SHocks: structure, AcceleRation, dissiPation

Work Package 3
Particle energization and dissipation processes at shocks

Deliverable D3.3
Heavy ion dynamics and heating

Prepared by: Michael Gedalin
on behalf of SHARP

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004131

Document Change Record

Issue	Date	Author	Details
1.0	24.02.2023	Gedalin	First version
1.1	1.03.2023	Gedalin	Revision 1
1.2	8.03.2023	Gedalin	Final version

Table of Contents

1 Summary

Heavy ions are affected by the same fields of the shock front as the protons are. Their motion depends on the charge-to-mass ratio. Distributions of all ions just behind the shock are non-gyrotropic. Gyrotropization and isotropization are gradual. Heating of each ion species is related to the onset of gyration of the directly transmitted ions and contribution of reflected ions. It was earlier shown that heating of ions with large mass-to-charge ratios is proportional to the mass (Gedalin, 2020). Dependence of the heating of the directly transmitted ions on their mass, charge, magnetic compression, and cross-shock potential is derived in Gedalin (2021). The ratio of the downstream temperature of a heavy ion species to the downstream proton temperature exceeds the mass ratio since the cross-shock potential affects stronger the particles will smaller mass. Heating of moderately heavy ions (thermal and superthermal populations) has been studied in Gedalin et al. (2023). For incident Maxwellian ions there are more reflected protons which enhances proton heating. For substantially superthermal distributions heavy ion reflection is stronger.

2 Introduction

Heavy ion dynamics is much less sensitive to the small scale details of the shock front and is determined by the global changes, that is, the magnetic field compression and the total cross-shock potential. Knowledge of the dependence of the postshock temperature of heavy ions is important for remote diagnostics using electromagnetic emission from ions. The study which was performed as a preparatory stage for SHARP (Gedalin, 2020) has shown that for large $m/q \gg 1$ the downstream temperature is proportional to the mass m of the species. This result is relevant for supernovae remnant shocks Miceli et al. (2019). In the heliosphere ions with $m/q > 1$ but not necessarily $m/q \gg 1$ are more abundant and may have substantially superthermal distributions. A very important example is pickup singly, He^{+}, and doubly, He^{++}, ionized helium. Another example is O^{6+} (see, e.g Berdichevsky et al., 1997). Measurements of heavy ion heating provides indirect information about the shock structure. Theoretical analysis of the heating mechanism and comparison with these observations would provide better understanding of shock physics.

3 Detailed account or results

In what follows we briefly describe the results of the two papers which complete the analysis of the ion heating.

3.1 Heating due to the directly transmitted ions

Analytical treatment of the ion motion at the shock crossing and the postshock gyration of directly transmitted ions provided the following estimate of the downstream temperature for thermal incident distributions

$$\frac{T_d}{mV_u^2} \approx \frac{1}{3}\left(\sqrt{1-s} - \frac{1}{R}\right)^2 \quad (1)$$

This expression is a simplified approximation of a more complicated dependence given in Gedalin (2021). Despite its simple form it properly presents the physics of the mechanism. Here $s = 2q\varphi/mV_u^2$ is the normalized cross-shock potential and $R = B_d/B_u$, while V_u is the upstream plasma velocity. Note that the normalized cross-shock potential depends on the species since it contains the species mass and charge. The downstream temperature also contains the corresponding mass. For large $m/q \gg 1$ the normalized cross-shock potential is negligible and therefore T_d/m depends only on the magnetic compression (and shock angle (Gedalin, 2021)). For $m/q \sim 1$ the cross-shock potential decreases heating, so that

$$\frac{T_h}{T_p} > \frac{m_h}{m_p} \quad (2)$$

This is valid even for He^+ and He^{++}, for which $m/q = 4$ and $m/2 = 2$, respectively. Most shocks in the solar wind (interplanetary shocks) are low Mach number shocks, in which directly transmitted ions are responsible for most of the heating. The above results explain the observed excess heating of heavy ions relative to protons in interplanetary shocks (Berdichevsky et al., 1997).

3.2 Heating due to reflected ions

In supercritical shocks reflected ions make major contribution into ion heating. Reflected ions have substantially larger gyration speeds than the directly transmitted ions. Since the contribution is proportional to the gyration speed squared, even a moderate fraction of reflected ions may significantly increase the downstream temperature. We have studied the effect of ion reflection on the downstream heating using test particle analysis in a model *subcritical* shock exploring thermal Maxwellian distributions and superthermal Vasyliunas-Siscoe (VS) distributions (Vasyliunas and Siscoe, 1976) for protons and helium ions (singly and doubly ionized). The advantage of this approach is that Maxwellian ions are not reflected at such shocks while VS ions are. The reflection is mainly due to the cross-shock potential, so that the fraction of reflected VS protons, ($m/q = 1$), is larger than that of VS H^{++}, ($m/q = 2$). The fraction of reflected VS H^+, ($m/q = 4$), is the smallest. Therefore, the enhancement of ion heating due to ion reflection is the strongest for protons and becomes progressively weaker with the increase of m/q. The findings are illustrated by the following two figures. Figure 1 shows the gyrotropic distribution function $f_d(v_\parallel, v_\perp)$, calculated in the de Hoffman-Teller frame, for incident Maxwellian distributions of H^+, He^{++}, and He^+. Parallel and perpendicular refer to the direction of the downstream magnetic field vector. Figure 2 shows the gyrotropic distribution function $f_d(v_\parallel, v_\perp)$, calculated in the de Hoffman-Teller frame, for incident VS distributions of H^+, He^{++}, and He^+.

Although the particular test particle analysis has been performed with a model typical for a subcritical shock, the conclusions hold for superctritical shocks also. The only difference is that at supercritical shocks ion reflection occurs for incident Maxwellian ions too.

4 Conclusions

To summarize, we have found the following:

- For large mass-to-charge ratios the downstream ion temperature scales with the mass.
- In low-Mach number shocks with no or negligible ion reflection ion heating is due to the gyration of the directly transmitted ions. The dependence of the downstream temperature on the magnetic compression, shock angle, and cross-shock potential is derived analytically.
- Ion reflection contributes significantly to the downstream temperature. In the same shock front contribution of reflected ions into the downstream temperature is larger for smaller mass-to-charge ratios.
- Differences in the heating of different species and thermal vs superthermal distributions are quantified.

5 References

D. Berdichevsky, J. Geiss, G. Gloeckler, and U. Mall. Excess heating of $^4He^{2+}$ and O^{6+} relative to H^+ downstream of interplanetary shocks. *JGR*, 102, 2623, 1997. doi:10.1029/96JA02541.

M. Gedalin. Preferential Heating of Heavy Ions in Shocks. *ApJ*, 900, 171, 2020. doi:10.3847/1538-4357/abaa49.

M. Gedalin. Shock Heating of Directly Transmitted Ions. *ApJ*, 912, 82, 2021. doi:10.3847/1538-4357/abf1e2.

M. Gedalin, N. V. Pogorelov, and V. Roytershteyn. Shock heating of incident thermal and superthermal populations of different ion species. *ApJ*, 945, 50, 2023. doi:10.3847/1538-4357/acb13a.

M. Miceli, S. Orlando, D. N. Burrows, K. A. Frank, C. Argiroffi, F. Reale, G. Peres, O. Petruk, and F. Bocchino. Collisionless shock heating of heavy ions in SN 1987A. *Nature Astronomy*, 3, 236, 2019. doi:10.1038/s41550-018-0677-8.

V. M. Vasyliunas and G L Siscoe. On the flux and the energy spectrum of interstellar ions in the solar system. *JGR*, 81, 1247, 1976. doi:10.1029/JA081i007p01247.

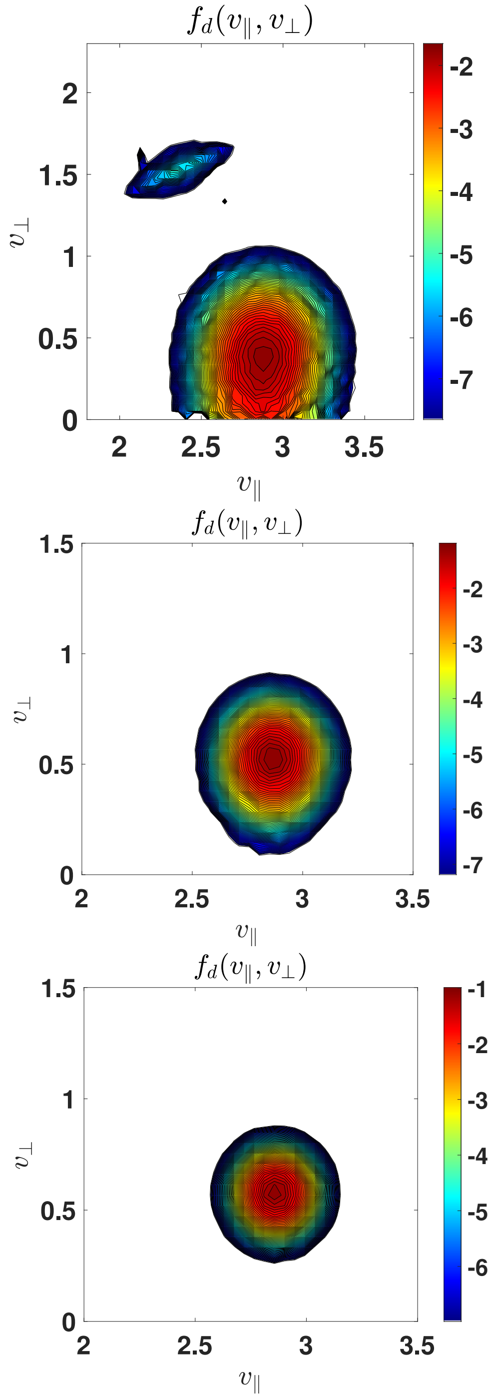

Figure 1: Gyrotropic distribution function $f_d(v_\parallel, v_\perp)$ for incident Maxwellian distributions from top to bottom: H^+, He^{++}, and He^+. Log scale, velocities are normalized on V_u.

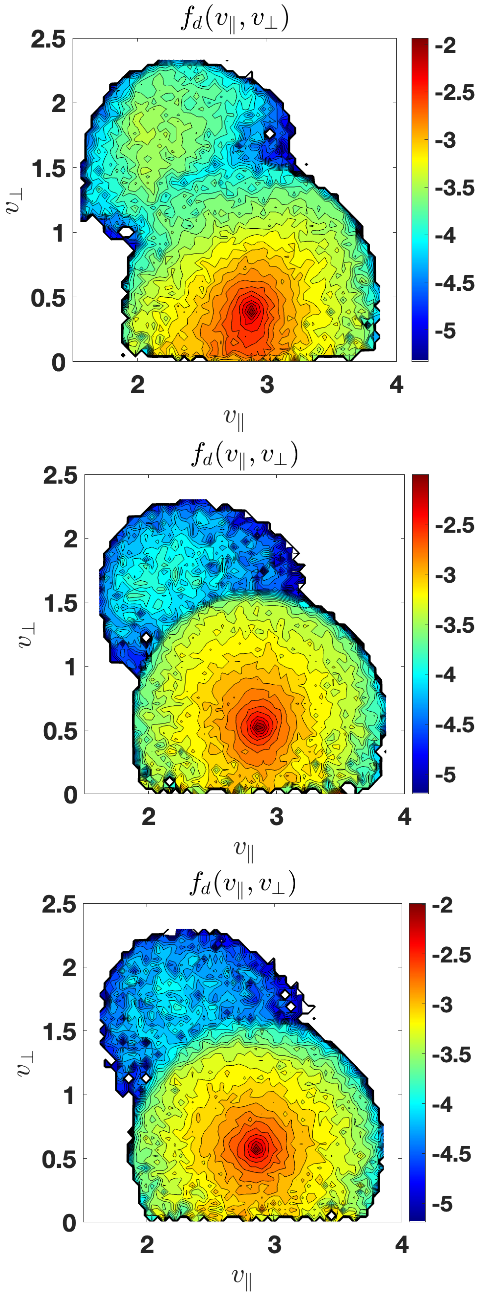

Figure 2: Gyrotropic distribution function $f_d(v_\parallel, v_\perp)$ for incident VS distributions from top to bottom: H^+, He^{++}, and He^+. Log scale, velocities are normalized on V_u.