Electron acceleration in supernova remnants

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Abstract

Supernova remnants (SNRs) are believed to produce the majority of galactic cosmic rays (CRs). SNRs harbor non-relativistic collisionless shocks responsible for the acceleration of CRs via diffusive shock acceleration (DSA), in which particles gain their energy via repeated interactions with the shock front. Since the DSA theory involves pre-existing mildly energetic particles, a means of pre-acceleration is required, especially for electrons. Electron injection remains one of the most troublesome and still unresolved issues and our physical understanding of it is essential to fully comprehend the physics of SNRs. To study any electron-scale phenomena responsible for pre-acceleration, we require a method capable of resolving these small kinetic scales and particle-in-cell simulations that fulfill this criterion. Here, I report on the latest achievements made by utilizing kinetic simulations of non-relativistic high Mach number shocks. I discuss how the physics of SNR shocks depends on the shock parameters (e.g. the shock obliquity, Mach number, the ion-to-electron mass ratio) as well as the processes responsible for the electron heating and acceleration.

Keywords: cosmic rays, supernova remnants, electron acceleration, particle-in-cell simulations

(Some figures may appear in colour only in the online journal)

1. Electron injection problem

More than a century ago, the Hess balloon experiment provided evidence that proved the existence of ionized radiation at altitudes above 1 km [1], clearly indicating its extraterrestrial origin. It is now well established that the cause of these measurements is cosmic rays (CRs) composed of high-energy particles reaching the Earth from space. Despite the fact that CRs have been studied for over a century, their origin remains one of the most fundamental unresolved problems in modern astrophysics.

Low-energy CRs are produced by the Sun, while CRs with energies above $10^9$ eV originate from one of the astrophysical accelerators, such as supernova remnants (SNRs), pulsar wind nebulae, jets from active galactic nuclei, gamma-ray bursts, galaxy clusters, etc. Among these sources, SNRs are always of particular interest, because they are known as efficient CR accelerators and a source of the majority of galactic CRs due to nonthermal radiation in various wavebands [2–4]. Since the late 70s it has been known that CR particles are accelerated via diffusive shock acceleration (DSA), a first-order Fermi process (see, e.g. [5–9]), in which particles gain their energy from repeated interactions, with the shock front resulting from a supernova explosion. However, it is crucial that DSA works only for high-energy particles whose energy is larger than the injection energy ($\epsilon_{\text{inj}}$), and whose gyroradius is larger than the width of the shock transition layer. Therefore, particles should be preaccelerated or, in other words, injected into the DSA process. This puzzling and still unresolved issue is known as the injection problem.

The particle energy distribution at a shock with an efficient particle acceleration mechanism consists of three particle populations [10] (figure 1): heated at the shock thermal Maxwellian bulk, the supra-thermal tail of preaccelerated particles...
(red curve), and high-energy particles with energies above $\varepsilon_{\text{inj}}$ and those that are represented by a power-law distribution (green line). A particle during the injection process is picked up from the thermal bulk and accelerated up to the injection energy by jumping over the injection gap. Since the plasma consists of various particle species (e.g., protons and electrons) their injection processes are also different. For example, a proton is already injected if its gyroradius is a few times larger than the shock ramp width $r_{inj,p} \approx \xi d_{\text{amp}}$, where $\xi \approx 3$. The shock ramp is the region where rapid changes in plasma density, temperature and velocity occur; its width is approximately equal to the gyroradius of the thermal proton $r_{th,p}$. Therefore, the proton injection energy is about ten times larger than the thermal energy ($\varepsilon_{inj,p}/\varepsilon_{th,p} = \xi^2 \approx 10$) and this injection gap can be overcome with one or two cycles of shock drift acceleration (SDA) [11]. However, the situation with electrons is much more difficult. The gyroradius and momentum of the injected electron are by definition the same as for the proton ($p_{\text{inj},e} = p_{\text{inj},p}$), which implies a much higher injection energy for an electron, and the electron injection gap is considerably larger. The ratio of the initial electron energy to the electron injection energy depends on the proton-to-electron mass ratio and the shock speed and can be estimated as follows:

$$\frac{\varepsilon_{\text{inj},e}}{\varepsilon_{\text{th},e}} \approx 2\xi \frac{m_p}{m_e} \frac{c}{v_{sh}} \approx 10^5 - 10^6.$$  

This huge injection gap is the reason the electron injection problem is extremely challenging.

For a proper modeling of the nonthermal radiation emitted by relativistic electrons we should know how many of them are involved in radiation processes. Therefore, we should explain how electrons are accelerated through all these orders of magnitude in energy up to the injection energy where they continue to be accelerated via a much better-understood DSA process. The injection problem can be solved by revealing mechanisms responsible for electron energization, which usually occur in two stages: thermalization (redistribution of the upstream electron energy and transfer of the proton upstream energy) and consequent acceleration via shock internal mechanisms.

The injection problem requires a tool capable of describing the entire shock microphysics accounting for all participating particle species. Observations [12–14] and laboratory experiments [15, 16] combined with theoretical studies [17–19] can reveal some aspects of shock physics. However, due to their limited resolution or restrictions on the laboratory environment, they can only approximately show where and how particles are accelerated. The only possible way to uncover the still hidden electron acceleration microphysics is plasma simulations, such as fully kinetic treatment, e.g., particle-in-cell (PIC) simulations [20, 21], which consider all particle species as individual particles moving in a self-generated electromagnetic field. PIC simulations allow us to obtain all necessary information about particles and electromagnetic fields at any given point in space and time and, therefore, to describe all details of particle acceleration processes. Consequently, this technique is a core tool for the solution of the electron injection problem.

In this article, we discuss how the electron injection problem can be understood from a fully kinetic plasma simulation point of view, focusing on the structure of nonrelativistic SNR shocks and electron heating/acceleration processes operating there.

### 2. SNR shock physics

The interaction of supernova ejecta with the interstellar medium after supernova explosions results in SNR shocks. It is well known that SNR shocks propagate with nonrelativistic velocities [22] ($v_{sh} \approx (1000–10000)$ km s$^{-1}$ = (0.003–0.03)c, where $c$ is the speed of light) and are characterized by high sonic and Alfvénic Mach numbers ($M_s, M_A \approx 20–1000$). At high Mach number shocks are supercritical [23], which means that part of the upstream kinetic energy is dissipated via particle reflection by the shock potential hosting suitable conditions for various types of two-stream instabilities. Depending on the shock obliquity angle, $\theta_{\text{Bn}}$ (the angle between the upstream magnetic field and the shock normal vector) the shock reflected particles (protons, electrons, etc) may escape the shock driving waves and disturb the upstream medium through which the shock propagates (e.g. [24]). Based on $\theta_{\text{Bn}}$, shocks can be split into three classes (figure 2): perpendicular (75° $\leq \theta_{\text{Bn}} \leq 90°$), oblique (50° $\leq \theta_{\text{Bn}} \leq 75°$) and parallel (0° $\leq \theta_{\text{Bn}} \leq 50°$) shocks. Note that the choice of boundaries among the three shock classes is not very strict and may depend on upstream conditions or shock parameters.

Perpendicular shocks are characterized by a sharp shock transition for which the width is of the order of the upstream proton gyroradius ($d_{\text{sh}} \sim r_p$), because neither electrons nor protons can escape the shock towards the upstream. These shocks have been thoroughly studied using PIC simulation [25–36], and the results are described in section 3. The shock physics becomes much more difficult when $\theta_{\text{Bn}}$ is small enough for energetic particles to escape a shock traveling far upstream. Therefore, the shock transition becomes much longer ($d_{\text{sh}} \gg r_p$). The narrow shock foot is replaced by a broad, turbulent foreshock (also known as the shock precursor).
that extends far into the upstream flow. At oblique shocks, only electrons escape the shock forming an extended electron foreshock filled with electrostatic and electromagnetic waves resulting in efficient electron scattering. These shocks with PIC simulations have only been studied over the last 5 years [37–41], and the results are discussed in section 4. At parallel shocks, the foreshock physics is dominated by ions and it was mostly studied with hybrid simulations [42–44] where ions are represented as particles and electrons are a massless fluid. For PIC simulations, only a few papers [45, 46, 48, 49] are dedicated to parallel shock studies due to their extreme complexity and significantly higher computational costs compared to perpendicular shock simulations. The results from these studies are discussed in section 5.

3. Perpendicular shocks

3.1. Shock structure

In perpendicular shocks, the reflected ions cannot escape the shock and after half a gyration in the upstream region they are advected downstream of the shock. On their way, reflected ions interact with incoming ions and electrons, driving two-stream instabilities. Perpendicular shocks are mediated by the electrostatic Buneman [50] and the ion–ion two-stream Weibel [51, 52] instabilities, making the shock a highly dynamical and complex system (figure 3). The magnetic field inside the shock is strongly amplified by the Weibel instability, $B_{sh}/B_0 \propto \sqrt{M_i}$ [36], allowing for magnetic reconnection [29, 34] and efficient particle scattering. It is interesting that the growth rate of the Weibel instability (if normalized to the ion upstream gyrot ime) does not depend on the unrealistically high shock velocity or the reduced ion-to-electron mass ratio, which permits the direct comparison of PIC simulations with real shocks [36]. The resulting shock width is about $d_{sh} \approx 0.5 r_i$, where $r_i$ is the upstream ion gyroradius. Comparison of 2D [31] and 3D [37] simulations has demonstrated that 2D PIC simulations can reproduce realistic 3D physics of these shocks, and most of the 3D shock physics can be studied with much less computationally demanding 2D simulations. Note that simulation by Matsumoto is done with oblique configuration ($\theta_{sh} \approx 74.3^\circ$). However, the simulation time is short and the shock structure is still representative of perpendicular shocks. In figure 3, the presented shock structure is also supported by laboratory experiments [15] as well as in situ measurements [36, 53] demonstrating that perpendicular high Mach number shocks are indeed Weibel mediated and that the presented shock structure is most likely physically correct.

3.2. Electron heating

The shock converts part of the upstream kinetic energy into the thermal particle energy. If there is no energy exchange between ions and electrons inside the shock transition, the Rankine–Hugoniot jump conditions for temperature predicts the downstream temperature ratio of $T_e/T_i = m_e/m_i$. However, both in situ measurements of the high Mach number Saturn’s bow shock [54] and telescope observations [12–14] of SNR shocks show that some energy is transferred from ions to electrons and the resulting temperature ratio is larger than expected at $T_e/T_i \approx (0.05–0.5) \gg m_e/m_i$.

Bohdan et al [35] proposed an analytical model of electron heating in order to explain the temperature ratio measured using data taken by the Cassini spacecraft, which measures plasma parameters on scales close to PIC simulations. This shows that the ion flow energy is transferred to electrons via five channels: shock-surfing mechanism, shock potential, magnetic reconnection, stochastic Fermi acceleration (SFA) and adiabatic compression. This model accounts for dependencies of individual heating processes on the shock parameters, such as $v_{sh}$, $M_A$, $M_i$, $m_i/m_e$ and $\beta$. The new electron heating model predicts simulation results for a wide range of shock parameters. Moreover, after using realistic shock velocity and the proton-to-electron mass ratio, it estimates the downstream temperature ratio in the range of $T_e/T_i \approx (0.09–0.25)$, which matches Cassini’s in situ measurements within error bars (figure 4). Note that the predictions of the new model may deviate from some in situ measurements (see two measurements with $T_e/T_i \approx 0.05$ in figure 4) since PIC simulations consider shocks propagating through the ideal homogeneous medium, and the shock structure should not deviate too much from the structure discussed above. The Cassini spacecraft was also able to reliably measure only the downstream electron temperature, while other plasma and shock parameters were determined by the Saturn’s bow shock model, which may introduce additional systematic errors, explaining the observed mismatch.
Figure 3. Perpendicular shock. Main panel—electron density in the shock region; left inset panel—electron density and the in-plane component of the magnetic field (arrows) in the region of the Weibel filament with magnetic reconnection; right inset panel—electrostatic field strength in the Buneman instability region. Shock transition includes the foot, ramp and overshoot regions and it spans from $x/r_i = 2.5$ to $x/r_i = 3$; the upstream is at $x/r_i > 3$ and the downstream is at $x/r_i < 2.5$. Shock parameters are $v_{sh} = 0.263c, M_A = 68.9, M_s = 106, m_i/m_e = 400$ [32].

Figure 4. Electron heating model derived using PIC simulations of perpendicular shocks [34] (green) and Cassini’s in situ measurements [54] (red). Green solid line represents the model and the green dashed lines represent the one-sigma deviation levels for the model.

Although $T_e/T_i$ derived from telescope observations are similar to those from PIC simulations, it remains debatable how to execute a proper comparison since these approaches cover temporal and spatial scales orders of magnitude apart from each other. This would require much longer PIC simulations and better modeling of electron behavior in the shock downstream, including synchrotron cooling, charge exchange, Coulomb interaction, etc.

3.3. Electron acceleration

At perpendicular shocks, electrons can be accelerated via the shock-surfing acceleration (SSA) mechanism in the Buneman wave region [27, 31, 32], magnetic reconnection [29, 34] and the SFA mechanism [31, 33].

SSA is capable of accelerating electrons to energy tens of times larger than the upstream electron bulk energy for a wide range of shock Mach numbers if the so-called trapping condition is satisfied [27, 32]. However, if a realistic mass ratio is applied, SSA preacceleration can be heavily spoiled by the heating processes discussed above [33].

During magnetic reconnection, electrons can be accelerated via a number of mechanisms [29, 34]: interaction with outflows, X-points, first-order Fermi acceleration, vortex contraction, SFA. For higher Mach numbers, magnetic reconnection becomes particularly active due to strong saturation of the Weibel instability and almost all electrons participate in magnetic reconnection if $M_A \geq 70$ [34]. However, the overall acceleration efficiency via magnetic reconnection is going down due to a smaller amount of available magnetic field energy [36], which potentially can be converted into electron heating and acceleration.

The most efficient electron acceleration mechanism in perpendicular shocks is SFA. It is responsible for the production of the most energetic electrons; the maximal energy is proportional to the ion-to-electron mass ratio [33]. Therefore, even if a realistic mass ratio is applied, the downstream electron spectra will contain suprathermal electrons with energies much larger than those of thermal electrons.

The resulting suprathermal electron fraction is usually of the order of 0.5% [33]. Most of them are accelerated via SFA, especially in simulations with high mass ratios. However, the biggest problem with perpendicular shocks is that in this case no particles can escape the shock and the turbulence necessary for DSA cannot be triggered self-consistently. Consequently, the maximal achieved energy of electrons is just 10–100 times larger than the thermal energy of the downstream electrons, and the injection does not occur. It is noted that DSA can potentially be triggered in perpendicular shocks using additional ingredients such as seed CRs [55], neutral particles [56] or preexisting turbulence [57].

4. Oblique shocks

4.1. Shock structure

As mentioned above, in oblique shocks fast electrons can escape the shock towards the upstream region (figure 5, bottom panel). Consequently, the shock transition becomes much wider, and the shock foot is replaced by a broad, turbulent foreshock that extends far into the upstream flow, generating
electrostatic and electromagnetic waves. The shock width in this case is about \( d_{sh} \approx 12.5 r_i \). This structure is captured both with 1D [38, 39] and 2D [40, 41] PIC simulations. The only 3D simulation [37] is unfortunately too short to capture the electron foreshock structure. Note that around the shock transition (see figure 5, \( x/\lambda_{ce} \approx (1000–1100) \)) both Buneman and Weibel instability can be found. However, their structure is somewhat modified due to waves excited in the foreshock.

In [40] periodic boundary condition, simulations were used to identify new instabilities appearing in the foreshock. The phase-space distribution of both particle species in the near and far foreshock regions is derived with the shock simulation and then used as initial conditions for simulations with periodic boundary conditions. We find that the observed electron-beam instabilities agree very well with the predictions of a linear dispersion analysis. The electrostatic electron-acoustic instability dominates in the far upstream of the foreshock, while the denser electron beams in the near upstream drive the oblique-whistler instability gyroresonant with the shock reflected electrons. Whistlers are responsible for the creation of the foreshock turbulence with \( \delta B / B \sim 1 \). The magnetic field is likely amplified by a combination of whistler waves and Weibel instability. In the latest stages of the shock simulation, the energy distribution of the escaping electrons becomes stable and allows for extrapolation further upstream. Knowing the triggering conditions for the whistler waves and the electron acoustic instability, one can estimate the simulation time needed to cover the entire foreshock in its steady state. Slightly more than 300 \( \Omega_{r1}^{-1} \) is required [40] to cover the entire electron foreshock and reach the steady-state stage of the shock with \( M_A = 30 \). The shock width in the steady state is expected to be about \( d_{sh} \approx 200 r_i \). This poses one of the biggest challenges to studying oblique shocks because their evolution cannot be captured within several \( \Omega_{r1}^{-1} \) like perpendicular shocks, and they require substantially more computational resources.

### 4.2. Electron heating

To date, there has been no study dedicated to electron heating in oblique high Mach number shocks. However, some indirect results can be discussed here. First, the downstream electron temperature for 2D simulations of perpendicular shock [32] is consistent with that for the oblique shock from [40] within 20% margin (figure 6). Note that these two simulations utilize almost the same set of plasma parameters. Second, the data of Cassini spacecraft for Saturn’s bow shocks show that measurements for different obliquity angles [54] are characterized by similar values consistent within error bars. The expected electron-to-ion temperature ratio would be about \( T_e / T_i \approx (0.1–0.3) \). However, this topic also requires extensive studies because we still do not know how much energy can be provided by the different mechanisms that contribute to electron heating, especially processes connected to the recently identified whistler and electron-acoustic waves in the foreshock region.

### 4.3. Electron acceleration

Since the structure of oblique shocks is more complicated compared to perpendicular shocks, they provide a few more
possible mechanisms for electron acceleration. In addition to those already mentioned in section 3.3, SSA, SFA and magnetic reconnection, electrons can be energized via interactions with whistler and electron-acoustic waves, and stochastic shock drift acceleration (SSDA).

Interaction with the electron-acoustic mode may deflect the upstream electrons and sometimes even turn them back upstream, contributing to the beam of shock reflected electrons [41]. As a result, the electrons may increase their energy by a factor of $\sim 10-50$. However, this mechanism does not contribute a lot (less than 0.1% of the incoming electrons are affected) because the electron-acoustic waves carry little energy compared to the electron upstream kinetic energy.

Since whistler waves in the foreshock are gyroresonant with the shock reflected electrons, they should strongly affect electron trajectories providing efficient scattering and, possibly, DSA-like acceleration. As a result, the nonthermal electron population, which can be represented by a power-law distribution with an index of about 2.7 (figure 6), roughly consistent with previous 1D simulations by [38], is formed. This acceleration mechanism can be particularly efficient in shocks, with high Mach numbers accelerating up to 7% of the electrons.

Another very promising candidate for electron injection in oblique shocks is SSDA, which was first observed in 3D shock simulation by [37]. This is a combination of the classical DSA with the pitch-angle scattering provided by waves excited around the shock ramp. A semi-analytical theory was developed to describe SSDA mechanism [58], which is proved to be consistent with in situ observations of Earth’s bow shock where scattering happens due to whistler waves close to the shock ramp [59]. Further development of this theory [60] demonstrates that SSDA is potentially able to accelerate electrons very efficiently, bridging the injection gap in oblique shocks if proper conditions are met.

Note that in oblique shock simulation, electrons sometimes reach the injection energies for the chosen ion-to-electron mass ratio and the shock velocity due to a smaller injection gap $(v_{inj,e}/v_{th,e} \approx 10^3$ and $(\gamma - 1)_{inj,e} \approx 35$ for the shock parameters from [40]). However, the behavior of the responsible mechanisms in systems with realistic parameters is still not well understood and requires additional study.

5. Parallel shocks

5.1. Shock structure

At parallel shocks, both ions and electrons are able to overcome the shock barrier and travel back upstream much farther compared to oblique shocks. Figure 7 demonstrates the shock transition region from the longest 2D parallel shock simulation by [48, 49]. At the very first stages, the Weibel instability [51, 52] grows much faster [61] than the resonant streaming instability [62]. In the later stages (shown in figure 7), the shock is purely mediated by Alfvénic-like modes that are seeded by the return current via a non-resonant streaming Bell instability [63, 64] responsible for magnetic field amplification and production of turbulence. The size of the shock (including the foreshock or precursor) is about $d_{sh} \approx 160r_i$. However, in hybrid simulations it can be up to $10^3r_i$ [43]. Unfortunately, the transverse size of the presented 2D simulation does not allow us to capture the full 2D physics of driven turbulence (e.g. the shock rippling [30]) and the shock physics becomes quasi-1D similar to the 1D simulation done by [45, 46]. Note also that simulations with small ion-to-electron mass ratios cannot capture the entire spectrum of driven turbulence. For example, the intermediate scale instability can only be captured in simulations with a realistic mass ratio of shocks with moderate Mach numbers $M_A \approx 20$ [47].

Therefore, more 2D and 3D simulations, including proper parameters scans for better estimations of upstream turbulence and its ability to scatter particles, are needed.

5.2. Electron heating

2D PIC simulations by [48, 49] suggest that electrons and ions are almost in thermal equilibrium in the downstream ($T_e/T_i \approx 0.5-1$) of the parallel shock, which was also observed in earlier 1D simulations ($T_e/T_i \approx 1$ in [45], $T_e/T_i \approx 0.5$ in [46]). However, these results should be treated with some caution. First, 1D simulations are unable to reproduce certain instabilities. For example, the Weibel instability, which is known to be present in perpendicular shocks, is not excited in 1D simulations [65, 66] or 2D simulations with an out-of-plane magnetic field configuration [27, 31], but can be triggered only in 2D simulations with an in-plane configuration or 3D shock simulation [37]. Second, $T_e/T_i$ may depend on the shock parameters not discussed in [45, 46, 48, 49] and should be studied carefully using 2D and 3D PIC simulations.

5.3. Electron acceleration

The longest 2D (narrow box) parallel shock simulation by [48, 49] demonstrates the formation of a nonthermal tail in both electron and ion spectra. Indeed, the conditions generated upstream by the shock turbulence in parallel shocks host appropriate conditions for particle scattering and efficient acceleration. The nonthermal tail of the electron energy spectra can be represented by a power-law distribution $\sim c^{-\gamma}$ (figure 8). The same result was obtained with 1D simulation [45], which suggests that the relevant acceleration physics is similar in 1D and 2D shocks. Park et al [45] demonstrated that the upstream cold electrons, after being reflected off the shock due to magnetic mirroring [67], remain trapped between the shock front and the upstream waves. At each subsequent interaction with the shock, the electron may undergo a new cycle of SDA, which results in strong energy gain. This combination of SDA and scattering on Bell-like waves is also very likely responsible for the formation of the nonthermal electron population in 2D simulations [48, 49]. However, the applicability of the described mechanisms should still be verified with a large number of 2D and 3D simulations covering all multidimensional effects.

As is the case in oblique shocks, in [48, 49] electrons reach the injection energy, demonstrating that electrons can indeed be injected into the DSA process. However, the difference
between the thermal and injection energies is much smaller \(\left(\varepsilon_{\text{inj},e}/\varepsilon_{\text{th},e} \approx 50 \text{ and } (\gamma - 1)_{\text{inj},e} \approx 10\right)\) than in SNR shocks. Therefore, we still need to understand how the obtained results can be extrapolated to real systems. The electron preacceleration efficiency may also depend on the shock velocity, mass ratio or Mach number and should be clarified in further studies for successful scaling up to a realistic parameter range.

6. Summary

Perpendicular, oblique and parallel shocks are studied to a different degree, mostly due to the vast difference in complexity of these systems and the amount of computational resources needed to study them. In addition, even if we know the general structure of a shock with predefined upstream conditions, the use of non-realistic parameters (the shock velocity, mass ratio, etc) does not permit direct application to SNR shocks or \textit{in situ} measurements. In many cases (especially oblique and parallel shocks), we still need more PIC simulations to study the scaling properties of the shock microphysics for reliable comparison with real shocks and testing of theoretical models. All results discussed in this paper are summarized in table 1.

### Table 1. Current status of the electron injection problem.

| Structure | Heating | Acceleration |
|-----------|---------|--------------|
| Perpendicular | +       | +            |
| Oblique    | ±       | −            |
| Parallel   | ±       | ±            |

\(+'\)—well studied, \(\pm\)—partially studied, \(−\)—not studied.

6.1. Perpendicular shocks

We understand all three aspects of the perpendicular shock physics and can successfully rescale simulation results to compare them with \textit{in situ} measurements of planetary bow shocks. The shock is mediated by Buneman and Weibel instabilities. The latter is responsible for strong magnetic field amplification inside the shock. Electrons can be heated via SSA, shock potential, magnetic reconnection, SFA and adiabatic compression. The downstream electron spectra are represented by a Maxwellian distribution with a not very prominent suprathermal tail populated with electrons mostly accelerated via SFA. The contribution of SSA and magnetic reconnection is minor. Since DSA cannot be self-consistently triggered in perpendicular shocks, this case is not very important in the astrophysical sense. However, perpendicular shocks share some similarities in structure with oblique shocks and already obtained knowledge can be used to better understand more complex oblique shocks.
6.2. Oblique shocks

Oblique shocks still require thorough studies. However, we have some understanding of the shock structure and electron acceleration mechanisms. In comparison with perpendicular shocks, two additional types of waves (whistlers and electron-acoustic waves) are excited in the foreshock region by the shock reflected electrons. Whistler waves together with the Weibel instability drive strong electromagnetic turbulence responsible for particle heating and acceleration. The electron temperature in the shock downstream is likely to be very similar to that in perpendicular shocks. However, we still do not know the processes responsible for electron heating and lack an explanation for the observed electron temperature. There are at least six processes responsible for particle acceleration in oblique shocks: SSA, SFA, magnetic reconnection, interaction with whistler and electron-acoustic waves, and SSDA. The electron downstream spectra are described by a Maxwellian with a noticeable suprathermal tail that can be represented by a relatively soft power-law distribution ($\sim e^{-\varepsilon}$). These high-energy electrons are either produced during interaction with whistler waves or via SSDA. In simulation, electrons can potentially reach the injection energy due to a much smaller injection gap compared to real shocks. Therefore, additional studies are still needed to understand the scaling properties of already known acceleration mechanisms and apply the obtained results to real systems.

6.3. Parallel shocks

Parallel shocks began to be intensively studied only recently. Therefore, we already have some understanding of their structure and electron acceleration mechanisms. The shock is mediated by Bell-like waves during its late stage evolution creating the turbulent precursor where $\delta B/B \sim 1$. Unfortunately, the very high simulation costs restrict the transverse size of the simulations done so far and in the final phases the shock structure is rather one-dimensional. Electrons and ions are in thermal equilibrium. However, we still do not have an explanation for that. The electron downstream energy distribution is described by a Maxwellian with a prominent suprathermal tail that can be represented by a power-law distribution ($\sim e^{-\varepsilon}$). The most energetic particles are accelerated via a combination of SDA with scattering provided by the foreshock waves. As in oblique shocks, electrons can reach the injection energy in simulations. However, the proper extrapolation of simulation results is still needed to derive realistic injection efficiency. The biggest problem is that the known physics tends to be 1D (due to the small transverse size of available 2D simulations) and more simulations should be performed to clarify the influence of multidimensional effects on the electron injection.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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