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COMMENT

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This article is a comment on Omidi et al. (2019), https://doi.org/10.1029/2018JA026243.

Key Points:

- ARTEMIS P2 ion moments in Omidi et al. (2019) are incorrectly calculated during wake crossing
- Additional population of energetic ions is not required to accurately model the lunar wake
- Energetic solar wind ions do not dominate the structure of the lunar wake

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Comment on "The Dominant Role of Energetic Ions in Solar Wind Interaction With the Moon" by Omidi et al.

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Abstract Omidi et al. (2019) recently published a case study analysis of the lunar wake crossing by the ARTEMIS P2 spacecraft that occurred on 24 June 2015 by comparing P2 observations of plasma and magnetic fields in the lunar wake with a hybrid plasma model using upstream plasma conditions measured by ARTEMIS P1. As presented in Omidi et al., the ARTEMIS P2 ion moments during the lunar wake crossing show anomalously high temperatures and low velocities. This is due to both the lack of subtraction of background counts from penetrating radiation and the application of moment analysis during times when no ion flux was observed by ARTEMIS P2. Additionally, the hybrid results show large discrepancies with the ARTEMIS data, from which Omidi et al. concluded that an additional smaller population of suprathermal ions was required to accurately reproduce the ARTEMIS observations. This conclusion is at odds with previous investigations and, thus, deserves further study. Here we have used the Amitis hybrid plasma model to simulate the lunar wake with upstream plasma conditions determined from the ARTEMIS P1 reference observations, identical to those used in the Omidi et al. "Run-0" hybrid model. We found that the Amitis hybrid model can successfully reproduce the structure of the lunar wake and the ARTEMIS P2 observations with good fidelity, without the inclusion of any additional high energy ion populations. We therefore conclude that energetic ions do not dominate the structure and behavior of the lunar wake, in contrast to the conclusions of Omidi et al.

1. Introduction

The fundamental mode of interaction between the Moon and the solar wind is the formation of a downstream plasma wake, caused by solar wind particle absorption by the upstream lunar hemisphere (e.g., Halekas et al., 2015). The lunar wake has been observed by numerous spacecraft including Explorer 35 (Colburn et al., 1967; Ness et al., 1968), Wind (Bale et al., 1997; Farrell et al., 1996; Farrell et al., 1997; Ogilvie et al., 1996; Owen et al., 1996), Lunar Prospector (Halekas et al., 2005), Kaguya (Nishino, Fujimoto et al. 2009; Nishino, Maezawa et al. 2009), Chandrayaan (Dhanya et al., 2016; Futaana et al., 2010), and ARTEMIS (Halekas et al., 2011, 2014; Zhang et al., 2012, 2014, 2016). These missions have provided a wealth of observational data that have in turn been used to define the lunar wake structure in both case-by-case studies and statistically averaged maps. Furthermore, these data have been compared to numerous simulations, including magnetohydrodynamic (Xie et al., 2012), hybrid (Fatemi et al., 2012; Holmström et al., 2012; Poppe et al., 2014; Wang et al., 2011; Wiehle et al., 2011), and particle-in-cell studies (Farrell et al., 1998), which, along with more theoretical studies (e.g., Hutchinson, 2013; Kallio, 2005; Michel, 1968; Trávniček et al., 2005; Vernisse et al., 2013) have established a data-validated global picture of the lunar wake.

The results of Omidi et al. (2019) stand in sharp contrast to these previous works by (i) claiming that ARTEMIS P2 observations of ion moments in the lunar wake show extremely high temperatures ($T_i \approx 2$ keV) and low velocities ($v_i \approx 100$ km/s) and (ii) suggesting that a high energy component of the solar wind distribution is responsible for the structure of the lunar wake, instead of the core solar wind ion population. As we discuss in detail below, both of these conclusions are erroneously drawn due to technical errors in the data analysis of ARTEMIS observations and incorrect treatment of vacuum regions in the hybrid modeling.

2. ARTEMIS Data Analysis

We note here two points of concern regarding the analysis of ARTEMIS P2 observations on 24 June 2015. First, several solar flares erupted 21–25 June 2015, and at approximately 13:30 UT on 24 June 2015, an associated coronal mass ejection arrived at the Earth/Moon system (Baker et al., 2016; Gopalswamy et al.,

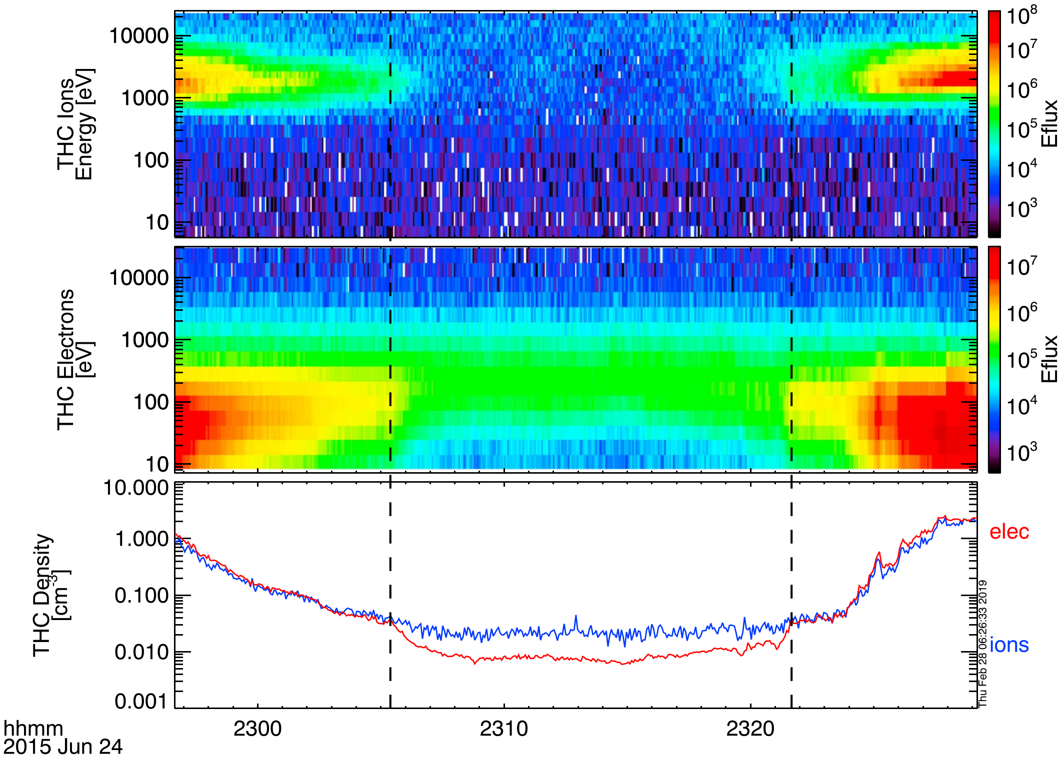

Figure 1. The ARTEMIS P2 (THC) ion energy spectrum, electron energy spectrum, and ion and electron densities during the 24 June 2015 P2 lunar wake crossing. Vertical dashed lines denote the time period between which the calculated ion and electron densities disagree, in turn denoting the period during which the ARTEMIS ion ESA is only measuring background counts.

2018; Piersanti et al., 2017) and was observed by both ARTEMIS probes. Elevated densities and temperatures persisted for more than 24 hr, including during the 24 June 2015 wake crossing by ARTEMIS P2. While the upstream conditions during the P2 wake crossing itself were reasonably steady, it should be noted for clarity that such conditions are not considered “nominal” solar wind.

Second, the data analysis of the THEMIS/ARTEMIS Electrostatic Analyzer (McFadden et al., 2008, 2008) performed in Omidi et al. (2019) has not taken into account a proper subtraction of background counts from the instrument, which has yielded spurious values for the ion moments observed by P2. During wake crossings, especially at low lunar altitudes, much, if not all of the core solar wind has been absorbed by the Moon. Leaving open the possibility that high energy ions can gyrate into the wake (Dhanya et al., 2016; Nishino, Fujimoto et al. 2009), one must note that with primary ion fluxes decreasing, background noise from penetrating radiation increasingly dominates the observed ElectroStatic Analyzer (ESA) counts. This background contamination appears as an isotropic signal across all energies and, if not properly subtracted, typically yields high temperatures (since there are background counts at all energies) and low velocities (since penetrating radiation appears isotropic). No such subtraction was performed by Omidi et al. (since they state that they used onboard calculated moments), and thus, the ion velocity and temperature moments presented in their Figures 1 and 3 should be considered suspect.

We can assess the degree of background count contamination on the ESA ion observations by comparing ESA ion and electron measurements during the wake crossing. Figure 1 shows the ARTEMIS P2 ion energy spectrum, electron energy spectrum, and electron and ion density moments, for the 24 June 2015 P2 wake crossing. On the ingress and egress wake flanks, the ion and electron density moments agree very well, tracking even small perturbations together (e.g., at 23:25 UT). Within the core of the wake (denoted by the vertical dashed lines), however, the ion density moment flatlines at ≈ 0.02 cm^{-3}, while the electron density moment continues to decrease to a minimum of ≈ 0.007 cm^{-3}. The ion ESA instrument has thus reached the lower noise floor due to penetrating radiation, while the electrons, as a lighter, more mobile species, have greater flux than ions at equivalent densities and still continue to register appreciable, physical counts in the electron ESA instrument (one can also see the persistent electron fluxes across the lunar wake in the electron

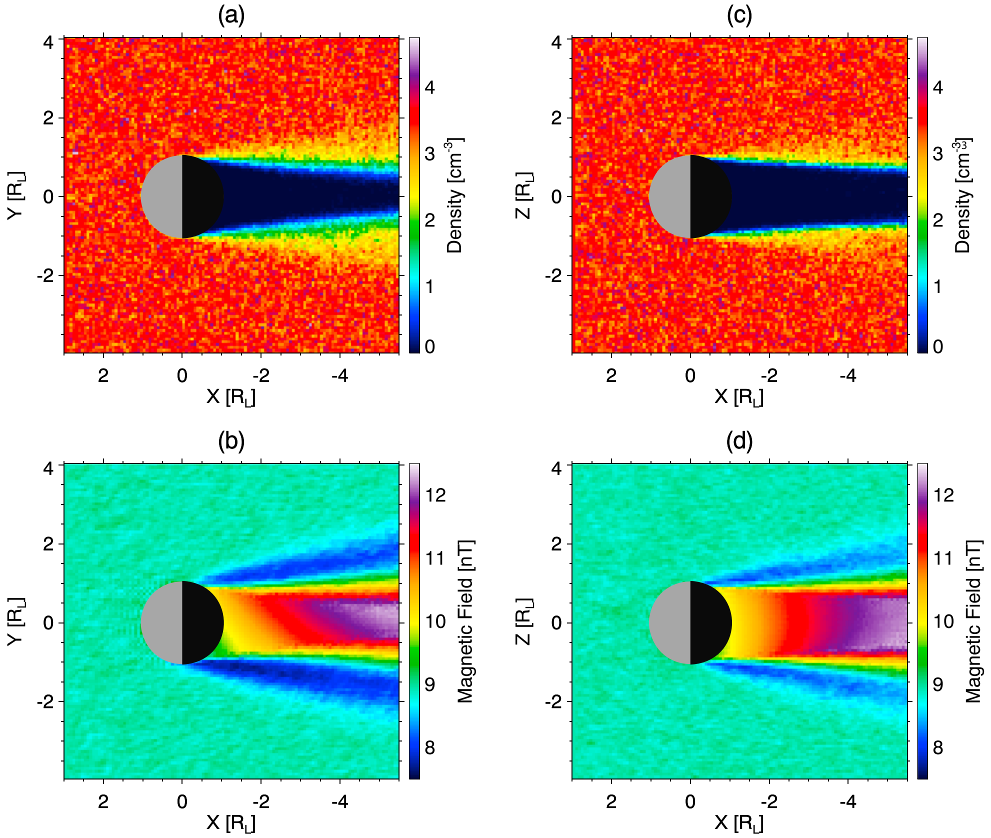

Figure 2. The density and magnetic field magnitude from the Amitis hybrid model in (a,b) the rotated X-Y plane and (c,d) the rotated X-Z plane.

energy spectrum). Based on this analysis, we conclude that the ion moments presented in Omidi et al. from the ARTEMIS P2 ESA observations during the lunar wake crossing are entirely spurious and should not be taken as evidence of a high energy population of solar wind ions accessing the lunar wake. Importantly, we wish to note that we do not argue that high energy ions cannot access the lunar wake (as indeed they can), but only that the ARTEMIS ESA instrument does not provide evidence of their existence within the wake in this case.

3. Hybrid Modeling of the Lunar Wake

In addition to the analysis of ARTEMIS observations, we also wish to comment on the simulation results from Omidi et al. (2019), which show significant differences in the basic structure of the lunar wake compared to previous hybrid models. We have used the Amitis hybrid plasma model (Fatemi et al., 2017) to simulate the interaction of the Moon with the ambient plasma on the 24 June 2015 date studied by Omidi et al. As described in Fatemi et al. (2017), Amitis is a standard, three-dimensional hybrid model of plasma (particle ions and fluid electrons) adapted to run on a single central processing unit-graphics processing unit (CPU-GPU) pair. Amitis has been rigorously benchmarked against standard metrics for hybrid models (Fatemi et al., 2017) and previously used to model the solar wind interaction with the Moon with comparisons to ARTEMIS observations (Fatemi et al., 2017), asteroid 16 Psyche (Fatemi & Poppe, 2018), and Mercury (Fatemi et al., 2018). We used upstream plasma parameters identical to that used in Omidi et al.'s Run 0, including an upstream density of 3.5 cm^{-3}, flow velocity of 610 km/s, and ion and electron temperatures of 22 eV. Similar to our previous work in performing data-model comparisons of the lunar wake (Poppe et al., 2014), we rotated the observed interplanetary magnetic field (IMF) such that we eliminated the off-axis solar wind velocity components and the out-of-ecliptic magnetic field components. This yielded an effective upstream interplanetary magnetic field of [−8.1, 3.8, 0.0] nT. The simulation domain extends from $-5 < X < +3$ R$_L$ and $-4 < Y, Z < +4$ R$_L$ with cell sizes of 125 km. The Moon is a fully resistive plasma absorber with radius set to $R_L = 1,750$ km. The model used approximately 5×10^6 macroparticles (all pro-

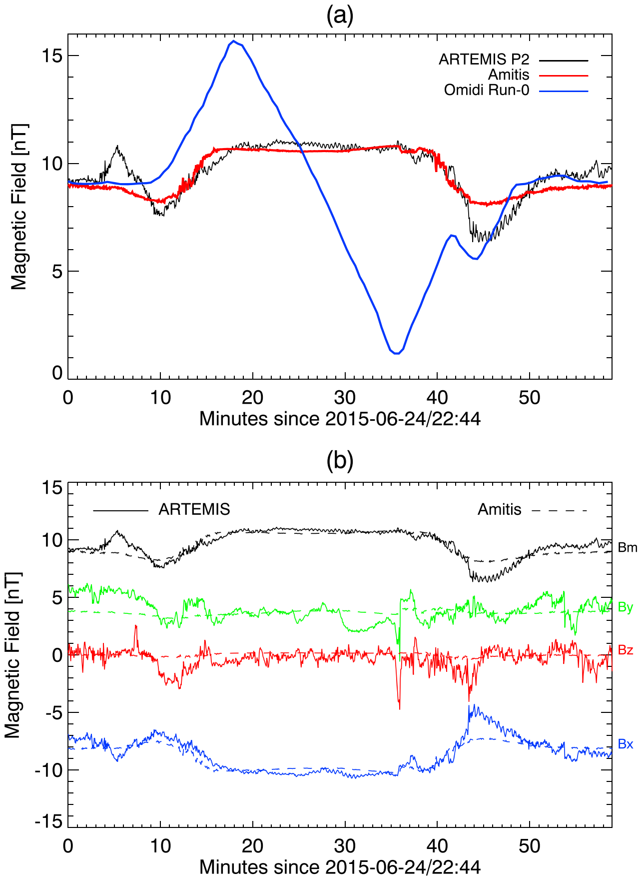

Figure 3. (a) A comparison of ARTEMIS P2 magnetic field magnitude with the Amitis results and the Omidi et al. Run-0 results. (b) A comparison of magnetic field magnitude and components between the ARTEMIS P2 observations and the Amitis hybrid results.

tons) and was run for $t = 75$ s or approximately 87 ion gyroperiods, ensuring that the simulation came to steady state.

Figure 2 shows the Amitis hybrid simulation results for the inputs described above. Figures 2a and 2b show the plasma density and magnetic field in the rotated X-Y plane, respectively, while Figures 2c and 2d show the same quantities in the rotated X-Z plane, respectively. The structure of the lunar wake in these results is in general agreement with previous hybrid models of the lunar wake (Fatemi et al., 2013; Holmström et al., 2012; Kallio, 2005; Poppe et al., 2014; Vernisse et al., 2013; Wang et al., 2011). The solar wind is absorbed by the upstream surface of the Moon, leaving a deep plasma void extending more than 12 lunar radii downstream. Particle refilling of the wake is especially restricted in this case given the relatively field-aligned flow. The magnetic fields show the classic rarefaction wings spreading outward from the lunar wake (decreasing magnetic field strength down to ~7 nT) and the magnetic compression within the wake center (increasing magnetic field strengths peaking at over 12 nT). The Amitis simulations show no evidence of a “compressional wake” as noted by Omidi et al. in their Run 0, a feature that is typically associated with the presence of lunar crustal magnetic fields near the lunar limb that locally perturb and deflect the solar wind flow (Fatemi et al., 2014; Halekas et al., 2014; Russell & Lichtenstein, 1975). Neither Omidi et al. nor we have included such local perturbations, and thus, one should not expect to see any compressional features along the wake flank.

In particular, the Amitis results shown here in Figure 2 should be critically compared with Omidi et al.'s Run 0 (their Figure 3). The Omidi et al. Run-0 results show several anomalous and unexplained results, including (i) the lack of a compression in the central lunar wake (sometimes referred to as a “diamagnetic” enhancement), (ii) a deep minimum in the magnetic field in the lunar wake where the compression should be the strongest, (iii) a highly asymmetric “compressional wake” in both the X-Y and X-Z planes, and (iv) rounded features downstream of approximately 7 R_L (the lattermost presumably due to not running the simulation to steady state throughout the domain). Omidi et al. do not discuss these features in detail and do not compare their Run-0 results to previous hybrid runs of the lunar wake by others. After comparing their hybrid results along the ARTEMIS P2 trajectory to fields observed by ARTEMIS P2, Omidi et al. simply state only that, "we conclude that comparison between the simulation results and observations show little agreement between the two." Indeed, Figure 3a shows a comparison of the magnetic field magnitude from ARTEMIS P2, our Amitis run, and the Omidi et al. Run-0 results, while Figure 3b shows a component-by-component comparison between ARTEMIS P2 and Amitis. The Amitis results capture the rarefactions on both sides of the wake and the central compression of the magnetic field. Small discrepancies in the magnitudes of the rarefaction minima from the Amitis run are most likely due to the finite cell size (see similar discussion in Poppe et al., 2014). In contrast, the Omidi et al. Run 0 shows essentially no agreement with either the ARTEMIS P2 measurements or the Amitis results, despite the fact that the Amitis run and the Omidi et al. Run 0 used nearly identical upstream conditions.

4. Conclusion

Based on the misapplication of moment analysis with respect to the ARTEMIS ESA instrument and the lack of agreement between the Omidi et al. Run-0 and Amitis hybrid run or ARTEMIS P2 data, we conclude that the findings of Omidi et al., in particular with respect to the dominance of energetic ions on the structure of the lunar wake, are erroneous. Successful modeling of the lunar wake does not require the presence of an additional population of energetic ions; rather, the lunar wake is governed by the core plasma population. This is in agreement with a series of previous hybrid modeling studies of the lunar wake (Fatemi et al., 2013; Holmström et al., 2012; Kallio, 2005; Poppe et al., 2014; Vernisse et al., 2013; Wang et al., 2011). As we are not intimately familiar with the hybrid model of Omidi et al., we are hesitant to ascribe reasoning for the anomalous features observed in Omidi et al.'s Run 0; however, we suspect that the use of a cold, relatively dense (5% the upstream solar wind density), and "stationary" plasma (as clarified in Omidi et al.'s Reply) as a minimum density in the lunar wake is responsible. In essence, the hybrid model of Omidi et al. has placed plasma akin to a cold, dense planetary ionosphere within the vacuum regions of the lunar wake, which then prevents the IMF from properly convecting through the lunar wake vacuum, yielding the so-called "compressional wake" identified in the Omidi et al. Run-0 results. Furthermore, this then explains why the simulation results are apparently restored to agreement with previous modeling and ARTEMIS data when high energy ions are included, since the access of these ions into the lunar wake vacuum allows for sufficient conductivity that the IMF is no longer stagnated by the artificial cold, dense plasma placed in the lunar wake vacuum region. We also point out the need to run models to complete steady state throughout the simulation domain in order to ensure that all transient features have subsided and are no longer interfering with the physical system under study.

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