Influence of He$^{++}$ and shock geometry on interplanetary shocks in the solar wind: 2D Hybrid simulations

L. Preisser$^1$, X. Blanco-Cano$^1$, D. Trotta$^2$, D. Burgess$^2$, P. Kajdič$^1$

$^1$Instituto de Geofísica, UNAM, Mexico City

$^2$School of Physics and Astronomy, QMUL, London

Corresponding author: preisser@igeofisica.unam.mx

EGU-Online General Assembly, May 2020

Just published in JGR, please click https://doi.org/10.1029/2019JA027442
Outline

Motivation & Summary

Simulation Setup

Simulation Results: Magnetic Field

Simulation Results: Temperature Anisotropy

Simulation Results: Velocity Distribution Functions

Simulation Results: Density Behavior

Simulation Results: Mirror Mode and IC Instability

Conclusions

Acknowledgements
Motivation & Summary

- Alpha particles ($\text{He}^{++}$) constitute typically about 5% of SW.
- Different charge-to-mass ratio $H^+$ and $\text{He}^{++} \Rightarrow$ Different acceleration at shocks.
- \( \Rightarrow \) Changes in the VDFs for both species.
- \( \Rightarrow A = T_\perp / T_\parallel > 1 \) (considered to be the energy source for Mirror/IC waves for instance)
- But... How $T_\perp / T_\parallel$ and shock structure depend on the percentage of $\text{He}^{++}$ and $\theta_{Bn}$ is not well understood.
- We have performed various 2.5-D local hybrid simulations of IP-shock varying the initial $\theta_{Bn}$ and $\text{He}^{++}$ percentage.
- We have found changes in the shock transition behavior as well as in temperature anisotropy as functions of both the shock geometry and $\text{He}^{++}$ particle abundance.
- Change in $\theta_{Bn}$ leads to variations of the efficiency with which particles can escape to the upstream region facilitating or not the formation of compressive structures in the magnetic field that will produce increments in perpendicular temperature.
Simulation Setup

- 2.5-D hybrid (kinetic ions/fluid electrons) simulations using HYPSI code.
- Spatial and temporal scales in units of $d_i = c/\omega_p$ and $\Omega_p^{-1}$ respectively.
- $n_x \times n_y = 1000 \times 800$ with cell sizes $\Delta x = \Delta y = 0.5 \ c/\omega_p$
- $V, B$ and $E$ field vectors including all 3D components.
- $\Delta t$ was chosen so that $\Omega_p \Delta t = 0.005$
- Initially $V_{in} = 3.3 \ V_A$ along $x$ with $B$ in $x$-$y$ plane
- Upstream $H^+$ and $He^{++}$ with Maxwellian VDF and $\beta = 0.5$
- We perform different runs with initial $\theta_{Bn} = 15^\circ, 30^\circ, 50^\circ, 65^\circ$
- For each $\theta_{Bn}$ we vary the relative number density fraction of $He^{++}$ i.e. $n_\alpha/n_p = 0.01, 0.05, 0.10$
- We perform a total of 12 simulations (see Figure 1).
**Simulation Results: Magnetic Field**

Figure 1: Figure matrix showing the time evolution of total magnetic field (averaged over y-axis) for all the runs in this work. $\theta_B n$ increases from left to right while the He$^{++}$ number density fraction increases from top to bottom. The change in color from navy to aqua occurs at $B \sim 1.25$ while the change from green to yellow occurs at $B \sim 1.5$. 
Figure 2: Total magnetic field profile (average over y-axis) for the all the different $\theta_Bn$ values used in this work when the shock arrives to $\sim 250 \, d_i$. The $\theta_Bn$ angle increases from top to bottom, He$^{++}$ number density fraction is indicated by different colors (black: 1%, red: 5%, blue: 10%).
Simulation Results: Temperature Anisotropy

**Figure 3:** Figure matrix showing the time evolution of temperature anisotropy for protons (averaged over y-axis) for all the runs in this work. $\theta_{Bn}$ increases from left to right while the He$^{++}$ number density fraction increases from top to bottom. The color palette is chosen to show anisotropy values less (in blue) and greater (in yellow-red) than 1.
Figure 4: Semi-log temperature anisotropy profiles (average over y-axis) for protons (blue) and He$^{++}$ (orange) at the time when the shock arrives to $\sim 250 \, d_i$ for all the $\theta_{Bn}$ values and He$^{++}$ percentages in this work. The vertical dashed line indicates the shock localization and the horizontal dashed line indicates $T_\perp / T_\parallel = 1$. 
Simulation Results: VDFs

**Figure 5:** Simulation with $\theta_{Bn}=15^\circ$ when the shock arrives to $x=250 \, \text{d}_i$: a) $\mathbf{B}$ and b) $\mathbf{B}$ along two cuts at upper (blue) and lower (red) dashed lines in panel a) for case with 1% of He$^{++}$. Panels c) and d) show the same results for case with 10% of He$^{++}$. VDF’s for both species for the case with 10% of He$^{++}$ contained inside the left (upstream) magenta box on panel c) are shown in panels e). The same results for the right (downstream) magenta box on panel c) are shown in panels f).
Figure 6: Simulation with $\theta_{Bn}=65^\circ$ when the shock arrives to $x=250\, d_i$: a) $B$ and b) $B$ along two cuts at upper (blue) and lower (red) dashed lines in panel a) for case with 1% of He$^{++}$. Panels c) and d) show the same results for case with 10% of He$^{++}$. VDF’s for both species for the case with 10% of He$^{++}$ contained inside the left (upstream) magenta box on panel c) are shown in panels e). The same results for the right (downstream) magenta box on panel c) are shown in panels f).
Figure 7: Contour plots of protons and He$^{++}$ densities corresponding to the simulations with $\theta_{Bn} = 15^\circ$ for a) 1% and b) 10% of He$^{++}$ and with $\theta_{Bn} = 65^\circ$ for c) 1% and d) 10% of He$^{++}$. The time of the plots correspond to those magnetic field magnitude plots in Figures 5 and 6.
Simulation Results: Mirror Mode and IC Instability

Figure 8: B-field and $A_p$ along downstream region at $y = 200 \, d_i$ for simulations with $\theta_{Bn} = 65^\circ$ and a) 1% and b) 10% of He$^{++}$. $A_p$ and the parameters $M = 1 + 1/\beta_\perp$ (red) and IC$ = 1 + \beta_\parallel^{0.5}$ (blue) are shown in bottom panels. The condition for the growing of the mirror instability is fulfilled by the threshold $T_\perp / T_\parallel > M$, the condition for ion/cyclotron instability is $T_\perp / T_\parallel < IC$. The plots time are the same as in Figure 7.
Conclusions

▶ We have shown with the help of hybrid simulations that both, geometry and He$^{++}$ content can modify the interplanetary shock profile and the the upstream and downstream characteristics affecting $T_\perp/T_\parallel$, VDFs properties and $\delta B$ growth.

▶ Variation of $\theta_{B_n}$ changes the efficiency with which particles can escape to the upstream side of the shock influencing the formation of compressive structures and the $B$ profile.

▶ $B$ profile is affected by $\theta_{B_n}$: $B$ jump at shock is more abrupt as $\theta_{B_n}$ increases, while $\delta B$ is attenuated as as $\theta_{B_n}$ increases.

▶ $A_{p,\alpha}$ depend on $\theta_{B_n}$: For $15^\circ$, $30^\circ$, $A_\alpha < A_p$ upstream and $A_\alpha > A_p$ downstream. For $50^\circ$ $A_\alpha > A_p$. For $65^\circ$, $A_{p,\alpha} \sim 1$ upstream and $A_\alpha > A_p$ downstream. An $A_\alpha$ peak is formed at shock transition ($\forall \theta_{B_n}$) tending to be larger as $\theta_{B_n}$ increases.

▶ VDFs are affected by $\theta_{B_n}$: For $15^\circ$ backstreaming $H^+$ and He$^{++}$ are observed upstream in contrast with the $65^\circ$ case. An He$^{++}$ ring-like distribution is formed downstream. Downstream VDFs for $H^+$ are more isotropic and thermalized for $15^\circ$ than for the $65^\circ$ case.
He$^{++}$ content affects $\mathbf{B}$ profile: As He$^{++}$ increase compressive $\delta \mathbf{B}$ on both sides of the shock reach higher amplitudes for $15^\circ$, $30^\circ$. For $50^\circ$, the He$^{++}$ content does not affect their amplitude. For $65^\circ$ downstream $\delta \mathbf{B}$ reach larger amplitudes as He$^{++}$ increases.

Upstream zones where $A_p > 1$ coincide with those with compressive $\delta \mathbf{B}$. For the quasi-parallel cases ($15^\circ$, $30^\circ$) upstream zones with $A_p > 1$ are less fragmented as He$^{++}$ content increases. For $50^\circ$ this behavior is repeated. Comparing $A_p$ and $A_\alpha$ the He$^{++}$ content does not affect the peak shape at shock for $15^\circ$, $30^\circ$ cases. For $50^\circ$ an increment is observed as He$^{++}$ increases. For $65^\circ$ the peak decreases as He$^{++}$ increases.

He$^{++}$ content affects the VDF distributions making them more spread as He$^{++}$ increases in both quasi-parallel and quasi-perpendicular cases.
We thank Dirección General de Cómputo y de Tecnologías de Información y Comunicación (DGTIC) of the Universidad Nacional Autónoma de México (UNAM) for the allocation and support received in the use of the HP Cluster Platform 3000SL supercomputer (MIZTLI). Contract grant sponsor: DGTIC-UNAM resources (project LANCAD-UNAM-DGTIC-337). The authors acknowledge support from the Royal Society Newton International Exchange Scheme (Mexico) grant NI150051. L.P. thanks CONACYT becas nacionales 2015-2019 grant 174700. X. B. C. is supported by CONACyT grant (255203) and DGAPA project (IN105218-3). D. B. was supported by the UK Science and Technology Facilities Council (STFC) grant ST/P000622/1. D.T. acknowledges support of a studentship funded by the Perren Fund of the University of London. P.K. is supported by PAPIIT grant (IA101118).