PROCEEDINGS OF SCIENCE

Excitation of the non-resonant streaming instability around sources of Ultra-High Energy Cosmic Rays

Alessandro Cermenati[a,*] **and Roberto Aloisio, Pasquale Blasi, Carmelo Evoli**[a,b]

[a] *Gran Sasso Science Institute,*
Viale Francesco Crispi 7, 67100 L'Aquila AQ, Italy

[b] *INFN/Laboratori Nazionali del Gran Sasso*
via G. Acitelli 22, 67100, Assergi (AQ), Italy

E-mail: alessandro.cermenati@gssi.it, roberto.aloisio@gssi.it, pasquale.blasi@gssi.it, carmelo.evoli@gssi.it

The ultra-high energy cosmic ray sources are most likely extragalactic. For the commonly invoked luminosities of the potential sources, the electric current associated with escape flux of cosmic ray may be very large. The plasma instabilities associated with the cosmic ray streaming create magnetic perturbations that can scatter particles, forcing them to diffuse rather than stream freely, as usually assumed. The non-resonant branch of the streaming instability is excited if the level of the background magnetic field is below its saturation value $B_{sat} \sim 10$ nG, in agreement with actual bounds. We investigate the growth of the instability and its effect on the particle's transport close to the source. We argue that, for typical values assumed for the source parameters, cosmic rays of energy $E \lesssim 10^{17}$ eV are confined in the source proximity, and the cosmic ray spectrum propagating in the Universe is suppressed below this energy.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1131

1. Introduction

Sources of Ultra-High energy cosmic rays (UHECRs), charged particles of extra-galactic origin with energies above $\sim 10^{18}$ eV, are still to be found. The latest results of the Pierre Auger Observatory (AUGER) exclude a pure proton composition above $10^{18.5}$ eV and show that the fraction of heavy nuclei increases with energy [1]. The spectra of extragalactic nuclei are required to be so hard that they might suggest the existence of a low energy cutoff or suppression, either associated to the sources or to propagation effects on cosmological scales [2]. As discussed in [3], a possible source of low energy suppression in the flux of extragalactic CRs may be the self-confinement close to sources, due to the excitation of the non resonant streaming instability (NRSI) in the inter galactic medium (IGM). If the NRSI is efficiently excited, the particle motion becomes diffusive in the source vicinity and low-energy particles are confined within a distance $d \sim 1 - 10$ Mpc for a time longer than the age of the Universe. The excitation of this instability and its growth rate depend to some extent on the strength and structure of the large-scale magnetic field that permeates the Universe. Upper limits on such magnetic field can be inferred using measurements of the Faraday rotation of the light coming from radio-sources [4], [5], [6]. These observations exclude values larger than $\sim$ nG on a correlation scale larger than Mpc. The validity of these estimates with respect to the mass distribution in the Universe is discussed in [7]. Lower limits can be obtained from the non-observation of γ-ray emission at low energies ($\sim 0.1 - 10$ GeV) from sources of TeV gamma rays [8]. The latest results published by the H.E.S.S. and Fermi-LAT collaboration [9] set this limit roughly between 10^{-16} - 10^{-14} G.In this work we investigate under which conditions the Bell instability is excited close to an extra-galactic source of UHECRs, and how the self-induced confinement impacts the spectrum of particles leaving the source. As in [3], we will not speculate upon the origin of the specific sources. We only assume that UHECRs are accelerated by some extra-galactic object and focus on their propagation in the intergalactic space outside the parent galaxy.

2. Model

We consider a source of UHECRs injecting a spectrum $q(E) \propto E^{-2}$ continuously in time into the intergalactic space, assumed to be permeated by a uniform magnetic field with a correlation length $\lambda_B = 10\lambda_{10}$ Mpc. Cosmic rays with Larmor radius smaller than the correlation length of the magnetic field are forced to move spiraling along the field lines, with a drift velocity that we take to be the mean velocity for an isotropic distribution in pitch angle, $v_D = c/2$. The energy of these particles is constrained as follows:

$$E < eB_0\lambda_B \sim 9.25 \times 10^8 \text{ GeV } B_{-10}\lambda_{10}, \tag{1}$$

where e is the elementary charge and B_{-10} is the magnetic field strength in units of 10^{-10} G. The differential density of cosmic rays in the IGM is easily obtained assuming that cosmic rays fill a cylinder of radius $R(E) = max[R_s, R_L(E)]$ and length $v_D t$, being R_s the radius of the source and $R_L(E)$ the Larmor radius of a particle of energy E:

$$n_{CR}(E) = \frac{2q(E)}{\pi R^2(E)c} = \frac{2L_{CR}}{\pi R^2(E)\Lambda c}E^{-2}, \tag{2}$$

where $\Lambda = \ln \frac{E_{max}}{E_{min}}$ and L_{CR} is the source luminosity between E_{min} and E_{max}. The associated current $J_{CR}(> E) = eEn_{CR}v_D$ can give rise to the non-resonant streaming instability if the associated energy flux divided by the speed of light is greater than the magnetic energy density:

$$\frac{EJ_{CR}(> E)}{ec} > \frac{B_0^2}{4\pi}, \tag{3}$$

which is equivalent to requiring that the fastest growing mode k_{max} of the instability is excited at scales smaller than the Larmor radius of the particles which dominate the current, $k_{max}R_L(E) >> 1$, with:

$$k_{max} = \frac{4\pi}{c}\frac{J_{CR}(> E)}{B_0}. \tag{4}$$

This requirement sets an upper limit on the strength of the background magnetic field for which the instability is excited:

$$B_0 < B_{sat} = \sqrt{\frac{4L}{\Lambda R_s^2 c}} \sim 8.4 \times 10^{-9}\ \mathrm{G}\ \frac{L_{44}^{1/2}}{\Lambda_{20} R_{s,Mpc}}. \tag{5}$$

This limit is independent of the energy of particles dominating the current since the source spectrum has been assumed to be $\propto E^{-2}$. If the condition (5) is fulfilled, the instability grows exponentially, with a growth rate that is independent on the seed value of the magnetic field:

$$\gamma_{max} = V_A K_{max} = \frac{1}{\sqrt{4\pi\rho}}\frac{4\pi}{c}J_{CR}(> E), \tag{6}$$

where we made use of the definition of Alfvén speed and ρ is the density of the IGM. Since the unstable modes are initially excited at non-resonant wavelengths, the particle's transport is affected by the instability only if the waves have enough time to raise the level of the magnetic field up to its saturation value (5) and transfer the power injected by the cosmic rays to longer wavelengths. The growth of the instability is possible only if they are not absorbed by the thermal ions in the plasma, namely if their wavelength is larger than the Larmor radius of thermal ions (see [10]).

$$k_{max}\frac{\sqrt{2m_p c^2 k_B T}}{eB_0} < 1, \quad \Rightarrow \quad B_0 > 5.5 \times 10^{-14}\ \mathrm{G}\ \frac{L_{44}^{1/2} T_4^{1/4}}{\Lambda_{20}^{1/2} R_{s,Mpc} E_{min,PeV}^{1/2}}, \tag{7}$$

where k_B is the Boltzmann constant and T_4 the temperature of the IGM in unit of 10^4 K. This limit depends on the energy of the particles dominating the current and is less severe if the minimum energy of the particles reaching a given location is larger. The two conditions (5) and (7) are plotted in figure 1. For reasonable values of the source luminosity, the expected level of the magnetic field in intergalactic space can easily fulfill the requirements for the excitation of the NRSI.

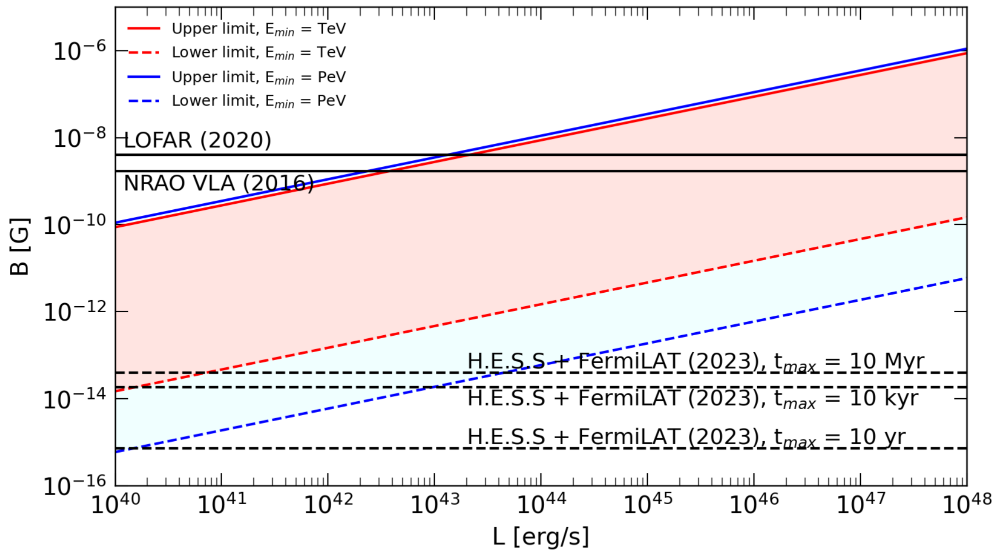

Figure 1: Plot of the magnetic field limits as function of the source luminosity. Upper (solid lines) and lower limits (dotted lines) obtained from (5) and (7) are plotted for E_{min} = 1 TeV (red) and E_{min} = 1 PeV (blue). The shaded area represents the region allowed for the instability to take place. Black lines show actual upper bounds (solid), taken from [4] and [5], and lower bounds (dotted), taken from [9], on the magnetic field in the IGM. The size of the source is fixed at 1 Mpc, the IGM temperature at 10^4 K.

3. Timescales

The growth of the instability happens in very short timescales. Numerical simulations [11] suggest that the saturation of the magnetic field is typically reached after 5 − 10 e-folds, namely $\gamma_{max} t \sim$ 5-10. For the sake of definiteness we assume that the saturation occurs when $t\gamma_{max} = 5$, corresponding to:

$$\tau_{sat}(E) = \frac{5}{\gamma_{max}} \sim 16 \text{ yr } \frac{\rho_b^{1/2} R_{s,Mpc}^2 \Lambda_{20} E_{0,GeV}}{L_{44}}. \quad (8)$$

The non linear evolution of the instability leads to the development of larger perturbations up to the scale corresponding to the Larmor radius of the particles dominating the current: while the instability grows, the Lorentz force due by the cosmic ray current and the amplified magnetic field acts on the plasma to cause a displacement Δx such that $\frac{d^2\Delta x}{dt^2} \sim \frac{J_{CR}\delta B(t)}{\rho c}$, with $\delta B(t) = \delta B_0 \exp(\gamma_{max} t)$. The simple criterion that the saturation of the instability happens when the mean displacement of the plasma equals the Larmor radius of cosmic rays in the amplified field returns an energy independent estimate of the amplified field [3]:

$$\frac{\delta B^2}{4\pi} \sim \frac{E J_{CR}(> E)}{ec}, \quad \Rightarrow \quad \delta B = \sqrt{\frac{4L}{\Lambda R_s^2 c}} \sim 8.4 \times 10^{-9} \text{ G } \frac{L_{44}^{1/2}}{\Lambda_{20}^{1/2} R_{s,Mpc}}, \quad (9)$$

where ρ_b is the IGM baryonic density. After a timescale τ_{sat}, particle's transport becomes heavily affected by the instability. Being the estimate of the amplified field (9) much larger than the original magnetic field and scale independent, it is reasonable to assume that the power injected in magnetic perturbations is equally transferred to all the wavelengths, and particle propagation behaves as diffusive with a Bohm diffusion coefficient. This assumption is also supported by numerical simulations of the NRSI in the strong turbulence regime ($\delta B > B_0$), which found agreement with Bohm diffusion at the resonant energies [12].:

$$D(E) = \frac{c}{3}\frac{E}{e\delta B} \sim 3.7 \times 10^{24} \text{ cm}^2/\text{s} \frac{E_{GeV} R_{s,Mpc}}{L_{44}^{1/2}}. \tag{10}$$

The diffusion coefficient becomes so small that particles get trapped in the source proximity. Particles injected into the IGM later than the corresponding $\tau_{sat}(E)$ drift away from the source with suppressed velocity, due to the low diffusion coefficient they feel in the immediate neighbourhood of the source. Being τ_s the age of the source, the instability has the time to grow up to the energy:

$$E_{sat} \simeq \begin{cases} 6.25 \times 10^7 \text{ GeV } \frac{\tau_{s,Gyr} L_{44}}{\rho_b^{1/2} R_{s,Mpc}^2 \Lambda_{20}} \\ 1.16 \times 10^8 \text{ GeV } \frac{\tau_{s,Gyr}^{1/3} L_{44}^{1/3} B_{-10}^{2/3}}{\rho_b^{1/6} \Lambda_{20}^{1/3}}, \end{cases} \tag{11}$$

which depends non trivially on the source size and the correlation length of the original magnetic field. At energies for which the spread orthogonal to the direction of the magnetic field is dominated by the Larmor radius of particles, the current of cosmic rays drops as E^{-4}, and the saturation time of the instability grows as E^3 (see fig. 2, left).

We consider other two phenomena that affect the particle transport in the IGM: first, as soon as particle scattering becomes efficient, the cosmic ray energy density develops a strong pressure gradient in the direction parallel to the magnetic field, pushing the background plasma and forcing it into motion. Following the same argument as in [13], we assume that an equilibrium state is reached when both the plasma and the bulk of cosmic rays drift at the Alfvén speed in the amplified field:

$$V_A = \frac{\delta B}{\sqrt{4\pi\rho}} \sim 3.7 \times 10^6 \text{ cm/s } \frac{L_{44}^{1/2}}{\Lambda_{20}^{1/2} R_{s,Mpc} \rho_b^{1/2}}. \tag{12}$$

Second, we assume that particles of energy greater than (11) suffer small pitch-angle scattering on the growing waves, feeling a diffusion coefficient $\propto E^2$, motivated by previous results on the parallel diffusion coefficient in the regime $kR_L(E) > 1$, obtained from numerical simulations (see [12] for a more comprehensive treatment). For particles with energy such that the growth time of the instability is larger than the age τ_s of the source, the crossing time of a correlation length is the largest between $\tau_{cr} \sim \lambda_B/c$ and $T_{dif} = \lambda_B^2/D(E)$, with $D(E) \propto E^2$ (transport cannot be superluminal). On the other hand, for particles of energy such that the growth of the perturbations occurs on time scales shorter than τ_s, the crossing time is the shortest between $T_{adv} = \lambda_B/V_A$ and $T_{dif} = \lambda_B^2/D(E)$, where $D(E)$ is now due to the self-generated perturbations (see fig. 2, right). With the reasonable assumption that the effective confinement in the near-source region is realized at low enough energies that transport is either due to advection or diffusion in self-generated perturbations, one can estimate that the confinement time becomes longer than the age of the universe for energies below:

$$E_{cut} \sim 3.8 \times 10^8 \text{ GeV} \frac{L_{44}^{5/12} \lambda_{10} B_{-10}^{1/3}}{R_{s,Mpc}^{1/2} \Lambda_{20}^{5/12} \rho_b^{1/12}}. \tag{13}$$

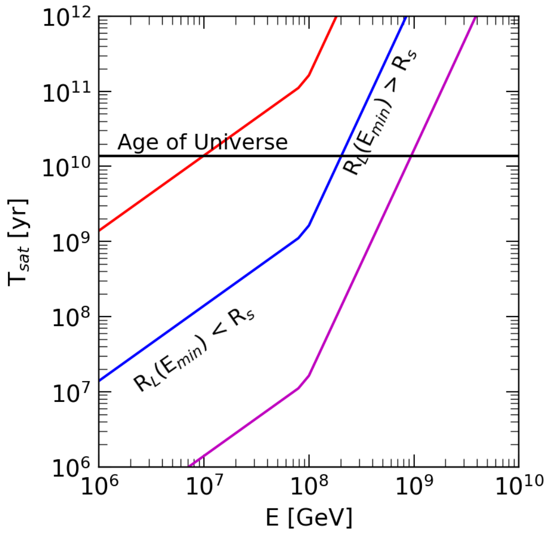

Figure 2: Left panel: saturation time as a function of energy. Right panel: escape time of cosmic rays for a source active for a time comparable with the age of the Universe. Dotted lines show T_{adv}, solid lines the escape time. Different colors refer to different source luminosities: $L = 10^{42}$ erg/s (red), $L = 10^{44}$ erg/s (blue), $L = 10^{46}$ erg/s (purple). Labels refer to the blue lines. The size of the source is taken to be $R_s = 1$ Mpc, the IGMF $B_0 = 10^{-10}$ G, $\lambda_B = 10$ Mpc, and the IGM density is the baryonic critical density $\rho = \rho_b = \rho_{cr}\Omega_b$.

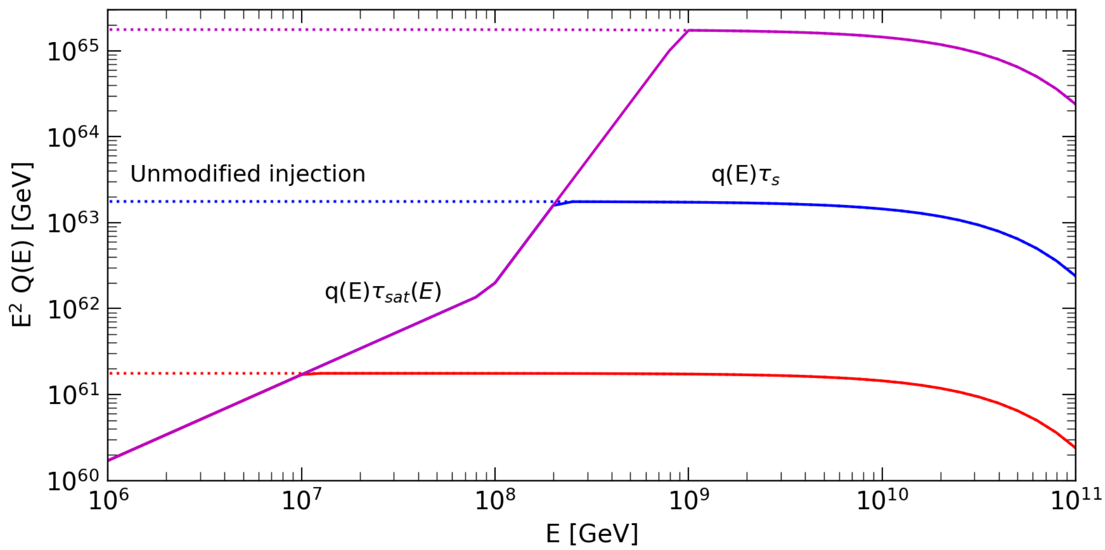

Figure 3: Solid lines represent the injection modified by the NRSI, integrated over the age of the Universe, for a correlation length of the magnetic field $\lambda_B = 10$ Mpc. The size of the source is taken to be $R_s = 1$ Mpc, the initial magnetic field $B_0 = 10^{-10}$ G. Dotted horizontal lines represent the unmodified injection. Red lines refer to $L = 10^{42}$ erg/s, blue lines to $L = 10^{44}$ erg/s, and purple lines to $L = 10^{46}$ erg/s

The reference values we have assumed for the source and IGMF properties lead to the conclusion that particles only escape in small pitch-angle scattering regime.

If the correlation length of the original magnetic field is short enough, cosmic rays are able to escape also in the Bohm diffusion regime, namely for:

$$\lambda_B \lesssim 7 \text{ Mpc } R_{Mpc}^{1/2} B_{-10}^{1/3} L_{44}^{-1/12}. \tag{14}$$

The escape in the advective regime is possible for even shorter λ_B, but the maximum energy of particles that flow into the tube is reduced (eq. (1)), and the instability cannot grow at the energy scale of interest. We emphasize that this phenomenon is led by the cosmic ray current, which is conserved even when the transport changes from ballistic to diffusive (see also [3] and [13]). The flux of cosmic rays that cross a given surface does not change, but their motion is slowed down. We evaluate the total injection of one source, integrated in time, from the conservation of the flux (see fig. 3): particles of energy E escape ballistically for a time $\tau_{sat}(E)$, and the flux that crosses one correlation length of the field is $q(E)$. After the corresponding saturation time, the cosmic rays injected by the source menage to escape the magnetized region only if their escape time $\tau_{esc}(E)$ is smaller than the time left $\tau_s - \tau_{sat}(E)$.

4. Conclusions

We explored the conditions under which the non-resonant streaming instability is excited in the regions surrounding the sources of UHECRs. We found that, for reasonable assumptions on the IGMF and the source luminosity, magnetic field amplification due to the NRSI can take place. The saturation of the instability leads to a net magnetic field in the region around a source of UHECRs (5), and the production of regions where cosmic rays are effectively confined, as first pointed out in [3]. We derived the timescales associated with the developing of the phenomenon and the particle's transport across the magnetized region. The escape time is increased by orders of magnitude, producing a low energy cutoff in the instantaneous flux of cosmic rays leaving the environment. A better modeling of the relation between the evolution of the instability, the type of sources and the circum-source medium is needed to obtain better predictions in terms of observable spectrum, mass composition and production of secondary particles.

References

[1] A. Aab, P. Abreu, M. Aglietta, I.A. Samarai, I. Albuquerque, I. Allekotte et al., *Combined fit of spectrum and composition data as measured by the pierre auger observatory*, *Journal of Cosmology and Astroparticle Physics* **2017** (2017) 038.

[2] R. Aloisio, V. Berezinsky, P. Blasi, A. Gazizov, S. Grigorieva and B. Hnatyk, *A dip in the uhecr spectrum and the transition from galactic to extragalactic cosmic rays*, *Astroparticle Physics* **27** (2007) 76.

[3] P. Blasi, E. Amato and M. D'Angelo, *High-energy cosmic ray self-confinement close to extra-galactic sources*, *Physical Review Letters* **115** (2015) 121101.

[4] M.S. Pshirkov, P.G. Tinyakov and F.R. Urban, *New limits on extragalactic magnetic fields from rotation measures*, *Physical review letters* **116** (2016) 191302.

[5] S. O'Sullivan, M. Brüggen, F. Vazza, E. Carretti, N. Locatelli, C. Stuardi et al., *New constraints on the magnetization of the cosmic web using lofar faraday rotation observations*, *Monthly Notices of the Royal Astronomical Society* **495** (2020) 2607.

[6] A. Arámburo-García, K. Bondarenko, A. Boyarsky, A. Neronov, A. Scaife and A. Sokolenko, *Revision of faraday rotation measure constraints on the primordial magnetic field using the illustristng simulation*, *Monthly Notices of the Royal Astronomical Society* **515** (2022) 5673.

[7] P. Blasi, S. Burles and A.V. Olinto, *Cosmological magnetic field limits in an inhomogeneous universe*, *The Astrophysical Journal* **514** (1999) L79.

[8] A. Elyiv, A. Neronov and D. Semikoz, *Gamma-ray induced cascades and magnetic fields in the intergalactic medium*, *Physical Review D* **80** (2009) 023010.

[9] S. HES, F.-L. Collaborations, F. Aharonian, J. Aschersleben, M. Backes, V. Barbosa Martins et al., *Constraints on the intergalactic magnetic field using fermi-lat and hess blazar observations*, *arXiv e-prints* (2023) arXiv.

[10] E.G. Zweibel and J.E. Everett, *Environments for magnetic field amplification by cosmic rays*, *The Astrophysical Journal* **709** (2010) 1412.

[11] A. Bell, *Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays*, *Monthly Notices of the Royal Astronomical Society* **353** (2004) 550.

[12] A. Marcowith, M. Lemoine and G. Pelletier, *Turbulence and particle acceleration in collisionless supernovae remnant shocks-ii. cosmic-ray transport*, *Astronomy & Astrophysics* **453** (2006) 193.

[13] P. Blasi and E. Amato, *Escape of cosmic rays from the galaxy and effects on the circumgalactic medium*, *Physical Review Letters* **122** (2019) 051101.

PoS(ICRC2023)1131