On the maximum energy of protons in the hotspots of AGN jets

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INTRODUCTION

Type II Fanaroff-Riley (FR) radiogalaxies exhibit well collimated jets with bright radio synchrotron knots (hotspots) at the termination region, as in Figure 1. Electrons radiating in the hotspot are locally accelerated in the jet reverse shock, and they reach a maximum energy $E_{e,\max}$ inferred from the Infrared (IR)/optical cut-off frequency (ν_c) of the synchrotron spectrum:

$$\frac{E_{e,\max}}{\mathrm{TeV}} \sim 0.8 \left(\frac{\nu_c}{5\times 10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{1}{2}}, \qquad (1)$$

where B is the magnetic field. Ions can also be accelerated in the jet reverse shock. Given that hadronic losses are very slow in low density plasmas such as the termination region of FR II radiogalaxy jets, protons might achieve energies as large as the limit imposed by the size of the system, usually called "Hillas limit" (Hillas 1984). In particular, shocks with velocity $v_{\rm sh} = c/3$ might accelerate particles with Larmor radius $r_{\rm g} \sim R_{\rm j}$, where $R_{\rm j}$ is the jet radius at the termination region. Particles with such a large $r_{\rm g}$ have energy

$$\frac{E_{\rm Hillas}}{\mathrm{EeV}} \sim 100 \left(\frac{v_{\rm sh}}{c/3}\right)\left(\frac{B}{100\,\mu\mathrm{G}}\right)\left(\frac{R_{\rm j}}{\mathrm{kpc}}\right), \qquad (2)$$

as expected for Ultra High Energy Cosmic Rays (UHECRs) Bell et al. (2018) examine the maximum energy to which Cosmic Rays (CR) can be accelerated by relativistic shocks, showing that acceleration of protons to 100 EeV is unlikely.

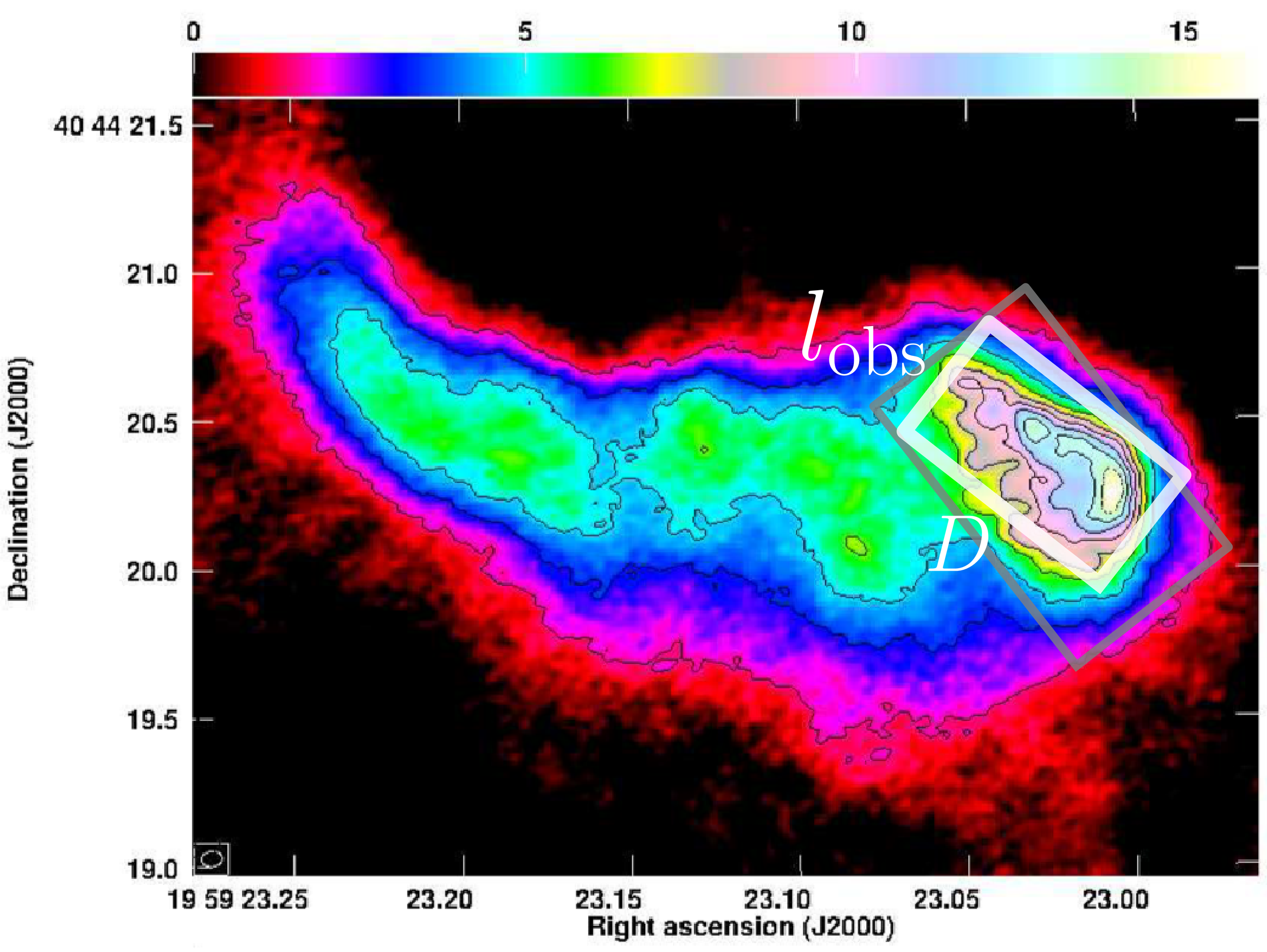

Figure 1: Cygnus A primary hotspot at 43 GHz, adapted from Pyrzas et al. (2015).

REVISING THE REIGNING PARADIGM

It is commonly assumed that $E_{e,\max}$ is determined by synchrotron losses. By equating the synchrotron cooling time with the acceleration timescale $t_{\rm acc} \propto \mathcal{D}/v_{\rm sh}^2$, where the diffusion coefficient is $\mathcal{D} = \lambda c/3$ and λ is the mean-free path, we find that

$$\frac{\mathcal{D}}{\mathcal{D}_{\rm Bohm}} = \frac{\lambda}{r_{\rm g}} \sim 10^7 \left(\frac{v_{\rm sh}}{c/3}\right)^2 \left(\frac{\nu_c}{5\times 10^{14}\,\mathrm{Hz}}\right)^{-1}. \qquad (3)$$

$\mathcal{D}_{\rm Bohm} = r_{\rm g} c/3$ is the Bohm diffusion coefficient and $r_{\rm g} = E_{e,\max}/(eB)$ is the Larmor radius of $E_{e,\max}$-electrons in a turbulent field B. In the small-scale turbulence regime $\lambda = r_{\rm g}^2/s$, where s is the plasma-turbulence scale-length. Therefore, in the "reigning paradigm"

$$s \sim \frac{r_{\rm g}^2}{\lambda} = r_{\rm g}\frac{\mathcal{D}_{\rm Bohm}}{\mathcal{D}} \sim 10^6 \left(\frac{\nu_c}{5\times 10^{14}\,\mathrm{Hz}}\right)^{\frac{3}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{1}{2}} \left(\frac{v_{\rm sh}}{c/3}\right)^{-1} \mathrm{cm}. \qquad (4)$$

Surprisingly, in a jet with density $n_{\rm jet}$, s is smaller than the ion-skin depth $c/\omega_{\rm pi} \sim 10^9 (n_{\rm jet}/10^{-4}\mathrm{cm}^{-3})^{-0.5}$ cm, unless B is smaller than

$$\frac{B_{\max,s}}{\mu\mathrm{G}} \sim 4 \left(\frac{\nu_c}{5\times 10^{14}\,\mathrm{Hz}}\right)\left(\frac{n_{\rm jet}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{\frac{1}{3}}. \qquad (5)$$

The hotspot magnetic field needed to explain the synchrotron flux at 43 GHz in the region indicated by the white rectangle in Figure 1 is $B_{\min} < B < B_{\rm eq}$, where $B_{\rm eq}$ is the magnetic field in equipartition with non-thermal particles, and $B_{\min}$ is obtained by imposing the extreme condition of giving all the jet kinetic energy density to non-thermal electrons (Araudo et al. 2018). We see in Figure 2 (*Left*) that $B_{\min} > B_{\max,s}$ for all possible values of $n_{\rm jet}$, and therefore $E_{e,\max}$ cannot be determined by synchrotron cooling in the primary hotspot of Cygnus A, in disagreement with the standard assumption as was pointed out by Araudo et al. (2016). Note that to reach this conclusion we have only used well resolved radio emission at 43 GHz and the requirement $s > c/\omega_{\rm pi}$.

BELL INSTABILITIES IN PERPENDICULAR SHOCKS

The maximum energy is ultimately constrained by the ability to scatter particles back and forth across the shock. Relativistic shocks are characteristically quasi-perpendicular, i.e. $\mathbf{B}_{\rm j} \perp \mathbf{v}_{\rm sh}$, where $B_{\rm j}$ is the jet magnetic field. To accelerate particles up to an energy $E_{e,\max}$ in perpendicular shocks, the mean-free path in turbulent magnetic field in the shock downstream region, $\lambda_{\rm d} \sim (E_{e,\max}/eB)^2/s$ has to be smaller than Larmor radius $r_{\rm g0}$ in the ordered (and compressed) field $B_{\rm jd} \sim 4B_{\rm j}$ in order to avoid the particles following the $B_{\rm jd}$-helical orbits and cross-field diffusion ceasing (e.g. Kirk & Reville 2010). The condition $\lambda_{\rm d} < r_{\rm g0}$ is marginally satisfied when the magnetic-turbulence scale-length is

$$s_\perp = \frac{E_{e,\max}}{eB}\left(\frac{B_{\rm j}}{B}\right) \sim 2\times 10^{12} \left(\frac{\nu_c}{5\times 10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B_{\rm j}}{\mu\mathrm{G}}\right)\left(\frac{B}{100\mu\mathrm{G}}\right)^{-\frac{5}{2}} \mathrm{cm}. \qquad (6)$$

In Figure 2 (*Right*) we plot $s_\perp$ for $B = B_{\rm eq}$ and $B = B_{\min}$ and fixing $B_{\rm j} = 1\,\mu$G. Note that $s_\perp > c/\omega_{\rm pi}$ indicating that the magnetic field is not generated by the Weibel instability (that has a characteristic scale length of $c/\omega_{\rm pi}$).

Turbulence on a scale greater than $c/\omega_{\rm pi}$ may be excited through the Bell instability, which can grow until s reaches the Larmor radius of the highest energy CR driving the instability (Bell 2004, 2005). The condition for magnetic field amplification by the Bell instability in perpendicular shocks is $\Gamma_{\max} t_\perp > 10$, where $t_\perp = 4r_{\rm g0}/v_{\rm sh}$ is the time during which the plasma flows through a distance $r_{\rm g0}$ in the downstream region at velocity $v_{\rm sh}/4$, and $\Gamma_{\max}$ is the maximum growth rate (e.g. Matthews et al. 2017). The condition $\Gamma_{\max} t_\perp > 10$ leads to a lower limit on the CR acceleration efficiency

$$\eta > \eta_{\min} = 0.057 \left(\frac{v_{\rm sh}}{c/3}\right)^{-1}\left(\frac{B_{\rm j}}{\mu\mathrm{G}}\right)\left(\frac{n_{\rm jet}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-\frac{1}{2}}. \qquad (7)$$

In order to check whether this condition is satisfied in the primary hotspot of Cygnus A, we consider that CRs are accelerated in the jet reverse shock following a power-law energy distribution with the same index as non-thermal electrons, and with the same total energy density ($U_e = U_p$). To satisfy the condition $\eta > \eta_{\min}$ for efficient magnetic field amplification by the Bell instability in a perpendicular shock, the jet (unperturbed) magnetic field has to be

$$\left(\frac{B_{\rm j}}{\mu\mathrm{G}}\right) < 0.24 \left(\frac{n_{\rm jet}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-\frac{1}{2}}\left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.28}. \qquad (8)$$

In such a case, $E_{e,\max}$-CRs have sufficient energy density to generate non-resonant turbulence on scale $s_\perp$ and amplify the magnetic field by a factor $\sim 100-1000$ in the primary hotspot of Cygnus A.

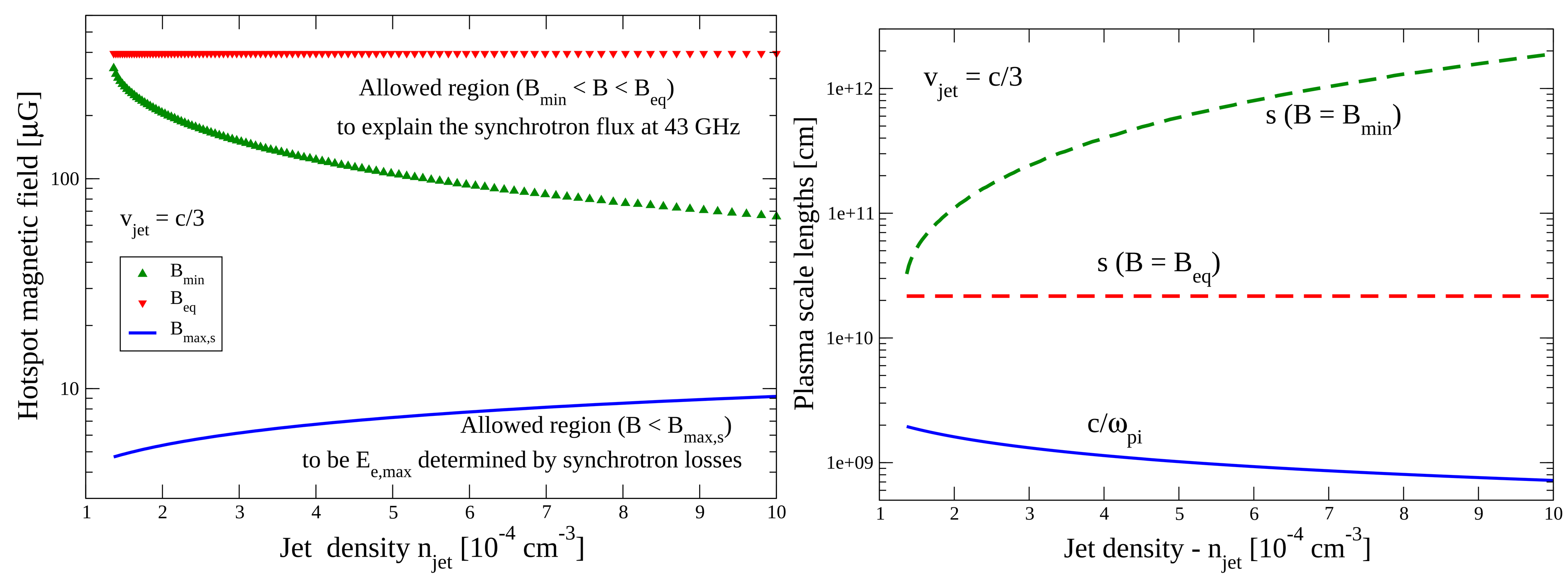

Figure 2: *Left:* Comparison between the magnetic field required to explain the synchrotron flux at 43 GHz ($B_{\min} \leq B \leq B_{\rm eq}$) and the magnetic field required to satisfy the condition $s \leq c/\omega_{\rm pi}$ ($B \leq B_{\max,s}$). *Right:* $s_\perp$ (dashed lines) and ion-skin-depth $c/\omega_{\rm pi}$ (Araudo et al. 2018).

CONCLUSIONS

We conclude that $E_{e,\max}$ is not constrained by synchrotron cooling, as traditionally assumed. The maximum energy $E_{e,\max}$ is ultimately determined by the scattering process. By assuming that the shock is quasi-perpendicular, particles cannot diffuse further than a distance $r_{\rm g0}$ downstream of the shock. To satisfy the condition $\lambda_{\rm d} < r_{\rm g0}$, the magnetic turbulence scale-length has to be $s_\perp \sim 2\times 10^{12}$ cm, that is $\sim 1000\, c/\omega_{\rm pi}$, and therefore B is not amplified by the Weibel turbulence. On the other hand, the Bell instability amplify the magnetic field on scales larger than $c/\omega_{\rm pi}$ and we show that Bell-modes generated by CRs with energies $E_{e,\max}$ can grow fast enough to amplify the jet magnetic field from ∼1 to 100 μG and accelerate particles up to energies $E_{e,\max} \sim 0.8$ TeV observed in the primary hotspot of Cygnus A radiogalaxy. The advantage of magnetic turbulence being generated by CRs current is that B persists over long distances downstream of the shock, and therefore particles accelerated very near the shock can emit synchrotron radiation far downstream.

Finally, if $E_{e,\max}$ is determined by the diffusion condition in a perpendicular shock, the same limit applies to protons and therefore the maximum energy of ions is also ~ 0.8 TeV. As a consequence, relativistic shocks in the termination region of FR II jets are poor cosmic ray accelerators.

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