PIC SIMULATIONS OF SNR'S SHOCK WAVES WITH A TURBULENT UPSTREAM MEDIUM*

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Investigation of astrophysical shocks has major importance in understanding the physics of the cosmic rays acceleration. Electrons to be accelerated at shocks must have suprathermal energy, which implies that they should undergo some pre-acceleration mechanism. Many numerical studies examined possible injection mechanisms, however, most of them considered homogenous upstream medium, which is an unreal assumption for astrophysical environments. We will investigate electron acceleration at high Mach number and low plasma beta shocks using a 2D3V particle-in-cell simulations with a turbulent upstream medium. Here, we discuss a method of generation of the compression-dominated turbulence. It is sufficiently long-living to be inserted into a shock simulation and its parameters represent the high Mach number and low beta regime.

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1. Introduction

The origin and production of cosmic rays (charged particles which reach the Earth surface, CR) continue to be an unsolved problem in modern astrophysics. Observations of supernova remnants (SNR) show non-thermal X-ray emission, which confirms the presence of accelerated electrons there. It is widely accepted that the particles gain energy via diffusive shock acceleration (DSA) on non-relativistic collisionless shocks, formed during the interaction of supernova ejecta, and the interstellar medium. However, to participate in this mechanism, a particle's Larmor radius must be comparable to the shock width, *i.e.* some initial energy is required for the particle

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to be injected into DSA. Thermal electrons do not satisfy this requirement, thus some mechanism has to operate before the main acceleration. Possible electron pre-acceleration mechanisms are the topic of current investigations.

Capturing physics on the electron kinetic scales requires using particle-in-cell (PIC) simulations. The PIC algorithm is an *ab-initio* method for the kinetic plasma theory, which solves the Vlasov–Maxwell equations with the method of characteristics. It is a commonly used tool in studies of astrophysical shocks, see *e.g.* [1]. Considering that full 3D simulations are computationally expensive, the usual way to save resources is tracking only 2-spatial components of the individual particles in plasma. Whereas all 3 velocity components are followed, the code is called 2D3V, and in that approach, the base code, TRISTAN, was modified [2].

SNR shocks are collisionless — in short, particle dynamics is dominated by particle-wave interactions, and fast, $v_{\mathrm{sh}} \approx 10,000$ km/s. The shock speed can be characterized by Mach number (shock speed to sound speed ratio), which is high in the SNR case. Shock physics also depends on the large-scale magnetic field obliquity, which is described by the angle between the shock normal and the magnetic field vector, θ_{Bn}. Numerous PIC simulations examined in detail perpendicular SNR shock waves, $\theta_{\mathrm{Bn}} = 90^\circ$ [3–7]. In the case of oblique angles, $\theta_{\mathrm{Bn}} \approx 60^\circ$–$70^\circ$, particles can be reflected back upstream (unshocked region) at the shock front, which significantly expands the area of particle-shock interactions. This requires using larger simulation boxes, and spends more computational resources. Even so, research in high Mach number and oblique shocks is active, see *e.g.* [8] and references therein. These studies assumed that the upstream medium is homogenous, thus all turbulence there had to be driven only by reflected particles. Nevertheless, space plasma research shows that pre-existing fluctuations are crucial for electron acceleration at interplanetary shocks [9]. Our goal is to check if it happens to be the case for SNR shock waves.

We investigate effects of pre-existing turbulence on electron acceleration using shock simulations with a turbulent upstream medium. Recently, [10] there were presented results of hybrid kinetic shock simulations with non-homogenous upstream medium, where the turbulence is established separately in magnetohydrodynamic code, and then inserted into the main simulation. Our technique is similar, but since we want to fully resolve electron-scale phenomena, we have to use the PIC code. The turbulence is generated independently in periodic box simulation, and the outcome is quasi-seamalessly inserted into a shock simulation. The above requires matching plasma slabs in different states. Here, we discuss the method of turbulence generation and the matching algorithm.

2. The turbulence generation

In ordinary shock simulations, the upstream plasma flows towards the shock, and so it has to be continuously added in a thin layer. It cannot be done for the turbulent upstream, because the slabs with pre-existing fluctuations have to be established separately, and then injected into the simulation. Therefore, we pre-fabricate a turbulent slab in a square simulation box with periodic boundaries, whose size corresponds to the transversal size of the shock simulation. Fluctuations are obtained by imposing the initial perturbation as a superposition of longitudinal and transversal waves [11].

The first studies have been performed for compressive velocity fluctuations, *i.e.* local disturbance of the bulk velocity. These compression waves have randomly chosen wavelengths, orientation (with respect to the x-axis), amplitudes, and phases. Periodic boundaries require that the wavevector components have to fulfill the following identities: $k_x L = n\pi$ and $k_y L = m\pi$, where L is the box size and n, m are random integers. The initial spectrum strongly depends on combinations of n, m pairs, but it changes as the system evolves.

The method described above efficiently generates compressive turbulence, whose well-developed structure is shown in Fig. 1. The right panel shows the level of ion-velocity fluctuations. The medium-scale bulk velocity is averaged over elements of 10×10 grid cells (the size of the simulation box is 960×960). This quantity represents the initial fluctuations scale, and it varies in association with the density fluctuations. Over time these fluctuations decay and their energy turns into heat. This is an essential feature of every kind of turbulence. The decay time exceeds $2\,\Omega_i^{-1}$, and so fluctuations

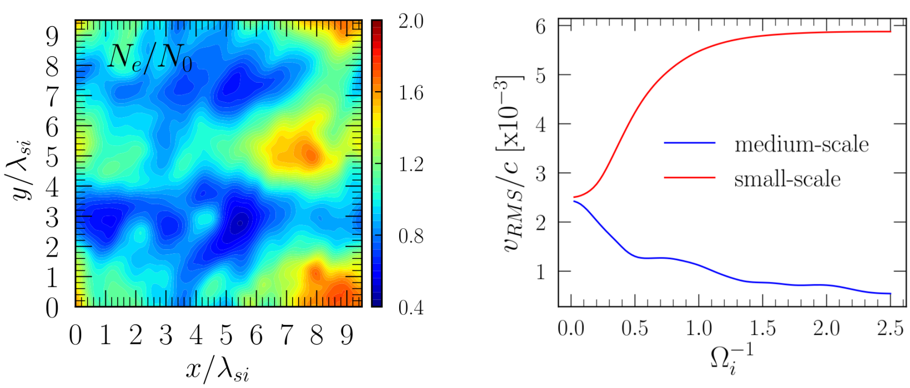

Fig. 1. Left: Normalized electron density map showing the well-developed structure of the compressible turbulence, after approximately $1\,\Omega_i^{-1}$. Right: Time evolution of the velocity fluctuation amplitude on a medium scale and on a microscopic (thermal) scale.

are sufficiently long-lived to be inserted into a shock simulation. The temperature of particles at the end state corresponds to the high-Mach-number regime, which is consistent with the earlier SNR shock simulations.

3. The turbulence injection

After separately establishing the compressive turbulence in a periodic box simulation, the outcome can be inserted into a shock simulation. There, a large slab of plasma moves towards a reflecting wall. Particles are reflected and their interaction with incoming plasma forms a shock wave. In this "reflection wall" setup, the upstream plasma needs to be continuously replenished. If the upstream medium is homogenous, it can be done easily by a frequent plasma injection in a thin layer. In contrast to this, in the case of turbulent medium, the whole pre-fabricated plasma slab is attached. It must be matched to the adjacent plasma to prevent from transient building, *i.e.* fields and currents need to be smoothly merged.

Usually, in the reflection wall setup, plasma approaches from the right side. Then one has to consider two plasma slabs: the left one (old, at the end of the upstream plasma), which is adjacent to the right one (new, the pre-fabricated turbulent slab). The matching is done for each cell in the selected region in the outer right part of the left slab (transition zone). Values of the magnetic field there are replaced by the weighted sum of values from the left and the right slab

$$B_{\mathrm{M}}(i,j) = w(i)B_{\mathrm{L}}(i,j) + [1 - w(i)]B_{\mathrm{R}}(i,j)\,, \tag{1}$$

where subscripts "L" and "R" denote left and right slab, subscript "M" stands for the matched value, and i, j are cell numbers in the x- and y-direction, respectively. The same is done for the electric field. Simple calculations show that imposing weights for fields does not contribute to large factors in Ampère's law and Faraday's law.

Despite the fields, the currents also need to be matched. In the PIC code, the current is deposited by particles, which means that a smooth transition in the velocity distribution function of each species is required. All particles in the transition zone are deleted and the new ones are generated combining their properties from both slabs. Distribution of a particle velocity component is assumed to be a normal distribution, whose moments (mean and RMS velocity) are calculated using particles from the left and the right slab (multiplied by weights). Since we use approximately 20 particles per cell to reduce estimation error, the mean and the RMS velocity are calculated in 3×3 cells. A number of newly generated particles is the integer part of the weighted sum of number of particles from both slabs. This rounding gives the additional charge noise which does not satisfy Gauss law,

$\rho - \nabla \cdot \boldsymbol{E} = \delta\rho$. It must be corrected by an additional electric field, $\delta\boldsymbol{E}$, such that $\delta\rho - \nabla \cdot \delta\boldsymbol{E} = 0$, because our code does not explicitly solve the Gauss law. This minor current correction is the topic of our current investigations.

4. Summary

The pre-existing turbulence in the upstream of a shock wave may influence the electron pre-acceleration in the high-Mach-number regime. Earlier SNR shock simulations were run with homogenous plasma and we will repeat a selection of them using the new setup with turbulence. Here, we discussed how the turbulence is generated and how it is inserted into a shock simulation. The initial local bulk velocity perturbation in a form of superposition of compressible standing waves is an efficient way to establish turbulence, which reflects SNR shocks conditions. Inserting the pre-fabricated turbulent slab into a shock simulation requires matching it to the end of the plasma in the simulation. We currently work on the matching algorithm, which will allow us to avoid production of any transients. A separate type of turbulence, the Alfvénic one, also can exist in the circumstellar medium around SNRs. It can be established in PIC simulations with a so-called Langevin antenna method [12]. We will use it to examine differences between both types.

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