# SHocks: structure, AcceleRation, dissiPation

## Work Package 3
## Particle energization and dissipation processes at shocks

## Deliverable D3.1
## Ion distributions in the shock front

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 | 15.08.2022 | Gedalin | First version |
| 1.1 | 26.08.2022 | Gedalin | Update |
| 1.2 | 27.08.2022 | Gedalin | Revision 1 |
| 1.3 | 29.08.2022 | Gedalin | Final version |

# Table of Contents

# 1 Summary

Ion distributions in the shock front are formed due to the interaction with the macroscopic electric and magnetic fields of the shock. Postshock gyration is responsible for ion heating. Upon crossing the shock ion distributions are non-gyrotropic. Farther from the shock the distributions become gyrotropic but anisotropic and subsequently tend to isotropize. Rankine-Hugoniot conditions change during isotropization and the magnetic field should change also (Gedalin et al., 2022b). The heating of superthermal populations occurs differently from the heating of thermal populations (Gedalin et al., 2022c). The heating of ions with different mass-to-charge ratios is also different. In shocks with substantial ion reflection, ion phase holes are a common feature. Derived distributions of thermal and pickup ions are in good agreement with observations (Smith et al., 2022). Heating of incident distributions with long tails (kappa) is different from the heating of Maxwellians (Gedalin and Ganushkina, 2022). Probabilities of ion scattering at the shock front are directly related to the downstream distribution shape (Gedalin et al., 2022a). MHD Rankine-Hugoniot relations and ion kinetics at the shock front are related using ion tracing (Gedalin, 2022). Overshoots and undershoot reduce anisotropy. Backstreaming ions are found only in shocks with sufficiently small shock normal angles.

# 2 Introduction

Ion heating at the shock front was first associated with the turbulence in the shock front and later with reflected ions (Paschmann et al., 1982; Gosling et al., 1982; Schwartz et al., 1983; Sckopke et al., 1983; Gosling et al., 1984; Thomsen et al., 1985; Burgess, 1987; Burgess et al., 1989; Gosling et al., 1989; Sckopke et al., 1990). It took some time until it was realized that ion heating is the direct result of ion gyration behind the shock front, whether these are directly transmitted ions or reflected ions (Gedalin, 1997), and until the kinematic relaxation was confirmed by direct observations (Pope et al., 2019). While the basic features of the downstream distributions are understood, their dependence on shock parameters is still under study. With the great improvement in measurement resolution, especially of MMS, it became possible to study the details of the distributions and their relation to the shock structure. As an example, ion phase space holes are observed and interpreted in various ways (rippling, reformation). A combination of theoretical/numerical methods together with the observations provides better insight.

# 3 Detailed account or results

In what follows short descriptions of the problems formulated in the studies and findings are given. The corresponding published and submitted papers are attached.

### 3.1 Analytical derivation of probabilistic shock crossing

One of the central problems of shock physics is finding the relation between the upstream and downstream ion distributions. This issue is crucial for establishing Rankine-Hugoniot relations (RH) connecting the upstream and downstream states. the RH relations are nothing but the density, momentum, and energy conservation laws, applied in two asymptotically uniform regions. Usually, the RH relations are used on the magnetohydrodynamic (MHD) scales where the distributions are assumed to be isotropic and some equation of state for plasma is chosen. In most cases, the heliospheric shocks do not arrive at the state which can be described by MHD. Near shock transitions, the conservation laws should take into account the non-gyrotropic distributions and corresponding coherent oscillations of the magnetic field. Farther from the shock and with some spatial and/or temporal averaging the distributions become gyrotropic but anisotropic. Higher Mach number shocks are believed to be time dependent and/or non-planar. In this case, the fluxes are only approximately constant throughout the shock. Upon appropriate spatial and temporal averaging the gyrophase information is lost and magnetic oscillations are smoothed out. Gyrotropic RH relations correspond to the equality of the upstream and downstream fluxes after gyrophase averaging. In oscillating, rippled, or reforming shocks, or when waves are propagating across the shock, there is no one-to-one correspondence between the upstream momentum of an ion and its momentum at each coordinate $x$ in the downstream region. When the gyrophase information is lost or averaged out, an ion with the reduced initial momentum $(p_{i,\parallel}, p_{i,\perp})$ will not have a definite $(p_{f,\parallel}, p_{f,\perp})$ at a chosen point $x$ but there will exist some probability of the ion having $(p_{f,\parallel}, p_{f,\perp})$ at the point $x$. Such a probabilistic approach can be applied for arbitrarily turbulent shock transitions. Instead of trying to solve the deterministic equations of motion, we can describe ion motion as probabilistic scattering at the shock front. Unfortunately, an analytical calculation of the scattering probability is not possible in the general case, and numerical methods are to be used. This approach has been successfully implemented already for high energy particles at a shock front. In this study, the problem of finding the downstream distribution function is reformulated in terms of the scattering probability. This approach is not restricted to only stationary and planar shocks but can be applied to rippled and reforming shocks as well since the scattering probabilities connect the asymptotic upstream and downstream regions, where the fields are uniform and time independent while the distributions are gyrotropic and also uniform and time independent. In general, finding the scattering probabilities is not an easy problem. However, they can be found numerically using test particle analysis in a model or measured shock front. When using a model no consistency of the chosen shock profile with the particle distribution is required. Indeed, the probabilities are determined by the fields upon spatial and temporal averaging. In the present paper, the scattering probability of directly transmitted ions was found analytically in the limit of a narrow shock. The approach is applicable to the core of the solar wind in a planar stationary shock, even if the shock is super-critical, provided the downstream magnetic oscillations damp quickly behind the ramp. The approximation is directly applicable to laminar and nearly laminar low-Mach shocks where kinematic collisionless relaxation is observed. The published paper (Gedalin et al., 2022a) is attached.

## 3.2 Isotropization and change of magnetic compression

Observations at the Earth bow shock clearly show that downstream ion distributions are anisotropic well beyond the shock transition. Figure 1 shows a histogram

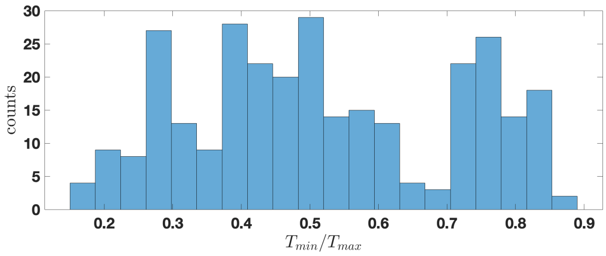


Figure 1: Histogram of $T_{min}/T_{max}$ for 300 MMS1 shock crossings.

of $T_{min}/T_{max}$ for 300 MMS1 shock crossings. This ratio is the mean ratio of the eigenvalues of the temperature tensor in the range 30-60 sec after the shock crossing. The total pressure of the plasma is dominated by the ion pressure, so that proper boundary conditions, aka Rankine-Hugoniot relations, should take into account this anisotropy. It is often expected that at some distance behind the shock the plasma becomes isotropic, as a step toward reaching thermal equilibrium (note that equilibration of the temperatures among the species may not occur yet at the scale of isotropization). If this happens and the approximations of planarity and stationarity are equally applicable in the anisotropic region and the isotropic region, with the same normal direction, the density should increase with the isotropization, so that the plasma should experience additional deceleration along the shock normal. In quasi-perpendicular shocks, the density increase is accompanied with the magnetic field increase, while in nearly-parallel shocks the magnetic field may decrease. These different density and magnetic compressions in isotropic and anisotropic regimes should be taken into account when applying theoretical Rankine-Hugoniot relations to observations. At present, it is not clear whether these changes can be observed in the heliospheric observations, since isotropization may occur at scales that exceed the inhomogeneity scale. In any case, if isotropy is assumed in calculations or simulations, it is important to not compare the magnetic compression with that observed in the region where the plasma is still anisotropic. The difference may be substantial. The submitted paper is attached (Gedalin et al., 2022b).

## 3.3 Differential heating

Heating of thermal (Maxwellian, M), as well as superthermal (Vasyliunas-Siscoe, VS), protons, singly charged helium, and $\alpha$-particles, is analyzed by tracing ions in a model shock front. Figure 2 illustrates the findings (paper in preparation). The distributions functions $f(v_\|, v_\perp)$ are derived from the ion distributions sufficiently far behind the shock front in the de Hoffman-Teller frame. The subscripts $\|$ and $\perp$ refer to the direction of the downstream magnetic field. There is a weak reflection

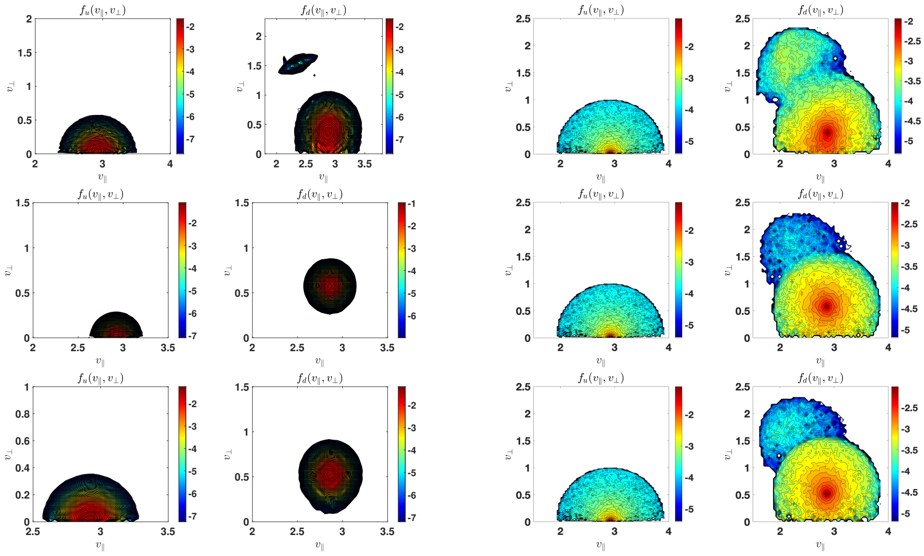

Figure 2: The upstream and downstream reduced distribution functions $f(v_{\parallel}, v_{\perp})$. Top row: protons. Middle row: singly charged helium. Bottom row: $\alpha$-particles. Left column: Maxwellian. Right column: VS.

of Maxwellian protons but no reflection of heavier Maxwellian species. For VS ions reflection is substantial in all cases, but for heavier species, it is weaker.

## 3.4 Long-tail distributions

Most of the heating analyses, including numerical simulation, performed so far, assumed Maxwellian distribution for incident ions. However, the actual distribution of ions in the solar wind may differ and is often found to be better described as a $\kappa$-distribution. Since the Maxwellian and $\kappa$ distributions have different tails, one may expect to observe differences in the ion distributions formed at the shock crossing, even if the velocity dispersion is the same. In this study, the downstream distributions formed from the incident Maxwellian and $\kappa$ are compared. Longer tails of the distribution function of incident ions result in stronger heating and smaller anisotropy of the downstream distribution. Both effects are due to stronger ion reflection since the reflected ions come from the tail of the distribution. Longer tails may be also responsible for filling the ion phase space holes. The distribution of reflected ions is much more diffuse for $\kappa$-distributed ions than for Maxwellian distributed ions. The submitted paper (Gedalin and Ganushkina, 2022) is attached.

## 3.5 Combining MHD and kinetics

MHD Rankine-Hugoniot relations are used to derive the magnetic compression for given Mach number, shock angle, and upstream $\beta$. These parameters are used for the model shock profile used in ion tracing. Theoretical estimate (**?**) is used for adding the cross-shock potential. Ion tracing is used to check if the magnetic field, derived from the pressure balance with the numerically obtained ion distributions, is consistent with the model shock. Good agreement is found for a shock with a small overshoot, which is not expected to affect ion dynamics. For a higher Mach number shock, with substantial overshoot and undershoot, adding these features to the shock model allows us to further improve the connection between MHD and kinetics. The submitted paper (Gedalin, 2022) is attached.

### 3.6 Comparison with observed distributions

The observed omni-directional 1D distribution functions of solar wind protons and pickup ions, measured by Ulysses SWICS and SWOOPS at the shock crossing on DOY 2003/333.5, are compared with the distributions obtained numerically with the test particle tracing (Smith et al., 2022). The upstream solar wind is fitted to a $\kappa$-distribution and the upstream PUI are fitted to a plateau. Theory and observations are found to be in good agreement, except for the high-energy tail which was not included in the analysis. The comparison is shown in Figure 3 which is taken from the published paper Smith et al. (2022).

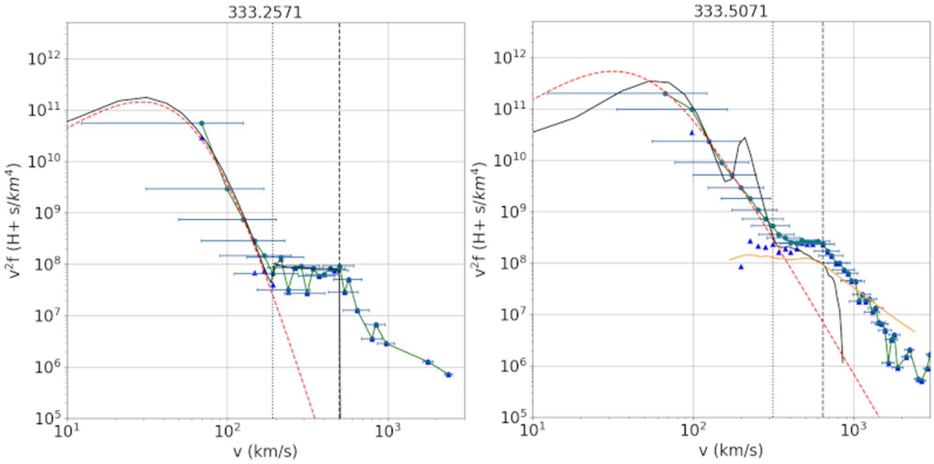


**Figure 7.** Proton spectra ahead (the left panel) and behind the shock (the right panel) that crossed the Ulysses trajectory on DOY 333.5. The distribution functions are shown with green lines and blue circles. The dashed red lines are used to fit the observational data in the thermal range with kappa distributions. The blue triangles show the difference between the input distribution function and the thermal ion distribution. The black line on the right panel shows the ion distribution function obtained with the test-particle simulation. The smaller extremum in this distribution corresponds to reflected PUIs. The orange line shows the VDF based on the diffusive shock acceleration theory.

Figure 3: Histogram of $T_{min}/T_{max}$ for 300 MMS1 shock crossings.

# 4 Conclusions

To summarize, we have achieved the following:

- The probabilistic approach is applied to the formation of downstream distributions of directly transmitted ions.
- It is shown that the magnetic compression should evolve during isotropization of the downstream distributions.
- Differences in the heating of different species and thermal vs superthermal distributions are quantified.
- Effects of long tails on the shape of the downstream distribution and heating amount are elucidated.

- Theory has been compared with observations of solar wind and pickup ions.

Now a new result has been obtained for backstreaming ions: they are produced only in shocks with the angle below 55°. This requires a) re-assessment of the existing observations at quasi-perpendicular shocks, and b) extension of the analysis on the time-dependent rippled shocks. The latter is planned and is already working. The reported results are a part of Task 3.1.

# 5 References

D Burgess. Simulations of backstreaming ion beams formed at oblique shocks by direct reflection. *Annales Geophysicae*, 5:133–145, June 1987.

D Burgess, W P Wilkinson, and S J Schwartz. Ion distributions and thermalization at perpendicular and quasi-perpendicular supercritical collisionless shocks. *J. Geophys. Res*, 94:8783, July 1989. doi: 10.1029/JA094iA07p08783.

M Gedalin. Ion heating in oblique low-Mach number shocks. *Geophys. Res. Lett.*, 24(2):2511–2514, October 1997. doi: 10.1029/97GL02524.

J T Gosling, M F Thomsen, S J Bame, W C Feldman, G Paschmann, and N Sckopke. Evidence for specularly reflected ions upstream from the quasi-parallel bow shock. *Geophysical Research Letters*, 9:1333, December 1982. doi: 10.1029/GL009i012p01333.

J T Gosling, S J Bame, W C Feldman, G Paschmann, N Sckopke, and C T Russell. Suprathermal ions upstream from interplanetary shocks. *Journal of Geophysical Research*, 89:5409, July 1984. doi: 10.1029/JA089iA07p05409.

J T Gosling, M F Thomsen, S J Bame, and C T Russell. Ion reflection and downstream thermalization at the quasi-parallel bow shock. *Journal of Geophysical Research*, 94:10027–10037, August 1989. doi: 10.1029/JA094iA08p10027.

G Paschmann, N Sckopke, S J Bame, and J T Gosling. Observations of gyrating ions in the foot of the nearly perpendicular bow shock. *Geophysical Research Letters*, 9:881, August 1982. doi: 10.1029/GL009i008p00881.

S A Pope, M Gedalin, and M A Balikhin. The First Direct Observational Confirmation of Kinematic Collisionless Relaxation in Very Low Mach Number Shocks Near the Earth. *J. Geophys. Res*, 165(1):3–15, March 2019. doi: 10.1029/2018JA026223.

S J Schwartz, M F Thomsen, and J T Gosling. Ions upstream of the earth's bow shock - A theoretical comparison of alternative source populations. *Journal of Geophysical Research*, 88:2039, March 1983. doi: 10.1029/JA088iA03p02039.

N Sckopke, G Paschmann, S J Bame, J T Gosling, and C T Russell. Evolution of ion distributions across the nearly perpendicular bow shock - Specularly and non-specularly reflected-gyrating ions. *J. Geophys. Res*, 88(A8):6121–6136, August 1983. doi: 10.1029/JA088iA08p06121.

N Sckopke, G Paschmann, A L Brinca, C W Carlson, and H Luehr. Ion thermalization in quasi-perpendicular shocks involving reflected ions. *J. Geophys. Res*, 95:6337, May 1990. doi: 10.1029/JA095iA05p06337.

M F Thomsen, J T Gosling, S J Bame, and M M Mellott. Ion and electron heating at collisionless shocks near the critical Mach number. *J. Geophys. Res*, 90(A1): 137, January 1985. doi: 10.1029/JA090iA01p00137.

M. Gedalin, N. V. Pogorelov, and V. Roytershteyn, Probabilities of ion scattering at the shock front, J. Plasma Phys., 88 , 905880110, 2022. doi: 10.1017/S0022377822000034.

M. Gedalin, M. Golan, N. V. Pogorelov, and V. Roytershteyn, Change of Rankine-Hugoniot relations during post-shock relaxation of anisotropic distributions (submitted).

M. Gedalin, N. V. Pogorelov, and V. Roytershteyn, Differential heating of species in shocks: Thermal vs superthermal populations (in preparation).

M. Gedalin and N. Ganushkina, Different heating of Maxwellian and kappa distributions at shocks (accepted).

M. Gedalin, Combining Rankine-Hugoniot relations, ion dynamics in the shock front, and the cross-shock potential (submitted).

W. P. Smith, K. Renfroe, N. V. Pogorelov, M. Zhang, M. Gedalin, and T. K. Kim, Bulk properties of pickup ions derived from the Ulysses solar wind ion composition spectrometer data, Astrophys. J., 933, 124. 2022. doi: 10.3847/1538-4357/ac73f2.