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# The Cosmic Ray Anisotropy Instability in MHD-PIC Simulations

Xiaochen Sun[1], Xue-Ning Bai[1,2],
[1] Institute for Advanced Study, Tsinghua University, [2] Institute for Advanced Study, Tsinghua University
sxc18@mails.tsinghua.edu.cn

Cosmic rays (CRs) are relativistic charged particles, pervading galaxies and beyond. With the substantial energy density, CRs play a dynamically important role on galactic scale via magnetic fields, heating the thermal gas and potentially driving galactic outflows, which is known as the CR feedback. The microphysics for the CR feedback relies on how efficiently plasma waves scatter CRs, which is poorly understood. For low-to-medium-energy CRs (~GeV) which comprises the bulk CR energy density, it is believed that the main source of plasma waves that scatter the CRs, arise from the CR gyro-resonant instabilities. In particular, when the CR pressure becomes anisotropic, potentially driven by macroscopic expansion or compression, the system is subject to the CR anisotropy instability (CRAI), which is one type of the CR gyro-resonant instabilities. The outcome of the CRAI is by far rarely explored.

To self-consistently simulate the CRAI, we implement the MHD-PIC method on top of the Athena++ MHD code. In the MHD-PIC method, we treat the thermal gas as MHD fluid and kinetically integrate the CRs, including CR backreaction and capturing the wave-particle interactions from first principles. The MHD-PIC method allows us to study the CRAI over a large dynamical range at modest computational costs. We employ the $\delta f$ method to reduce the numerical noise. To mimic the macroscopic expansion and to measure the CR scattering rate, we further implement the expanding box framework which continuously drives an anisotropic CR pressure.

We carry out 1D simulations with parameters approaching realistic regimes. The simulations demonstrate the expected plasma wave growth and the quasi-linear diffusion of CRs. In the saturated state, the level of CR anisotropy is determined by the balance between driving (expansion/compression) and quasi-linear diffusion. In the meantime, the growth of the CRAI is balanced by wave damping. This steady state balance allows us to characterize the CR scattering rates from first principles, which provides the microphysical basis for understanding CR feedback.

References
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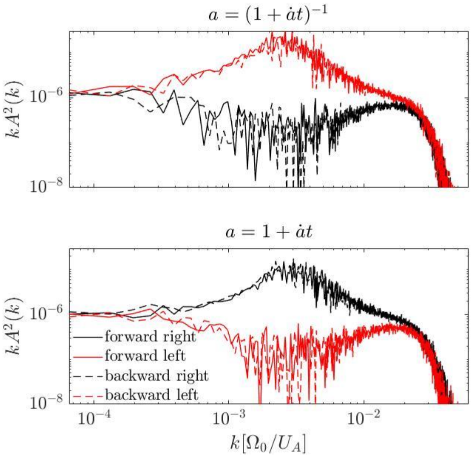

Figure 1. Wave power spectra, $kA^2(k)$, for CRAI for shrinking (top) and expanding (bottom) boxes, with the shrinking/expanding rate $\dot{a} = 1 \times 10^{-5}\Omega_0$ at $t = 6 \times 10^3\Omega_0^{-1}$. Forward and backward propagating waves are in solid and dashed lines. Left and righthanded branches are marked in black and red respectively

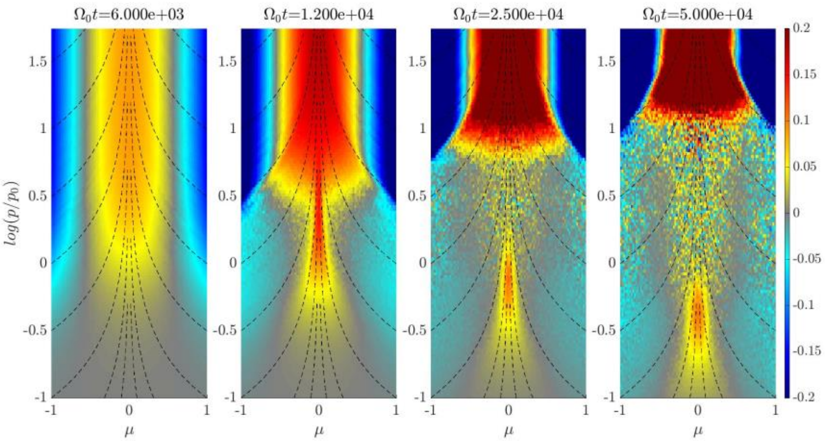

Figure 2. The CR distribution function $(f/\langle f\rangle_\mu - 1)$ for the expanding box simulation ($a = 1 + \dot{a}\,t,\ \dot{a} = 1 \times 10^{-5}\Omega_0$). The dashed lines refer to the same resonant wave whose $k = \Omega_0 m/(p\mu)$.