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Tapping Jet Energy for Cosmic Ray Acceleration

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This study examines the conditions governing the acceleration and reacceleration of cosmic rays (CRs) by ultra-relativistic jets. We demonstrate that cylindrically symmetric jets cannot reaccelerate external CRs. Without symmetry breaking, e.g., significant CR scattering, the jet-boosted magnetic and motional electric fields lead to specular reflection of incoming CRs. The one-dimensional particle dynamics, resulting from jet symmetry, categorizes CRs into passing particles and those bound by the jet's magnetic and motional electric fields. Passing particles exhibit energy consistency, originating and returning to the jet exterior with the same energy, necessitating trapping through scattering or other orbit distortions to access the jet's energy reservoir. These findings challenge some claims in the literature suggesting that outer CRs can achieve up to $2\Gamma^2$ energy gain in a "one-shot" scenario, briefly encountering a jet with a bulk Lorentz factor Γ and experiencing no significant scattering within it. We establish that scattering within the jet facilitates CRs to traverse the separatrix between passing and trapped particles, thus potentially unlocking the jet energy for CRs. Additionally, we investigate the magnetic pumping acceleration mechanism, which requires CR trapping unless they are initially seeded within the jet. We illustrate how CR acceleration via magnetic pumping is contingent upon CR scattering. Consequently, our results underscore the critical role of particle scattering and symmetry-breaking mechanisms in efficiently accelerating particles through conducting fluid motions.

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1. Introduction

AGN- and other powerful jets have garnered considerable interest as potential locations for UHECR acceleration and reacceleration. Jets might appear capable of accelerating particles without scattering. However, in a jet with *cylindrical symmetry and stationary B-field* components B_z, B_ϕ, particles gain no net energy. The sole energy source for it could be in the radial motional electric field E_r generated by the toroidal magnetic field B_ϕ. As E_r depends solely on the radial coordinate r, the work it does on a particle toward the axis is negated on the return path. Consequently, the cylindrical symmetry must be broken (e.g., by scattering) before the jet energy may become accessible to the particle.

Nevertheless, an interesting suggestion of a single-shot Γ^2 CR-boosting by a jet [2] has been entertained in the literature, e.g., [6], claiming no "evidence of pitch-angle scattering." A gradual axial decrease of the jet's $B_\phi(z)$ implemented the required symmetry breaking. It is unclear how the energy gain depends on the crucial for it symmetry-breaking parameter and how much energy particles seeded well outside of the jet (to test reacceleration) may gain after being ejected from it. The analogy with scatter-free Γ^2 energy gain from the first particle encounter of a perpendicular relativistic shock, as suggested in [2, 6], is not convincing, as the motional electric field in the latter case aligns with the particle displacement caused by the shock, resulting in no work cancellation [3]. The particle dynamics are fully integrable in the basic settings, allowing us to predict the outcomes by particle ingress parameters (see [5] for the shocks and below for the jets). In plain language, the analogy with a moving "relativistic wall" proposed in [2, 6] is not convincing either because the shock moves across its surface. In contrast, the jet moves along it, making its potential to energize particles very different from the shock. The analogy works for particles entering the jet from its head. As the jet Lorentz factor $\Gamma \sim 1$ there, this option

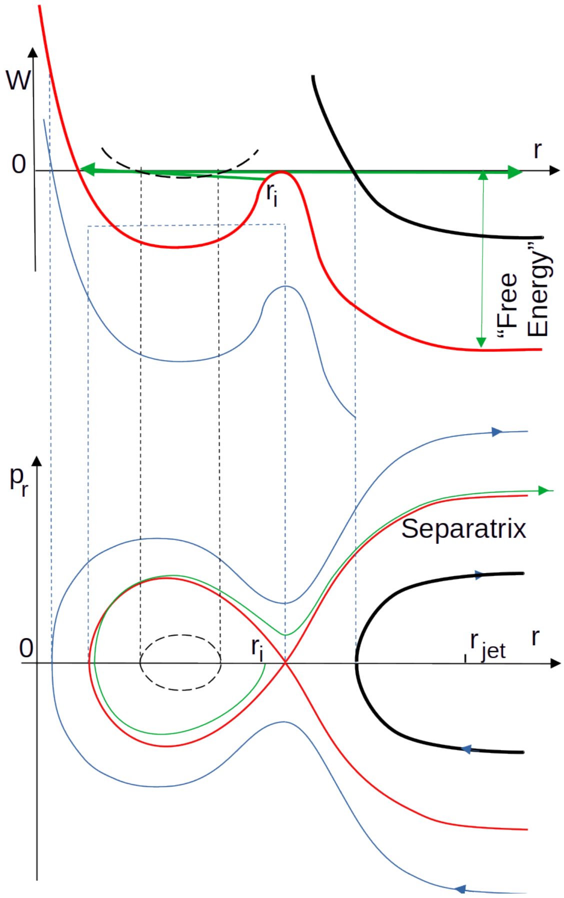

Figure 1: Top: Potential $W(r)$ for particles interacting with the jet magnetic and motional electric fields. It is shown for four different sets of integrals of motion. Bottom: The respective particle orbits are shown as contourplots of $p_r^2 + W(r) = 0$ on a phase plane (r, p_r), where $p_r = \gamma \dot{r}$. Black lines: particles, reflected from the outer barrier; Blue lines: particles, reflected from the centrifugal barrier; black dashed: trapped particles; red lines correspond to the separatrix and the green lines show particle detrapping event that occurred by small perturbations of the particle invariants.

is much less promising for the search of the UHECR origin.

Unfortunately, the numerical results of [6] related to azimuthally symmetric jets are given for planar orbits (passing through the jet axis, $p_r = p$). Apart from comprising a measure-zero subset of all possible, the shown orbits seemingly start inside the jet, and it is unclear how they can testify for the reacceleration of external CRs (see Sec.2).

To better understand the conditions under which CRs can extract the jet energy, this paper distinguishes between two particle categories: trapped and passing (reflected from the jet). Particle scattering allows the jet to trap the passing particles and accelerate them. Otherwise, orbits are periodic or unbounded in symmetric jets. Trapping, in turn, facilitates other forms of acceleration. Our investigation encompasses the magnetic pumping mechanism, which capitalizes on the combined effects of the betatron acceleration induced by an oscillating magnetic field and particle scattering.

2. Regular Particle Orbits in Cylindrically Symmetric Jets

When considering a particle interacting with a cylindrically symmetric jet, the conservation of canonical momentum components (P_z, P_ϕ) and energy (E) leads to effectively a radial motion. To examine the possibility of a "single-shot" reacceleration, we must focus on particles originating from outside the jet, which will exit after a single excursion toward its axis gaining no energy. However, if a particle is seeded inside where $E_r \neq 0$ it may emerge with increased energy, as illustrated in Fig.1 with a green line, indicating the particle's initial access to the jet's free energy (cf. Figure 1 in [6]).

To demonstrate the above assertions, we adopt a cylindrical coordinate system (r, ϕ, z) and assume the jet's motion is directed in the z axis with a Lorentz factor $\Gamma = \left[1 - u^2(r)\right]^{-1/2}$. The magnetic field components are given by $B_\phi = -\partial A_z/\partial r$ and $B_z = r^{-1}\partial\left(rA_\phi\right)/\partial r$. Utilizing a Lagrangian in cylindrical coordinates,

$$L = -\frac{mc^2}{\gamma} + \frac{e}{c}\dot{z}A_z(r) + \frac{e}{c}r\dot{\phi}A_\phi(r) - e\Phi(r), \text{ where } \gamma = \left(1 - \frac{\dot{r}^2}{c^2} - \frac{\dot{z}^2}{c^2} - \frac{r^2\dot{\phi}^2}{c^2}\right)^{-1/2}$$

and $-\partial\Phi/\partial r = (u/c)\,\Gamma B_\phi$ is the motional electric field, we will adopt units $m = e = c = 1$ and measure distances in the jet radii, $r_{\rm j}$, time in $r_{\rm j}/c$, velocities in c, particle momentum in mc, and potentials A, Φ - in mc^2/e. We will use the ISM frame in which the radial electric field is $-\partial\Phi/\partial r = -u\partial A_z/\partial r$. As the Lagrangian depends only on r, (cylindrical symmetry) there are three integrals of motion:

$$(P_z, P_\phi) = \left(\frac{\partial L}{\partial \dot{z}}, \frac{\partial L}{\partial \dot{\phi}}\right) = \left(\gamma\dot{z} + A_z, \gamma r^2\dot{\phi} + rA_\phi\right) = const, \tag{1}$$

$$H = P_i\dot{q}_i - L = \gamma + \Phi = E = const, \tag{2}$$

where the Lorentz's factor γ can be expressed using the integrals P_ϕ, P_z,

$$\gamma = \sqrt{1 + p_r^2 + \frac{\left(P_\phi - rA_\phi\right)^2}{r^2} + \left(P_z - A_z\right)^2}, \tag{3}$$

and where the radial momentum $p_r = \gamma\dot{r}$. We will also use the following function $\gamma(r, E) \equiv E - \Phi(r)$, based on eq.(2). We assume that $u\partial A_z/\partial r = \partial\Phi/\partial r \to 0$ for $r \to \infty$, which does not imply $B_\phi \to 0$. However, as $\Gamma = 1/\sqrt{1-u^2} \gg 1$ (strong boost of B_ϕ inside of the jet), we impose conditions $A_z, A_\phi \to 0$ at $r \to \infty$, which allows us to maintain the cylindrical symmetry, while extending the orbit range to $0 < r < \infty$.

The energy conservation requires

$$(\gamma \dot{r})^2 + W(r, P_\phi, P_z, E) = 0 \tag{4}$$

where

$$W(r) = \frac{(P_\phi - rA_\phi)^2}{r^2} + (P_z - A_z)^2 + 1 - \gamma^2(r, E) \tag{5}$$

is a "potential" of 1D particle motion with its conserved parameters P_ϕ, P_z and E, which determine integral curves on the (p_r, r) plane, Fig.1. We can interpret eq.(4) as a sum of the kinetic and potential energy of a 1D oscillator, which can be solved by quadrature. There is a three-parameter (P_ϕ, P_z, and E) family of profiles $W(r)$ and, thus, orbits on the (r, p_r) phase plane. Nevertheless, we can characterize essential types of orbits to understand how particles increase energy after exiting the jet.

We first observe that as $r \to 0$, $W \sim P_\phi^2 r^{-2}$ (centrifugal barrier), assuming "reasonably regular" behavior of A_z and A_ϕ near the origin. The behavior of W as $r \to \infty$ relies on that of A_z, A_ϕ, and u. Considering that $u(r) \to 0$ as $r \to \infty$ and $\Phi(\infty) = 0$ (eq. 5), if $B(r)$ also diminishes promptly, then $W \to -p_r^2(\infty)$ for $r \to \infty$, causing certain particles to approach from infinity and return with the same Lorentz factor. Consequently, we ascertain that a stationary and cylindrically symmetric jet cannot reaccelerate CRs. This finding aligns with the earlier observation of work cancellation on particles, as highlighted in the Introduction.

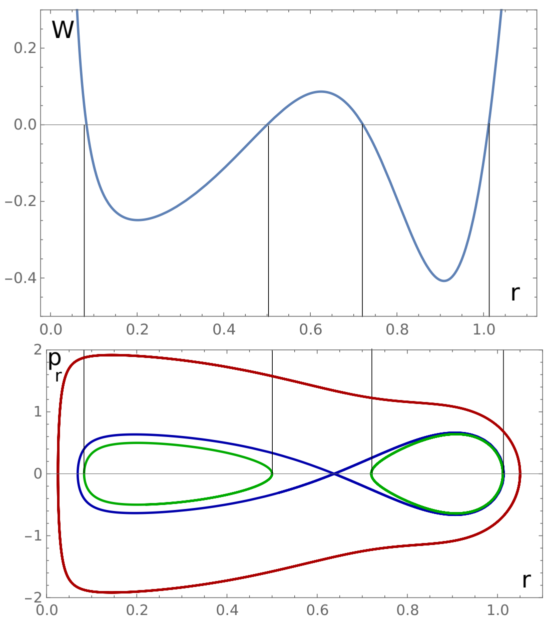

Figure 2: Top Panel: Double-well potential of a jet given by eq.(5) with $P_\phi = 0.05$, $A_\phi = 0$, $P_z = -7.7$ and $E \approx 0.25$. **Bottom Panel**:Phase portrait of the system given by eqs.(4-5) and showing two orbits (in green) trapped in separate potential wells with the same energy $E \approx 0.25$. Two branches of a separatrix, corresponding to the energy $E \approx 0.26$, are shown with blue lines. An orbit that embraces all three and corresponds to $E \approx 0.45$, is shown with the red line.

Let us now select P_ϕ, P_z, and E in such a way that $W(r)$ has a local maximum. Particles seeded inside the jet (to the left from the maximum) with very small negative p_r can pass the maximum of $W(r)$ after being reflected from the centrifugal barrier. The maximum may be lowered by, e.g., an adiabatic decrease of B_ϕ [6] along the particles' axial drift. They will then leave the jet as free particles with extra energy, but this will not be a reacceleration of external particles, as they started with $W(r) > W(\infty)$, as we already mentioned. We conclude that if the magnetic field, $(0, B_\phi, B_z)$ and velocity u of a jet depends only on r, CRs impinging on it are specularly reflected, thus gaining no energy, as shown in Fig.1.

Examples of Unperturbed Particle Trajectories To investigate the dynamics of cosmic rays (CRs) entering the jet from an arbitrary distance, we assume the ambient magnetic field vanishes at $r \to \infty$ faster than $1/r$. In this case, CRs can traverse from infinity to the jet and back. Focusing on a radial profile of the toroidal magnetic field B_ϕ and jet velocity u, we consider

$$B_\phi = \frac{B_0 \Gamma_0 r}{1 + r^4}, \quad u = \frac{u_0}{1 + r^8}, \tag{6}$$

The motional electric field in this jet points toward its axis ($E_r < 0$, $B_0 < 0$), attracting protons.

With fixed integrals of motion P_ϕ and P_z while varying E, three types of particle orbits emerge due to the potential $W(r)$, Fig2. Decreasing E tightens the orbits to each potential well's minimum. The motion at the bottom corresponds to particles circulating along the local toroidal field line, where the radial force from E_r balances the Lorentz force from the particle motion along the jet axis. Upon further increase in $E > E_s$, a family of closed orbits surrounding the first two types, including the separatrix, is found.

The separatrix branches enclose bound states inside the jet (left branch) and orbits reaching the jet's edge, allowing external CRs to enter this part of the phase space through scattering on a wave or other field perturbations. Trapped particles close to the separatrix saddle at $r \approx 0.6, p_r = 0$ can transition over the potential barrier under a slight perturbation, possibly maintaining the same values of the three integrals. Alternatively, particles with increased energy, even slightly, can enclose both separatrix branches, spending some of their period outside the jet but reaching closer to its axis than the other two groups.

Identifying separatrices is vital for understanding CR reacceleration by jets, and this phenomenon has parallels with Poincaré's work on separatrix splitting and stochastic layers [8] filled with particles that can transition among the domains around the saddle point when passing close to it. For that reason, passing a saddle point vicinity is challenging for numerical orbit integration, as tiny round errors cause large orbit deflections. A simple criterion of the computation accuracy in cylindrically symmetric jets is maintaining the orbit periodicity, regardless of the separatrix proximity.

3. Particle Scattering

Local Scattering An energetically efficient change of CR integrals of motion occurs through particle elastic scattering in the jet-comoving frame. However, the particle's energy will generally be altered in the ISM frame. We assume that $A_z(r)$ and $\Phi(r)$ remain constant during the scattering event, which is justified for resonant particle interactions with short-waves ($kr_{\rm jet} \gg 1$).

Fig. 3 illustrates such scattering events, where particles can transition to significantly different orbits by pitch-angle scattering in a locally comoving jet frame. After jumping to a trapped orbit, a particle's energy in the ISM frame changes further due to additional

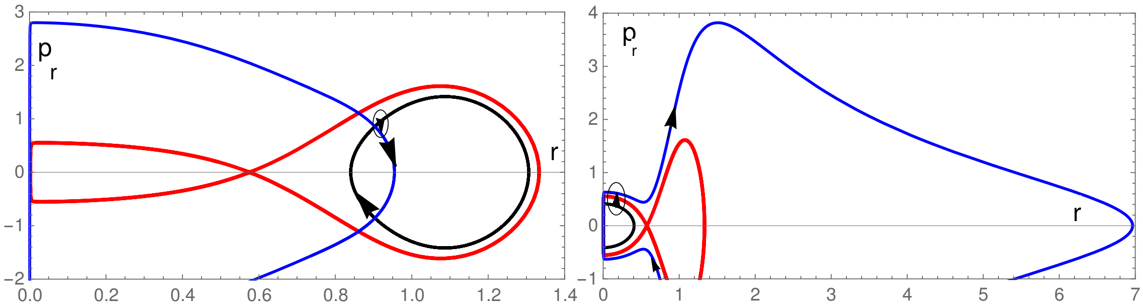

Figure 3: Examples of particle scattering leading to separatrix crossing (see text). **Left panel**: A particle, moving largely outside of the jet, scatters to a trapped state, after which it moves entirely inside of the jet. **Right panel**: Trapped particle scatters to effectively a free state, assuming that after traveling to $r \approx 7$, it will not return to the jet. Some essential parameters are: $B_0 = -1,\ B_z = 0,\ \Gamma = 20$.

scattering, even if the scattering is elastic in the jet frame. Ultimately, the particle may be scattered back to a free orbit and exit the jet. If the net energy change is positive, the particle is reaccelerated. Calculating the reacceleration efficiency necessitates a comprehensive understanding of the particle phase portrait and the scattering characteristics. Furthermore, the energy gain is directly linked to the nature and extent of scattering.

Separatrix Crossing It follows that the promise for a "one-shot" acceleration mechanism, (e.g., *espresso* mechanism, suggested in [2]) can only be in the entrainment of the trapped CRs by the jet flow and scattering them back to the ISM at a favorable position in the phase space.

To examine whether this is a plausible scenario, let us consider the first integral for the particle orbit given by eq.(4). We need to answer two questions. The first is whether a particle's elastic scattering can lead to the separatrix crossing, namely to particle trapping by the jet. The second question is whether these CRs will leave the jet with energy exceeding their initial energy. Assuming again $kr_{\rm jet} \gg 1$, the scattering changes $\dot{r}$,P_ϕ, and P_z, while the particle momentum $(\gamma\dot{r})^2 + (P_\phi - rA_\phi)^2 r^{-2} + (P_z - A_z)^2 = inv$ in the jet's comoving frame (pitch-angle scattering). As the integral of motion P_ϕ and P_z are different before and after the scattering, so are functions $W(r)$, thus making trapping or detrapping possible.

After being trapped for a sufficiently long time, particles may undergo various types of acceleration; however, it is essential to emphasize that this scenario does not look like the "one-shot" acceleration but a continuing acceleration inside the jet, by whatever mechanism dominates (DSA, shear, etc., e.g., [4, 7]) We will explore this aspect in depth in a more comprehensive study. In the context of our current investigation, it is worth noting that trapped particles may encounter one of the internal shocks in the jet and get accelerated. Simultaneously, the jet's magnetic field will likely experience significant magnetic perturbations due to factors like the kink or screw and sausage instability or through interactions with its surrounding environment. The following section briefly examines the magnetic pumping mechanism as a notable example.

4. Magnetic Pumping

We introduce a turbulent component to the jet's magnetic field, incorporating low wave number and low-frequency perturbations. This turbulence breaks the axial and azimuthal symmetry of the jet, including its time dependence, leading to a blurred separatrix. Consequently, particles can cross the separatrix, as evident from eqs. (4), (5), and Fig.3.

Trapped energetic CRs within the jet may undergo a type of acceleration known as magnetic pumping. This process relies on a slow evolution of the first adiabatic invariant $p_\perp^2/B \approx const$. For effective magnetic pumping, the field variations must be slower than the particle's Larmor rotation and longer in scale than the particle's Larmor radius. Under these conditions, the particle's perpendicular momentum traces the magnetic field strength. Even weak Larmor-scale magnetic perturbations can induce resonant pitch-angle scattering, ensuring that the excess perpendicular momentum produced during field increases is partially transferred to the parallel degree of freedom upon its decrease. This combination results in a net increase in the particle momentum.

To describe magnetic pumping, we adopt a simple model, following [1]. The gyrophase-averaged perpendicular and parallel components of the particle momentum, $p_\perp$ and $p_\parallel$, are governed by the equations:

$$\begin{aligned} \dot{p}_\perp &= \frac{\dot{B}}{2B} p_\perp + \nu \left(p_\parallel - p_\perp \right) \\ \dot{p}_\parallel &= \nu \left(p_\perp - p_\parallel \right) \end{aligned} \tag{7}$$

Here $B(t)$ is the magnetic field and ν is the particle scattering frequency. If $\nu = 0$, then $p_\perp^2/B$=const. If $\dot{B} = 0$ and $\nu \neq 0$, then the pitch-angle anisotropy $p_\perp - p_\parallel$ decays at the rate 2ν.

We explore the weak pumping regime, characterized by $\dot{B}/B \ll \nu$. We introduce a small parameter $\epsilon \ll 1$, representing $\dot{B}/2B$ as $\epsilon \dot{F}$. Employing a multi-time expansion and imposing the following ordering: $\left| \overline{p}_\perp - \overline{p}_\parallel \right| / \overline{p}_\perp \sim \epsilon^2$, $\left| p_{\parallel,\perp} - \overline{p}_{\parallel,\perp} \right| / \overline{p}_\perp \sim \epsilon$, we obtain solutions for $\overline{p}_\perp$ and $\overline{p}_\parallel$ as functions of slow time $\tau = \epsilon^2 t$ and fast-time dependent quantities. Considering for now τ as an extra variable, formally independent of the "fast time", t, and thus replacing $\partial_t \to \partial_t + \epsilon^2 \partial_\tau$, and introducing the notation

$$\epsilon^2 \delta \overline{p}(\tau) \equiv \overline{p}_\parallel - \overline{p}_\perp, \quad \epsilon \tilde{p}_\perp \equiv p_\perp - \overline{p}_\perp(\tau), \quad \epsilon \tilde{p}_\parallel \equiv p_\parallel - \overline{p}_\parallel(\tau), \quad \delta \tilde{p} \equiv \tilde{p}_\parallel - \tilde{p}_\perp, \tag{8}$$

after averaging over the fast time (e.g, over the period of $B(t)$, i.e., $2\pi/\omega$), we have

$$\begin{aligned} \partial \overline{p}_\perp / \partial \tau &= \overline{\dot{F} \tilde{p}_\perp} + \nu \delta \overline{p} \\ \partial \overline{p}_\parallel / \partial \tau &= -\nu \delta \overline{p} \end{aligned} \tag{9}$$

from which and eq.(7) we obtain

$$\begin{aligned} p_\perp &= \overline{p}_\perp(0) \left[1 + \frac{\nu\omega \sin(\omega t) - \left(\omega^2 + 2\nu^2 \right) \cos(\omega t)}{\omega^2 + 4\nu^2} \right] e^{\sigma t} \\ p_\parallel &= \overline{p}_\perp(0) \left[1 - \nu \frac{\omega \sin(\omega t) + 2\nu \cos(\omega t)}{\omega^2 + 4\nu^2} \right] e^{\sigma t} \end{aligned}$$

The perturbative approach yields explicit expressions for $p_\perp$ and $p_\parallel$, showing their time evolution with ωt and growth rate $\sigma = \frac{1}{4} \epsilon^2 \nu \omega^2 / \left(\omega^2 + 4\nu^2 \right)$. Comparing analytical and numerical results (Fig.4), we observe close agreement, except near $\omega t \lesssim 1$, where initial fast time relaxation to $\overline{p}_\perp \approx \overline{p}_\parallel$ influences the results.

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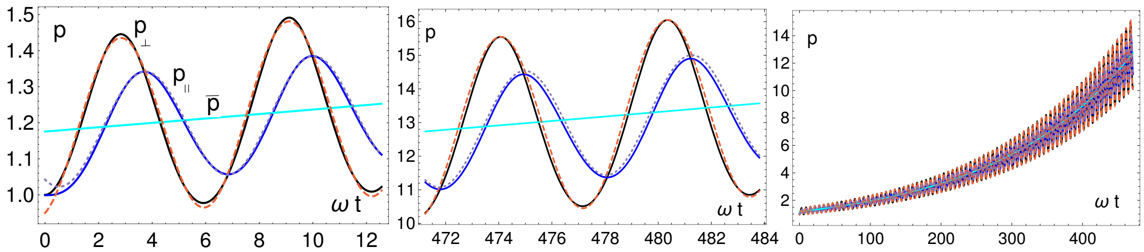

Figure 4: Left and middle panels: numerical (solid lines) and analytical (dashed lines) solutions of magnetic pumping equations, shown at early and late integration periods. Significant deviations are seen only at $\omega t \lesssim 1$, due to the nature of analytic expansion based on averaging (see text). A fast-time averaged value of $p_\perp$ is shown with a cyan line. The right panel shows the complete integration. The model parameters are $\epsilon = 0.3$ and $\nu/\omega = 0.8$. Observe the time lag between $p_\parallel$ and $p_\perp$, underpinning the magnetic pumping mechanism.

The described magnetic pumping mechanism, relying on turbulent perturbations and pitch-angle scattering, contributes to the efficient acceleration of trapped particles in the jet, supplementing our investigation.

5. Conclusions

Our study reveals that cylindrically symmetric jets cannot reaccelerate external cosmic rays (CRs). A *significant* scattering process, which effectively breaks the symmetry, is imperative for enabling the reacceleration. This scattering plays a vital role in particle trapping within the jet and subsequently detrapping from it. Trapped particles can undergo various forms of acceleration while inside the jet. Particularly noteworthy is the efficient magnetic pumping mechanism, which may significantly contribute to UHECR production.

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