavior of the data between these two situations are similar. On the same date, the values inside of the LW are the same as the values we expect to see when THB is in LW, especially when the ion density decreases this much. The spikes in electron density between 14:08 and 14:12 and between 15:09 and 03:12 exactly coincide with the LW boundaries, which can cause increases in the electric field, as expected from the first graphic. We see waves in the magnetic field here too, this time faster. Although the Z component behaves similarly to that measured by the spacecraft outside of LW, the X and Y components can be said to draw one and a half waves, unlike the previous one. Even more interesting is that, as can be easily read from the graph, the ion velocity components and the change in the magnetic field are in a linear relationship to each other. Both have wave action at almost the same time, which is not what we saw in the first graph. The fluctuation in electron velocity may indicate intense electron turbulence in the measured region.

4 Discussion and Conclusion

We investigated behavior of the solar wind plasma around the Moon when the Moon is inside and outside of the Earth's magnetosphere. We encountered differences in some basic behaviors, such as the linear relationship between the particles that make up the solar wind and its magnetic field when the Moon is outside of the magnetosphere. Change in y component of the magnetic field (wavelength) is smaller when the Moon is outside of the magnetosphere rather than inside of the magnetosphere, we cannot clearly attribute this to whether it is inside or outside of the magnetosphere, and this may be due to the entry angle of the studied satellite into LW. More precise interpretations can be made with more observations and simulations on different dates.

Although the Mach number is expected to be lower because the particle temperature in the magnetosphere is much higher than outside, there is not much difference since the flow velocity is slower, because the thermal Mach cone angle is proportional to the velocity divided by temperature of the plasma, we could not observe an extreme magnitude difference in the Mach cone either. Additionally, we have seen that the fluctuation in electron velocity is much greater when the Moon is outside of the magnetosphere. To study the turbulence of electrons, one can solve MHD equations for the behavior of the Solar Wind, when the Moon is inside and outside of the magnetosphere. Turbulence can be investigated by calculating the Magnetic Reynolds number, which is particularly related to the irregularity of the flow.

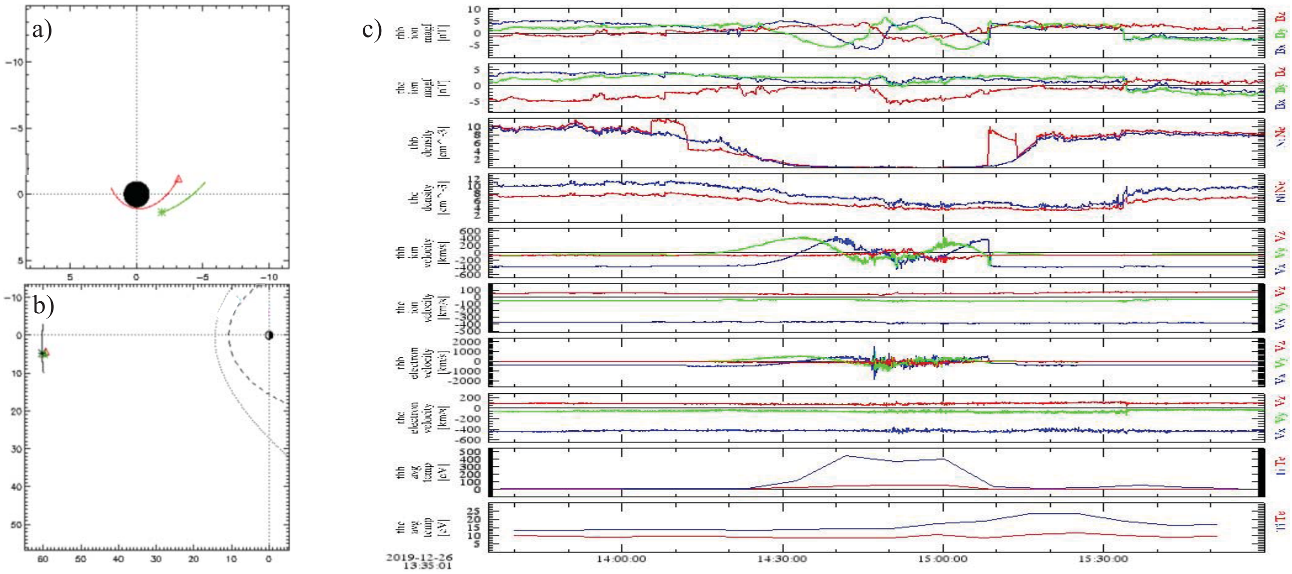

Figure 3. a) The orbits of THB and THC projected 14.00-16.00 UTC interval on 26 December 2019, where the object in the origin in the figures on the top line is representing the Moon, the red triangle is representing THB, the green asterisk THC on the x-y plane in SSE. b) Where object in the origin in the figures on the second is representing the Earth, the black asterisk is Moon, dotted lines are Bow Shock, dashes are Earth's magnetopause on x-y plane in GSM coordinate system. c) An overview plot of THB and THC observations of the solar wind flow and magnetic fields measured in 26.12.2019 between 13:35:01 to 16:00 UTC while Moon's outside of the Earth's Magnetopause. Panels are the same as for Figure 2c.

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