ON THE DISTRIBUTION FUNCTION OF PARTICLES AT QUASI-PARALLEL COLLISIONLESS SHOCKS

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Abstract. The departure of particle distributions from the Maxwellian is commonly observed in space plasmas. These non-Maxwellian distributions which are typical for plasmas that are not in thermal equilibrium, can be modeled with Kappa distribution function. Kinetic simulations of quasi-parallel collisionless shocks show that proton distribution is a composite of thermal, supra-thermal, and non-thermal parts, which correspond to thermalized, pre-accelerated, and diffusive-shock-accelerated protons, respectively. By using particle-in-cell shock simulations, we show that Kappa distribution adequately fits thermal and supra-thermal parts together, as one continuous distribution in early proton spectra. We find that the index kappa of the distribution increases with the distance from the shock, following the decrease in supra-thermal part. In the far downstream, initially strong supra-thermal part almost completely fades, leaving the proton distribution composed of a Maxwellian and a power-law.

κ - distribution

It is shown by Livadiotus (2017) that the state of a plasma which has not reached the thermodynamic equilibrium, can be characterized by κ - momentum distribution:

$$\frac{dN}{dp} = 4\pi p^2 f(p) = \mathcal{N}\frac{4\pi p^2}{(\pi\kappa p_0^2)^{3/2}}\frac{\Gamma(\kappa+1)}{\Gamma(\frac{\kappa}{2}-1)}\cdot\frac{1}{\left[1+\frac{p^2}{\kappa p_0^2}\right]^{\kappa+1}}$$

Such distributions are common to the space plasmas (Livadiotis G. & McComas D.J. 2011). Because of the self-reforming behaviour, the collisionless shocks are expected to produce an out-of-the-equilibrium plasma. Indeed, the non-Maxwellian particle distributions are observed at the shock of supernova remnants (Raymond et al. 2010). It is shown by kinetic simulations (Caprioli et al. 2014) that the plasma distribution downstream of the shock can be decomposed to thermal, super-heated, and non-thermal (accelerated particles) components. Furthermore, by including the finite duty cycle of a reforming shock barrier, one can easily model the suprathermal transition observed in the particle spectra. As described in Caprioli et al. (2014), some ions can gain extra energy by performing a few gyrations while drifting along the shock surface (the shock drift acceleration - SDA). This process leads to the simultaneous production of both, thermal and suprathermal ions, the later providing the seed particles for the diffusive shock acceleration (DSA) mechanism. In order to model both these components as different features of a single, non-stationary plasma, we introduce a κ - distribution.

PIC simulations

The initial particle spectrum is clearly not Maxwellian. This can be seen in the spectra plot in Caprioli & Spitkovsky (2014). Rather soon a non-thermal particles emerge, and over time, initially strong supra-thermal part almost completely fades, leaving the proton distribution composed of a Maxwellian and a power-law. Alternatively, the distribution can be described with the so-called Minimal model of Caprioli et al. (2014). However, this does not describe the maximum in the spectra.

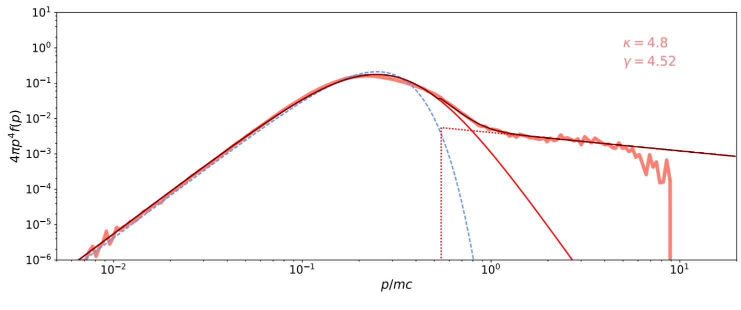

Figure 1. The near downstream ion spectrum. The dashed blue line denotes Maxwellian fit; the thin red line is κ - distribution fit; the dotted red line is a power law fit; the brown line is the best κ + power law fit; the data is plotted as a thick, light-red curve. The measured parameter κ and spectral slope γ of the momentum distribution $f(p) \sim p^{-\gamma}$, are given in the upper right corner.

We run the particle-in-cell simulation of an initially parallel collisionless shock with the parameters shown in Table 1. We here report that the thermal and suprathermal components in ion spectra may correspond to a plasma that is in the transient state, which is ideally fitted by the κ - distribution function (see Fig. 1). We fit the whole momentum spectra by the sum of κ and power law distributions. Moreover, from the best fit we get that the momenta p_{inj} at which ions are injected into DSA (a point where the power-law starts), strongly matches the one predicted by the Minimal model (Caprioli et al. 2014).

m_i / m_e	σ	υ_{sh} [c]	M_A	M_S	t [ω_{ci}^{-1}]
16	0.6 x 10^{-3}	0.4	16	35	2011

Table.1. The parameters of the run from left to the right: ion-to-electron mass ratio, magnetization (the ratio of magnetic to kinetic energy density), the shock velocity in the lab frame, the Alfven and sonic Mach numbers, and the simulation end time, respectively.

In Fig. 2, we show the ion spectra captured at different regions in the downstream. As moving farther from the shock, the κ - index in the particle distribution increases. This means that the plasma farther from the shock, appears to be closer to its equilibrium state. In the limiting case, an infinite value of κ would correspond to the equilibrium case with the Maxwellian distribution.

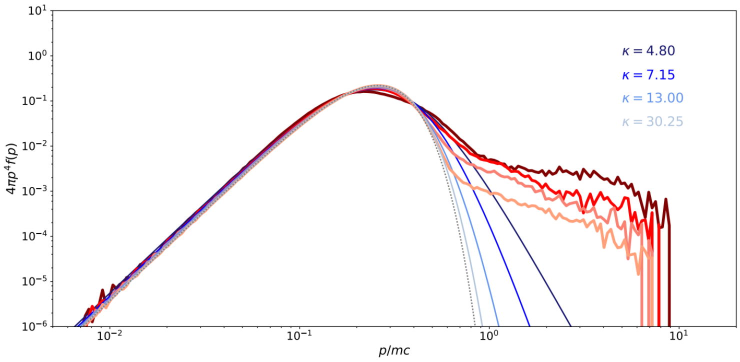

Figure 2. The downstream ion spectra at different distances from the shock. The data is plotted in red: the darker lines correspond to the regions closer, and the lighter lines to the regions farther from the shock. The κ - distribution fits are represented by blue lines, each fit-line corresponding to the data-line with the same intensity level. The same color coding holds for the κ - parameters given for each fit (the upper right corner). The Maxwellian fit of the spectrum corresponding to the farthermost downstream region, is plotted by the dotted grey line.

By tracing the time evolution of the ion spectrum right behind the shock, we find that the value of κ - index varies in the range ~ 4-7. This however holds over the simulation time period, but may be subject to changes over the longer periods, or given the different shock parameters and inclinations relative to the magnetic field.

Conclusions

1. The sum of thermal and suprathermal components in the downstream ion spectrum can be represented by the single κ - momentum distribution, which is used to describe non-equilibrium plasmas.

2. The spectra closer to the shock imply the non-equilibrium plasma states. Farther from the shock, the plasma settles down, the κ - index increases, and κ - distribution takes the shape of a thermal Maxwellian distribution. The far downstream spectrum is thus composed only of a Maxwellian and a power law.

3. The κ + power law best fitting procedure implies p_{inj} as predicted by the Minimal model of ion injection. The obtained injection momentum p_{inj} remains nearly the same throughout the downstream.

4. The further theoretical work is required in order to show whether the κ - distribution is indeed produced in SDA cycles at the reforming shock barrier.

References

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