Consequences of electron reflection back upstream in oblique shocks

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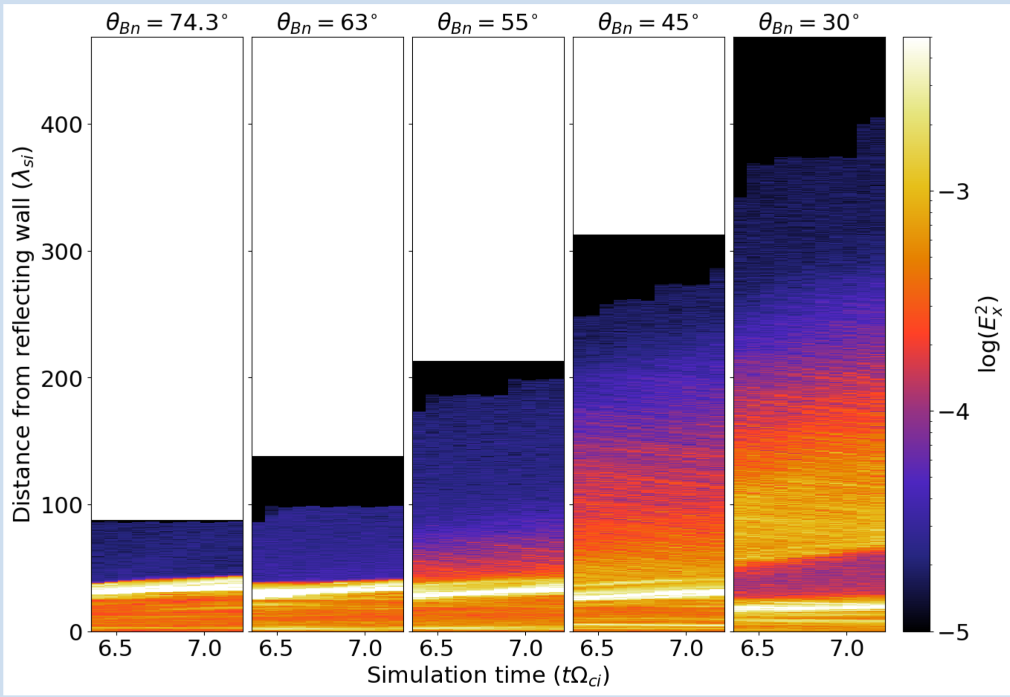
Abstract

Astrophysical shocks are believed to efficiently accelerate charged particles, yet electrons need to undergo pre-acceleration to be energetic enough to cross the shock and join the game of acceleration. To better understand the mechanisms involved, we undertake particle-in-cell (PIC) simulations of oblique shocks with varying obliquity angle, θ_{Bn}. Our analyses focus on the reflection of incident electrons back upstream, with these particles capable of generating upstream turbulence and transferring energy away from the shock itself and to the upstream plasma. Our results indicate that these reflected electrons can generate electrostatic waves, which can reflect upstream electrons, and could compromise the efficiency of electron injection at the shock.

Particle-in-cell Simulations



ABOVE: PIC simulations for varying θ_{Bn}. The x-axis shows a time range of the simulations, and the y-axis shows the logarithm of the average E_x^2 over the transverse size of the box. For smaller θ_{Bn}, a region of larger E_x is present further downstream, and is generated by electrons which are reflected at the shock. Similar occurs for E_y.

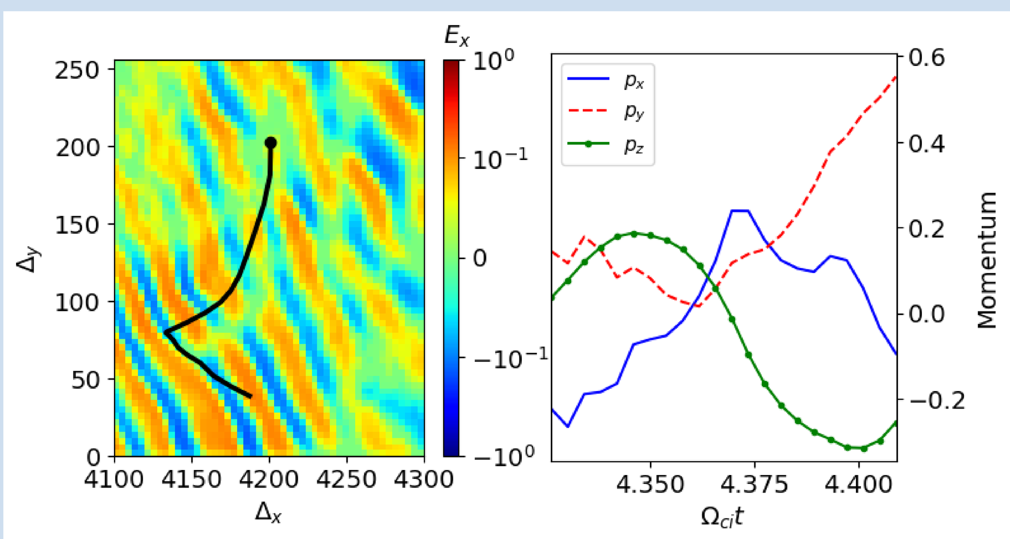
In this work, we complete PIC simulations of varying Obliquity angle, θ_{Bn}, which is defined as the angle between the upstream magnetic field and shock normal ($\theta_{Bn} = [30, 45, 55, 63, 74.3]$). All other parameters are kept constant, and are consistent with those in [1]

Reflection Mechanism

Previous work has established that electrons can be reflected back upstream if they can outrun the shock. Mathematically, this criteria is [2],

$$v_e \cos\theta_{Bn} > v_{sh} \qquad (1)$$

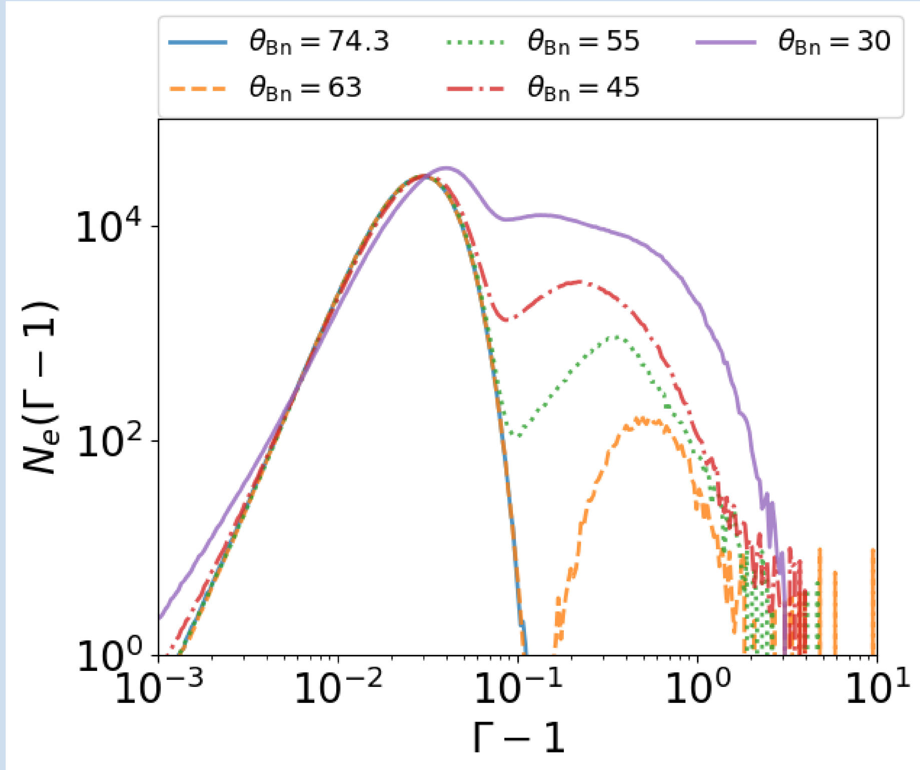
where v_e and v_{sh} are the electron and shock velocities, respectively.

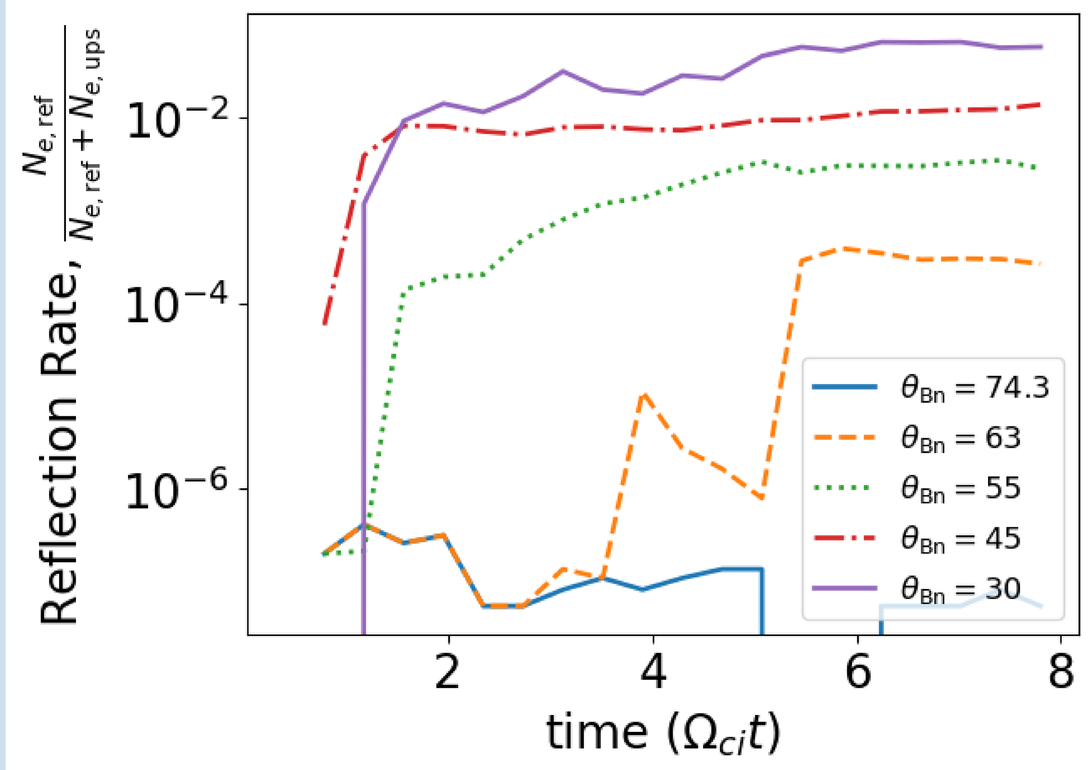


LEFT: An incoming electron is captured by the potential well of a Buneman wave. The colourmap shows E_x, and E_y is also similar. RIGHT: electron momenta for the time period indicated by the electron trajectory. This process can energise the electrons in the x and y directions.

Incoming electrons can be captured by the potential well of a Buneman wave and undergo shock surfing acceleration [3]. If they gain enough energy in this process to satisfy Eqn. 1, they can be reflected and escape downstream. This process is more likely to occur for more energetic electrons as a larger transverse momentum permits them to enter the potential well of the Buneman wave more easily.

Spectra of Reflected Electrons

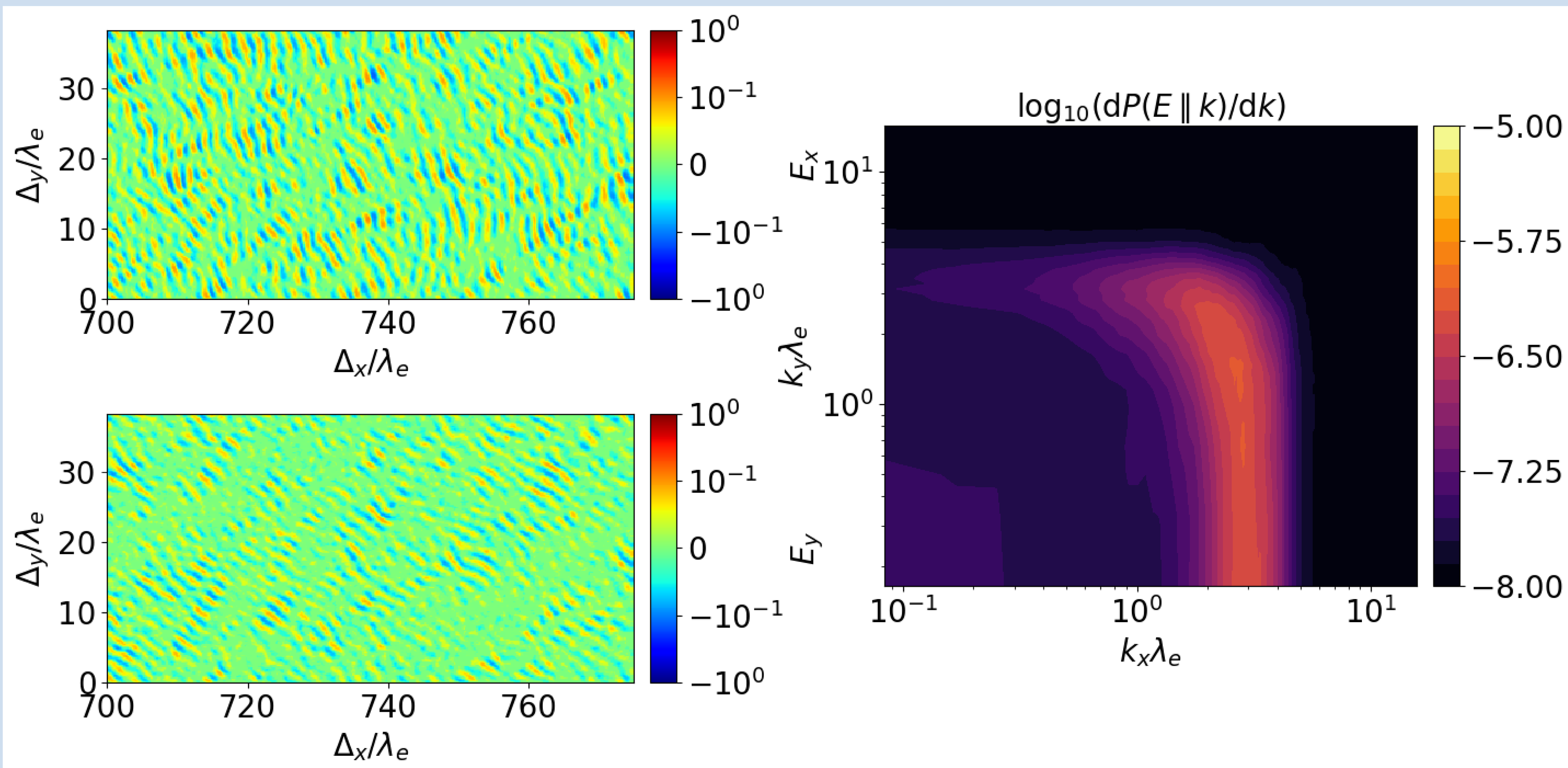




LEFT: Spectra of the upstream electrons (left peak) and reflected electrons (right peak) for the simulations presented here. RIGHT: Electron Reflection Rates as a function of simulation time, denoted in multiples of ion gyro-periods. These figures are computed from a region upstream of the shock transition.

The figures above show that more electrons are reflected for smaller values of θ_{Bn}, and that the peak value of $\Gamma - 1$ shifts to higher values for larger θ_{Bn}. Using Eqn. 1, and noting that here we fix $v_{sh} \approx 0.264c$, electrons require larger v_e for larger values of θ_{Bn} else they cannot be reflected. As for larger values of θ_{Bn} only electrons with a larger v_e can be reflected, the peak value of $\Gamma - 1$ increases as is shown above. We find that despite reflected electrons carrying on average more energy upstream for larger θ_{Bn}, the higher reflection rates at low θ_{Bn} mean there is more energy in total carried away from the shock by reflected electrons.

Upstream Waves Generated by Reflected Electrons



LEFT: Simulation maps of E_x (upper panel) and E_y (lower panel) for part of the electron foreshock region in the simulation with $\theta_{Bn} = 30$. RIGHT: Discrete Fourier transform of these fields to assess the relevant spatial scales of the generated electrostatic waves in units of $[c/(m_e c \omega_{p,e})]^2$.

The above figures illustrate that electrostatic waves driven by reflected electrons occur on length scales of $k\lambda_{SE} \sim 2$, which is comparable to the scale of Buneman waves. We find that the energy density of these electrostatic waves correlates strongly with the electron reflection rate.

Conclusions

- A higher percentage of incoming electrons are reflected back upstream for smaller θ_{Bn}. $\sim 5\%$ 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 θ_{Bn}. This is because they require velocities $v_e \cos\theta_{Bn} > v_{sh}$. Despite this, the greater number of electrons reflected in shocks with smaller θ_{Bn} means overall more energy is carried back upstream than for larger θ_{Bn}.
- These reflected electrons drive electrostatic waves on scales comparable to Buneman waves in the electron foreshock upstream.

References

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