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Implications of cosmic-ray self-confinement in the Galaxy

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The transport of Galactic cosmic rays (CRs) is likely due to an interplay between self-generated and extrinsic magnetic turbulence. In particular, close to their sources and close to the Galactic disk, CR diffusion is likely enhanced by the large CR currents that drive the streaming instability. We investigate the onset of the resonant and non-resonant streaming instabilities and their influence on CR transport by performing self-consistent hybrid particle-in-cell simulations. On Galactic scales, we study how the self-generated diffusion coefficient is expected to vary from the disk to the halo, which might be crucial for both CR confinement and for providing sub-grid models in models of galaxy evolution that include CR physics.

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1. Introduction

Understanding the transport properties of cosmic rays (CRs) is crucial for explaining a multitude of observations and physical phenomena. On Galactic scales, CRs diffuse inside a magnetized halo extending a few kpcs above and below the Galactic disc. In this picture, the escape flux from the halo balances the injection of new particles resulting in stationary CR fluxes in the disc and at Earth. The diffusion coefficient inside the halo can be inferred from high-precision measurements of CR fluxes at Earth by experiments such as PAMELA [1], AMS-02 [2], DAMPE [3] and CALET [4]. These measurements revealed new spectral features present in CR fluxes and secondary-to-primary ratios, such as the hardening around $\sim 300\,\mathrm{GV}$ [1, 5], that can be related to a non-separable spatial dependence of the diffusion coefficient [6] or the transition of scattering regimes from scattering off self-generated turbulence to scattering off extrinsic turbulence [7, 8]. The latter illustrates the intrinsic non-linearity of CR transport due to the excitation of plasma instabilities by CRs and implies that CRs below a few hundred GV self-confine themselves on Galactic scales.

Responsible for the self-confinement is assumably the resonant streaming instability [9] which generates Alfvén waves on a scale comparable to the gyroradius of the generating particles. Due to its resonant nature, particles of a given energy create their own scattering centers, efficiently scatter off them and diffuse with a diffusion coefficient that depends on the saturated level of magnetic turbulence. The instability is often assumed to saturate due to a balance between its growth rate and the dominant damping mechanism [10]. Assuming a fixed halo scale height, one can estimate the growth rate for CRs diffusing in the Galactic halo. Balancing this growth rate with the damping rate of non-linear Landau damping leads to a level of magnetic turbulence strong enough to efficiently scatter CRs within the halo [10]. However, how does the halo form in the first place? Is such a commonly-assumed, fixed halo size achievable in a simplified one-dimensional picture such as the escape from the Galaxy?

In simulations of Galaxy formation [11, 12], the halo exists with a fixed size since the creation of our Galaxy and CRs immediately diffuse; a situation that is hard to imagine if the turbulence in the halo is an effect of CRs themselves. It seems more plausible that the halo forms during the Galaxy's evolution. A scenario that is able to explain its formation assumes that turbulence is injected at large scales in the disc and cascades down to smaller scales while being advected outwards [13]. This introduces an effective halo size below which turbulence is dominantly self-generated due to a lack of time for the turbulent cascade to develop and above which the diffusion coefficient increases rapidly with distance.

In this work, we study the above phenomena from first principles employing self-consistent hybrid particle-in-cell simulations with the code dHybridR [14]. In particular, we focus on the onset of self-confinement of particles escaping from the Galactic disc, the formation of a magnetized halo and its further evolution with time searching for stationary solutions. We investigate whether the escape flux can balance the injection flux and a stationary situation can emerge in this context which might have important implications for our understanding of CR transport and Galaxy formation. We first describe our simulation setup in Sec. 2. Then, we present and discuss our results in Sec. 3 and conclude in Sec. 4

2. Hybrid kinetic simulations

For studying CR self-confinement and the possible formation of a halo, we perform 1D simulations with dHybridR [14], a relativistic hybrid code with kinetic ions and (massless, charge-neutralizing) fluid electrons. Physical quantities like lengths, time, velocities, number densities and magnetic fields in our simulations are normalized to the ion inertial length $d_i = v_A/\Omega_{ci}$, the inverse ion cyclotron frequency Ω_{ci}^{-1}, the Alfvén speed v_A, the number density (n_0) and the magnetic field strength (B_0) of the initial background plasma respectively. The temperature of the background ions is chosen such that the thermal ions gyroradius $r_{g,i} = d_i$, i.e., $\beta_i = 2v_{th,i}^2/v_A^2 = 2$. The speed of light is set to $70\,v_A$. We retain in all simulations all three velocity and field components. The simulations are discretized on a grid of size $300000 \times 40\,d_i^2$, with 600000×80 cells. For the CRs and the plasma, we impose open boundary conditions in the x-direction and periodic in the y-direction. The simulation box is filled with a background magnetic field along the x-direction with a strength B_0. The background plasma is initialized with $N_{\mathrm{ppc}} = 4$ particles per cell, following a Maxwellian with density n_0, while CRs are injected with $N_{\mathrm{ppc}} = 4$ at $x = 100000$ isotropically with momentum $p_{\mathrm{total}} = 70\,mv_A$, i.e. Lorentz factor $\gamma \approx \sqrt{2}$. The injection of CRs is continuous in time with $n_{\mathrm{CR}} = 6 \times 10^{-4} n_0$ and $n_{\mathrm{CR}} = 6 \times 10^{-3} n_0$ for two separate cases respectively.

This one-dimensional simulation setup should correspond to situations where the vertical extent of the CR source is much larger than their gyroradius, e.g., particles injected in the Galactic disc and leaving into the halo. As described above, we test different scenarios with different injection efficiencies in order to see if there is a qualitative difference between self-confinement due to the resonant [9] or non-resonant streaming instability [15, 16]. The two regimes are determined by the value of the parameter $\tilde{\sigma} = \frac{n_{\mathrm{CR}} p_{\mathrm{CR}} v_d}{n_0 m v_A^2}$ with the CR density n_{CR}, their momentum p_{CR}, the Alfvén speed v_A, their mass m and the background gas density n_0. If $\tilde{\sigma} \gg 1$, we are in the non-resonant regime and vice-versa. Our test cases correspond to $\tilde{\sigma} \approx 0.5$ and $\tilde{\sigma} \approx 5$.

3. Results

In this configuration, particles start escaping ballistically from the injection point, i.e., the disc, corresponding to the first CRs injected into the Galaxy. After several growth times of the instabilities, the magnetic field becomes strong enough to confine them inside a region surrounding the injection point. In Fig. 1, we show the CR density profile that emerges, which seems universal for both the resonant and non-resonant instability. The profile can be divided into several regions: The central bell-shaped region is the most prominent feature, in which the density exceeds the initially injected density ($n_{\mathrm{inj}} = 6 \times 10^{-4} n_0$ and $n_{\mathrm{inj}} = 6 \times 10^{-3} n_0$ respectively), by orders of magnitude. This region is what we identify as the Galactic halo. The particles' transport is determined by two competing processes: advection and diffusion due to scattering off their self-generated magnetic turbulence. This leads to an isotropic distribution function and a drift velocity away from the center on both sides of the order of a few times the Alfvén speed v_A. Note that the region is expanding linear in time at a similar speed due to the dynamic feedback of CRs suggesting that the particles' transport is dominated by advection rather than diffusion. In fact, the additional pressure component due to CRs in the central region pushes the background gas outwards. In the non-resonant case,

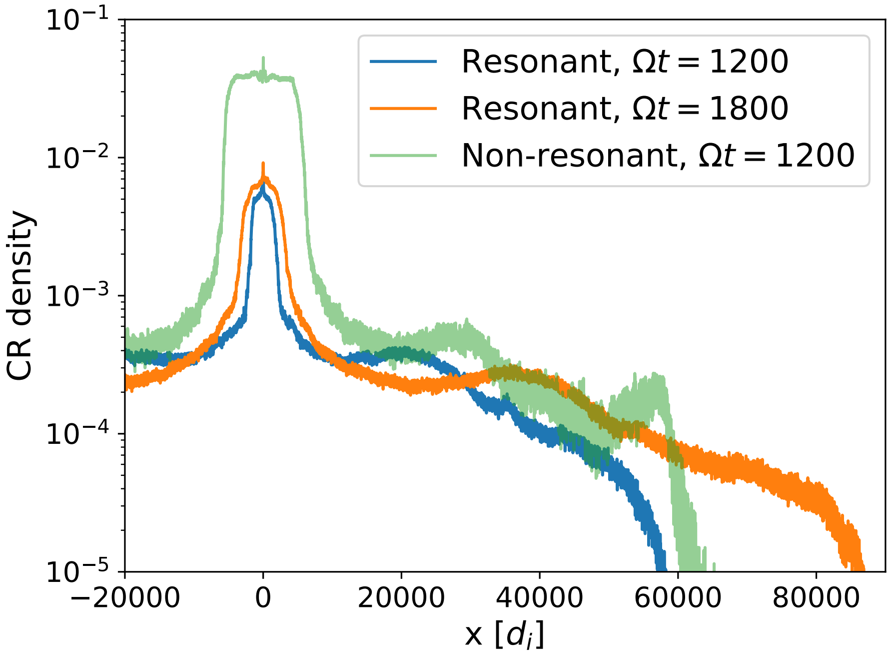

Figure 1: Cosmic ray density in code units for our resonant and non-resonant instability cases at times $\Omega t = 1200$ and $\Omega t = 1800$ to illustrate the emerging density profile from CR self-confinement.

the region expanded further and faster at any given time compared to the resonant case due to the larger overpressure in CRs.

Outside the central region, the particle density forms a plateau with a comparable density in both cases, see Fig. 1, although the injected particle density is a factor 10 higher in the non-resonant case. The plateau consists of escaping particles that get scattered by the turbulence created by the particles that passed through earlier in time. While perfect isotropy is not achieved inside this plateau, the pitchangle distributions are flat nonetheless and the particles' drift velocity increases steadily from a few v_A close to the halo to the speed of the individual particles $\sim c$ at the right edge of the plateau.

The sharp dropoff on the right-hand side of the CR density is a transient due to only the fastest particles with $\mu = \pm 1$ reaching so far. Only the particles injected in the beginning with $\mu = \pm 1$ travel without any scattering up to the maximum distance $x_{\max} = vt$. At smaller distances, the density increases towards the plateau due to a combination of two effects: 1. Particles injected initially with smaller μ can reach each given point in space together with particles injected at later times with $\mu = \pm 1$. 2. Particles that would travel further in space get scattered by the generated turbulence and slow down. In particular, the second effect leads to a density increase up to the point where the excited turbulence is enough to change the direction of the particles, at which point the plateau forms.

Even at late times, the central region is not showing any indication of slowing down and keeps expanding linearly with time. Hence, it seems at first that no stationary size is achievable. A different way to assess the possibility of a steady state is to look at how the rate of escaping particles

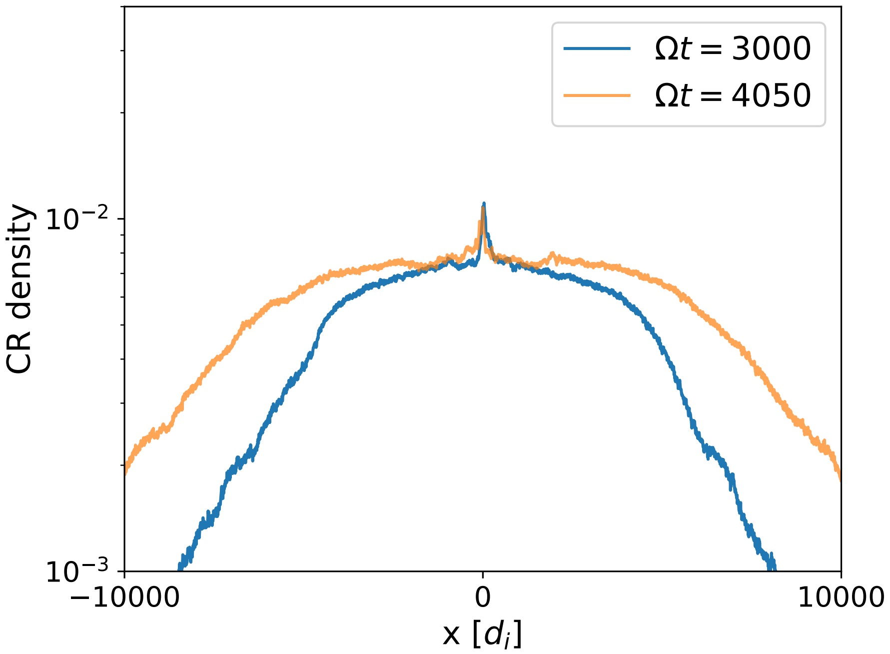

Figure 2: Cosmic ray density in code units for our resonant case at times $\Omega t = 3000$ and $\Omega t = 4050$ to illustrate the convergence of the central density to a constant value.

compares to the injection rate. In both cases, the rate of particles escaping from the halo is much smaller than the injection rate, indicating that a significant fraction of particles stay trapped inside the central region. In such a configuration, it is hard to imagine a steady state since new energy stays constantly trapped at the injection point, driving the halo expansion. However, this might be an effect of reduced dimensionality and requires further testing. Nonetheless, even in one dimension, the CR density in the center remarkably reaches a stationary value that stays constant in time, see Fig. 2. Thus, an observer at Earth would not feel the effect of an expanding halo and would measure stationary CR fluxes, similar to the picture with a fixed size halo where the injection is balanced by the escape. As a result, the observation of a halo of kpc scale might be the result of a continuously expanding bubble of self-confined CRs that started at the early evolutionary stages of our Galaxy. In this scenario, the CR feedback on the Galaxy might change and influence the results of Galaxy formation simulations.

4. Conclusions

There is an increasing amount of indications suggesting that the diffusive halo around the Galactic disc might be created by self-generated turbulence. Such a scenario seems to be able to produce a sufficient amount of turbulence [10] and in combination with the existence of extrinsic turbulence, it can explain the hardening at 300 GV [7, 8]. However, most scenarios invoke a stationary halo size around the disc. In this proceeding, we investigated the possibility to form such a stationary halo due to CR self-confinement in a one-dimensional problem employing 1D, hybrid particle-in-cell simulations. Our simulations test both the non-resonant and resonant regimes of the streaming instability. The resulting density profiles are comparable, independent of the responsible instability, with a bell-shaped central overdensity, a plateau and a sharp drop. Our preliminary results suggest that self-confinement unavoidably leads to an expanding overdense region, the halo. Contrary to the standard assumption of the escape flux from the halo being equal to the injected flux, we find that the bulk of the injected particles stays confined inside the halo independently of generating the resonant or non-resonant instability. Their dynamic feedback drives the expansion of the confinement region with a speed close to the local Alfvén speed v_A. These results suggest that a stationary halo size cannot be achieved. However, this needs to be tested in higher dimensions. Although the halo keeps expanding, the CR density remarkably approaches a stationary value nonetheless, suggesting that stationary flux measurements at Earth can be self-consistently achieved in a self-generated, expanding halo. Our results are similar to the ones of ref. [13] investigating the formation of the halo as a phenomenon of CR feedback. However, in our case, the halo forms purely due to self-confinement, as there is no extrinsic turbulence that is cascading. The formation and expansion of a halo over cosmological time scales might change our understanding of how Galaxies form and might be relevant for CR feedback on Galaxy formation.

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