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Acceleration of UHECRs in AGN jets and backflows

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The origin of the ultra high energy cosmic rays is still under debate. Although observational data indicate that the arrival direction of UHECRs is coincident with starburst galaxies and Active Galactic Nuclei (AGN), the former do not have enough power to accelerate particles up to ultra high energies. On the other hand, recent theoretical advances indicate that backflows in the termination region of AGN jets can accelerate particles up to the Hillas limit. In addition, the interaction of stars with the AGN jet can serve as an effective mechanism for the jet mass loading; needed to explain the heavy composition of UHECRs as indicated by Pierre Auger data. In the present contribution we review these results and present our future perspectives.

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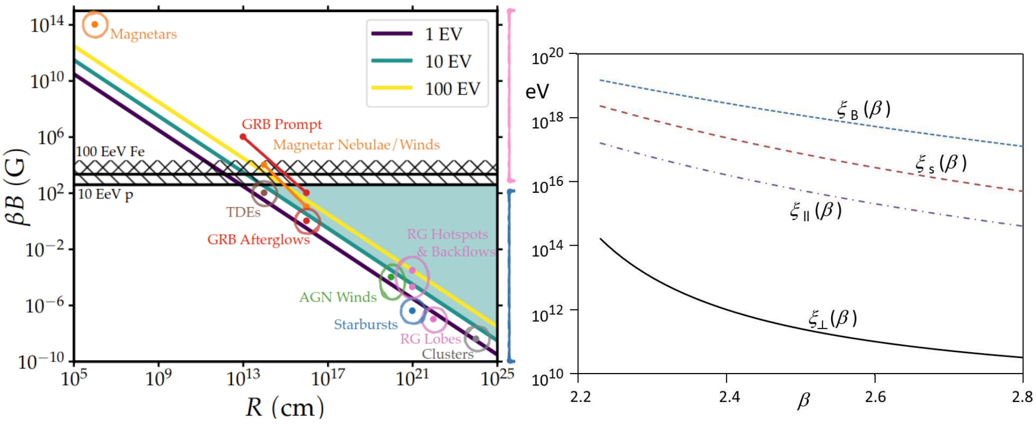

Figure 1

1. Introduction

Ultra High Energy Cosmic Rays (UHECR) are particles having an energy of $\sim 10^{18} - 10^{20}$ eV and arriving on Earth from outside of the Galaxy, but their origin remains unknown. In a plasma with velocity u and magnetic field B the maximum energy that particles with electric charge eZ can achieve is the Hillas energy

$$\frac{E_{\rm Hillas}}{\rm EeV} = 100\, Z \left(\frac{u}{c}\right)\left(\frac{B}{100\mu{\rm G}}\right)\left(\frac{L}{\rm kpc}\right) \tag{1}$$

when they are accelerated by an electric field with magnitude uB over a distance L. For a source with magnetic power $P_{\rm mag} = L^2 u B^2/(8\pi)$ to accelerate a particle up to $E_{\rm Hillas}$ the total source power must be [1, 2]

$$P_{\rm total} > P_{\rm mag} = 10^{44}\left(\frac{E_{\rm Hillas}}{100\,{\rm EeV}}\right)\left(\frac{u}{c}\right)^{-1} {\rm erg\,s^{-1}}. \tag{2}$$

Although starburst galaxies and radiogalaxies are coincident with the hotspots detected by PA and TA, only the later ones satisfy the condition in Eq. (2). In the present contribution we review our latest results on acceleration of UHECRs in radiogalaxies. In Section 2 we show that hotspots in the jet termination region are very poor accelerators, whereas in Section 3 we show that the backflows can accelerate parties up to $0.6E_{\rm Hillas}$.

2. Hotspots

The jet termination region in FR II radiogalaxies is characterized by a double shock structure separated by a contact discontinuity, as it is sketched in the left panel of Fig. 2. Hotspots are the downstream region of the jet reverse shock with velocity $u_{\rm sh}$, where particles accelerated by the shock emit synchrotron radiation. The synchrotron spectrum turnover at frequency $\nu_{\rm c} \sim 10^{14}$ Hz typically observed in the hotspots indicates that the maximum energy of non-thermal electrons is $E_{e,\rm max} \sim 0.1$ TeV when the magnetic field is 0.1 mG. The traditional assumption is that $E_{e,\rm max}$ is determined by synchrotron cooling. We demonstrated that extreme conditions in the jet plasma would be required for this assumption to be true. We conclude therefore that $E_{e,\rm max}$ is not determined by synchrotron cooling, and explore other possibilities.

Steep CR spectrum. Relativistic shocks generate CR energy spectra that are steeper than $\beta = 2$. Consequently, there is less energy in the high energy CR component to drive the turbulence and amplify the magnetic field that scatters the high energy CR and determines the rate at which CR are accelerated. In the generous assumption of energy equipartition between CRs at energy T and the magnetic field amplified by CRs at energy T, and in Bohm diffusion, the maximum energy of paticles determiend by the Lagagge Cesarsky limit is

$$\frac{E_{p,\rm max,Bohm}}{\rm eV} = \xi_{\rm B} \left(\frac{B_{0\perp}}{\mu \rm G}\right)^{-\frac{1}{\beta-2}} \left(\frac{n_{\rm jet}}{10^{-4}\,\rm cm^{-3}}\right)^{\frac{1}{2\beta-4}}, \quad \text{where} \quad \xi_{\rm B} = 10^{\frac{9\beta-22.7}{\beta}}. \tag{3}$$

Small scale turbulence. Because CR do not penetrate far upstream of relativistic shocks and because anisotropy in the CR momentum distribution decays rapidly downstream of the shock, the $\mathbf{j}_{\rm CR} \times \mathbf{B}$ force, where $\mathbf{j}_{\rm CR}$ is the CR electric current, has time to drive turbulence only on scales much smaller than a UHECR Larmor radius and consequently does not effectively scatter UHECR.

$$\frac{E_{p,\rm max,s}}{\rm eV} = \xi_{\rm s} \left(\frac{B_{0\perp}}{\mu \rm G}\right)^{-\frac{1}{\beta-2}} \left(\frac{n_{\rm jet}}{10^{-4}\,\rm cm^{-3}}\right)^{\frac{1}{2\beta-4}}, \quad \text{where} \quad \xi_{\rm s} = 10^{\frac{9\beta+6.24}{\beta-0.8}}. \tag{4}$$

Quasi-perpendicular shocks. CRs are accelerated at a relativistic quasi-perpendicular shock only if CRs are strongly scattered within a distance of one Larmor radius $r_{\rm g0} = E/eB_0$ downstream of the shock. That is, the scattering mean free path immediately downstream of the shock must be $\lambda < r_{\rm g0}$. Since $\lambda = r_{\rm g1}^2/s$, where $r_{\rm g1} = E/eB_1$, the condition $\lambda < r_{\rm g0}$ imposes a requirement of strong magnetic field amplification: $(B_1/B_0)^2 > r_{\rm g0}/s$ which shows that the scale-size s of the turbulence can be smaller than $r_{\rm g0}$ provided the amplified field B_1 is larger than B_0. It means that significant magnetic field amplification is needed during the time $t \sim r_{\rm g0}/c$ in which the plasma advects a distance of $r_{\rm g0}$. This condition for CR acceleration can be written as $\Gamma_{\rm max} t > 5$, where $\Gamma_{\rm max}$ is the maximum growth rate of the Non-Resonant Hybrid instability [3, 4]. The condition $\Gamma_{\rm max} r_{\rm g0}/c > 5$ leads to

$$\frac{E_{p,\rm max\perp}}{\rm eV} = \xi_{\perp} \left(\frac{B_{0\perp}}{\mu \rm G}\right)^{-\frac{1}{\beta-2}} \left(\frac{n_{\rm jet}}{10^{-4}\,\rm cm^{-3}}\right)^{\frac{1}{2\beta-4}}, \quad \text{where} \quad \xi_{\perp} = 10^{\frac{9\beta-16.8}{\beta-2}}. \tag{5}$$

This analysis assumes that $r_{\rm g0}(E_{p,\rm max\perp}) = E_{p,\rm max\perp}/(eB_0) < R_{\rm jet}$. This condition only holds if $B_0 > B_{\rm crit}$, where $B_{\rm crit} = E_{p,\rm max\perp}/eR_{\rm j}$. When $B_0 < B_{\rm crit}$ the shock behaves as quasi-parallel and the time available for magnetic field amplification is therefore $t = R_{\rm jet}/c$. The condition $\Gamma_{\rm max} R_{\rm jet}/c > 5$ leads to a maximum energy

$$\frac{E_{p,\rm max\parallel}}{\rm eV} = \xi_{\parallel} \left(\frac{R_{\rm jet}}{\rm kpc}\right)^{-\frac{1}{\beta-1}} \left(\frac{n_{\rm jet}}{10^{-4}\,\rm cm^{-3}}\right)^{\frac{1}{2\beta-2}}, \quad \text{where} \quad \xi_{\parallel} = 10^{\frac{9\beta+1.1}{\beta-1}}. \tag{6}$$

In the left panel of Fig. 2 we plot $\xi_{\rm B}$, $\xi_{\rm s}$, $\xi_{\parallel}$ and $\xi_{\perp}$. Note that for the fiducial parameters in the termination region of AGN jets, $B_{\rm crit}$ is very low and therefore we expect that the maximum energy of protons is $E_{p,\rm max\perp}$. Electrons are accelerated in the turbulence generated by protons and therefore they behave as test particles. By comparing Eqs. (3) and (11) we can see that $E_{e,\rm max} \leq E_{p,\rm max\perp}$, as expected in the test-particle approximation.

3. Backflows

The diffusion coefficients across and parallel to the magnetic field are $D_\perp = D_{\rm Bohm}/(\omega_{\rm g}\tau_{\rm scat})$ and $D_\parallel = D_{\rm Bohm}(\omega_{\rm g}\tau_{\rm scat})$, respectively, where the scattering time is $\tau_{\rm scat} > 1/\omega_{\rm g}$, and $\omega_{\rm g}$ is the gyro frequency. Note that $D_\parallel D_\perp = D_{\rm Bohm}^2$. The diffusion through the sides of the flux tube is controlled by the product $D_\parallel D_\perp$ which is independent of the strength of the turbulence (represented by $\tau_{\rm scat}\omega_{\rm g}$). In particular, for a single strong shock, the acceleration time is $\tau_{FI} = 20D_\parallel/u_{\rm s}^2$, whereas the diffusion loss timescale from the sides of the flux tube is $\tau_{\rm diff,\perp} \sim l^2/D_\perp$. By equating $\tau_{FI} = \tau_{\rm diff,\perp}$ we obtain $E_{\rm max} = 0.35qu_{\rm s}Bl \sim 0.6E_{\rm Hillas}$, and making acceleration in flux tubes very efficient.

4. Summary and conclusions

References

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