# A Kinetic Study of the Saturation of the Bell Instability

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## The problem

Collisionless shock waves near supernova remnants (SNRs) are believed to be the primary source of galactic cosmic rays (CRs), up to the "knee" energies of $\sim 10^{15}$ eV, through the diffusive shock acceleration (DSA) mechanism. For efficient CR acceleration through DSA, CRs must be confined close to the shock, which requires the presence of very strong, turbulent magnetic fields. The generation of such strong magnetic field structures is still an open question. The *nonresonant cosmic ray-driven instability*, predicted by Bell (2004), to which we refer as the *Bell instability*, has important implications for the confinement of CRs near the shock, and thus for DSA at SNRs.

In this work we study the Bell instability from first principles using the self-consistent *dHybridR* simulations, with kinetic ions and fluid electrons. We focus on 2-dimensional simulations in the $x - y$ plane, considering all three components of the fields. We initialize the box with a thermal population of particles as our background plasma and inject CR particles in the box at a constant rate, moving parallel to the zeroth-order background ambient magnetic field $B_0\hat{\mathbf{x}}$. The CR current density drives the Bell instability which amplifies the small magnetic field perturbations, $\delta B \ll B_0$, that are perpendicular to $B_0$.

## Results

We find that the saturation of the Bell instability depends on the initial CR parameters, specifically on the CR relativistic momentum and number density. The instability stops growing when the magnetic field has grown enough so that CRs get scattered off it, which leads to momentum transfer from the CRs to the backgroud plasma. This in turn leads to the reduction of the CR current in the reference frame of the plasma, which eventually inhibits any further growth of the Bell instability. The final magnetic field's pressure is found to be proportional to the anisotropic CR momentum flux, $\Pi_{\rm cr}$, which allows us to predict the amplified magnetic field using the formula:

$$\frac{B_z^2}{2} \approx \Pi_{\rm cr} = n_{\rm cr}\gamma_{\rm iso}\left[1 + \left(\frac{p_{\rm iso}}{\gamma_{\rm iso} mc}\right)^{2/3}\right]\frac{p_{\rm cr}^2}{\gamma_{\rm cr}} \ .$$

In this equation, we define the final magnetic field based on its $z-$component, $B_z$, while the right-hand side corresponds to the "01" component of the stress-energy tensor, $\Pi_{\rm cr} \equiv T^{01}$, expressed in terms of the CR parameters: the CR number density $n_{\rm cr}$, their drift momentum $p_{\rm cr}$, their isotropic momentum $p_{\rm iso}$, and the corresponding Lorentz factors $\gamma_{\rm cr}$ and $\gamma_{\rm iso}$.