Galaxy formation from plasma kinetic to cosmological scales

Resonant cosmic ray streaming instabilities – non-linear evolution and impact of inhomogeneities

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In Short

- We conduct kinetic simulations of the cosmic ray (CR) streaming instability to study the interplay of wave growth and damping leading to non-linear saturation with realistic streaming velocities.
- One of our objectives is to quantify the impact of background inhomogeneities in density and magnetic field on instability growth, saturation, and CR scattering rate and hence the type of propagation, i.e., whether CRs stream or diffuse for these realistic background inhomogeneities.
- Our simulations are scientifically important because they address the unsolved problem of CR transport and feedback in galaxy formation. To this end, we will then coarse-grain the kinetic simulations and derive effective CR transport coefficients that we will apply in modern theories of CR hydrodynamics in galaxy formation.

Our Galaxy is pervaded by a population of relativistic particles, called cosmic rays (CRs), that balances the pressures of magnetic fields, thermal plasma and turbulence in the midplane of the Milky Way, suggesting that CRs play an important dynamical role in maintaining the energy balance of the interstellar medium. Interestingly, CRs are virtually collisionless and interact via collective phenomena mediated by kinetic-scale plasma waves and large-scale magnetic fields 1. As CRs are streaming super-Alfvénically, they excite the streaming instability 2 that governs their mode of propagation. By scattering off of Alfvén waves, CRs can exchange energy and momentum with the thermal plasma, thereby dynamically modifying the formation and evolution of entire galaxies 3: as CRs stream and diffuse ahead of the thermal plasma into the galactic halo, they build up a pressure gradient. Once this gradient overcomes the gravitational attraction of the disk, it accelerates the thermal plasma, thereby driving a strong galactic outflow and quenching subsequent star formation. To date, it is unclear how much energy and momentum feedback is delivered by CRs, when in cosmic history this is particularly important and which galaxy masses are most affected.

The strength of CR feedback in galaxies is intimately related to the coupling strength of CRs to the thermal plasma: *weak wave damping* implies strong coupling and causes CRs to stream with Alfvén waves while *strong wave damping* diminishes the wave amplitudes to a level that is unable to maintain frequent CR scatterings so that faster CR diffusion prevails. Such fast CR diffusion weakens their gradients and forces involved and implies a smaller dynamical impact on the ambient plasma. The enormous separation of kinetic and global scales requires first a full understanding of kinetic processes via particle-in-cell (PIC) plasma simulations, which shall be the central topic of this proposal. In a second step, this insight of kinetic physics will be coarse grained and modeled in our novel macroscopic CR transport theory 1 to perform global magneto-hydrodynamic simulations of galaxy formation.

The transport speeds also impact the non-thermal radiative signatures of CRs from the radio to gamma rays. A faster transport yields broader CR distributions so that the more distant CR electrons probe smaller magnetic fields and radiation densities, which decreases the synchrotron and inverse Compton signal, respectively. Equivalently, more distant CR protons find smaller target gas densities to hadronically interact and to generate secondary decay products such as relativistic electrons, positrons, gamma-rays and neutrinos 4. These considerations provide an excellent motivation for an ab initio study of the plasma physics of CR transport, which will be the centerpiece of the proposal.

The pioneering nature of this proposal lies in the fact that we will perform targeted, state of the art, high resolution PIC and fluid-PIC simulations of the physics of CR streaming. In particular, we will perform such first-principle calculations of the involved kinetic physics using one of the most advanced numerical techniques, namely a higher-order accurate, massively parallel PIC code SHARP 5. This algorithm conserves charge and momentum exactly and improves energy conservation by about three orders of magnitude in comparison to common second-order schemes at only a small extra computational cost, thus enabling accurate simulations of cold, relativistic plasma over long periods. Recently, we have successfully applied this code in PIC simulations of CR driven instabilities 6.

At high Alfvén velocities near the speed of light, $v_{\mathrm{a}} \sim 0.1c$, magnetic bottles saturate exponential wave growth by trapping CR particles as they undergo mirror interactions with the peaks in transverse magnetic fluctuations that they subsequently

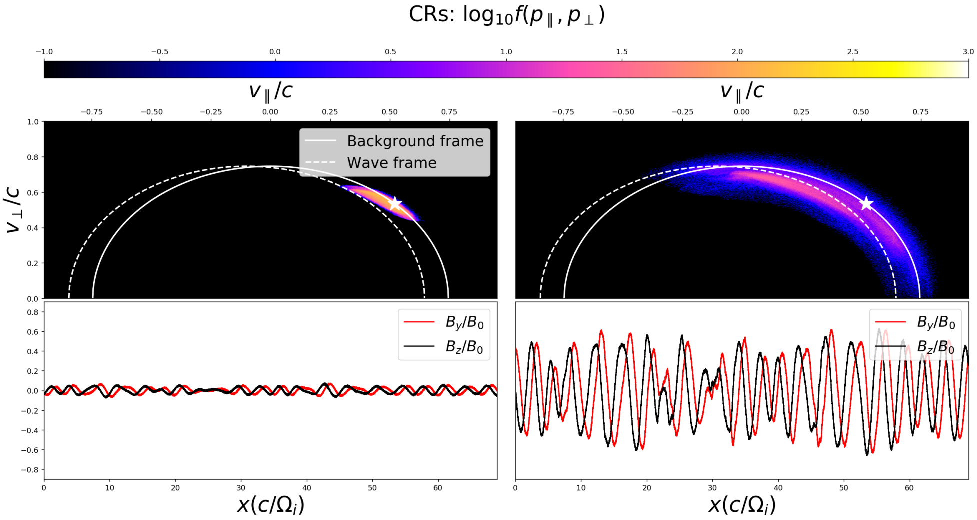

***Figure 1:** Particle-in-cell simulation of the CR streaming instability. The upper panels show the velocity space distribution of CRs that were initially distributed in a gyrotropic ring (white star) and measured in the background frame at early ($t = 34\,\Omega_B^{-1}$, left) and late stages of development ($t = 57\,\Omega_B^{-1}$, right). During linear growth, CRs loose energy at the expense of growing Alfvén waves through the resonant instability so that the CR distribution slowly starts to migrate towards the equal-energy surface in the Alfvén frame (dashed contour), in which there are no electric fields implying CR energy conservation along this energy surface. The lower panels show the corresponding snapshots of the transverse magnetic field components $\delta B_{y,z}$. The large anisotropy of the CR distribution results in the growth of right-handed (negative-helicity) Alfvén waves where the B_z component leads B_y (Shalaby et al., in prep.).*

encounter 7, cf. our recent PIC simulation in Fig. 1. By contrast, in the regime of non-relativistic Alfvén velocities the CR streaming instability excites Alfvén modes that interfer to produce a long-wavelength beat Alfvén wave that damps via Landau interactions with the background ion fluid; this process is called non-linear Landau damping. Resolving this physics requires larger simulation domains that capture the larger gyroradii in these weaker magnetic fields. This motivated our development of a new fluid-PIC code that also enables simulations in multiple spatial dimensions. In detail, our objectives are:

- Which processes non-linearly saturate the CR streaming instability as a function of v_a?
- Inhomogeneities in the background density grow individual modes faster or slower, depending on the sign of change of the Alfvén speed. Is the net effect a modified effective growth rate that scales with the average density?
- A spatially varying magnetic field implies CRs to quickly get out of resonance but at the same time allows for the excitation of a broader spectrum of unstable waves, each of which resonates with CRs of a different energy (similar to beam-plasma instabilities that encounter density inhomogeneities 8). What is the net effect of these two opposing effects on the growth rate in the linear and non-linear regimes? How do inhomogeneities affect the CR scattering rate and type of CR propagation?
- Finally, we will coarse-grain the kinetic simulations and derive effective CR transport coefficients for our novel macroscopic CR transport theory 1. Does quasi-linear theory describe CR transport well on galactic scales?

More Information

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