## Particle Acceleration in Shearing Flows: Efficiencies and Limits

FRANK M. RIEGER<sup>1, 2</sup> AND PETER DUFFY<sup>3</sup>

 <sup>1</sup>ZAH, Institute of Theoretical Astrophysics, University of Heidelberg Philosophenweg 12, 69120 Heidelberg, Germany
 <sup>2</sup>Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
 <sup>3</sup>School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

#### ABSTRACT

We examine limits to the efficiency for particles acceleration in shearing flows, showing that relativistic flow speeds are required for efficient gradual shear acceleration. We estimate maximum achievable particle energies for parameters applicable to relativistic AGN jets. The implications of our estimates is that if large-scale jets are relativistic, then efficient electron acceleration up to several PeV, and proton acceleration up to several EeV energies appears feasible. This suggests that shear particle acceleration could lead to a continued energization of synchrotron X-ray emitting electrons, and be of relevance for the production of ultra-high-energy cosmic-ray particles.

Keywords: Acceleration of particles – galaxies: active – galaxies: active – X-rays – cosmic rays

# 1. INTRODUCTION

Shear flows are expected to be present in various astrophysical environments. Prototypical examples include black-hole accretion flows and the relativistic outflows or jets in gamma-ray bursts and Active Galactic Nuclei (AGN) (Rieger & Duffy 2004). The jets in AGN, for example, are likely to exhibit some internal velocity stratification from the outset, shaped by a highly relativistic, ergo-spheric driven (electron-positron) flow that is surrounded by a slower moving (electron-proton dominated) wind from the inner parts of the disk (e.g., Martí 2019; Fendt 2019, and references therein). As these jets propagate, interactions with the ambient medium is know to excite instabilities and to induce mass loading, enforcing further velocity shearing (e.g., Perucho 2019, and references therein). Radio images of parcec-scale jets in AGN indeed provide phenomenological evidence for internal jet stratification, examples including limb-brightened structures or boundary layers with parallel magnetic fields (e.g., Giroletti et al. 2008; Blasi et al. 2013; Piner & Edwards 2014; Nagai et al. 2014; Gabuzda et al. 2014; Boccardi et al. 2016). When

Corresponding author: Frank M. Rieger f.rieger@uni-heidelberg.de taken together, this suggests that transversal velocity stratification and shear is a generic feature of AGN-type jets. Given the diversity of observed emission properties, this has in recent times generated new interest in multi-zone or spine-shear-layer acceleration and emission models (e.g., Sahayanathan 2009; Laing & Bridle 2014; Tavecchio & Ghisellini 2015; Rieger & Duffy 2016; Liang et al. 2017; Chhotray et al. 2017; Liu et al. 2017; Kimura et al. 2018; Webb et al. 2018).

Shear flows can in principle facilitate particle acceleration by several means (see Rieger 2019, for recent review). One prominent possibility includes a stochastic Fermi-type mechanism, in which particle energization occurs as a result of elastically scattering off differentially moving (magnetic) inhomogeneities (e.g., Berezhko & Krymskii 1981; Earl et al. 1988; Webb 1989; Rieger & Duffy 2006; Lemoine 2019). In gradual shear particle acceleration these inhomogeneities are considered to be frozen into a background flow whose bulk velocity varies smoothly in the transverse direction. The scattering center's speeds are thus essentially characterised by the general bulk flow profile. Given recent developments, the present paper studies the requirements for this mechanism to operate efficiently and discusses the resultant limits on the achievable maximum energies when applied to AGN-type jets.

# 2. PARTICLE SPECTRA

As a stochastic particle acceleration process, the space-independent part of gradual shear acceleration obeys a diffusion equation in momentum space (e.g., Earl et al. 1988; Rieger & Duffy 2006). While moving across the velocity shear the particle momentum relative to the flow changes, so that in the local scattering frame a net increase in momentum can occur. Hence particle acceleration is closely tied to the diffusive transport across the flow. This, however, also implies that particles can diffusively escape from the system, impacting on the shapes of possible particle spectra. This becomes particularly relevant for non-relativistic flow speeds where cross-field escape counterbalances efficient particle acceleration. When diffusive escape and radiative losses are neglected, non-relativistic gradual shear acceleration is known to lead to power-law particle spectra  $n(p) \propto p^2 f(p) \propto p^{-(1+\alpha)}$  for an energetic particle diffusion coefficient scaling as  $\kappa \propto p^{\alpha}$  (Berezhko 1982; Rieger & Duffy 2006). With reference to an analytical steady state model based on the full particle transport equation, Webb et al. (2018, 2019) on the other hand recently showed that such hard power-law spectra are only achieved in relativistic shear flows, while the expected spectra become significantly softer for non-relativistic flow speeds. The present paper aims to explore and recapture this by means of a simple analysis.

Starting point is the standard momentum-space diffusion equation with spatial escape incorporated by means of a simple momentum-dependent particle escape term  $f/\tau_{\rm esc}(p)$ , i.e.,

$$\frac{\partial f}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D_p \frac{\partial f}{\partial p} \right) - \frac{f}{\tau_{\rm esc}} \,. \tag{1}$$

Here,  $D_p$  denotes the momentum-space shear diffusion coefficient given by (Rieger & Duffy 2006)

$$D_p = \Gamma p^2 \tau_s \propto p^{2+\alpha} \,, \tag{2}$$

where  $\tau_s(p)$  is the (momentum-dependent) mean scattering time assumed to follow a parameterization  $\tau_s(p) = \tau_0 (p/p_0)^{\alpha}$ .  $\Gamma$  denotes the shear coefficient. For a simple shear flow velocity profile  $\vec{u} = u_z(r)\vec{e}_z$ , appropriate for a cylindrical outflow, one finds (Rieger & Duffy 2004; Webb et al. 2018)

$$\Gamma = \frac{1}{15} \gamma_b(r)^4 \left(\frac{\partial u_z}{\partial r}\right)^2, \qquad (3)$$

where  $\gamma_b(r) = 1/(1 - u_z^2(r)/c^2)^{1/2}$ . Following eq. (1) the characteristic (co-moving) particle acceleration time scale can be expressed as (e.g., Rieger 2019)

$$t_{\rm acc}(p) = \frac{c}{(4+\alpha)\Gamma\lambda} \propto p^{-\alpha}, \qquad (4)$$

where  $\lambda(p) = \tau_s(p)c$  is the particle mean free path. The typical escape time, on the other hand, is determined by cross-field transport, i.e.

$$\tau_{\rm esc}(p) \simeq \frac{(\Delta r)^2}{2 \kappa(p)} \propto p^{-\alpha} \,, \tag{5}$$

where  $\kappa(p) = \lambda(p)c/3$  is the spatial diffusion coefficient and  $\Delta r$  the width of the velocity shear region. Note that  $t_{\rm acc}$  and  $\tau_{\rm esc}$  have the same momentum-dependence.

The approach in eq. (1) is somewhat analogous to the leaky-box model used to describe cosmic ray transport in the Galaxy, in which spatial diffusion and convection is replaced by an escape term. In such models particles are considered to propagate freely with a small probability  $(1/\tau_{\rm esc})$  of escape each time they reach the boundaries. The probability of a particle remaining in the box then is  $\exp(-t/\tau_{\rm esc})$ , and the particle distribution inside the containment region is uniform.

Looking for steady-state solutions of eq. (1) and employing a power-law Ansatz

$$f(p) = f_0 \, p^{-s}, \tag{6}$$

the power-law index above injection  $p_0$  is given by

$$s = \frac{(3+\alpha)}{2} + \sqrt{\frac{(3+\alpha)^2}{4} + (4+\alpha)\frac{t_{\rm acc}}{\tau_{\rm esc}}} \,.$$
(7)

Consequently, only for  $t_{\rm acc} \ll \tau_{\rm esc}$ , i.e. only for fast shear flows with  $(\partial u_z/\partial r)(\Delta r) \rightarrow c$ , is the power law  $f(p) \propto p^{-(3+\alpha)}$  recovered, in which case the exponent only depends on the momentum dependence of the diffusion coefficient.

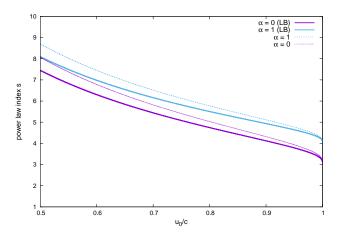
For illustration, consider a linearly decreasing velocity profile  $u_z(r) = u_0 - (\Delta u_z/\Delta r) (r - r_0)$  with  $\Delta u_z/\Delta r = (u_0 - u_2)/(r_2 - r_0)$ , where the subscript 2 refers to quantities at the outer shear boundary, and where for the following we assume  $u_2 = 0$  and  $r_0 = 0$ . Then,  $(\partial u_z/\partial r) = (\Delta u_z/\Delta r)$ , and formally

$$\frac{t_{\rm acc}}{\tau_{\rm esc}} = \frac{10}{(4+\alpha)\gamma_b(r)^4 \left(\frac{\Delta u_z}{c}\right)^2}.$$
(8)

To treat the *r*-dependence in this expression, noting the second-order dependence on the velocity gradient, we replace  $\gamma_b(r)^4$  by  $\langle \gamma_b(r)^2 \rangle^2$ , where  $\langle \rangle$  denotes averaging over *r*. This yields

$$s = \frac{(3+\alpha)}{2} + \sqrt{\frac{(3+\alpha)^2}{4} + 40 \left(\ln\frac{(1+u_0/c)}{(1-u_0/c)}\right)^{-2}}.$$
(9)

The evolution of the power-law index s as a function of  $u_0$  is shown in Fig. 1. Obviously, for non-relativistic flow



**Figure 1.** Power-law index s for the particle distribution  $f(p) \propto p^{-s}$  as a function of the on-axis velocity  $u_0$ . A linearly decreasing velocity profile u(r) with  $u_0$  at  $r_0$  and  $u_2 = 0$  at  $r_2$  has been assumed. The curves show the evolution in the assumed leaky box (LB) approach for a scattering time  $\tau_s \propto p^{\alpha}$  with  $\alpha = 0$  and 1, respectively. For comparison, results of analytical solutions of the full particle transport equation are shown as thin (dotted and dashed) lines.

speeds  $u_0$  the spectra can be much steeper, approaching the limiting value  $s = (3 + \alpha)$  only at relativistic speeds  $u_0 \rightarrow c$ . In Fig. 1 we also show the evolution of the power-law index based on analytical solutions f(r, p)of the full particle transport equation (Webb et al. 2018) for comparison. No one-to-one correspondence is expected, though, as a specific r-dependence of the scattering time  $\tau_s(r, p)$  has been assumed in the derivation of these solutions (typically resulting in  $\tau_s \to \infty$ as  $r \to 0$ , and as the leaky-box approach implies a simplified treatment of spatial diffusion. Nevertheless, the qualitative behaviour is reasonably well reproduced, deviations being at the ~ 10% level. For  $\gamma_b(r_0) = 4$ for example, one obtains s = 3.6 ( $\alpha = 0$ ) and s = 4.5 $(\alpha = 1)$ , respectively. Note, however, that the expected power-law index s is in general sensitive to the employed velocity profile, with steeper shapes towards lower speeds being possible (e.g., Webb et al. 2019). However, this effect becomes less important in the relativistic limit and a detailed analysis is left to a future paper.

The results shown here nicely illustrate that efficient shear acceleration requires relativistic velocity gradients. In principle such velocity gradients appear to be possible in AGN, not only on smaller (sub-parsec) but also on larger (kilo-parsec) jet scales, in particular in view of recent jet simulations showing that backflow speeds in AGN can be substantial (e.g., Perucho & Martí 2007; Rossi et al. 2008; Matthews et al. 2019; Perucho et al. 2019). We note that even for a less powerful FR I jet source such as M87, superluminal motion has been seen on kpc-scales (e.g., Meyer et al. 2017; Snios et al. 2019).

#### 3. MAXIMUM ENERGIES

While experiencing shear acceleration, particles can also lose energy via synchrotron radiation on a characteristic (comoving) timescale  $t_{\rm syn} = \frac{9m^3c^5}{4e^4\gamma B^2}$ . This becomes particularly relevant for electrons. One can estimate achievable maximum energies ( $\gamma_{\rm max}$ ) by equating the acceleration timescale (cf. eq. [4]) with the loss timescale. For simplicity we consider a quasi-linear type parameterisation for the particle mean free path (e.g., Liu et al. 2017) in the following, i.e.

$$\lambda \simeq \xi^{-1} r_g \left(\frac{r_g}{\Lambda_{\max}}\right)^{1-q} \propto \gamma^{2-q} \,, \tag{10}$$

where  $\xi \leq 1$  denotes the energy density ratio of turbulent versus regular magnetic field B,  $\Lambda_{\max}$  is the longest interacting wavelength of the turbulence,  $r_g$  is the particle Larmor radius,  $\gamma$  the particle Lorentz factor, and q is the power index of the turbulence spectrum (i.e., q = 1 for Bohm-, q = 3/2 for Kraichnan-, and q = 5/3 for Kolmogorov-type turbulence). In our notation,  $\alpha = 2 - q$ . Hence, for  $0 < \alpha < 1$  we obtain

$$\gamma_{\max} = \left[\frac{9 \,(4+\alpha) (mc^2)^{3+\alpha} (\Gamma/c^2) \,\Lambda_{\max}^{1-\alpha}}{4 \,\xi \,e^{4+\alpha} B^{2+\alpha}}\right]^{\frac{1}{1-\alpha}} \,, \quad (11)$$

with  $\gamma_{\text{max}}$ ,  $\gamma$  and B measured in the comoving frame. For  $\alpha > 1$ , on the other hand, acceleration, once operative, proceeds faster than synchrotron cooling. For a Kolomogorov-type turbulence ( $\alpha = 1/3$ ) and the linearly decreasing flow profile above with  $\gamma_b(r_0) = 3$ ,  $\xi = 0.2$  and  $\Lambda_{\text{max}} = \Delta r$ , where  $\Delta r$  is the lateral width of the shear layer, eq. (11) evaluates to

$$\gamma_{\rm e,max} \simeq 3.5 \times 10^8 \left(\frac{30 \ \mu \rm G}{B}\right)^{7/2} \left(\frac{0.1 \ \rm kpc}{\Delta r}\right)^2$$
, (12)

suggesting that electron Lorentz factors  $\gamma_e \sim (10^8 - 10^9)$ are in principle achievable in the large-scale jets of AGN. This would provide support to the electron synchrotron interpretation of extended X-ray emission in AGN jets that requires to sustain ultra-relativistic electrons along the jet (e.g., Harris & Krawczynski 2006; Georganopoulos et al. 2016). Note that for a Kraichnantype turbulence ( $\alpha = 1/2$ ), the numerical value, eq. (12), would be reduced by a factor of ~ 20. In principle, due to the inverse dependence of  $t_{\rm acc}$  on  $\gamma$  (eq. [4]) efficient electron acceleration typically requires the injection of energetic seed particles. The latter could, however, most likely be provided by conventional Fermi-type acceleration processes (Liu et al. 2017; Rieger 2019).

On the other hand, given their larger mean free path, shear acceleration of hadronic cosmic rays (CRs) is usually much easier to achieve. This could be of relevance for the origin of the highest energy CRs. Current evidence suggests that the CR composition around  $10^{18}$ eV is dominated by light primaries. Given the observed level of isotropy in arrival directions, these CRs have to be of extragalactic (possibly AGN-type) origin so as to avoid a large anisotropy towards the Galactic Plane. With increasing energy the composition then seems to become more heavier  $(\log(E_t[eV])=18.3 \text{ transi-}$ tion), with a trend that protons are gradually replaced by helium, helium by nitrogen etc, an iron contribution possibly emerging above  $\log(E[eV]) = 19.4$  (e.g., see Alves Batista et al. 2019; Kachelriess & Semikoz 2019, for reviews).

To enable shear acceleration of cosmic-ray protons to energies  $E_t$  in the laboratory frame, corresponding to  $E'_t = E_t / \gamma_b$  in the comoving frame, CR particles need to satisfy (cf., Liu et al. 2017; Webb et al. 2019) (i) the (lateral) confinement condition,  $\lambda(E'_t) \leq \Delta r$ , (ii) the efficiency condition  $t_{\rm acc} \leq t_{\rm syn}$  and (iii) the longitudinal confinement constraint  $t_{\rm acc} \leq t_{\rm dyn} = d/(u_z \gamma_b)$ , where d is the jet length, and  $t_{dyn}, t_{acc}, t_{syn}$  refer to the comoving frame. Figure 2 shows the parameter space (shear layer width  $\Delta r$  versus comoving magnetic field strength B) permitted by these constraints in the case of  $\alpha = 1/3$  for the linearly decreasing shear flow profile above with  $\gamma_b(r_0) = 3$ . A jet shear width-to-length ratio  $\rho_w = \Delta r/d = 0.02$ , and  $\xi = 1$  has been assumed in these calculations. For a magnetic field strength of  $10^{-5}$  G for example, a width  $\stackrel{>}{\sim} 0.1$  kpc would be required. Such conditions are likely to be satisfied in the large-scale jets of AGN. Inspection of Fig. 2 indicates that for a given jet width and magnetic field, the Hillas-type (Hillas 1984) confinement condition (i) usually imposes the tightest constraint on the maximum CR energy. This suggests that CR particles are able to reach

$$E'_{\rm CR} \simeq 3 \times 10^{18} Z \, \xi^{\frac{1}{\alpha}} \left(\frac{B}{30 \, \mu \rm G}\right) \left(\frac{\Delta r}{0.1 \, \rm kpc}\right) \, \rm eV \,, \quad (13)$$

where Z is the charge number. In the case of strong turbulence,  $\xi \sim 1$ , proton acceleration to  $E_t$  appears feasible, with the composition gradually becoming heavier. Note that due to the inverse scaling  $t_{\rm acc} \propto 1/\lambda$  efficient injection may take place at different energy thresholds, and detailed modelling would be required to estimate the relative CR contribution at the highest energies. Pick-up shear acceleration of PeV CR protons (similar to our own Galaxy), however, is possible in the case of

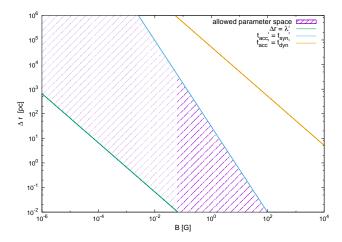


Figure 2. Allowed parameter range (shaded) for shear acceleration of CR protons to energies  $E'_p = 10^{18}$  eV for a particle mean free path  $\lambda' \propto p'^{\alpha}$  with  $\alpha = 1/3$  (corresponding to Kolmogorov type turbulence q = 5/3). A flow Lorentz factor  $\gamma_b(r_0) = 3$  has been assumed.

 $\alpha = 1/3 \text{ as } t_{\rm acc}/t_{\rm dyn} \simeq 2 \times 10^{-3} (100 \text{ kpc}/d)$ . The particle spectrum of cosmic rays escaping the acceleration region approximately follows  $\dot{n}_{\rm esc}(p) \propto p^2 f(p)/\tau_{\rm esc} \propto p^{2+\alpha-s}$ , and can thus be quite hard. We note that the present approach is complementary to the non-gradual ones discussed in Kimura et al. (2018) and Caprioli (2015), which are applicable for sufficiently narrow layers and ultra-fast ( $\gamma_b \sim 30$ ) flow speeds, respectively (e.g., see Rieger 2019, for discussion).

### 4. CONCLUSION

As shown here, fast shear flows can facilitate a continued Fermi-type acceleration of charged particles, capable of producing power law particle momentum distributions as long as the velocity shear persists. In general, however, relativistic flow velocities are required for this mechanism to operate efficiently. As discussed here, such velocities may be encountered in the jets of AGN. Evaluating achievable electron energies (synchrotronlimited to PeV  $[10^{15} \text{ eV}]$  energies) suggest that gradual shear acceleration could offer an interesting explanation for the extended high-energy emission observed in large-scale AGN jets. Similarly, EeV [10<sup>18</sup> eV] energies (confinement-limited) may be achieved for cosmicray protons, indicating that shear acceleration in AGN jets could play a relevant role in the energisation of the observed ultra-high energy cosmic rays. While these estimates are based on a simplified treatment and more extended studies are required, it seems hard to see, how velocity shear could not play a role in the energization of charged particles.

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# REFERENCES

Alves Batista, R., Biteau, J., Bustamante, M., et al. 2019, Frontiers in Astronomy and Space Sciences, 6, 23, doi: 10.3389/fspas.2019.00023 Berezhko, E. G. 1982, Soviet Astronomy Letters, 8, 403 Berezhko, E. G., & Krymskii, G. F. 1981, Soviet Astronomy Letters, 7, 352 Blasi, M. G., Lico, R., Giroletti, M., et al. 2013, A&A, 559, A75, doi: 10.1051/0004-6361/201321858 Boccardi, B., Krichbaum, T. P., Bach, U., et al. 2016, A&A, 585, A33, doi: 10.1051/0004-6361/201526985 Caprioli, D. 2015, ApJL, 811, L38, doi: 10.1088/2041-8205/811/2/L38 Chhotray, A., Nappo, F., Ghisellini, G., et al. 2017, MNRAS, 466, 3544, doi: 10.1093/mnras/stw3002 Earl, J. A., Jokipii, J. R., & Morfill, G. 1988, ApJL, 331, L91, doi: 10.1086/185242 Fendt, C. 2019, Universe, 5, 99, doi: 10.3390/universe5050099 Gabuzda, D. C., Reichstein, A. R., & O'Neill, E. L. 2014, MNRAS, 444, 172, doi: 10.1093/mnras/stu1381 Georganopoulos, M., Meyer, E., & Perlman, E. 2016, Galaxies, 4, 65, doi: 10.3390/galaxies4040065 Giroletti, M., Giovannini, G., Cotton, W. D., et al. 2008, A&A, 488, 905, doi: 10.1051/0004-6361:200809784 Harris, D. E., & Krawczynski, H. 2006, ARA&A, 44, 463, doi: 10.1146/annurev.astro.44.051905.092446 Hillas, A. M. 1984, ARA&A, 22, 425, doi: 10.1146/annurev.aa.22.090184.002233 Kachelriess, M., & Semikoz, D. V. 2019, Progress in Particle and Nuclear Physics, arXiv:1904.08160. https://arxiv.org/abs/1904.08160Kimura, S. S., Murase, K., & Zhang, B. T. 2018, Phys. Rev. D, 97, 023026, doi: 10.1103/PhysRevD.97.023026 Laing, R. A., & Bridle, A. H. 2014, MNRAS, 437, 3405, doi: 10.1093/mnras/stt2138 Lemoine, M. 2019, PhRvD, 99, 083006, doi: 10.1103/PhysRevD.99.083006 Liang, E., Fu, W., & Böttcher, M. 2017, ApJ, 847, 90, doi: 10.3847/1538-4357/aa8772 Liu, R.-Y., Rieger, F. M., & Aharonian, F. A. 2017, ApJ, 842, 39, doi: 10.3847/1538-4357/aa7410

Martí, J.-M. 2019, Galaxies, 7, 24, doi: 10.3390/galaxies7010024 Matthews, J. H., Bell, A. R., Blundell, K. M., & Araudo, A. T. 2019, MNRAS, 482, 4303, doi: 10.1093/mnras/sty2936 Meyer, E., Sparks, W., Georganopoulos, M., et al. 2017, Galaxies, 5, 8, doi: 10.3390/galaxies5010008 Nagai, H., Haga, T., Giovannini, G., et al. 2014, ApJ, 785, 53, doi: 10.1088/0004-637X/785/1/53 Perucho, M. 2019, Galaxies, 7, 70, doi: 10.3390/galaxies7030070 Perucho, M., & Martí, J. M. 2007, MNRAS, 382, 526, doi: 10.1111/j.1365-2966.2007.12454.x Perucho, M., Martí, J.-M., & Quilis, V. 2019, MNRAS, 482, 3718, doi: 10.1093/mnras/sty2912 Piner, B. G., & Edwards, P. G. 2014, ApJ, 797, 25, doi: 10.1088/0004-637X/797/1/25 Rieger, F. M. 2019, Galaxies, 7, 3. https://arxiv.org/abs/1909.07237 Rieger, F. M., & Duffy, P. 2004, ApJ, 617, 155, doi: 10.1086/425167 -. 2006, ApJ, 652, 1044, doi: 10.1086/508056 -. 2016, ApJ, 833, 34, doi: 10.3847/1538-4357/833/1/34 Rossi, P., Mignone, A., Bodo, G., Massaglia, S., & Ferrari, A. 2008, A&A, 488, 795, doi: 10.1051/0004-6361:200809687 Sahayanathan, S. 2009, MNRAS, 398, L49, doi: 10.1111/j.1745-3933.2009.00707.x Snios, B., Nulsen, P. E. J., Kraft, R. P., et al. 2019, ApJ, 879, 8, doi: 10.3847/1538-4357/ab2119 Tavecchio, F., & Ghisellini, G. 2015, MNRAS, 451, 1502, doi: 10.1093/mnras/stv1023 Webb, G. M. 1989, ApJ, 340, 1112, doi: 10.1086/167462 Webb, G. M., Al-Nussirat, S., Mostafavi, P., et al. 2019, ApJ, 881, 123, doi: 10.3847/1538-4357/ab2fca Webb, G. M., Barghouty, A. F., Hu, Q., & le Roux, J. A.

2018, ApJ, 855, 31, doi: 10.3847/1538-4357/aaae6c

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