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Similarities in the Plasma Wake of the Moon and Space Shuttle

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As a result of the Wind spacecraft encounters with the moon, a new view of the lunar wake in the high-density solar wind plasma has emerged. Specifically, the lunar wake was considered to be magnetosonic in nature but is now demonstrated to be a kinetically driven structure filling in via ion sonic disturbances. The structure appears to be determined via kinetic plasma microinstabilities, rather than a bulk magnetohydrodynamic shock. Examining the specific structure, it becomes apparent that the lunar wake and that of the space shuttle have many similarities, suggesting that the shuttle wake is also driven via kinetic instabilities. Comparisons of the two wakes are presented in detail, illustrating the dominance of the kinetic phenomena in the replenishment of both plasma voids. The general concepts presented in this study have applications to other structures immersed in a plasma flow, including the space station.

Nomenclature

a	=	ion acoustic velocity, km/s
f_p	=	plasma frequency, Hz
L	=	shuttle length (largest dimension), km
n	=	electron density, cm^{-3}
R_o	=	radius of obstruction, km
r	=	radius, km
r_g	=	electron gyroradius, km
r_{gi}	=	ion gyroradius, km
T_a	=	ambient temperature, K
T_w	=	wake temperature, K
V_0	=	flow speed, km/s
v	=	velocity, km/s
v_{the}	=	electron thermal velocity, km/s
v_{thi}	=	ion thermal velocity, km/s
w	=	shuttle width, km
X_{conv}	=	converging distance, km
X_{max}	=	wake extent, km
X_{stream}	=	instability distance, km

Introduction

THERE has been much recent interest in the plasma wake formed by the moon's obstruction with the solar wind. A number of studies presented in the late 1960s suggested that the structure was magnetosonic in nature, described primarily by converging Alfvenic disturbances and the formation of a magnetohydrodynamic (MHD) shock region at the convergence point located a few lunar radii down the tail.[1,2] Unfortunately, no subsequent studies of the structure occurred for nearly 25 years, until the Wind spacecraft made a series of maneuvers near the moon for gravity-assisted trajectory alterations. During these swingbys, the moon became a target of scientific opportunity, now with modern and sensitive magnetic, radio, and particle packages.

Investigations from these Wind encounters with the moon reveal a new picture of the anomalous plasma structure in the high-density solar wind. Specifically, the lunar wake appears to be driven and defined by the kinetic microinstabilites formed at the wake edge and interior [3–6] in contrast to being a predominant MHD disturbance. Further, the variable of merit that defines the structure is now considered the ion acoustic speed rather than the Alfven speed.[3]

Figure 1 illustrates the current view of the lunar wake based on the numerous Wind studies. The figure has distinct similarities to the picture of the typical ion sonic wake in Ref. 7. The main conclusions include the following:

1) The wake has been observed as far as 23 lunar radii downstream and possesses density reductions by as much as a factor of 50 as near as 7 lunar radii.[3,8] Such an extended wake was not predicted via MHD analysis presented previously.[1] We describe these new observations later.

2) Wake-ward directed ion beams form at the wake flanks and move inward and are primarily responsible for replenishing the lost plasma. At the wake flanks a large electrostatic potential is created when the thermal electrons move into the void more readily than the initially undeflected streaming ions.[3,6,9] This potential occurs naturally to retard the thermal electron flow, but also acts to accelerate ions into the wake, thereby forming the wake-ward directed ion beams. These inward-propagating ion beams were observed during Wind passages of the wake[3] and have also appeared in almost identical form in two separate electrostatic simulation studies of the lunar wake.[6,10] The inward accelerated ion flow is consistent with numerous models of an ion sonic wake disturbance.[9–13] The most basic model assumes quasi neutrality with a derivable common parameter in the continuity and momentum equation. Such an analytical solution is called a "self-similar" model of the wake.[9] More advanced models include a relaxation of quasi neutrality.[6,10–13]

3) In the central wake, about 5 lunar radii downstream, the ion beams from adjacent flanks merge, forming two counterstreaming ion beams, a situation that is unstable to the ion acoustic instability.[5,6,12] In fact, broadband electrostatic turbulence was observed by Wind to increase in the central lunar wake, collocated exactly where the ion beams merged, and in association with an ion-ion beam instability. Electrostatic fluctuations are then found in an extended tail running down the length of the central wake region as a result of the instability associated with these counterstreaming, merged ion beams.[5] Evidence for these electrostatic fluctuations

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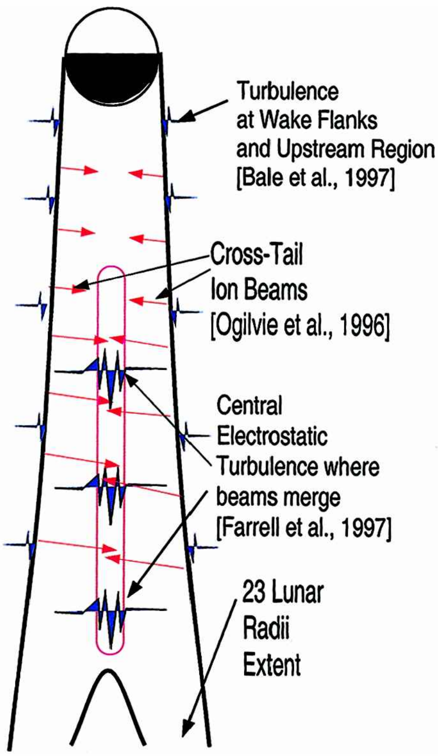

Fig. 1 Schematic illustration of the physical processes associated with the lunar wake. An ambipolar electric field at the wake flanks, caused by the quicker electron expansion into the void, accelerates ions into the central region (to form cross-tail beams). At locations where the beams merge, an electrostatic ion-ion beam instability occurs that acts to decelerate/stop the beams and thus replenish the wake plasma void.

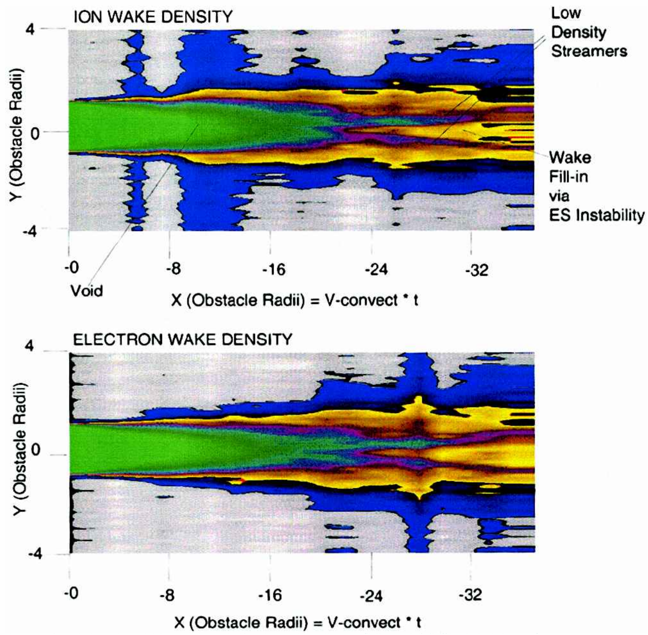

Fig. 2 Results of a particle-in-cell code of plasma expansion into a void, presented previously in Ref. 6. Note the long extension of the wake, to beyond 32 obstacle radii.

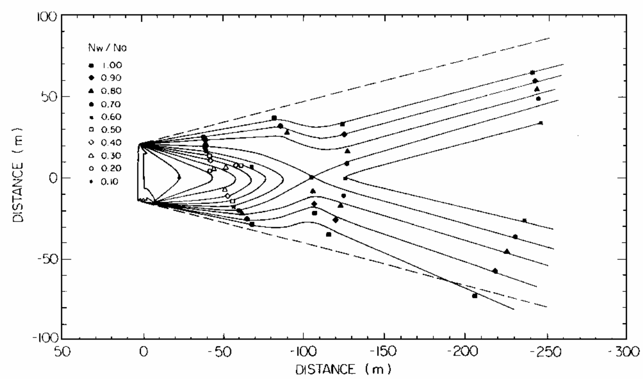

Fig. 3 Map of the shuttle wake (adapted from Tribble[15]) showing the low-density region trailing behind the shuttle. This map is based on Langmuir probe measurements located on an orbiting PDP that made several transits through the wake and vicinity.

exists in both Wind observations and two electrostatic simulations of the wake.

4) The electrostatic instability observed by Wind and replicated via simulations is critical for wake replenishment: It decelerates/stops the flank-created ion beams in the central wake region, thereby allowing them to fill in the plasma void.[5,6,10] Thus, the wake replaces its lost ions in two steps: The flank potential first creates an inward ion flow, and the central electrostatic instability then stops this flow for ion replenishment in the depleted tail. The region of ion deceleration in the tail starts in the central wake first, at the location of the initial beam merger, and moves increasing flankward from the center with increasing downstream distance. The result is the formation of two narrow filament structures (that is, density depletions) where the instability has yet to cause beam cessation. Figure 2 shows the electrostatic simulation of the plasma expansion into a void where these filaments (or low-density streamers) are quite clearly evident.[6]

Given the large number of lunar wake studies and the emerging kinetic picture of the structure, an obvious question remains: Is this a universal picture for all wakes formed in high-density plasma flows? An obvious comparison is the space shuttle that also forms a wake in the high-density ionospheric plasma.[14–17] During the 1985 Spacelab-2 (SL-2) flight of the shuttle, a small subpackage was released into a near-vicinity orbit of the shuttle. This Plasma Diagnostics Package (PDP), built at the University of Iowa, carried a Langmuir Probe, radio/plasma wave experiments, and particle experiments, and was specifically designed to measure the ionospheric plasma environment about the shuttle. In this presentation we will focus on the Langmuir probe measurements of shuttle wake density and temperature. The PDP also possessed a plasma wave instrument to measure electrostatic wave amplitudes.

An interesting result of the mission was the discovery by the PDP of an extended shuttle wake, measured as far as 250 m downstream. Given the irregular shape of the shuttle, an "obstacle radii" is difficult to define. The shuttle width is ~10 m (width of open payload doors) and its length is 35 m,[15] corresponding to an obstacle minimum radius of 5 m and maximum radius of 15 m. Figure 3 adapted from Ref. 16 shows a density map of the shuttle wake based on numerous PDP passages through the wake region. The downstream axis is defined as exactly opposite to the shuttle velocity vector $-\boldsymbol{v}$. Because the PDP made a series of cross-wake transits at various distances, measurements were also obtained in the wake flanks and wake central region.

Plasma expansion into a vacuum is a phenomena occurring in solar (flares), planetary (moons and satellites), ionospheric (spacecraft), and laboratory (obstacle) plasma environments. Reference 9 presented a substantial review of the subject, including a complete reference to previous theoretical studies. In this work they presented a unifying self-similar model, which suggests that wake-ward ion acceleration occurs at the wake flanks because of a potential that develops to retard the inward motion of faster thermal electrons. In this model an inward-propagating, ion beam defines plasma flow into the void. Associated with the expansion is an outward-propagating rarefaction wave that travels at the ion sonic speed back into the plasma medium. The self-similar picture has been demonstrated to explain the wake observations of both the lunar wake[3] and space shuttle wake.[14–17] Because the analytical self-similar solution necessarily requires limiting approximations (for example, quasi neutrality is enforced), one can learn more with a plasma simulation that allows neutrality to develop self-consistently by the dynamic interaction between electrons and ions. Plasma expansion into a void has been modeled analytically[12,13,17] and was recently modeled via

Table 1 Comparison of lunar and shuttle plasma flow environments

Object	Plasma flow V_0, km/s	Plasma frequency f_p, Hz	Cyclotron frequency f_c, Hz	f_p/f_c	Ion sound speed a, km/s	Electron thermal speed, km/s	Ion thermal speed, km/s	Sonic Mach V_0/a
Moon	450	20k	250	80	50	2800	20	9
Shuttle	7	2.8M	0.8M	3.5	1.6	180	1.1	4.8

particle-in-cell electrostatic simulation.[6,10] These self-consistent simulations reproduced the key features of the analytical self-similar solutions, including the development of cross-wake ion beams (see Fig. 2 of Ref. 6). In addition, they allow examination of the kinetic instabilities' effect on the plasma flow. The model results were compared with Wind observations of the lunar wake near 7 obstacle radii with very reasonable consistency (see Plate 3 of Ref. 6).

One can ask whether the plasma expansion model shown in Fig. 2 applies equally well to both the lunar and shuttle cases, simply by applying different flow (or convection) speeds. In other words, does the same general physics operate in the moon, shuttle, and simulated situations to create similar structures, with the structure location down the tail varying functionally with the applied flow speed in the given situation? This work will attempt to address that question. If the same physics is operating, then the model in Fig. 2 can be considered a common picture, with the tail extension a function of sonic Mach number. As such, we anticipate that much can be learned from a comparison of expansion processes associated with the shuttle, lunar, and simulated wakes.

Feature Comparisons

Table 1 compares and contrasts the magnetoplasma environments of the shuttle in the ionosphere and the moon in the solar wind. In the case of the lunar wake, the solar wind flows past the obstacle, whereas in the shuttle case there is orbital motion of the spacecraft in the quasi-static ionospheric environment. Even though the relative flow speed of the ionized gas past the obstructions is very different, the ion sound Mach numbers are not, both greatly exceeding unity. Also note from the table that the plasma-to-cyclotron frequency ratios in both cases are above unity (but much larger in the solar wind case). The lunar wake parameters were derived in Ref. 5, and the shuttle parameters were derived in Ref. 15.

Even though both the lunar and shuttle wakes have been previously identified as self-similar in nature,[3,15] the expansion also occurs in an ambient magnetic field that has an obvious effect on wake formation. For an insulating object with sonic Mach number greater than one, ions and electrons will be absorbed from the plasma leaving a trailing wake.[2] Exactly how the magnetoplasma reacts is a function of large number variables including the electron and ion gyroradius (r_g, r_{gi}, respectively). For objects smaller that an ion gyroradius, an electron disturbance develops forming a whistler-mode bow wave.[18,19] In both the lunar and shuttle cases the object in question is larger than the ion gyroradius ($r > r_{gi}$, r_{ge}), and thus both ions and electrons are disturbed. This disturbance couples more to an ion sonic mode. For the shuttle case $r_{gi} \sim 5$ m,[16] and the lunar case $r_{gi} \sim 50$ km. Further, in both cases the flow speed V_0 lies between the electron thermal and ion thermal speeds ($v_{the} \gg V_0 > v_{thi}$). The electron thermal speed is so large in comparison to V_0 that the electron gas can be considered a quasi-stationary but highly thermalized population. Because of the high thermal speed, the electrons immediately move into the void behind the object, these ahead of the slower, flowing ions. This electron flow initiates the self-similar expansion into the void. Specifically, the inflow of electrons ahead of the slower ions breaks quasi neutrality, and a cross-tail directed ambipolar electric field develops at the wake flanks. As long as this flank potential region is less than an ion gyroradii, the ions are simply deflected/accelerated into the void because of the qE force (see Fig. 3 of Ref. 3). The resulting ion flow from each flank appears as two separate counterstreaming ion beams along threading field lines.

Overall Extent

Although magnetohydrodynamic calculations of the lunar wake suggest a structure only 5 lunar radii in length,[1] Wind studies reveal a structure observable over 20 lunar radii downstream. Figure 4 shows a Wind/WAVES frequency-vs-time spectrogram during the lunar wake encounter at 0045 Univeral Time (UT) on 13 November 1996. Note that ion acoustic activity is observed in the central wake region, indicative of the presence of the electrostatic instability that slows the ion beams in the central region.[5] Emission at the local plasma frequency is labeled in the figure, and this emission is a direct indicator of the local ambient plasma density, $f_p = 9000n^{1/2}$ (n is electrons per cc). Note that the ambient plasma frequency before and after the wake encounter is near 27–30 kHz (corresponding to an ambient density of about nine particles/cc). However, near 0035 UT and again near 0047 UT two local density minima are present, flanking the central wake passage. These minima extend to about 20 kHz (or 5 particles/cc) at their lowest points. This double minimum in density is expected in the very deep tail of the wake[6] and in this case with a density dropout about 0.5 times the ambient level. Ion measurements by Wind's Solar Wind Experiment (SWE) reveal cross tail beams from the flank regions, which is a key feature of a wake encounter. Figure 2 of the simulated steady-state lunar wake indicates that the structure should extend over 30 lunar radii. The actual Wind observations at 23 lunar radii are the deepest known transits of the wake made by the spacecraft to date and is consistent with the simulated prediction of an unexpectedly extended wake. By comparison, MHD simulations[1] suggest a much smaller extension to the lunar wake.

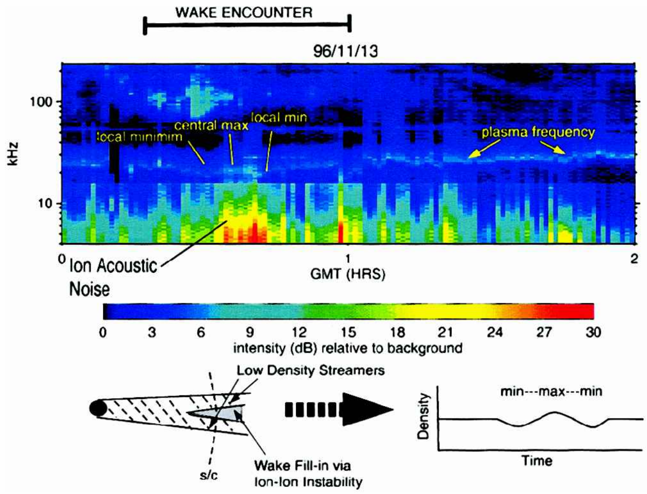

Fig. 4 Wind/WAVES spectrogram from the 13 November 1996 wake transit, occurring throughout the first hour of the day. This wake transit was obtained nearly 23 lunar radii behind the obstacle. The copious wave activity and density depletions presents strong evidence for an extended wake whose effects are felt far downstream.

The PDP orbiting the shuttle obtained a clear wake signature to near many 10s of obstacle size. The plasma density as measure by the PDP (from Ref. 15) is shown in Fig. 5. In the remote region of the shuttle wake, the PDP Langmuir probe measured density dropout to as low as 0.6 times the ambient density. A clear density minimum is found at 03:03, and a second is found in the fluctuating measurements near 03:09. Associated with each of these minima were electron temperature enhancements, which were also used to identify the wake region.[15]

Clearly, the wake does not replenish immediately, and its effects extend many 10s of obstacle radii downstream for both the shuttle and lunar cases. Based on the lunar and shuttle observations and the simulation, we can derive an empirical limit for the wake extent for self-similar situations and this is $X_{max} > 3.5(V_0/a)R_o$. For the lunar wake case the maximum wake extent is >23 lunar radii. In fact,

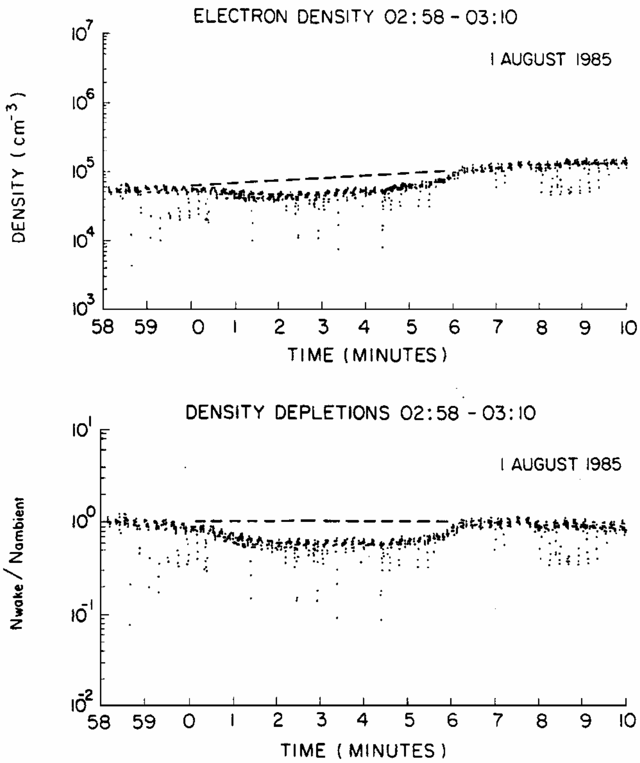

Fig. 5 Measurements from the shuttle-orbiting plasma diagnostics package of the shuttle wake out near 15 shuttle radii. Again, this observation strongly suggests a very extended wake structure (adapted from Tribble[15]).

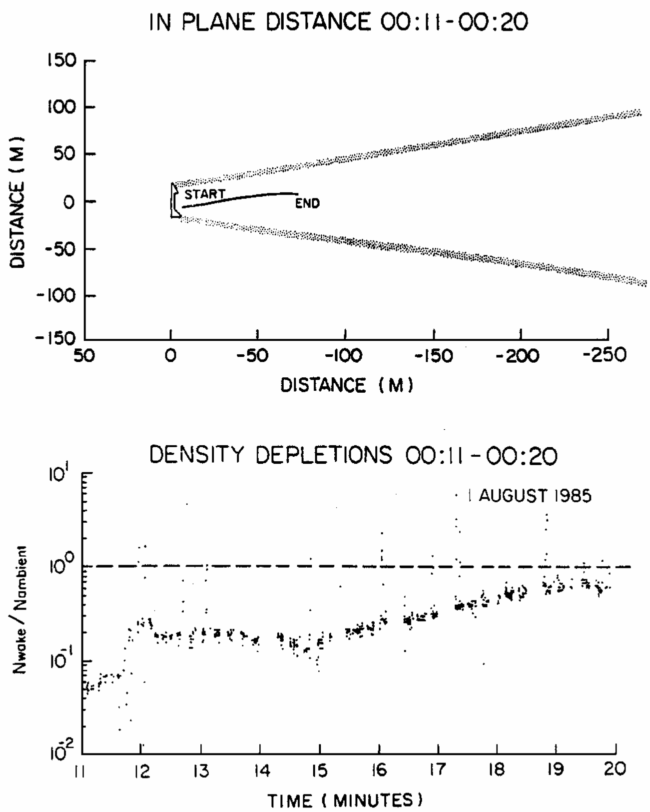

Fig. 6 Shuttle wake density measured by the Langmuir probe on the PDP during an excursion from the shuttle bay directly tailward. Note the steep gradient in density occurring near the 10-m point down the tail, which is indicative of the plasma merging location (adapted from Tribble[15]).

the simulation presented in Ref. 10 suggests a wake extension of at least 45 lunar radii down the tail. For the shuttle case the largest disturbance is generated by the projection of the largest shuttle dimension in the plasma flow (that is, the length L), corresponding to a maximum extent exceeding $X_{\max} \sim 3.5(V_0/a)(L/2) \sim 250$ m, consistent with observations. The $X_{\max}$ expression appears trivial, but has some important applications, as will be described next.

Plasma Converging Location

Whereas the wake extent defines the overall region of the wake structure, the converging location defines the spatial region downstream where the plasma inflow from the adjacent flanks first merges. In essence, this location represents where the void ends and the plasma from adjacent flanks first closes on itself. As described in Refs. 3 and 9, directly behind the obstacle a vacuum region exists because of the absorption of flowing plasma at the obstacle frontside. Electric fields at the flanks of the vacuum region develop because of the inward motion of the thermal electrons, ahead of the massive ions. These fields accelerate ions into the void at the ion sound speed a, and these inward-flowing ions merge downstream in the central wake region.

The lunar wake simulation of Ref. 6 indicates that this converging region is about 5 lunar radii downstream. This result consistent with the 24 December 1994 Wind transit at 7 lunar radii, where a merged, but very low density, plasma was observed in the wake region. The cross-tailed ion beams had just merged upstream of the Wind transit point.

In the case of the shuttle wake,[15,16] a very fortuitous trajectory during a PDP/shuttle transit occurred, taking the PDP from the shuttle bay tailward for almost 80 m down the central wake region. For the first 13 m of the passage, the wake densities were low (few percent), but nearly 13 m down the tail the wake-to-ambient density ratio abruptly jumped to about 0.25 in a step-like fashion, thus indicating location of initial convergence. The density during this downward transit is displayed in Fig. 6. In this case plasma flow about the narrowest point of the shuttle will define the initial merging location, this being about the open shuttle doors of 5-m half-width ($w/2$). As such, the shuttle plasma merging location is ~2–3 half-widths behind the obstacle.

Based on the preceding discussion, we surmise that the plasma converging region defining the end of the near-vacuum occurs relatively close to the obstacle. The converging location for the lunar wake is approximately $X_{\text{conv}} = \frac{1}{2}(V_0/a)R_o \sim 4.5$ lunar radii and for the shuttle case is $X_{\text{conv}} = \frac{1}{2}(V_0/a)(w/2) \sim 10$ m. The wake density still remains low behind this merging region. The wake density progressively increases down the tail (to the streamer region).

Low-Density Streamer Development

A feature common to both the lunar and shuttle ion sonic wakes is the development of streamers: low-density structures extending tailward at the ion sonic cone angle. The streamers are evident in Figs. 2 and 3. These features develop as a result of the electrostatic instability associated with the cross-streaming ion beams.[5,6] Specifically, the counterstreaming beams are unstable to the ion-ion instability and electrostatically interact via the ion acoustic mode to slow each other down. The instability is initiated at the point the beams meet at X_{conv}. However, the instability-related electrostatic fields are not strong enough to stop the beams until the instability is fully mature. For a steady flow in a time-stationary situation, this beam-stopping point occurs in the central flank farther down the tail, at a location we define as X_{stream}. At this point the instability electric field has just ended its linear growth (that is, is saturated) and thus is strong enough to alter/stop the ion beams. The process creates a new ion distribution with average cross-tail velocity of zero in the central region (see Plate 4 of Ref. 6). The beams actually cease in the center of the wake region first, creating a local density enhancement in the central region. This enhancement moves progressively outward to the wake flanks forming a "wedge," which is evident in Fig. 2 (that is, "wake fill-in region"). In essence, the real feature of interest is not the steamers, but the high-density wedge formed between the streamers where wakeward-directed ion flow ceases, and ion buildup occurs to replenish the wake void.[5,6] The streamers represent the regions that have yet to be filled in via this replenishment process.

In the case of the lunar wake, the simulation (Fig. 2) suggests these streamers should appear near 18 lunar radii and should be evident as two local minima in density. The 27 December 1994 crossing at 7 lunar radii possessed one distinct minimum.[3] However, as evident in Fig. 4, the transit near 23 lunar radii, on 13 November 1996, showed two distinct density depressions. As presented in the shuttle overview wake picture in Fig. 3, streamer regions were observed during the PDP transits of the shuttle wake out near 100 m (or ~8 shuttle half-lengths), and this structure was observed as far as 250 m (or 15 shuttle half-lengths).

Thus, based on the two cases presented and the simulation, the streamer region should form near $X_{\text{stream}} \sim 2(V_0/a)R_o$, with the streamers extending tailward to the full extent of $\gg 3.5(V_0/a)R_o$. The shuttle application scales similarly with R_o replaced by $L/2$.

Other Comparisons

The preceding discussion is a detailed comparison of wake density structures that are common to both the lunar and shuttle plasma voids. The conclusion is that both wakes have distinct features that are very similar at the detailed level. Other physical similarities between the two structures are discussed next.

One of the strongest pieces of evidence suggesting that the lunar wake is a kinetic phenomenon (and the MHD picture is not complete) is the presence of cross-tail ion beams within the plasma void.[3,5] Such cross-tail beams are a key feature of an ion sonic expansion process, and the Wind observations of these beams were the primary impetus for the paradigm shift from an Alfvenic to ion sonic view of the lunar wake. Ogilvie et al.[3] report on the discovery of cross-wake ion beams with relative speeds near 75 km/s in the tail region near 7 lunar radii downstream from the moon. The SWE ion distributions revealed two distinct and well-formed peaks, each separated by 150 km/s. In the central tail region at 7 lunar radii, the beams spatially merge, and associated ion-ion beam instability emission was also simultaneously observed.[6] Stone et al.[20] report on the very similar observation of cross-wake ion beams in the tail of the shuttle. The morphology of the ion beams in the two wakes is very similar. For example, the ion flow angle of attack (Panel 4 in Fig. 1 of Ref. 3 and Panel 1 in Fig. 2 of Ref. 20) is nearly identical, suggesting a common ion-beam formation process in both the lunar and shuttle cases. The shuttle inflow was modeled via Vlasov code,[13] which incorporates effects from anomalies in distribution functions. These preceding models are found to be consistent with the more recent particle-in-cell codes,[6,10] which also demonstrate the formation of cross-tail ion beams. Such ion anomalies in the particle distribution are not predicted/modeled in the previous MHD framework.[1] The ion beams observed in both cases represent significant evidence for a similar lunar and shuttle wake, making the case that both are ion sonic disturbances.

In both the lunar and shuttle wakes the electron temperature steadily increases from the wake flank to center. In the case of the lunar wake crossing on 27 December 1994,[3] the electron temperature displayed a distinct jump by a factor of two at the flank. The temperature then progressively rose in a linear fashion to $T_w/T_a \sim 4$ in the central region. A steady decrease and jump down were observed as Wind exited the wake. A cross-tail electron temperature gradient in the shuttle wake, with T_w/T_a peaking near 1.8 in the central region, was also observed during the numerous excursions by the PDP.[15] Electron temperature increases appear in both cases and are a common characteristic of ion sonic wakes, as proven by experiment[21] and by modeling.[22]

Another area of similarity is the electrostatic turbulence associated with the wake, which is indicative of kinetic processes. For the lunar case ion acoustic wave activity was observed to intensify both at the wake flanks[4] and in the central area of the lunar wake,[5] the latter forming an "electrostatic noise tail" behind the object. For example, in Fig. 4 ion acoustic waves occurs throughout the entire Wind cross-tail transit, starting at around 0025 UT, as Wind crosses the flank and continues to near 0057 UT, to just outside the wake flank. The region of most intense wave activity in the central region corresponds to the locations where the flank-generated counterstreaming ion beams intercept each other and become unstable. References 15 and 16 also reported increased ion acoustic turbulence within the shuttle wake. Near 100 m down the wake tail, at 1 kHz (ion acoustic wave frequencies), wave activity at the flanks increased by 2–6 dB over ambient levels. In the central region the activity was nearly 17 dB over ambient levels. Near 200–250 m down the tail, flank wave activity was about 4 dB over ambient levels and centrally about again 17 dB over ambient levels.

Conclusions

There are distinct similarities in the plasma structures of the lunar and shuttle wakes and the detailed comparison presented here suggests the two have more in common than already thought. Common features include a long extent, a beam merging location, streamers, wake-ward directed ion beams and electron temperature gradient, and increased ion acoustic wave activity within the structures.

Based on the measurements from two bodies in very different plasma environments and a simulation, some common features for these wakes become evident, including a total extent as far as $X_{\max} > 3.5(V_0/a)R_o$, a plasma converging location at approximately $X_{\text{conv}} = \frac{1}{2}(V_0/a)R_o$, and the development of streamers at $X_{\text{conv}} \sim 2(V_0/a)R_o$. For a time-stationary flow past the obstacle, the difference between X_{conv} and X_{stream} represents the distance (or time $= (X_{\text{stream}} - X_{\text{conv}})/V_{\text{flow}}$) required for the ion-ion beam electrostatic instability to grow linearly from start to saturation. Consequently, one would expect some variation in $X_{\text{stream}} - X_{\text{conv}}$ depending upon the details of the wave growth environment. Despite this functionality, the scaling does seem to apply at the qualitative level.

Given the similar structure and their scaling, the self-similar wakes formed by other structures, like the International Space Station (ISS), can now be considered. The ISS is a structure with a wing span extending 108.5 m in size and will be in an ionospheric environment similar to that of the space shuttle, with $V_0/a \sim 5$. It is anticipated that the ISS will possess a self-similar wake like that of the shuttle, only of grander size of nearly $X_{\max} \sim 1$ km in extent. A future project on the ISS could be to deploy a subpackage to understand the near-station environment. To map out the plasma wake, we suggest here to make measurements in the vacuum region close to the ISS, near the plasma converge region expected at $X_{\text{conv}} \sim 70$–125 m downstream from the station, at the streamer origin located at $X_{\text{stream}} \sim 0.5$ km downstream and within the extended wake tail beyond 2 km. In essence, we conclude that any deployed plasma subpackage to study the magnetoplasma environment about the ISS should be designed for large excursions (many kilometers) away from the station.

Besides the plasma wake caused by particle absorption and the resulting void from the shuttle, the spacecraft also outgasses water and other molecules into the ionosphere, which become ionized via collisional and photoionization process. These ions then get "picked up" by the geomagnetic field, forming a many kilometer tail behind the shuttle.[23] Consequently, any ISS-deployed subpackage should make large excursions to examine this process as well.

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