# Surfing the waves

## Microphysics of slow collisionless shocks in nonthermal sources of radiation

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### In Short

- We investigate electron pre-acceleration at shocks with realistic shock velocities for supernova remnants (SNRs), where $v_{\mathrm{sh}} \approx 10,000\ \mathrm{km/s}$.
- We have established that shock-reflected electrons at oblique shocks can drive electrostatic and electromagnetic waves upstream of the shock. Now we want to understand how these new waves affect electron dynamic and modify the physics of perpendicular shocks.
- For decades, it has been widely accepted that non-relativistic collisionless shocks can efficiently accelerate charged particles. As the theory involves pre-existing mildly energetic particles, a means of pre-acceleration is required, especially for electrons. The nature of that pre-acceleration, and its connection to the main acceleration, remain important open questions that we address with our simulations.

Astrophysical shocks occur ubiquitously in our universe, with detections of non-thermal X-ray emission from sources such as supernova remnants (SNRs) implying the presence of accelerated electrons. Diffusive shock acceleration [1] is widely accepted to be the primary acceleration mechanism, yet a prerequisite for it is that the Larmor radius of a particle needs to be comparable to the shock width, which is not the case for electrons at thermal energies. It follows that they therefore require some pre-acceleration, and our physical understanding of it is essential to fully comprehend many astrophysical phenomena.

To understand any electron-scale phenomena responsible for pre-acceleration, we require a method capable of resolving these small kinetic scales. Particle-in-cell (PIC) simulations fulfil this criterion and have previously helped us to establish the contribution to electron pre-acceleration in perpendicular shocks from mechanisms such as shock surfing acceleration, magnetic reconnection and stochastic Fermi acceleration [2–5].

At oblique shocks, where the angle between large-scale magnetic field and the direction of motion of the shock front is $\theta_{Bn} \approx 20°$–$70°$, reflected particles, in particular electrons, can escape upstream along the magnetic field lines, creating an extended region known as the foreshock [6]. Any particles upstream of an oblique shock must encounter the foreshock before reaching the shock, therefore its properties are important as any turbulence in this region has the opportunity to influence upstream plasma before it can encounter and be accelerated at the shock. Escaped electrons can drive additional instabilities in the far upstream region, which in turn disturb and heat the plasma. Furthermore, electrons can return to the shock and experience additional stages of acceleration. An investigation of this behaviour is of high importance in shock research.

Figure 1 illustrates the results of an earlier simulation. The colourmap of electron density relative to the initial upstream value shows cavities immediataly ahead (to the right) of the shock, that is located at $x \approx 80$. These regions correspond to electrostatic modes and are present in a region with strong ion reflection. Further ahead, where only reflected electrons are observed, there are electrostatic waves of so small a scale that they are not visible in the figure. Besides the electrostatic waves, there are also obliquely propagating electromagnetic modes. Figure 2 shows the magnetic-field fluctuations that correspond to these waves. The presence of these waves immediately raised a plethora of interesting questions: what shock parameters influence these modes? How to they effect the upstream plasma? Does this mode reach a saturation point? Answering these questions forms the basis of our proposed work programme.

All the modes far ahead of the shock are driven by reflected electrons, and so they are orientated along the direction of the large-scale magnetic field. It is therefore natural to assume that the obliquity angle plays a large role in determining the properties of these waves, and any other effects that arise consequentially. Preliminary analysis indicates that these waves are themselves capable of accelerating and reflecting upstream electrons further away from the shock, preventing them from reaching it and compromising injection. Further simulations need to establish the exact nature and properties of these waves, and what effects they may have on the upstream medium.

Preliminary results indicate that a higher percentage of incoming electrons are reflected back upstream for smaller $\theta_{Bn}$. About $5\%$ of electrons were reflected for $\theta_{Bn} = 30°$, but only $\sim 0.03\%$ for $\theta_{Bn} = 63°$. Although fewer in number, the peak energy of reflected electrons increases with increasing $\theta_{Bn}$. This is because they move along the increas-

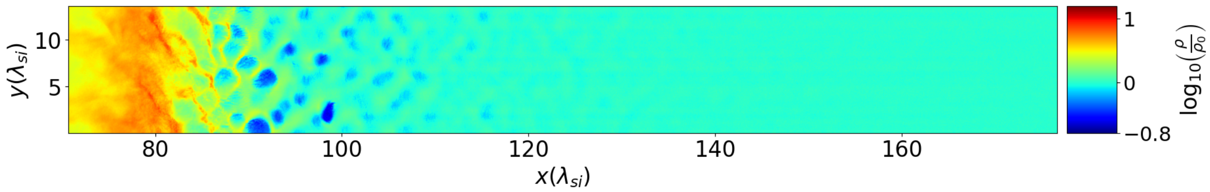

***Figure 1:*** *The shock structure in normalised electron density for a moderately slow shock. Immediately ahead of the shock, cavities are present that represent an oblique mode and correspond to the region with significant ion reflection.*

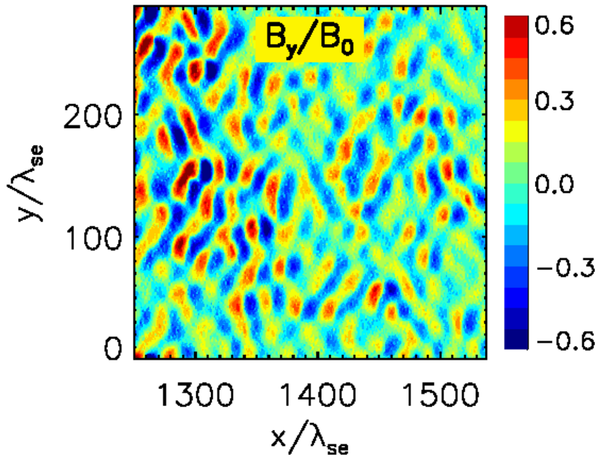

***Figure 2:*** *Map of the magnetic-field fluctuations carried by obliquely propagating electromagnetic waves ahead of the shock.*

ingly oblique magnetic field and need to be faster to escape from the shock. Despite this, the greater number of electrons reflected in shocks with smaller $\theta_{Bn}$ means overall more energy is carried back upstream than for larger $\theta_{Bn}$.

The previous simulations investigate too narrow a region, in which, e.g., the cavities visible in Figure 1 are only a few times smaller than the transverse size of the box. That limitation may affect and impede their evolution. The simulations were also too short. Their duration was sufficient to cover the feedback on electrons propagating back upstream. However, the entire electron dynamics still cannot be captured especially if one intends to capture the formation of an electron distribution extending over a few decades in energy. The acceleration of particles up to the highest energies is usually due to frequent deflection by electromagnetic turbulence, in which the maximum particle energy grows linearly with time. We emphasize that properly capturing this process also requires a large transverse size of the simulation box. New simulations are needed to address that.

Our main goal is to understand how our physical understanding of electron acceleration at perpendicular nonrelativistic shocks is modified in quasi-perpendicular shocks with an electron-generated turbulent foreshock and to address the following points:

- Identify how electrostatic and electromagnetic plasma waves/instabilities are generated by the shock reflected electrons at oblique shocks.
- What properties of the shock reflected electrons (density, velocity, temperature, etc.) are required to drive these electrostatic and electromagnetic modes? What Mach numbers are needed?
- How do electrostatic and electromagnetic modes affect the upstream electron dynamics? What are possible consequences for scattered electrons?
- What is the possible extent of electrostatic and electromagnetic foreshocks?
- Will the observed scattering of electrons lead to a power-low distribution and further diffusive shock acceleration?

## WWW

`http://www.physics.uni-potsdam.de/index.php`

## More Information

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## Project Partners

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