HYBRID MODELING OF QUASIPARALLEL COLLISIONLESS SHOCKS IN TWO-SPECIES PLASMAS: TRAJECTORIES OF SUPRATHERMAL PARTICLES

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Abstract: An individual-particle kinetic analysis of ion injection into the process of diffusive shock acceleration (DSA) is performed within a hybrid simulation of interstellar plasma for the case of two-species medium. It appears that only those ions, which are reflected from the shock front during their first interaction with it, are further injected into the efficient DSA.

Keywords: collisionless shocks in space plasmas, cosmic rays, hybrid simulation of plasmas.

Introduction

Collisionless processes often dominate the dynamics of astrophysical plasmas due to the relatively low densities of the interstellar medium, allowing Coulomb mean free paths of the ions to be much larger than the system size. Physical processes in such systems are governed by collective nonlinear interactions between charged particles and fluctuating electromagnetic fields. In particular, various plasma instabilities, magnetic field amplification, and non-Maxwellian distributions of particles are likely to develop, making the problem too complicated to be solved analytically. Therefore, advanced numerical techniques are required to model the mentioned systems and processes. One of the commonly used methods is the hybrid approach, where ions are treated as individual particles, while electrons are represented by massless fluid [1]. This approach allows one to maintain a reasonably good balance between precise modeling of nonlinear processes on ion scales and saving numerical resources due to neglection of individual electrons.

One of the long-standing and important problems of modern astrophysics is the origin of cosmic rays — accelerated particles of energies up to 10^{21} eV, registered both directly with space-borne spectrometers and indirectly via ground-based observations of extensive air showers. Galactic cosmic rays of energies up to 10^{15} eV are believed to originate from supernova remnants, where they are accelerated by collisionless shocks driven by super-Alfvenic particle flows. Quasi-parallel collisionless shocks, where the angle between the shock normal and the direction of the ambient magnetic field is substantially less than $\pi/4$, are considered efficient particle accelerators. In the vicinities of such shocks energetic particles undergo diffusive shock acceleration (DSA), which allows them to gain energy due to multiple shock crossings [2]. However, to get involved, the ions need to be sufficiently pre-accelerated to overcome the cross-shock potential. Particular details of such pre-acceleration are still not clear (the so-called “injection problem”). A recent work [3] associated the pre-accelerated particles with reflected ion beams, observed *in situ* in the Solar wind. The authors of [3] also presented hybrid modeling of particle reflection at a shock and showed how the system proceeds beyond the initial injection steps. In the present work we add to the results of [3], emphasizing that all the particles, which eventually gain energy substantial to be injected into the DSA, are initially reflected at the shock front. We also expand our investigation to the case of two-species (hydrogen and helium) plasmas and find that particles of both sorts get accelerated in a similar way.

Hybrid modeling of shock dynamics and ion injection

A plasma box containing a moving collisionless shock was modeled with the three-dimensional second-order accurate hybrid code with exact magnetic field divergence conservation, described in [4, 5]. All the physical parameters of the system were normalized to the upstream proton inertial length (l_i), ion gyrofrequency (Ω_i), Alfven velocity (V_A) and plasma density. The shock was initiated via a standard piston method, when the initial flow of super-Alfvenic ions moving in the negative *x* direction is reflected from a conducting wall at $x = 0$. The modeling considered an initially uniform magnetic field directed in the *x*-*z* plane and inclined by 10^o to the flow direction. Shock parameters typical for a supernova remnant were chosen: the

Afvenic Mach number of the initial flow M_A=10 (in the downstream reference frame), the upstream ratio of thermal to magnetic pressure β = 0.001. The medium consisted of 75% protons (by mass) and 25% He (+1) ions (by mass). The simulation was performed in a rectangular box of length 10000 x l_i on the time scale t = 850 Ω_i^{-1}.

Soon after the shock was initialized, the energy spectra of the ions showed characteristic power-law tails, indicating particle injection into the DSA. By the end of the simulation timescale the protons reached energies up to about 700 E_{sh}^{p}, and the He ions — up to 150 E_{sh}^{He} where E_{sh} is their far upstream kinetic energy (note that the maximal velocities of the protons appeared twice those of the He ions). For each sort we selected some dozens of most energetic particles and traced their coordinates and velocities, as well as electromagnetic fields, acting on them, back until the simulation start. We considered only those particles, which interacted with the shock front after its complete formation at about 250 Ω_i^{-1} in order to exclude possible unphysical influence of the boundary conditions. The resulting particle trajectories in physical space were confronted with time-dependent maps of magnetic field amplitudes and effective angles, thus highlighting the behavior of the injected particles. Those trajectories and maps were further confronted with x-V_x, x-V_y, x-V_z, and x-E phase spaces with pin-pointed positions of injected particles for successive evolution times.

Thereby, it became evident that all the particles, which eventually gain substantial energy, were reflected back during their first interaction with the shock front. This observation is consistent with the results of [3] and contradicts the so-called “thermal leakage injection” hypothesis, where thermal, but energetic (“the Maxwellian tail”) particles from the shock downstream penetrate upstream and are injected into the acceleration mechanism. The latter process seems to be in fact suppressed by strong magnetic field fluctuations in the vicinity of the shock front, which could be overcome only by the already supra-thermal ions.

Typical trajectories of injected particles of both sorts are illustrated on the top panel of Fig. 1 along with the evolution of the shock front itself. The middle panel shows the local magnetic field angle to the shock normal at the selected position, while the bottom panel illustrates the evolution of the ion energies.

It should be noted that injected particles of both sorts behave similarly: during the first interaction with the shock front they interact with the quasi-perpendicular component of the magnetic field and thus do not penetrate downstream, instead continuing to move along the shock front (this process is sometimes called the shock drift acceleration [SDA] and is characteristic for quasi-perpendicular field configuration [see the middle panel of Fig. 1]). During this first stage some preliminary energy gain occurs. Eventually, such a drifting particle reaches a quasi-parallel field zone and moves back upstream, thus completing the primary reflection stage to further enter the DSA. One may also note that for the He ions this first stage is longer, due to their larger gyroradii. For the same reason during the SDA stage the He ions penetrate slightly deeper into the shocked medium. However, the whole mechanism is similar for H and He ions, in contrast with [6], who proposed that heavier ions reflect not from the shock front, but from post-shock magnetic irregularities. That can be true for the ions, which have already gained sufficient energy, but, as it can be seen from the *proton2* trajectory in Fig. 1, it is not a unique property of all the heavy ions, but occurs only at a certain phase of the DSA.
As an ion is injected into the DSA process, its acceleration consists of multiple shock crossings and reflections both upstream and downstream. Comparing the top and the bottom panels of Fig. 1, one may conclude that most efficient energy gain is usually obtained during the shock reflection events.

Conclusions

An individual-particle modeling of ion injection into the process of diffusive acceleration (DSA) at an interstellar shock has been performed within a hybrid simulation for the case of two-species plasma. It was found that injected ions of both sorts enter the DSA process in similar ways, but for heavier ions each step is longer and acceleration is slower (by a factor of 2 in case of He[+1]) due to larger spatial and temporal scales. An important observation was made, that for 100% of sufficiently energized particles their acceleration started with a reflection from the shock front. However, this process consists of two consequent phases: a shock drift stage in an area of quasi-perpendicular magnetic field, and an upstream escape after the particle reaches a quasi-parallel field area. Subsequently, the accelerated particles gain energy via multiple reflections off upstream precursor waves and downstream magnetic irregularities.

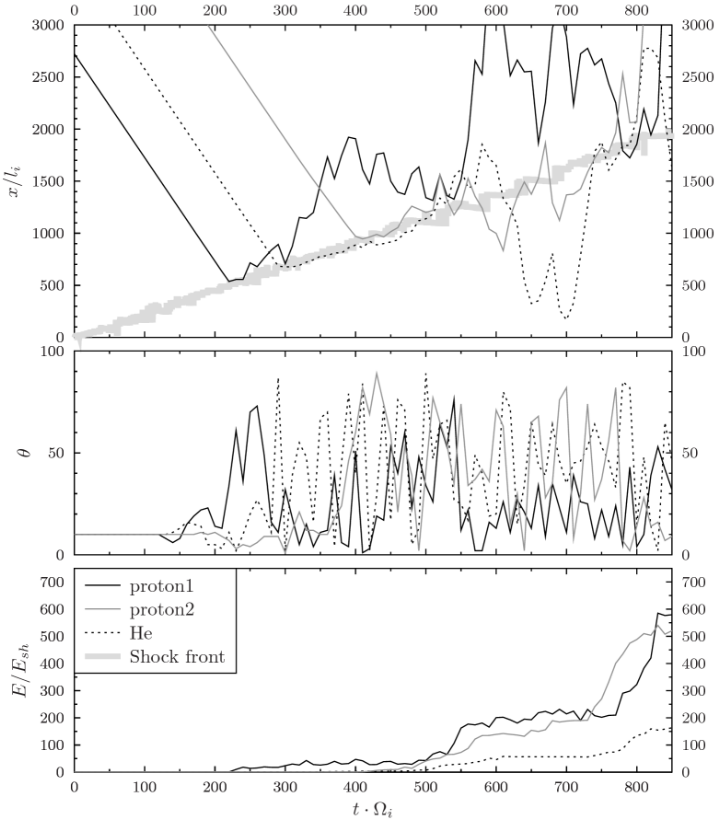

Fig. 1. Temporal evolution of injected particle trajectories (top panel), local magnetic field angles (middle panel) and particle energies (bottom panel). Two protons, denoted as *proton1* and *proton2*, and one He ion were chosen here to illustrate typical behavior of injected ions.

References

1. Matthews, A.P. Current Advance Method and Cyclic Leapfrog for 2D Multispecies Hybrid Plasma Simulations // J. Comp. Phys. 1994. n. 112, pp. 102–116.

2. Caprioli, D.; Spitkovsky, A. Simulations of Ion Acceleration at Non-relativistic Shocks. I. Acceleration Efficiency // ApJ 2014. vol. 783, i. 2, pp. 783:91.
3. Sundberg, T.; Haynes, C.T.; Burgess, D.; Mazelle, C.X. Ion Acceleration at the Quasi-parallel Bow Shock: Decoding the Signature of Injection // ApJ 2015. vol. 820, i. 1, id. 21, 15 pp.
4. Kropotina, Yu.A.; Bykov, A.M.; Gustov, M.Yu.; Krassilchtchikov, A.M.; Levenfish, K.P. Relaxation of heavy ions in collisionless shock waves in cosmic plasma // Technical Physics 2015. vol. 60, i. 2, pp. 231-239.
5. Kropotina, Yu.A.; Bykov, A.M.; Krasil'shchikov, A.M.; Levenfish, K.P. Hybrid simulation of collisionless shock waves in space plasma // Technical Physics 2016. vol. 61, i. 4, pp. 517-524.
6. Caprioli, D; Yi, D.T.; Spitkovsky, A. Chemical Enhancements in Shock-accelerated Particles: Ab-initio Simulations // eprint arXiv:1704.08252.

MODELING OF X-RAY STRIPES IN TYCHO'S SUPERNOVA REMNANT

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Abstract: Chandra observations of Tycho's supernova remnant (SNR 1572) allowed us to get high-resolution X-ray images of SNR. It was discovered that there are several series of coherent X-ray structures (bright, almost parallel stripes) in some regions of SNR. It is likely that the observed radiation of Tycho's SNR is synchrotron radiation of electrons with energies about 10^{14} eV. We develop a model, which represents synchrotron X-ray images of Tycho's SNR in order to reveal the physical mechanism of the observed structures formation. The model allows one to connect the bright stripes with a specific mechanism of the energetic particle transport in SNR. In particular, it is shown that the mirror instability, which evolves in plasma near SNR shock as a result of anisotropic