Physics of nonrelativistic perpendicular shocks of young supernova remnants.

Artem Bohdan[1], Martin Pohl[1,2], Jacek Niemiec[3], Takanobu Amano[4], Masahiro Hoshino[4], Yosuke Matsumoto[5]

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Abstract

It is generally assumed that the most part of galactic cosmic rays is produced by supernova remnants through diffusive shock acceleration (DSA). To be involved in DSA particles should be picked up from thermal pool. This issue is known as injection problem and still remains unresolved. Here we present results of 2D3V particle-in-cell simulations of nonrelativistic perpendicular shocks for the parameters applicable for supernova remnants. Physics of such shocks is governed by ions, part of which reflected back upstream by shock potential. That leads to the excitation of the electrostatic Buneman instability in the shock foot and to the formation of magnetic filaments in the shock ramp, resulting from the ion-beam-Weibel instability. Injection of electrons occurs in three different ways, namely, shock surfing acceleration, magnetic reconnection and stochastic Fermi-like acceleration. However efficiency of these processes strongly depends on shock parameters, such as Alfven Mach number and ion-to-electron mass ratio. Weibel instability in the shock transition also leads to redistribution of ion bulk kinetic energy into ion thermal, electron thermal, magnetic field energies and formation of turbulent magnetic field in the shock downstream.

Supernova remnant shocks

Physics of high Mach number perpendicular shocks is defined by the shock reflected ions. Reflected ions interact with the incoming plasma and produce two instabilities in the shock transition: electrostatic Buneman instability at the leading edge of the shock foot (Fig. 1c) and Weibel-type filamentation instability in the foot-ramp region (Fig. 1b).

The Buneman instability results from the interaction of the shock-reflected ions with the incoming electrons. Electrostatic waves can capture electrons which can be accelerated by convective electric field up to relativistic energy if the trapping condition is satisfied [1]. This acceleration mechanism is knowns as shock surfing acceleration (SSA) and efficiency of it strongly depends of the setup and physical parameters [2].

The Weibel-type instability is excited because of interaction of reflected ions with incoming from the upstream region ions. The incoming magnetic field lines are strongly deformed through the Weibel instability forming appropriate conditions for magnetic reconnection [3]. Magnetic reconnection converts the magnetic energy to the kinetic energy of particles through number of processes [4].

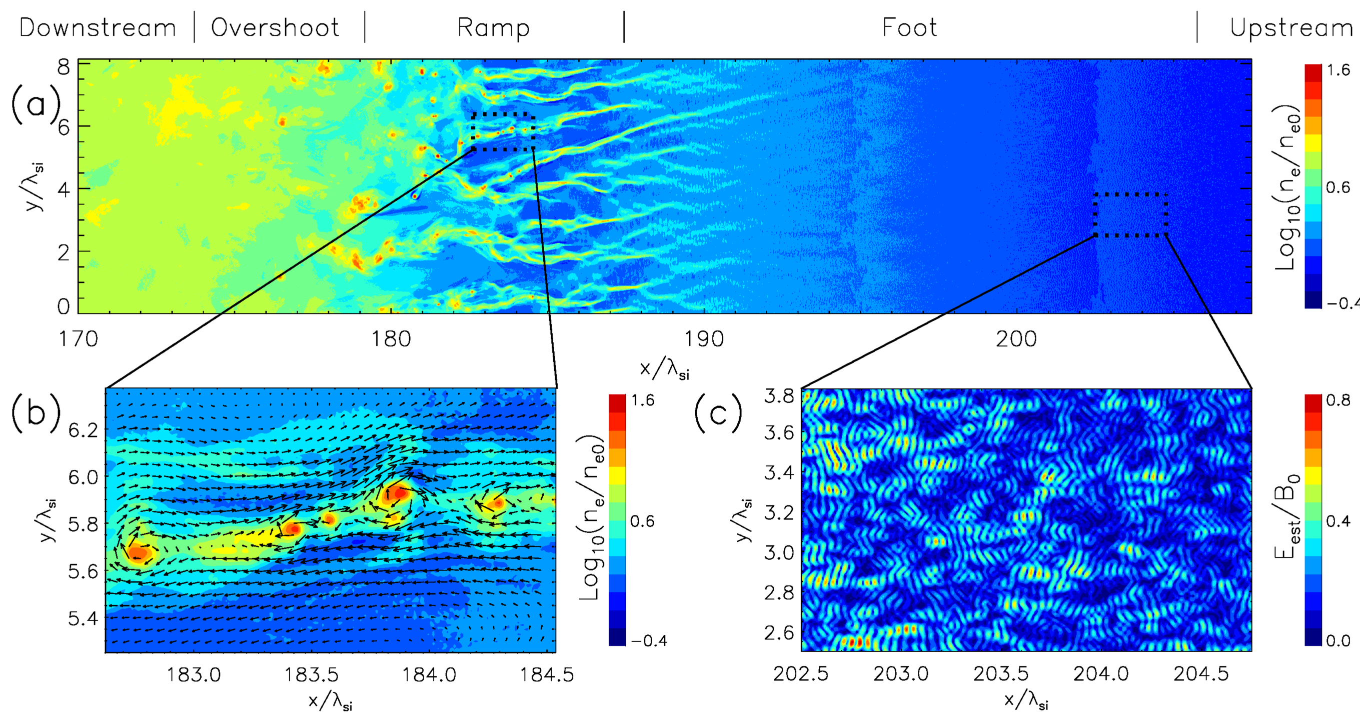

Figure 1: The structure of high Mach number perpendicular shock: (a) - electron density in the shock region; (b) - electron density with overlapped in-plane component of magnetic field in magnetic reconnection region; (c) - electrostatic field strength in the Buneman instability region. λ_{si} is the ion skin length.

Simulation setup

The simulation is performed by usage of the flow-flow method (Fig. 2). It considers an interaction of two counterstreaming electron-ion plasma flows. As a result of the two plasma slabs collision two shocks are formed propagating in opposite directions. The homogeneous magnetic field, $\vec{B_0}$, is perpendicular to the shock normal and lies in the *yz* plane.

The particle-in-cell (PIC) code we use is a 2D3V-modified and MPI-parallelized version of the relativistic electromagnetic PIC code TRISTAN [5,6].

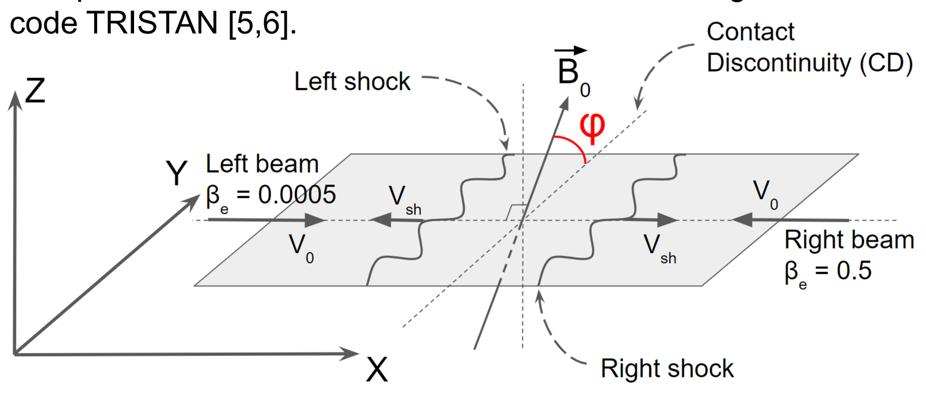

Figure 2: Illustration of the simulation setup.

Production of nonthermal electrons

Formation of a high energy tail

Interaction of upstream electrons with Buneman and Weibel instabilities leads to electron heating and acceleration. Influence of individual processes strongly depends of physical parameters used in simulation runs. Figure 3 illustrates the temporal evolution of the electron spectrum for a selected electron population that traverses the shock structure for **run E**. Two subsets of electrons are chosen for the analysis:

- The first subset is defined at time t_2 and consists of electrons with $(\gamma\text{-}1)>0.1$ that have been pre-accelerated in the Buneman instability region and populate the nonthermal tail in the spectrum.
- The second subset form electrons that at time t_4 have energies $E/(m_ec^2) > 5{\cdot}k_BT$, where T is the downstream temperature.

Only 6% of preaccelerated by SSA electrons (intersection of the green and red subsets) can be found in the high energy tail of the downstream region.

Most nonthermal electrons are produces in ramp-overshoot region via magnetic reconnection and chaotic interactions with magnetic turbulences.

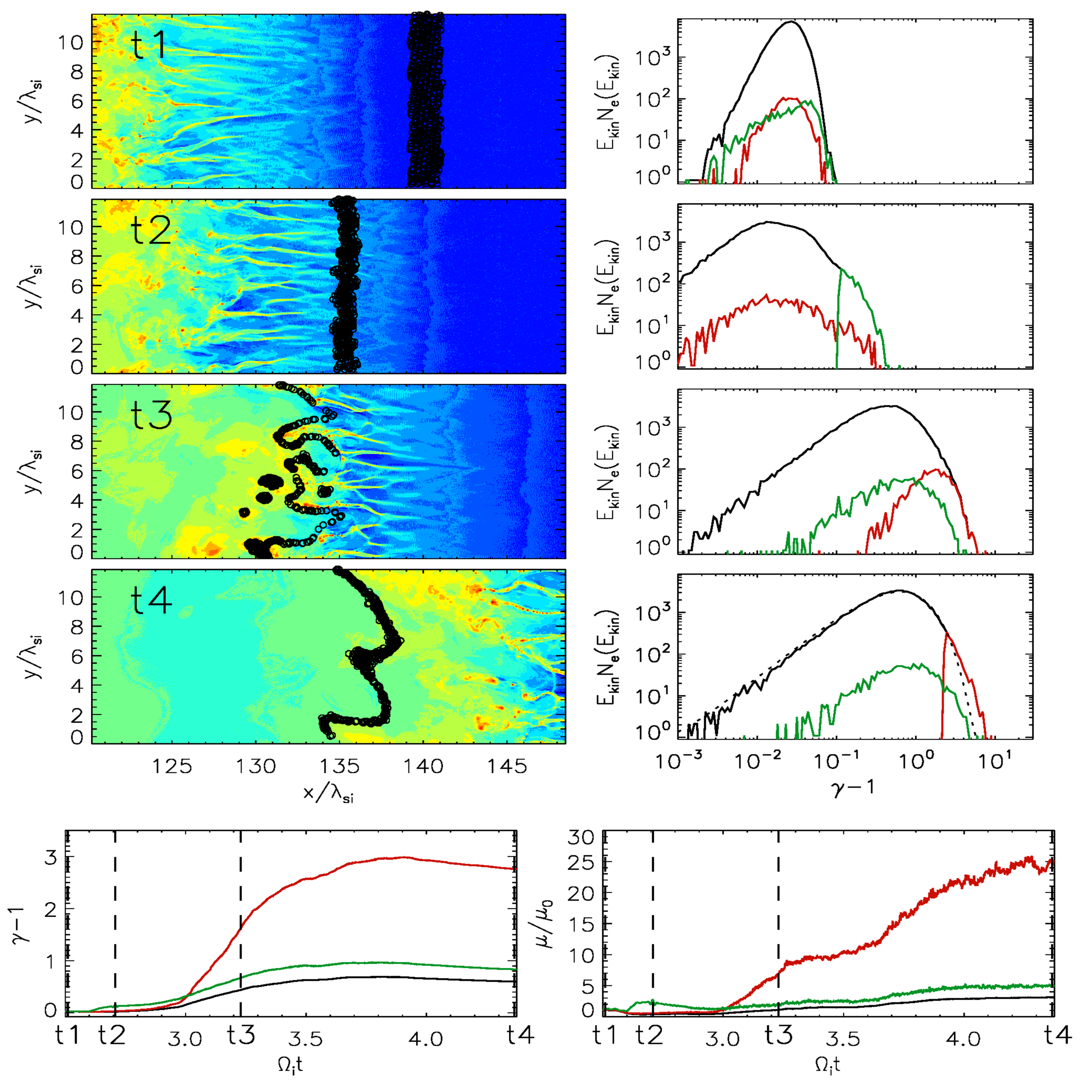

Figure 3: Energy and magnetic moment evolution of traced electrons. Four top panels from left side present density maps of the shock region and the positions of the traced electrons (black dots) at the time t_1, t_2, t_3 and t_4. Panels from right side shows energy spectra distributions. Two bottom panels are average energy and normalized average magnetic momentum evolution, correspondingly.

Contributions of SSA, magnetic reconnection and chaotic Fermi-like acceleration processes

Fraction of nonthermal electron produced via SSA smaller for higher ion-to-electron mass ratios because of stronger heating in the shock foot-ramp while SSA efficiency remains constant.

Magnetic reconnection produces substantial part of nonthermal electrons in large mass ratio cases and becomes a dominant acceleration process. Almost all particles are involved in magnetic reconnection in runs with high Alfven Mach numbers and ion-to-electron mass.

Remaining NTEF which is not covered by SSA or magnetic reconnection is treated as electrons associated with chaotic second-order Fermi-like acceleration process.

Run	m_i/m_e	M_A	NTEF [%]	NTEF produced via SSA [%]	NTEF produced via magnetic reconnection [%]	Fraction of particles involved in magnetic reconnection [%]
A	50	23	0.28	0.13	0.1	10
B	100	32	0.55	0.05	0.4	26
C	100	46	0.36	0.06	0.13	38
D	200	32	0.7	0.02	0.55	38
E	200	46	0.56	0.03	0.5	43
F	400	69	0.57	0.002	0.4	79

Table 1: NTEF – nonthermal electron fraction, it is calculated as excess over the Maxwellian fits to the low-energy part of the downstream spectra. Results are presented for right shocks with $\beta_e = 0.5$.

Energy redistribution and magnetic field amplification

Far upstream ions keeps the most part of the total plasma energy in weakly magnetized plasmas. In the shock transition ion kinetic energy is strongly redistributed. In the downstream region, where bulk ion and electron energies are negligible, the energy is distributed among thermal ions, thermal electrons and the magnetic field. The energy of an electric field is negligible.

Thermal ions keep about (80-85)% of total energy, thermal electrons ~ (10-16)% and magnetic field ~ (2-7)%.

The normalized downstream magnetic field energy is larger for shocks with higher Alfven Mach numbers.

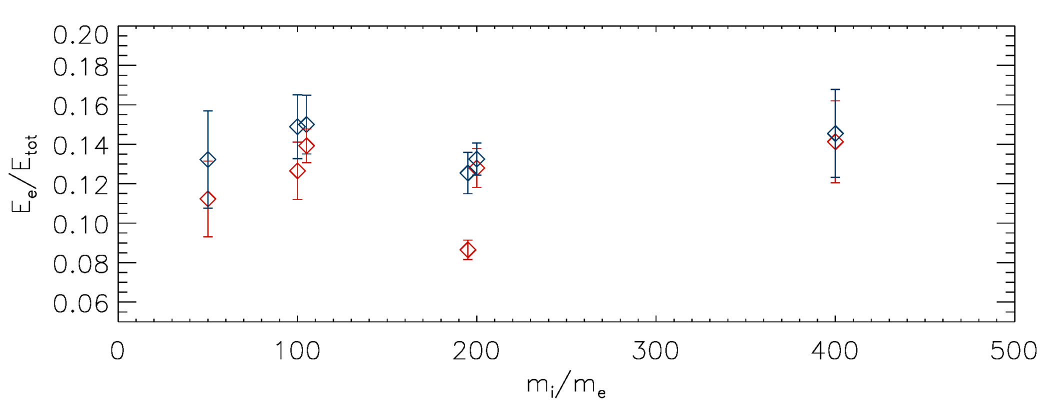

Figure 4: Fraction of energy transferred to the thermal electrons in the shock downstream.

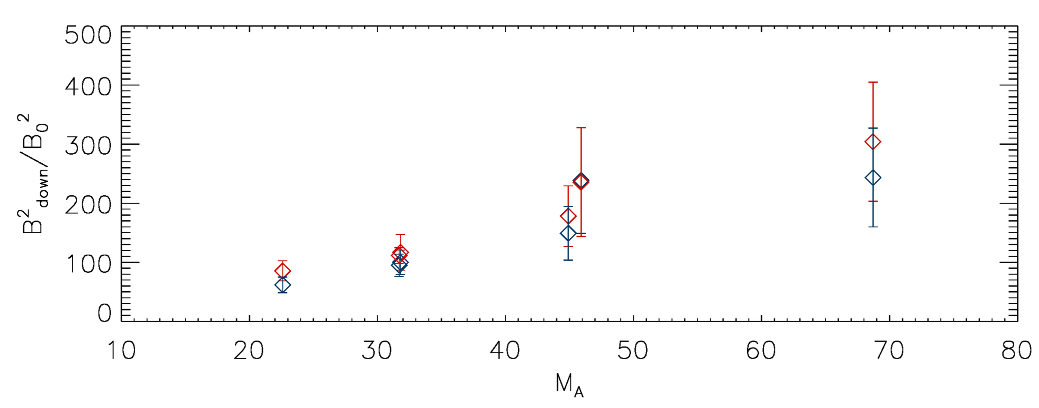

Figure 5: The downstream magnetic field energy (B^2_{down}) normalized by upstream magnetic field energy (B_0^2).

Conclusions

- **Nonthermal electrons are mainly produced in ramp-overshoot region.**
- **Three acceleration mechanisms operate in the shock transition: SSA at the leading edge of the shock foot (Buneman instability region), acceleration via magnetic reconnection in the shock ramp (Weibel instability region), chaotic second-order Fermi-like acceleration in the shock foot and ramp (Weibel instability region).**
- **Growth rate and capability to accelerate electros via SSA and magnetic reconnection strongly depends on Mach number and mass ratio. In case of high M_A and m_i/m_e SSA become less important while magnetic reconnection dominates in production of nonthermal electrons.**
- **Almost all particles are involved in magnetic reconnection caused by Weibel filaments decay in case of large mass ratio.**
- **The same fraction (~13%) of the upstream ion kinetic energy goes to the thermal electrons. The normalized downstream magnetic field energy increases with Alfven Mach number of the shock.**

References

[1] Matsumoto, Y., Amano, T., & Hoshino, M. 2012, ApJ, 755, 109
[2] Bohdan, A., Niemiec, J., Kobzar, O., & Pohl, M. 2017, ApJ, 847, 71
[3] Matsumoto, Y., Amano, T., Kato, T. N., & Hoshino, M. 2015, Science, 347, 974
[4] A. Bohdan et al., Proceedings of Science (ICRC2017), 587
[5] Niemiec, J., Pohl, M., Stroman, T., & Nishikawa, K.-I. 2008, ApJ, 684, 1174-1189
[6] Buneman, O. 1993, in Computer Space Plasma Physics: Simulation Techniques and Software, Eds.: Matsumoto & Omura, Tokyo: Terra, p.67

Affiliation

[1]DESY, Platanenallee 6, 15738 Zeuthen, Germany
[2]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany
[3]Institute of Nuclear Physics PAS, 152 Radzikowskiego Str., 31-342 Kraków, Poland
[4]Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan
[5]Department of Physics, Chiba University, 1-33 Yayoi, Inage-ku, Chiba 263-8522, Japan

Contacts

Artem Bohdan
Postdoc
Deutsches Elektronen-Synchrotron
Platanenallee 6, 15738 Zeuthen, Germany
+49 33762 7-7193
artem.bohdan@desy.de