A&A 677, L14 (2023)
https://doi.org/10.1051/0004-6361/202347554

Astronomy & Astrophysics

Letter to the Editor

The role of supernovae inside AGN jets in UHECR acceleration

V. Bosch-Ramon

Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, 08028 Barcelona, Spain
e-mail: vbosch@fqa.ub.edu

Received 25 July 2023 / Accepted 28 August 2023

ABSTRACT

Context. Jets of active galactic nuclei are potential accelerators of ultra high-energy cosmic rays. Supernovae can occur inside these jets and contribute to cosmic ray acceleration, particularly of heavy nuclei, but that contribution has been hardly investigated so far.
Aims. We carried out a first dedicated exploration of the role of supernovae inside extragalactic jets in the production of ultra high-energy cosmic rays.
Methods. We characterized the energy budget of supernova-jet interactions, and the maximum possible energies of the particles accelerated in those events, likely dominated by heavy nuclei. This allowed us to assess whether these interactions can be potential acceleration sites of ultra high-energy cosmic rays, or at least of their seeds. For that, we estimated the cosmic ray luminosity for different galaxy types, and compared the injection rate of cosmic ray seeds into the jet with that due to galactic cosmic ray entrainment.
Results. Since the supernova is fueled for a long time by the luminosity of the jet, the energy of a supernova-jet interaction can be several orders of magnitude greater than that of an isolated supernova. Thus, despite the low rate of supernovae expected to occur in the jet, they could still provide more seeds for accelerating ultra high-energy particles than cosmic ray entrainment from the host galaxy. Moreover, these interactions can create sufficiently efficient accelerators to be a source of cosmic rays with energies $\gtrsim$10 EeV.
Conclusions. Supernova-jet interactions can contribute significantly to the production of ultra high-energy cosmic rays, either directly by accelerating these particles themselves or indirectly by providing pre-accelerated seeds.

Key words. galaxies: active – galaxies: nuclei – galaxies: jets – supernovae: general – cosmic rays

1. Introduction

For a long time, the jets of active galactic nuclei (AGNe) have been considered possible sources of ultra high-energy cosmic rays (UHECRs; Hillas 1984; see also Rieger 2022; Matthews & Taylor 2023 for recent reviews). In fact, extragalactic radio jets were already viewed as likely sources of cosmic rays (CRs) much before the nature of these structures was well understood (e.g., Burbidge 1962), and in the last decades different jet regions and jet-medium interaction sites have been proposed to be efficient accelerators of UHECRs (e.g., Rachen & Biermann 1993; Romero et al. 1996; Ostrowski 1998; Aharonian et al. 2002; Dermer 2007; Matthews et al. 2019; Rieger 2022; Zirakashvili et al. 2023). Observations hint at starburst galaxies as somewhat more likely UHECR sources than AGN jets (e.g., di Matteo et al. 2023), although there is debate on the former's capability to accelerate nuclei up to those energies (e.g., Anchordoqui 2018; Romero et al. 2018), and both source types may in fact be needed to explain observations in time-dependent scenarios (e.g., Taylor et al. 2023, and references therein).

An important requirement for jets as UHECR accelerators is that the magnetic power of the jet must be sufficient to accelerate and confine ultra high-energy (UHE) charged particles. This power requirement is greatly reduced if the highest energy particles are significantly heavier than H or He (e.g., Lemoine 2009; Rieger 2022). Experimental results seem to indicate that UHECR nuclei are on average rather heavy (around CNO masses) at energies $\gtrsim$10 EeV (e.g., Aab et al. 2014; The Pierre Auger Collaboration 2019). This high metallicity, and the observed spectrum, may require that those UHECRs are accelerated out of a pool of rather heavy nuclei, and with a quite hard spectrum if source variability is not relevant (e.g., Taylor et al. 2015; Abdul Halim et al. 2023). If UHECR acceleration takes place within or around extragalactic jets, large amounts of heavy ions can reach the acceleration sites through winds of evolved stars (e.g., Wykes et al. 2013, 2015, 2018) or supernova (SN) ejecta (e.g., Vieyro et al. 2019; Torres-Albà 2019) inside the jet. Both of these channels are related, but the latter has not been discussed in detail in the context of UHECR production. Diffusive entrainment of heavy high-energy galactic cosmic rays from the host galaxy (GCRs) could be another possibility (e.g., Caprioli 2015; Kimura et al. 2018; Mbarek & Caprioli 2019; Seo et al. 2023). Large particle mean free paths are often needed for efficient acceleration, either to cross the jet-medium shear layer and/or to sample the internal jet velocity structure (e.g., Rieger 2022), so UHECR seeds may have to be quite energetic to engage in processes capable of accelerating them to UHE. For the aforementioned diffusely entrained GCRs, only those able to penetrate deep into the jet could also have the appropriate energies to participate in further acceleration (Caprioli 2015). On the other hand, for matter shed by SNe directly inside the jet, the associated interaction region could be an efficient accelerator itself (e.g., Vieyro et al. 2019; for evolved stars, see, e.g., Barkov et al. 2010; Torres-Albà & Bosch-Ramon 2019), and nuclei accelerated there may already reach UHE, or serve as pre-accelerated seeds for UHECR acceleration elsewhere in the jet (shear layers, shocks, etc.) and its termination region and subsequent backflow shocks (Matthews et al. 2019; Cerutti & Giacinti 2023).

In this work, to better understand the role of SNe occurring inside AGN jets in the production of UHECRs, we carried out a first exploration of these events either as UHECR acceleration sites, or as providers of pre-accelerated seeds. We did not focus on a specific AGN host type, as SNe of different types are expected in different sorts of galaxies. The convention $A_x = (A/10^x \text{ cgs})$ was adopted unless otherwise stated.

2. Supernovae in extragalactic jets

Evolved stars or compact stellar systems cross an extragalactic jet in $\sim r_\mathrm{j}/v_\star \approx 10^6 r_{\mathrm{j,100\,pc}}\, v_{\star,7}^{-1}$ yr, adopting a reference distance $\lesssim$1 kpc from the galactic plane (see below). These objects, unless very close to the base of the jet, should evolve unaffected by it because supersonic winds prevent the jet from reaching them (e.g., Barkov et al. 2010; Khangulyan et al. 2013; Araudo et al. 2013; Perucho et al. 2017). This is particularly true for the regions where most core-collapse (CC) and type Ia SNe take place. On those scales, a B0V-type star with wind mass rates and velocities $\sim 10^{-8}\, M_\odot\,\mathrm{yr}^{-1}$ and $\sim 10^8\,\mathrm{cm\,s}^{-1}$ (Krtička 2014), very conservative for stars close to becoming CC SNe, would create a bow-shaped interaction region at $\sim(3{-}30)\times 10^3\, L_{\mathrm{j},44}^{-1/2}\, R_*$ from the star, where $R_* \approx 10\, R_\odot$ is the stellar radius, L_j the jet power, and $\theta \sim 0.1$ rad the jet half-opening angle. Even for a solar-type wind one gets an interaction distance of $\sim(0.2{-}2)\times 10^2\, L_{\mathrm{j},44}^{-1/2}\, R_\odot$, which is a conservative estimate in type Ia SN single-degenerate progenitors as strong winds are expected from an evolved donor or white dwarf accretion; whereas in the very compact double-degenerate progenitors, jet influence is unlikely (see Liu et al. 2023, and references therein). Thus, both CC and Type Ia SNe should occur inside the jet.

The possibility of SNe exploding inside extragalactic jets have been occasionally considered in the literature (e.g., Blandford & Koenigl 1979; Fedorenko & Courvoisier 1996; Bednarek 1999; Vieyro et al. 2019; Torres-Albà 2019), but its consequences have been very rarely explored in detail. For instance, Vieyro et al. (2019) show that CC SNe, exploding at 50 pc from the jet base in an AGN hosted by a starburst galaxy, could produce detectable high-energy emission from some sources in the local Universe. It is worth noting however that CC SNe inside AGN jets are also expected in late-type hosts with moderate star formation on scales up to hundreds of parsecs from the galactic plane, whereas Type Ia SNe are expected in both late-type and early-type galaxies, with a larger spatial spread of approximately a kiloparsec (e.g., Gebhardt & Thomas 2009; Hakobyan et al. 2017; Cronin et al. 2021). For early-type galaxies, Torres-Albà (2019) propose that type Ia SNe occurring inside the jet could also lead to detectable high-energy radiation. To our knowledge though, the role of jet-ejecta interactions in UHECR production has not been explored so far, with the exception of a brief discussion in Bednarek (1999). Given that CC and type-Ia SN yields are either dominated by oxygen or iron, respectively (see, e.g., Table 2 in Dayal & Ferrara 2018), they could play an important role in explaining the medium-to-heavy composition of UHECRs at $\gtrsim$10 EeV. We note that SN remnants (SNRs) in the galaxy hosting an ANG jet, but located outside the jet, have already been considered to explain the UHECRs, which is a scenario complementary to ours (e.g., Caprioli 2015, if SNRs are behind the highest energy GCR).

In this work, we focus on SNe despite the fact that total mass shed by evolved stars in the jet should surpass that released by SNe (e.g., Hubbard & Blackman 2006). As shown below, the ejecta mass and release time are large and short enough, respectively, so the shocked ejecta can eventually cover the whole jet cross section while producing a relatively coherent interaction structure. This would be hard to achieve by a more gradual mass injection, although a proper assessment requires detailed investigation since the rare and strong mass-loss events that evolved stars can suffer might have similar consequences.

3. Jet-ejecta interaction energetics

For our exploration of the jet-ejecta interaction scenario, we took $L_\mathrm{j} = 10^{44}\,\mathrm{erg\,s}^{-1}$ as the reference value for the jet power because significantly less powerful jets should not be able to accelerate UHECRs to the highest energies (Lemoine 2009). On the other hand, significantly more powerful jets are very rare in the local Universe (see, e.g., Fig. 4 in Mingo et al. 2019), and UHECRs cannot come from significantly beyond 100 Mpc (e.g., Greisen 1966; Zatsepin & Kuz'min 1966). Thus, $L_\mathrm{j} = 10^{44}\,\mathrm{erg\,s}^{-1}$ is a reasonable choice (it incidentally coincides with the FRI/FRII radio galaxy divide; e.g., Perucho 2019, and references therein).

We adopted a simplified SN model with an energy reference value of $E_\mathrm{SN} = 10^{51}$ erg (e.g., Leahy 2017; Leahy & Filipović 2022), mostly in kinetic form, and homologously expanding as a sphere of uniform density and radius R_ej. The mass of the SN ejecta was fixed to $M_\mathrm{ej} = 2\, M_\odot$, in between typical type Ia and average CC SN values (Dayal & Ferrara 2018). The SN ejecta in reality is expected to present a strong density drop beyond a radius with flow velocity $\sim\sqrt{E_\mathrm{SN}/M_\mathrm{ej}}$ (slightly different depending on the SN type; see, e.g., Petruk et al. 2021, and references therein), but in the adopted model of unshocked ejecta the velocity at maximum radius is the following:

$$v_\mathrm{exp} \approx \sqrt{10 E_\mathrm{SN}/3 M_\mathrm{ej}} \approx 9.1\times 10^8\, E_{\mathrm{SN},51}^{1/2} (M_\mathrm{SN}/2\, M_\odot)^{-1/2}\,\mathrm{cm\,s}^{-1}. \quad (1)$$

The SN explosion was assumed to occur in a jet region with radius $r_\mathrm{j} = 0.1$ kpc, which for a jet with $\theta \sim 0.1$ rad implies a distance $z_\mathrm{j} \sim 1$ kpc from the jet base. Nevertheless, the relevant quantity here is r_j because it determines the jet ram pressure in the lab frame P_j, and $z_\mathrm{j} \sim 1$ kpc is useful just as a reference. The jet is expected to be moderately relativistic there (e.g., Mullin & Hardcastle 2009; Perucho et al. 2014; Reddy et al. 2023) since the jet may have endured different sorts of external and internal dissipative processes already (e.g., Perucho 2019), being still supersonic but relatively hot, mass-loaded, and slowed down. Given the uncertainty, for simplicity P_j was taken $\approx L_\mathrm{j}/\pi r_\mathrm{j}^2 c$.

The impact of the jet becomes relevant for the dynamics of the unshocked expanding ejecta when their ram pressures become similar (in the lab frame) at the ejecta side facing the jet. The jet stops the expansion on that side of the SN ejecta when the latter radius is as follows:

$$R_\mathrm{ej}^0 \approx (5 E_\mathrm{SN}/2\pi P_\mathrm{j})^{1/3} \approx 13.4\, E_{\mathrm{SN},51}^{1/3} L_{44}^{-1/3}\,\mathrm{pc}. \quad (2)$$

At this stage, the strong shock driven into the SN ejecta by the jet ram pressure moves with velocity $v_\mathrm{s} \approx v_\mathrm{exp}$ in the lab frame, derived from $\rho_\mathrm{ej} v_\mathrm{s}^2 \approx P_\mathrm{j}$, where ρ_ej is the unshocked ejecta density[1]. Later on, v_s grows because the pre-shock ρ_ej drops due to the unshocked ejecta expansion. The ejecta shock is equivalent to that in SNRs expanding in the interstellar medium, but here it is fueled by the jet impact.

Given that the unshocked ejecta still expands with velocity v_exp, at this stage the actual jet cross section covered by the ejecta grows with time as $\sigma_\mathrm{ej} \propto (R_\mathrm{ej}/R_\mathrm{ej}^0)^2 = (1+\hat{x})^2$, with $\hat{x} = v_\mathrm{exp} t / R_\mathrm{ej}^0$. On the other hand, ρ_ej in the unshocked region

[1] We neglect the velocity distribution of the unshocked ejecta, which should affect the shock speed only in a small fraction of ejecta volume.

homologously falls as $\propto 1/(1+\hat{x})^3$, so $v_s \propto (1+\hat{x})^{3/2}$. Finally, one must account for the expansion of the ejecta in the direction away from the jet-driven shock, increasing its length in that direction as $\propto(2+\hat{x})$. From all of this, the total jet-driven shock luminosity and total energetics are $L_s \sim \sigma_{ej}\rho_{ej}v_s^3/2 \propto (1+\hat{x})^{7/2}$ and $E_s \sim \int_0^{t_{max}}(1/2)\sigma_{ej}\rho_{ej}v_s^3 dt$, respectively, where t_{max} can be derived from $\int_0^{t_{max}} v_s dt \sim 2R_0 + v_{exp}t_{max}$. These equations lead to $\hat{x} \sim 1.5$, $v_s \approx 4\,v_{exp}$, and $E_s \sim 17 E_{SN}$ at $t_{max} \approx 1.5\,R^0_{ej,10\,pc} v^{-1}_{exp,9}$ kyr. Thus, the energy of the jet-driven shock crossing the ejecta is already significantly larger than E_{SN}, but as subsequently shown the whole jet-ejecta interaction energy, part of which may go to UHECR acceleration, may be much higher.

The jet is also shocked when colliding with the ejecta. The energy dissipating in the jet shock while the ejecta is being shocked is $\approx v_j/v_s \approx 10\,v^{-1}_{s,9.5}$ times higher than in the ejecta shock for $v_j \sim c$. The jet composition is in principle much lighter than in the SN ejecta, dominated by jet protons, $e^\pm$, and H and He (mostly) entrained from the jet immediate vicinity. Therefore, the nuclei accelerated by the jet shock might be too light to be behind a heavy UHECR component, although this may not be true because heavy GCR can reach the jet upstream of the shock (as in Caprioli 2015), or ejecta matter can reach the jet shock due to mixing in later stages of the interaction (see below).

The whole jet-ejecta interaction is longer than t_{max}, and strong jet energy dissipation can feed CR production as long as the ejecta material stays in the path of the jet and their relative velocity is high enough (Vieyro et al. 2019). Two possibilities can be realized: (i) The shocked ejecta could be accelerated up to a Lorentz factor $\sim\Gamma_j$, which would potentially involve as much energy as $E_s \sim \Gamma_j M_{ej} c^2 \approx 10^{55}\Gamma_{j,0.5}(M/2\,M_\odot)$ erg. Although a detailed characterization of the whole jet-ejecta interaction needs a thorough numerical investigation, which is left for future work, 2D relativistic hydrodynamic simulations (Vieyro et al. 2019) already show that the SN ejecta eventually covers the whole jet cross section and quickly gets disrupted. Some jet-ejecta mixing can occur. Since the jet is surrounded by a much denser medium, the latter effectively confines the disrupting ejecta, which is still pushed along the jet channel. (ii) The effective acceleration of the SN ejecta may however stop before it gets relativistic if the jet got disrupted as well. In that case, the medium, ejecta, and jet would get temporarily mixed, and the fresh jet material would have to clear its way before recovering a more or less steady configuration. The timescale in the lab frame of the whole process (t_{dyn}) in both (i) and (ii) is $\gtrsim t_{max} + z_j/v_j$, as the ejecta has to expand, accelerate, and/or be pushed aside (see, e.g., Barkov et al. 2012; Khangulyan et al. 2013, for the acceleration phase). Remarkably, even if both the ejecta and the jet became disrupted at the interaction region in (ii), the fresh jet flow could still suffer a strong shock due to a sudden deceleration (Vieyro et al. 2019). Taking $t_{dyn} \sim 10^4$ yr and $L_{j,44} \sim 1$ yields an estimate of the involved energy in (ii) of $E_s \sim t_{dyn}L_j \approx 3\times10^{55} t_{dyn,11.5} L_{j,44}$ erg.

4. CR maximum energy in jet-ejecta interactions

Nuclei accelerated in the jet-ejecta interaction can reach an energy E_{max} and escape the region in a time $<3\times10^4 z_{j,1\,kpc}\,v^{-1}_{j,9.5}$ yr before cooling or disintegrating via synchrotron, γ-meson production, $e^\pm$ creation, and photodisintegration (e.g., Hillas 1984; Matthews & Taylor 2023): given the cross sections of ~0.1−10 mb (synchrotron is negligible; Rachen 1996; Aharonian 2002; Kelner & Aharonian 2008), and adopting a local IR photon density of $n_{IR} \sim 10^3\,L_{IR,44}/z^{-2}_{j,kpc}$ cm^{-3} (also $\sim n_{CMB}$), the cooling and disintegration times are $>10^5$ yr. Assuming diffusive shock acceleration in the Bohm regime, taking reference values for the parameters typical for the ejecta shock, and a lab frame magnetic field $B \propto B_{eq}$ (where $B^2_{eq}/4\pi = P_j$, with $B_{eq} \sim 1\,L_{j,44} r^{-1}_{j,100\,pc}$ mG), one obtains the following:

$$E_{max} \sim 4\,Z_1 R_{ej,10\,pc} v_{s,9.5} (B/B_{eq}) L^{0.5}_{44} r^{-1}_{j,100\,pc}\ \mathrm{EeV}. \quad (3)$$

Adopting $B \sim B_{eq}$ is likely too optimistic, but for typical B values in large-scale jets (e.g., Ito et al. 2021), and given that B can be enhanced in the ejecta and jet shocks, $0.1 \lesssim B/B_{eq} \lesssim 1$ seems plausible. Thus, if efficient acceleration of nuclei occurs in a (mildly) relativistic jet shock, taking $v_s \sim 10^{10}$ cm s^{-1}, $R_{ej} \sim r_j$ (i.e., an expanded ejecta), and an intermediate B strength $\sim0.3\,B_{eq}$, E_{max} can reach $\sim30\,Z_1$ EeV.

We note that even if $v_j \to c$, limitations of acceleration in relativistic shocks may not actually apply (see, e.g., Cerutti & Giacinti 2023; Huang et al. 2023). In particular, in the present context, ≳EeV nuclei may bounce back and forth between the jet upstream and the shocked ejecta (see Bosch-Ramon 2012). This mechanism is similar to that studied in other scenarios (e.g., Bykov et al. 2021; Malkov & Lemoine 2023), and to the espresso mechanism (Caprioli 2015), as all of them allow for a high gain in each shock-crossing and a hard spectrum[2]. As a result of all of this, we conclude that the jet-ejecta interaction is a potential accelerator of UHECRs and, at the very least, can provide the seeds for UHECR production elsewhere in the jet and its surroundings.

5. CR injection rates from jet-ejecta interactions

It is informative to compare the rate of CRs potentially injected directly by SNe inside the jet with that of diffusive entrainment of GCRs. We recall that these processes can occur simultaneously, and do not preclude each other. For this comparison, we assumed co-spatial, uniform, and isotropic distributions of the GCR density and injection rate in a galaxy of radius R_{gal} and (half) height z_{gal}. We considered the following as well: the GCR injection rate proportional to the SN rate $\dot{N}_{SNR}$; galaxy and jet half volumes $V_{gal} \sim \pi R^2_{gal} z_{gal}$ and $V_j \sim \pi r_j^2 z_{gal}$, respectively; and galaxy and jet boundary surfaces for those volumes $S_{gal} \sim \pi R^2_{gal} + 2\pi R_{gal} z_{gal}$ (excluding the galaxy mid plane) and $S_j \sim 2\pi r_j z_{gal}$ (excluding the jet extremes), respectively. We also assumed that GCRs cross the jet-galaxy boundary at the same rate as they cross any other boundary, but we note that the jet-medium shear layer could affect GCR penetration. Finally, taking $z_{gal} = \xi R_{gal}$ and $r_j = \theta z_{gal}$ ($\xi \sim 0.1{-}1$ and $\theta \sim 0.01{-}0.1$ rad may be reasonable values), one can write the following: $V_{gal} \sim \pi\xi^{-2} z^3_{gal}$; $V_j \sim \pi\theta^2 z^3_{gal}$; $S_{gal} \sim \pi\xi^{-2} z^2_{gal} + 2\pi\xi^{-1} z^2_{gal}$; and $S_j \sim 2\pi\theta z^2_{gal}$. These assumptions and characterizations are affected by large uncertainties since the individual galaxy and jet properties are very diverse, and jet GCR entrainment and particle acceleration in jet-ejecta interactions are still poorly understood.

The energy rate with which the jet entrains GCRs is

$$\dot{E}_{GCR} \sim E_{SNR,CR}\dot{N}_{SNR}(S_j/S_{gal}) \propto 2\theta/(\xi^{-2}+2\xi^{-1}) \lesssim \theta\xi, \quad (4)$$

whereas the rate of CR energy injected by SNe within the jet is

$$\dot{E}_{s,CR} \sim E_{s,CR}\dot{N}_{SNR}(V_j/V_{gal}) \propto (\xi\theta)^2, \quad (5)$$

where $E_{SNR,CR}$ and $E_{s,CR}$ are the CR energy released by regular SNRs and jet-ejecta interactions (adding all the stages), respectively. Equation (4) is strictly valid only if GCRs come from

[2] A somewhat similar process expected to operate in more compact regions is the converter mechanism (Derishev et al. 2003; Stern 2003).

SNRs, but even if not SNRs may still be a good proxy to determine $\dot{E}_{\rm GCR}$. Equations (4)–(5) show that for $E_{\rm s,CR}/E_{\rm SNR,CR} > 1/\theta\xi$, SNe in AGN jets can dominate the injection of UHECR seeds over jet-entrained GCRs. As an example, for $\xi \sim 1$ (an elliptical host) and $\theta \sim 0.1$ rad, even ejecta shocks alone (the total $E_{\rm s}$ is in fact far larger) may surpass the entrained GCR contribution to the UHECR seeds.

Taking $t_{\rm dyn} \sim 10^4$ yr and a rate of SNe inside the jet of $t_{\rm SN,j}^{-1} \sim 10^{-3}\dot{N}_{\rm SN,1/century}\xi_{-1}^2\theta_{-1}^2$ century^{-1}, one obtains a percentage of ∼10% of AGN jets hosting some jet-ejecta interaction, with the duty cycle being $D \sim 0.1\, t_{\rm dyn,11.5}t_{\rm SN,j,12.5}^{-1}$. This allows us to derive the maximum luminosity that can go to CRs in these events, that is, $\dot{E}_{\rm s,CR} \lesssim 0.1\, D_{-1}L_{\rm j}$. Caprioli (2015) estimates that AGNe should produce $\gtrsim 10^{-3}$ of their bolometric luminosity in the form of CRs to fulfill the energy requirement to be UHECR sources, and SN-jet interactions appear to be able to fulfill that condition. Predictions for electromagnetic evidence are beyond the scope of this work, but these events may be hard to disentangle from other kiloparsec-scale jet dissipative processes; due to moderate $L_{\rm j}$ values and slow radiative losses, they should be faint neutrino sources.

6. Conclusions

Supernovae exploding inside AGN jets can naturally provide both light and heavy seeds to the processes accelerating UHECRs, which reach Earth with a rather heavy composition above ∼10 EeV. The energy involved in individual jet-ejecta interactions, $E_{\rm s}$, which is an upper-limit to the CR energy produced by them, can be very high. Considering $M_{\rm ej} = 2\,M_\odot$, $L_{\rm j,44} = 1$, and $E_{\rm SN,51} = 1$ as reference, one gets the following: after an initial $t_{\rm max} \sim 1$ kyr, one expects $E_{\rm s} \sim 10^{52}$ erg in the ejecta shock, and $E_{\rm s} \sim 10^{53}$ erg in the jet shock; and after $t_{\rm dyn} \sim 10$ kyr, $E_{\rm s} \sim 10^{55}$ erg, which is associated with the jet pushing on the ejecta during $t_{\rm dyn}$. Assuming a modest duty cycle of $D \sim 0.01$ and $E_{\rm s,CR} \sim 0.1\,E_{\rm s}$, the total time-averaged, CR luminosity per source is $\sim 10^{41}\,L_{\rm j,44}$ erg s^{-1}. The properties of these interactions seem adequate for the acceleration of nuclei with $Z \sim 10$ up to ∼1 EeV initially, and ∼30 EeV in later stages. The luminosities derived for these events could overcome that of jet-entrained GCRs in pre-accelerated seeds for the production of UHECRs inside the jets, and they may even directly contribute to the observed UHECRs significantly. We remark that rare and strong mass loss by evolved stars in the jet could present a similar phenomenology to that of SNe. We finish by noting that powerful and fast winds in non-jetted AGNe (Laha et al. 2021, and references therein) should also host SNe, with a total energy involved in wind-ejecta interactions that may be similar to the jet case.

Acknowledgements. We thank the anonymous referee for constructive and useful comments that really helped to improve the article. We are grateful to A. M. Taylor and D. Khangulyan for their insightful comments on the manuscript. V.B.-R. acknowledges financial support from the State Agency for Research of the Spanish Ministry of Science and Innovation under grants PID2019-105510GB-C31/AEI/10.13039/501100011033/ and PID2022-136828NB-C41/AEI/10.13039/501100011033/, and by "ERDF A way of making Europe" (EU), and through the "Unit of Excellence María de Maeztu 2020-2023" award to the Institute of Cosmos Sciences (CEX2019-000918-M). V.B.-R. is Correspondent Researcher of CONICET, Argentina, at the IAR.

References

Aab, A., Abreu, P., Aglietta, M., et al. 2014, Phys. Rev. D, 90, 122006
Abdul Halim, A., Abreu, P., Aglietta, M., et al. 2023, JCAP, 2023, 024
Aharonian, F. A. 2002, MNRAS, 332, 215
Aharonian, F. A., Belyanin, A. A., Derishev, E. V., Kocharovsky, V. V., & Kocharovsky, V. V. 2002, Phys. Rev. D, 66, 023005
Anchordoqui, L. A. 2018, Phys. Rev. D, 97, 063010
Araudo, A. T., Bosch-Ramon, V., & Romero, G. E. 2013, MNRAS, 436, 3626
Barkov, M. V., Aharonian, F. A., & Bosch-Ramon, V. 2010, ApJ, 724, 1517
Barkov, M. V., Aharonian, F. A., Bogovalov, S. V., Kelner, S. R., & Khangulyan, D. 2012, ApJ, 749, 119
Bednarek, W. Ł. O. 1999, in Plasma Turbulence and Energetic Particles in Astrophysics, eds. M. Ostrowski, & R. Schlickeiser, 360
Blandford, R. D., & Koenigl, A. 1979, Astrophys. Lett., 20, 15
Bosch-Ramon, V. 2012, A&A, 542, A125
Burbidge, G. 1962, Progr. Theor. Phys., 27, 999
Bykov, A. M., Petrov, A. E., Kalyashova, M. E., & Troitsky, S. V. 2021, ApJ, 921, L10
Caprioli, D. 2015, ApJ, 811, L38
Cerutti, B., & Giacinti, G. 2023, A&A, 676, A23
Cronin, S. A., Utomo, D., Leroy, A. K., et al. 2021, ApJ, 923, 86
Dayal, P., & Ferrara, A. 2018, Phys. Rep., 780, 1
Derishev, E. V., Aharonian, F. A., Kocharovsky, V. V., & Kocharovsky, V. V. 2003, Phys. Rev. D, 68, 043003
Dermer, C. D. 2007, arXiv e-prints [arXiv:0711.2804]
di Matteo, A., Anchordoqui, L., Bister, T., et al. 2023, Eur. Phys. J. Web Conf., 283, 03002
Fedorenko, V. N., & Courvoisier, T. J. L. 1996, A&A, 307, 347
Gebhardt, K., & Thomas, J. 2009, ApJ, 700, 1690
Greisen, K. 1966, Phys. Rev. Lett., 16, 748
Hakobyan, A. A., Barkhudaryan, L. V., Karapetyan, A. G., et al. 2017, MNRAS, 471, 1390
Hillas, A. M. 1984, ARA&A, 22, 425
Huang, Z.-Q., Reville, B., Kirk, J. G., & Giacinti, G. 2023, MNRAS, 522, 4955
Hubbard, A., & Blackman, E. G. 2006, MNRAS, 371, 1717
Ito, S., Inoue, Y., & Kataoka, J. 2021, ApJ, 916, 95
Kelner, S. R., & Aharonian, F. A. 2008, Phys. Rev. D, 78, 034013
Khangulyan, D. V., Barkov, M. V., Bosch-Ramon, V., Aharonian, F. A., & Dorodnitsyn, A. V. 2013, ApJ, 774, 113
Kimura, S. S., Murase, K., & Zhang, B. T. 2018, Phys. Rev. D, 97, 023026
Krtička, J. 2014, A&A, 564, A70
Laha, S., Reynolds, C. S., Reeves, J., et al. 2021, Nat. Astron., 5, 13
Leahy, D. A. 2017, ApJ, 837, 36
Leahy, D. A., & Filipović, M. D. 2022, ApJ, 931, 20
Lemoine, M. 2009, Nucl. Phys. B Proc. Suppl., 190, 174
Liu, Z.-W., Röpke, F. K., & Han, Z. 2023, Res. Astron. Astrophys., 23, 082001
Malkov, M., & Lemoine, M. 2023, Phys. Rev. E, 107, 025201
Matthews, J. H., & Taylor, A. M. 2023, arXiv e-prints [arXiv:2301.02682]
Matthews, J. H., Bell, A. R., Blundell, K. M., & Araudo, A. T. 2019, MNRAS, 482, 4303
Mbarek, R., & Caprioli, D. 2019, ApJ, 886, 8
Mingo, B., Croston, J. H., Hardcastle, M. J., et al. 2019, MNRAS, 488, 2701
Mullin, L. M., & Hardcastle, M. J. 2009, MNRAS, 398, 1989
Ostrowski, M. 1998, A&A, 335, 134
Perucho, M. 2019, Galaxies, 7, 70
Perucho, M., Martí, J. M., Laing, R. A., & Hardee, P. E. 2014, MNRAS, 441, 1488
Perucho, M., Bosch-Ramon, V., & Barkov, M. V. 2017, A&A, 606, A40
Petruk, O., Kuzyo, T., Orlando, S., Pohl, M., & Brose, R. 2021, MNRAS, 505, 755
Rachen, J. P. 1996, PhD Thesis, Max-Planck-Institute for Radioastronomy, Bonn
Rachen, J. P., & Biermann, P. L. 1993, A&A, 272, 161
Reddy, K., Georganopoulos, M., Meyer, E. T., Keenan, M., & Kollmann, K. E. 2023, ApJS, 265, 8
Rieger, F. M. 2022, Universe, 8, 607
Romero, G. E., Combi, J. A., Perez Bergliaffa, S. E., & Anchordoqui, L. A. 1996, Astropart. Phys., 5, 279
Romero, G. E., Müller, A. L., & Roth, M. 2018, A&A, 616, A57
Seo, J., Ryu, D., & Kang, H. 2023, ApJ, 944, 199
Stern, B. E. 2003, MNRAS, 345, 590
Taylor, A. M., Ahlers, M., & Hooper, D. 2015, Phys. Rev. D, 92, 063011
Taylor, A. M., Matthews, J. H., & Bell, A. R. 2023, MNRAS, 524, 631
The Pierre Auger Collaboration (Aab, A., et al.) 2019, arXiv e-prints [arXiv:1909.09073]
Torres-Albà, N. 2019, High Energy Phenomena in Relativistic Outflows VII, 5
Torres-Albà, N., & Bosch-Ramon, V. 2019, A&A, 623, A91
Vieyro, F. L., Bosch-Ramon, V., & Torres-Albà, N. 2019, A&A, 622, A175
Wykes, S., Croston, J. H., Hardcastle, M. J., et al. 2013, A&A, 558, A19
Wykes, S., Hardcastle, M. J., Karakas, A. I., & Vink, J. S. 2015, MNRAS, 447, 1001
Wykes, S., Taylor, A. M., Bray, J. D., Hardcastle, M. J., & Hillas, M. 2018, Nucl. Part. Phys. Proc., 297, 234
Zatsepin, G. T., & Kuz'min, V. A. 1966, Sov. J. Exp. Theor. Phys. Lett., 4, 78
Zirakashvili, V. N., Ptuskin, V. S., & Rogovaya, S. I. 2023, MNRAS, 519, L5