

Solar wind interaction with the Martian magnetosphere in the subsolar region under a radial interplanetary magnetic field

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ABSTRACT

Context. When supersonic solar wind encounters a conductive object, it can become subsonic, allowing for energy exchange between the local plasma and the solar wind. At objects such as Earth, this interaction primarily takes place in a collisionless shock. At Mars, there have been a number of studies where a shock has not been identified under a radial orientation of the interplanetary magnetic field (IMF).

Aims. In this study, we investigate whether the flow becomes subsonic under radial IMF conditions and the nature of the transition.

Methods. We used the 3D hybrid-kinetic model Amitis to investigate how the supersonic flow becomes subsonic for three different orientations of the IMF.

Results. The more radial the IMF becomes, the more upstream disturbances are found scattering the impinging solar wind, which decreases the solar wind momentum toward Mars, and the planetary plasma can expand to distances past the location of the nominal shock location. For a perfectly radial IMF, no shock forms in the subsolar region under the conditions we studied, and the impinging scattered solar wind interacts directly with the planetary plasma.

Conclusions. A radial orientation of the IMF greatly changes the interaction of the solar wind with the Martian magnetosphere such that the shock is not the only dominant process that decelerates the solar wind.

Key words. planets and satellites: individual: Mars – plasmas – methods: simulation

1. Introduction

The radial orientation of the interplanetary magnetic field (IMF) can greatly change the interaction of the solar wind with unmagnetized bodies such as Mars (Crismani et al. 2019; Jarvinen et al. 2022; Fowler et al. 2022; Zhang et al. 2024). Under typical conditions, the solar wind, viewed in the planetary reference frame, appears as a cold beam-like population that is supermagnetosonic (Halekas et al. 2017). The solar wind is slowed down in a collisionless shock (known as the bow shock) before interacting with the obstacle and its atmosphere (Russell 1985; Luhmann 1992). Here, the bow shock is identified as the boundary where the plasma moments change significantly and a change of the bulk speed from supersonic to subsonic occurs (Burgess 1995; Balogh & Treumann 2013; Mazelle et al. 2004). Behind the shock, where the primary solar wind is deflected around the object, is a turbulent region: the magnetosheath (Luhmann et al. 2002; Xu et al. 2023; Dubinin et al. 2018). Closer to the planet, the ion composition boundary (ICB) marks the transition where the planetary plasma begins to dominate the interaction dynamics (Xu et al. 2016; Matsunaga et al. 2017; Halekas et al. 2018; Holmberg et al. 2019).

However, when the IMF orientation is radial (here defined as when the angle between the IMF and the flow direction is $<10^\circ$), this interaction changes, and that is the motivation for the present work. The solar wind flow might encounter upstream ultra low frequency waves (Jarvinen et al. 2022) or foreshock cavities (Collinson et al. 2020). Zhang et al. (2024) ran hybrid sim-

ulations with an IMF orientation of $\theta = 4^\circ$ and found indications that no bow shock - identified by the magnitude in magnetic field strength - formed in the subsolar region (defined as $|SZA| < 30^\circ$). They also found that for $\theta = 4^\circ$, the heavy ions move primarily due to the IMF direction, resulting in the cross flow motion identified by Jarvinen et al. (2022). While the gyrating planetary ions can be mistaken for a cross flow plume, for small magnetic field angles, there is almost no convectional electric field, and almost all the motion in the planetary ions is due to gyromotion.

As for the solar wind flow across the ICB, the fraction of primary solar wind protons that pass through the shock and through the ICB under nominal conditions at Mars is on the order of 4% due to the system's small scale and large solar wind proton gyro radii (Brecht & Ledvina 2006; Ledvina et al. 2017; Brecht et al. 2016). When the MAVEN mission (Jakosky et al. 2015) observed radial IMF cases of the primary solar wind beam, much higher fluxes across the ICB were observed (Fowler et al. 2022; Girazian et al. 2024). Deep in the ionosphere-thermosphere, the effect of such proton fluxes has been observed (Crismani et al. 2019), potentially creating aurora (Chaffin et al. 2022).

Previous work has indicated that the Martian system behaves differently under radial solar wind conditions (Crismani et al. 2019; Jarvinen et al. 2022; Fowler et al. 2022; Zhang et al. 2024), but exactly how the solar wind slows down and whether there is a collisionless shock that makes the solar wind subsonic have not been investigated. With this work, our aim was to determine where and how the primary solar wind beam loses its momentum as it interacts with Mars under various IMF orientations.

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To evaluate how the inflowing ion distribution changes, a kinetic code is needed, and therefore we used Amitis, a hybrid kinetic plasma model (Fatemi et al. 2017). We compared three simulations: a standard Parker spiral case of $\theta = 57^\circ$, a radial case with a 5° angle, and a pure 0° angle case. To our knowledge, this work provides the first published results of a $\theta = 0^\circ$ simulation at Mars. A prolonged orientation of $\theta = 0^\circ$ is yet to be observed at Mars; however, small angles around $\theta = 5^\circ$ have been observed, which is why both cases have been included (Halekas et al. 2017; Liu et al. 2021).

2. Instrumentation and methods

The simulations were performed using Amitis (Fatemi et al. 2017), a highly parallelized 3D GPU-based hybrid model for space plasma physics. In this model, ions are represented by macroparticles, and the electrons are treated as a massless charge neutralizing fluid. The electric and magnetic fields and the charge and current densities are calculated on an evenly spaced grid. The particles are moved by the Lorentz force.

For the study, we used the Mars-centered Solar Orbital (MSO) coordinate system, where $+x$ axis points from Mars toward the sun, $+z$ points to the north pole of the Martian orbital plane, and $+y$ completes the right handed system. The simulation domain for all runs is $[-3.5, 14] R_M$, $[-7, 10] R_M$, and $[-7, 7] R_M$ in the x , y , and z direction, respectively, where $R_M = 3400$ km is the Mars radius. The domain was chosen so that more or less unperturbed solar wind conditions prevail at the upstream end of the simulation box and the sides of the box do not result in wave reflection interfering in the simulation. The cell size was 200 km, corresponding to a 1.5 proton inertial length in the solar wind.

The $+x$ face of the simulation box is an injection boundary, the $-x$ face is an absorption boundary, and the other faces are periodic. The inner boundary is a sphere with radius $R_{IB} = 3600$ km and is also an absorption boundary. The planetary species included are atomic and molecular oxygen, respectively O^+ and O_2^+ . The production profiles were chosen in best agreement with Egan et al. (2018), a modeling challenge at Mars. The same ionization rates were used for all runs in this study. Amitis has been validated for Mars with MAVEN data by Wang et al. (2023b) and Wang et al. (2024).

The solar wind consists of protons, injected with a density of 3 cm^{-3} , a velocity $v_x = -400 \text{ km/s}$, a temperature of 6 eV, and an IMF strength of 5 nT, which are similar to the typical solar wind plasma parameters near Mars (Halekas et al. 2021). The only change between our three runs was a change in IMF orientation. In the first run we used the average Parker spiral cone angle of $\theta = 57^\circ$, and in the two radial cases we used the angles $\theta = 5^\circ$ and 0° . The simulations were run until a steady state was reached, which is defined as when the boundaries fluctuate around a set point, rather than expand, and when the planetary ion escape rates become constant on average. This happened around 300 s. We then took snapshots at 425 s. The total oxygen escape rate (i.e., both atomic and molecular oxygen) in the nominal case is $7.8 \times 10^{24} \text{ s}^{-1}$, which is in good agreement with observations (Dubinin et al. 2011; Ramstad et al. 2015) as well as with most other models in the Mars modeling challenge (Egan et al. 2018). The total escape rates for the case of $\theta = 5^\circ$ and 0° are $1.1 \times 10^{25} \text{ s}^{-1}$ and $1.2 \times 10^{25} \text{ s}^{-1}$. This is in line with the results from Zhang et al. (2025), who similarly found the ion escape rate to be almost a magnitude larger, showing that ion escape is enhanced under a radial IMF at Mars.

Given the moments calculated by Amitis and the temperature as calculated from the thermal velocity of the particles, the Magnetosonic Mach number was calculated as follows:

$$M_{MS} = \frac{v_{sw}}{\sqrt{v_A^2 + v_S^2}}, \quad (1)$$

where v_{sw} is the solar wind speed, $v_A = B / \sqrt{\mu_0 \rho}$ is the Alfvén speed, and $v_S = \sqrt{\gamma P / \rho}$ is the sound speed. Both speeds were calculated for each grid point in the simulation. In this study, M_{MS} is only derived based on the proton population. Therefore, in the regions where the heavier planetary particles become the dominant species, M_{MS} is no longer valid, and M_{MS} is only reported when the H^+ density is at least 50% of the population. The simulation in this study does not contain crustal fields, so the question of how the crustal fields impact the interaction of the Martian system with a radial solar wind is left to future studies.

3. Results

The induced magnetospheres differed noticeably among the three cases, as illustrated by Figure 1. Each row in the figure corresponds to a different case of IMF orientation ($\theta = 57^\circ$, 5° , and 0° , respectively), while the columns show the magnetic field, solar wind H^+ density, and planetary O^+ density. All panels show cuts in the xy plane at $Z=0$. The simulation had a spatial resolution of 200 km, but in the figures each grid point has been averaged over neighboring points for smoother visualization, resulting in a spatial resolution of 400 km.

In the figure, the magnetic field exhibits a typical behavior for the Parker spiral angle case: compression at the nose and draping around the obstacle (panel (a)). A hyperbolically shaped boundary, consistent with a shock, is visible. Though direct comparison is difficult since the boundary position depends on upstream parameters, the position of the boundary in this simulation agrees well with previous research (Wang et al. 2020; Sui et al. 2023). Behind this boundary lies a sheath of enhanced magnetic field strength and proton density — the magnetosheath. The radial configurations, $\theta = 5^\circ$ and 0° , are displayed in panels (d) and (g), respectively. In neither case did we see indications of a fully formed shock. Although a study of M_{MS} is required to definitively classify the boundary as a shock (as we discuss later), only a partial magnetic field accumulation can be observed in the subsolar region in the $\theta = 5^\circ$ case, while the $\theta = 0^\circ$ case exhibits no pileup. Both cases show magnetic field enhancements on the flanks. From our results and from the results of Zhang et al. (2024), it seems shocks are created even at small angles, such that the diversion of the flow at the sides is enough to create a weak shock at the flanks. Due to magnetic flux conversion, some pileup of the magnetic field at the flanks is expected, and this creates the shock structures. Exactly what angle this occurs at likely depends on several solar wind parameters. Furthermore, for both cases, foreshock structures can be seen far upstream along the magnetic field direction, exceeding distances of $10 R_M$.

The proton density largely mirrors the magnetic field structures, as expected since the magnetic field is frozen into the plasma. For $\theta = 57^\circ$ (Fig. 1, panel (b)), a pronounced, hyperbolic density enhancement suggests both a shock and the formation of a magnetosheath. The proton density of the radial cases mirror their magnetic field configurations, with only partial or

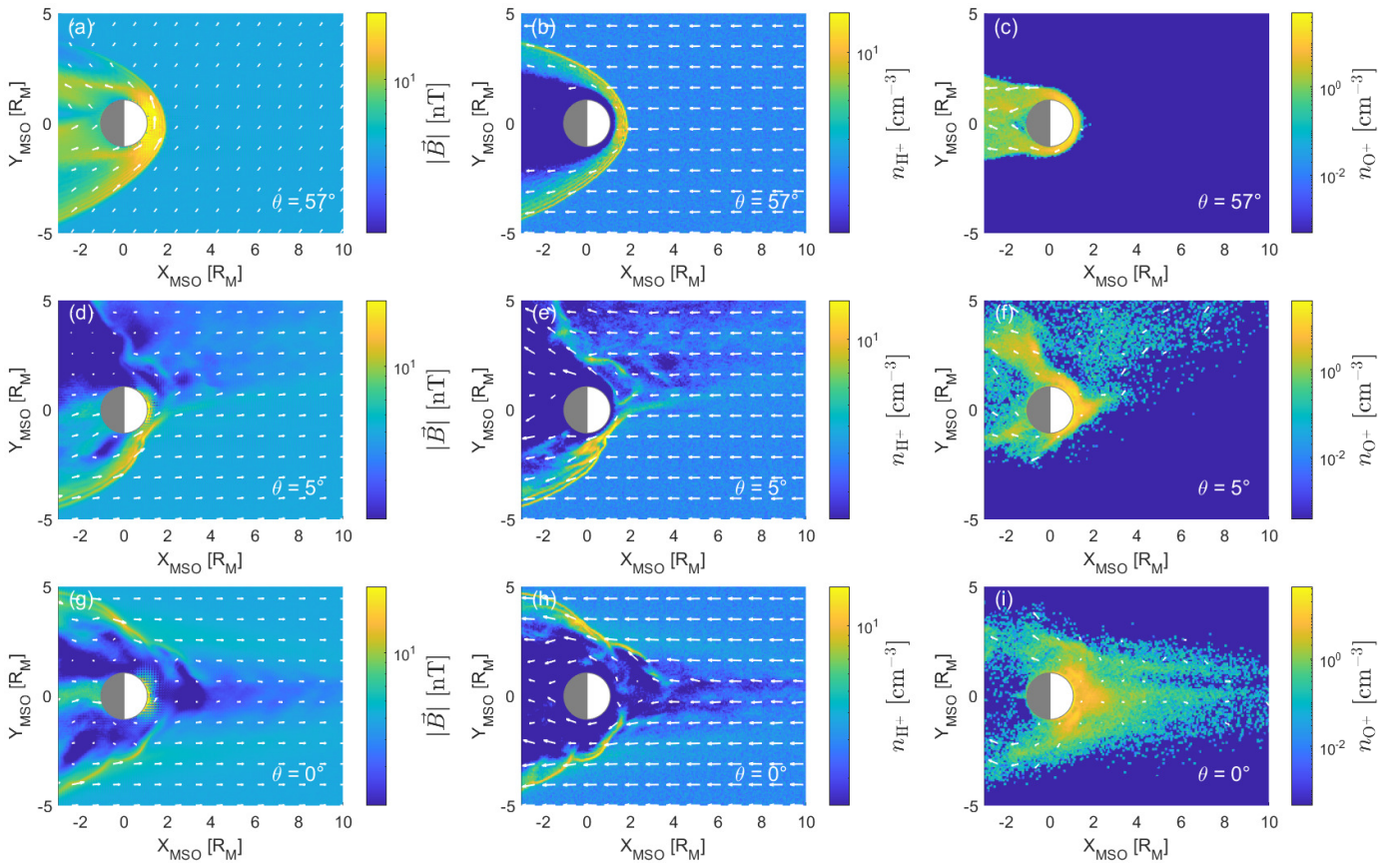


Fig. 1. Slices in the $z = 0$ plane of the magnetic field, proton density, and atomic oxygen density for $\theta = 57^\circ$, 5° , and 0° . Arrows show the direction of the magnetic field, the proton velocity, and atomic oxygen velocity projected to this plane. All data have been averaged over two grid cells.

no density increase in the subsolar region and with density decreases in the foreshock reaching far upstream. In particular, the $\theta = 0^\circ$ case demonstrates a decrease in upstream proton density, with panel (h) of the figure revealing low density up to $x = 8 R_M$ along with large-scale foreshock structures. Upstream, around $x = 2 R_M$, the proton density between panel (b) and (h) is quite different. In panel (b), the density is fairly stable until reaching the shock, while in panel (h) the density along the Sun-Mars line is significantly decreased and diverted to regions observed here at $\pm 1 R_M$ in the y -direction. We investigated the cause of this difference by evaluating the Mars-Sun line.

The O^+ populations also greatly differ between the nominal and the radial cases, as seen in panels (c), (f), and (i) of Figure 1. In the nominal case ($\theta = 57^\circ$, top row), panel (c) shows that planetary ions are predominantly compressed on the dayside. In contrast, the O^+ populations of the radial cases are more expanded. Panels (f) and (i) illustrate that the planetary ions travel much farther upstream, particularly for $\theta = 0^\circ$. Furthermore, expansion on the flanks is evident (panel (f)), in agreement with simulations by Jarvinen et al. (2022) and Zhang et al. (2024).

The magnetic field and ion densities give indications of shock structures, but to describe the flow and to ascertain whether a shock is present, the magnetosonic Mach number among other quantities needed to be investigated. Figure 2 presents profiles along the x -axis (i.e., for $y = 0$ and $z = 0$) of several quantities, including the velocity (and its components), the fraction of the solar wind beam, ion densities, the proton number flux $(\rho v)_p$, the magnetosonic Mach number (M_{MS}), and the magnetic field strength ($|B|$). The first six panels depict individual quantities, with all three cases superposed, whereas the

final three panels display three quantities per panel for each separate case. The dashed gray vertical lines in panels (g)–(i) indicate positions where the planetary ion density exceeds the proton density, and solid gray vertical lines denote locations where the M_{MS} drops below or is close to unity, signaling the transition to subsonic flow. The dashed vertical lines in panel (f) signal the same transition. In the nominal case, the proton density and magnetic field increases by approximately a factor of four, and the proton speed decreases by the same factor, as is common for bow shocks. The fact that the Mach number falls below unity in a sharp transition is how we define a shock (Balogh & Treumann 2013, p. 26). The nature of the cases where the transitions are more gradual are discussed in the following paragraph.

To study how the proton velocity differs between the three cases, the magnitude of the velocity is shown in Figure 2, panel (a). For $\theta = 57^\circ$, the velocity remains stable until approximately $1.9 R_M$, at which point it declines sharply. The transition is localized to less than $0.5 r_{gp}$. For $\theta = 5^\circ$ the velocity starts to decrease further upstream, around $2.4 R_M$. The case $\theta = 0^\circ$ exhibits an even more gradual decrease in velocity beginning after $5 R_M$, with no sudden drop.

A more detailed analysis of the velocity components is provided in panels (b)–(d) of Figure 2. For $\theta = 0^\circ$, V_x slows down for $x < 6 R_M$, and there is even a sunward flow between 2 – $3 R_M$. For $\theta = 5^\circ$, V_x slowly decreases, and around $1.6 R_M$ ($M_{MS} = 1$) the flow is sunward. Lastly, for $\theta = 57^\circ$, V_x is anti-sunward, a jump occurs at the shock, and it turns sunward below the ICB. For V_y and V_z , these components become similar to V_x for all cases below $2 R_M$.

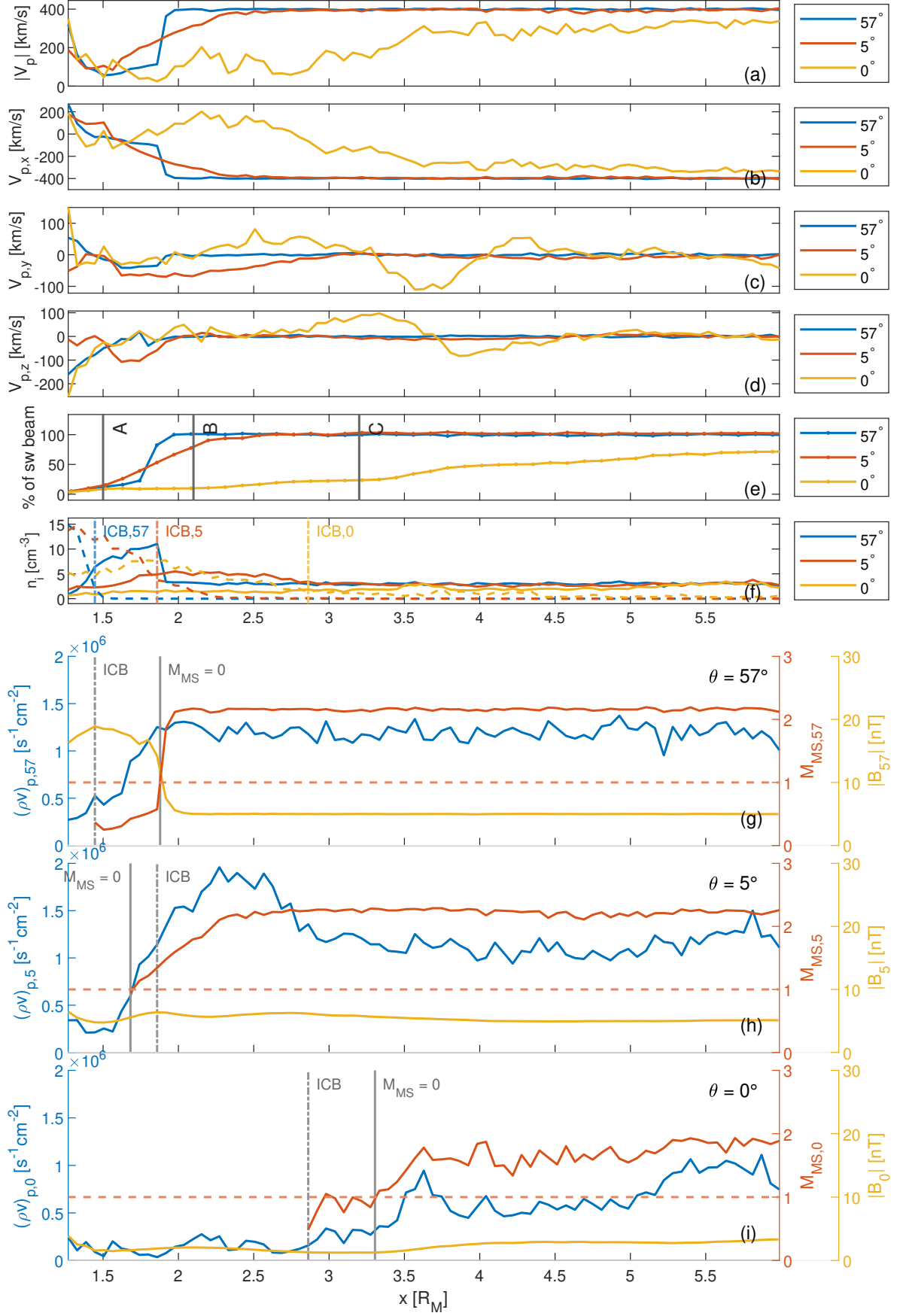


Fig. 2. Plasma quantities along the x-axis ($y = z = 0$). The first six panels show the same quantity for the three cases in the same panel. They portray (a) the magnitude of the velocity, $|V|$; (b) the V_x component; (c) the V_y component; (d) the V_z component; (e) the percentage of the solar wind beam; and (f) ion densities, where the solid lines are the proton densities, the horizontal dashed lines are the atomic ion densities, and the vertical dashed lines show the ICB. The vertical lines of panel (e) show the center of the reference boxes for the velocity distribution in Figure A.10. The last three panels (g-i) each feature one case, and for each the proton flux, $(\rho v)_p$; the proton Magnetosonic Mach number, M_{MS} ; and the magnitude of the magnetic field, $|B|$, are shown.

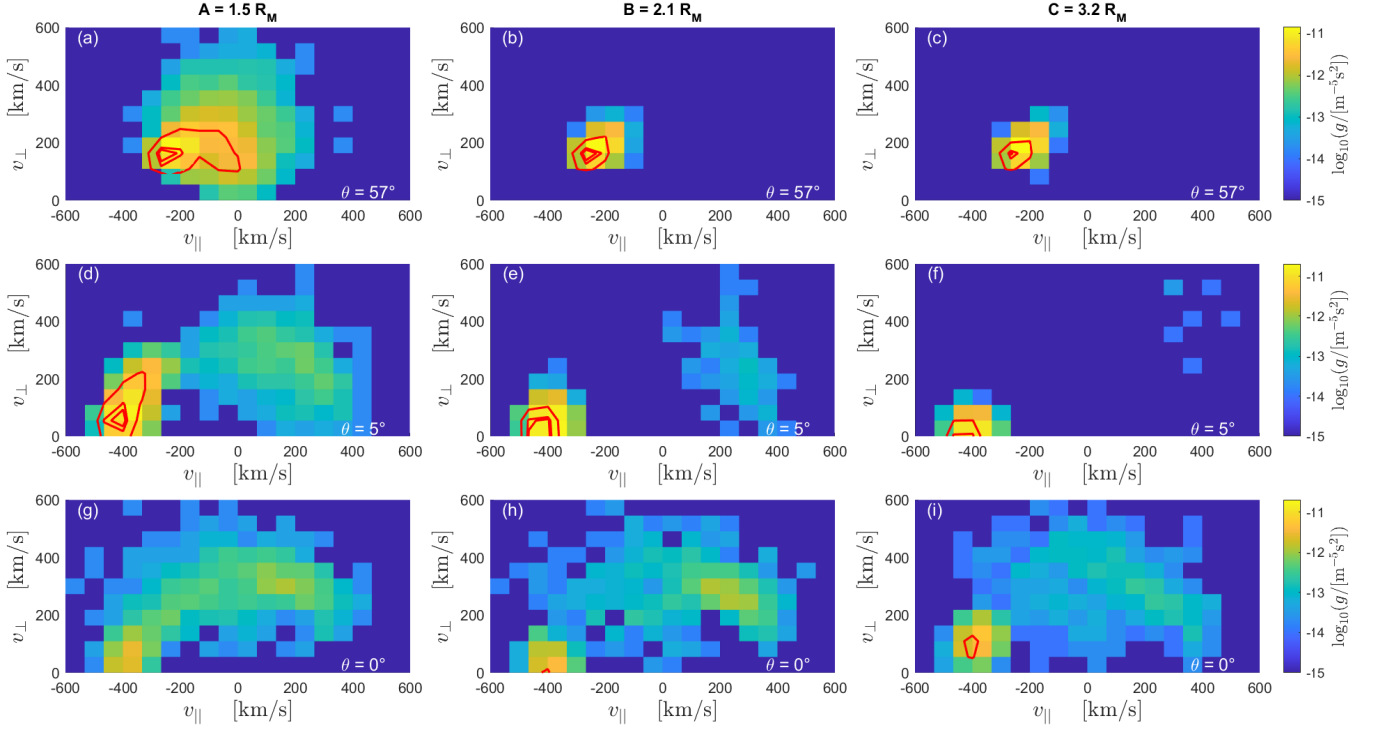


Fig. 3. Velocity distribution functions for each case. The reference box for each distribution is centered at three different locations on the x-axis. The distributions are shown for the velocity parallel and perpendicular to the magnetic field, $v_{\parallel}$ and $v_{\perp}$, respectively. Each reference box has the volume $0.2 \times 0.2 \times 0.1 R_M$. The red contours show the flux at $\log_{10}$ of -11.5 , -11 , and -10.9 .

As mentioned earlier, the motivation of the present study was to see where and how the primary solar wind beam loses its momentum. This is best investigated by studying whether the bulk distribution has been redirected, such as in the case of a bow shock. If only part of the distribution has been changed, this would indicate the absence of a classical shock. We conducted an investigation of what fraction of the primary beam is intact as the solar wind reaches the planet, which is made possible by the selected hybrid model. The percentage of particles with solar wind speed and direction is presented in Figure 2 panel (e). This analysis reveals that in the $\theta = 0^\circ$ case, the solar wind beam begins to deteriorate beyond $5 R_M$, whereas for $\theta = 5^\circ$ the decline starts at approximately $2.3 R_M$. In the nominal case, the reduction occurs only at the shock.

To better quantify how the planetary ions expand for different IMF conditions, we show the ion densities in Figure 2 panel (f). The solid lines portray H^+ densities, and the dashed lines show the O^+ densities. The dot-dashed vertical lines signify where O^+ becomes the dominant species, i.e., when its number flux becomes larger than that of the protons. We note that this is the ICB boundary. It is immediately obvious that the O^+ population expands for a radial IMF. For $\theta = 0^\circ$, the ICB lands at over $2.8 R_M$, and for $\theta = 5^\circ$, this boundary stands at $1.8 R_M$. When comparing to the nominal case, which stands at $1.45 R_M$, this is an increase in distance of 93% and 24%, respectively.

The next three panels in the figure show $(\rho v)_p$, M_{MS} , and $|B|$. Since M_{MS} is calculated for protons only, we only show M_{MS} when protons are the dominant species, and they are therefore cutoff behind the ICB when planetary ions become the dominant species, with the exception being for $\theta = 5^\circ$, where the M_{MS} is cutoff after the transition to subsonic proton flow. To better investigate what happens in the individual cases, we plotted each

case separately, shown in the last three panels of Figure 2. In the following, we describe our observations for each case.

Nominal case ($\theta = 57^\circ$): As shown in panel (g), the quantities remain largely constant until the shock (indicated by a solid vertical line where M_{MS} falls below unity) is encountered. Behind the shock, the proton number flux, $(\rho v)_p$, initially increases and then declines sharply as the obstacle is approached, while $|B|$ exhibits the expected increase. The dashed vertical line marks the region where the planetary ion density overtakes the proton density, defined as the ICB.

Radial case ($\theta = 5^\circ$): In panel (h), an increase in both ρv and $|B|$ can be observed upstream of the transition to subsonic, followed by a sharp decline. Here, the location at which planetary ion density dominates (dashed vertical line) nearly coincides with the shock, indicating that the solar wind interacts almost directly with the planetary plasma and that a distinct magnetosheath is not present. The fact that a bow shock did not develop resulted in the solar wind protons never being thermalized, and consequently, a magnetosheath where the thermal and magnetic field pressure dominates did not develop either.

Radial case ($\theta = 0^\circ$): Panel (i) shows that the proton flow becomes subsonic at $3.4 R_M$ after gradually decreasing. The proton number flux, $(\rho v)_p$, is markedly reduced, and $|B|$ does not exhibit significant pileup. Upstream, periodic enhancements in $(\rho v)_p$ suggest the presence of wave activity, likely similar to the structures observed in the $\theta = 5^\circ$ scenario just prior to the flow becoming subsonic. For $\theta = 0^\circ$, the proton density in the region $2-2.5 R_M$ is below the solar wind density, which is not the case for the other runs.

In the case of $\theta = 0^\circ$ and 5° , the ICB and the transition to subsonic proton flow varied during the simulation. Under radial IMF conditions, the environment becomes much more dynamic compared to nominal conditions. This is in part due to the large-scale

foreshock structures, which alter the location of these boundaries much more than when under nominal conditions.

To illustrate how the proton population changes velocity as it approaches the obstacle in the three cases, we show its velocity distribution for three distances for each case in Figure 3. Each row shows a case, and each column shows a different distance to the obstacle. The distributions are shown for the velocity parallel and perpendicular to the IMF, $v_{\parallel}$ and $v_{\perp}$, which results in the location of the primary beam being different for the three cases. The distances are the center along the x-axis of reference boxes of volume $0.2 \times 0.2 \times 0.1 R_M$. The contours are set at three different values of differential particle flux and are set at the same values for all plots. The contours are shown to illustrate how the flux changes at different distances and for the different cases, and the value of the flux contour itself is not of importance.

For the nominal case, the box centered around $1.5 R_M$ is inside the shock, and the 2.1 and $3.2 R_M$ boxes are in the solar wind. The first row of panels in Figure 3 show this clearly: The boxes in the solar wind show cold beam populations that then broaden as the flow travels into the magnetosheath. The middle row, showing the $\theta = 5^\circ$ case, shows how the distributions differ for a radial IMF. A reflected component at $2.1 R_M$ can be seen, and even more at $1.5 R_M$. However, the distribution remains narrower compared to the nominal case at $1.5 R_M$, indicating that the protons do not thermalize as efficiently under a radial IMF. The perfectly radial case, $\theta = 0^\circ$, is shown in the bottom row. The beam is slightly less narrow, together with having a lower flux. The distribution stays narrow as it approaches the obstacle, and a reflected population is visible even at $3.2 R_M$.

The incident solar wind population for the nominal Parker case can be seen in Figure 3 panel (b) – this case also represents the solar wind population for all cases since the solar wind parameters are nearly identical except for the IMF direction. In the nominal Parker case, the primary solar wind beam changes between $1.5 R_M$ and $2.1 R_M$, where the shock is located. The $2.1 R_M$ is far enough to show any back-streaming ions from the bow shock (Yamauchi et al. 2012), and the $1.5 R_M$ distribution demonstrates the redirection of the primary beam together with the thermalization of the solar wind. This is what is expected at a bow shock.

For the $\theta = 5^\circ$ case (middle row in Fig. 3), the distribution already shows scattering at $3.2 R_M$, but the largest change is between $2.1 R_M$ and $1.5 R_M$, where in addition to the scattered population, a reflective part can be seen. Observation of this population depends on which pixel is selected and the angle of the IMF. Therefore, the lack or presence of this population when only looking at the pixels along the Mars-Sun line should not be misinterpreted. Thus, in this work, no detailed discussion of this population is made.

For the $\theta = 0^\circ$ case (bottom row in Fig. 3), a counter-streaming population can be seen, and the highest peak of the distribution is at a lower flux (compared to panel (c)). In this case, scattering impacts the particles even far upstream (Fig. 2i), and momentum is significantly changed.

4. Discussion

A shock is a transition from super-magnetosonic to magnetosonic or sub-magnetosonic flow that takes place over a short distance (Balogh & Treumann 2013, p.26). Conservation laws, such as the Rankine-Hugoniot conditions, can be useful in making predictions, but in their general form, they always apply and are therefore not suited as definitions of shocks (Omid & Winske 1987, p. 13,423). We used the definition by Balogh &

Treumann (2013), and while how abrupt a transition must be in order to be called a shock remains a topic for discussion, the question of how the plasma is slowed down is more important than whether it can be labeled a shock or not.

Our simulation results demonstrate that the IMF orientation plays a critical role in shaping the response of the solar wind to the obstacle. Through Figure 2 we investigated the difference between the nominal and the radial solar wind interaction with Mars. Upstream of Mars ($>10 R_M$) the plasma consists only of solar wind-originating protons in the simulations. For the radial cases, the primary beam loses particles continuously, as seen in panel (e), while the plasma velocity moment upstream does not drop equally, as seen in panel (a). The absolute velocity moment decreases (i.e., loses kinetic energy), the V_x component decreases (and even reverses), and already $3 R_M$ upstream less than 30% of the primary solar wind beam is unaffected (panel (e)). The result is a depleted solar wind beam, leading to low solar wind density close to the obstacle. Furthermore, the radial orientation of the IMF only leads to a partial or non-existent magnetic field pileup in the subsolar region while the density is lowered, in agreement with previous research (Fang et al. 2018; Wang et al. 2023a). In these cases, density increases are minimal or even eroded below initial conditions, indicating that the solar wind plasma does not experience the pileup typical of a shock.

The low solar wind density in front of the obstacle under a radial IMF, and therefore the lower external pressure, enables the planetary ions to expand outward. In panel (f) of Figure 1 ($\theta = 5^\circ$), O^+ expands in the $+y$ direction (where solar wind density is low) and in the direction E_{conv} , and the gyroradii effect drives the heavy ion motion. The perfectly radial case $\theta = 0^\circ$ expands into the low solar wind density region. Ionospheric plasma can expand to large distances under low solar wind conditions, according to Shaver et al. (2024). In that study the solar wind almost disappeared, and the ICB was identified far upstream, similar to the conditions the $\theta = 0^\circ$ case displays in Figure 2 (f)–(i).

The expansion of the planetary ions leads to the interesting phenomenon where the ICB and any shock that forms will essentially coincide. As seen from Figure 2 panel (h), the ICB and the boundary where the flow becomes subsonic almost overlap. The ICB is only 200 km, or one cell size, away from this location, meaning that these boundaries are essentially overlapping from the perspective of the solar wind protons. That raises the question of whether that boundary can be called a shock, as a shock is a discontinuity where the same plasma undergoes a change in density, velocity, and magnetic field. However, if the dominant species are different on each side of the boundary, it is unclear whether the boundary can still be considered a shock. One could also say it is not a free-standing shock, that is, it is not disconnected from other plasma populations. This also means that no magnetosheath forms in this region, as the magnetosheath is the sheath of decelerated and deflected solar wind plasma between the shock and the inner boundary (e.g., the ICB). For $\theta = 0^\circ$, no shock-like boundary forms in the subsolar region, but the proton flow becomes subsonic, as seen from Figure 2i. In this study we have only looked at the subsolar region, but future studies could look at the flanks of both $\theta = 0^\circ$ and 5° to investigate whether the structures there are free-standing shocks or not.

These changes in the solar wind–Mars interaction create an environment where the solar wind directly impacts the planetary plasma, and one will consequently observe heavy proton precipitation in the ionosphere. Under nominal conditions, about 4% of the solar wind beam reaches the inner obstacle boundary. This value agrees with previous simulations (Brecht 1997). For a ra-

dial IMF, though, the flow has decreased gradually, around 15% of the solar wind proton flux still remains and directly impacts the inner boundary. This is in line with Fowler et al. (2022), who observed solar wind protons down to an altitude of 230 km.

5. Conclusion

We have used the hybrid model Amitis to simulate three cases of IMF orientation, $\theta = 57^\circ$, 5° , and 0° , in order to study how it affects the interaction of the solar wind with the Martian plasma system. We studied the magnetic field, the protons, and the planetary oxygen, and we analyzed their behavior for the different IMF orientations. Our main conclusions are the following:

- Under a radial IMF, the solar wind moments and the magnetic field are impacted far upstream. Starting at many Mars radii upstream, the solar wind primary beam is scattered by upstream processes, causing it to lose particles as it approaches the planet.
- The planetary plasma expands in the case of low solar wind density. The radial IMF creates similar conditions to disappearing solar wind, resulting in the planetary plasma expanding outward.
- In the radial case, there is not a fully formed shock. The location where the plasma becomes close to subsonic is not well separated from the planetary plasma. For the radial IMF orientations, in the subsolar region, there is no sheath, and the solar wind impacts the planetary plasma directly.

For a radial IMF, a different type of plasma-interaction region is demonstrated where the electromagnetic turbulence upstream of the conductive object is significant enough to scatter the solar wind and the solar wind pressure. The energy from the solar wind to the system is still there, but the coupling is less organized and more turbulent.

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