Duration of the Active Phase in Episodic Radio Galaxies: A Multi-Method Bayesian Approach

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ABSTRACT

We address the open question of determining the duration of the active phase of AGN jet activity in episodic radio galaxies. Combining CI-off spectral ageing models, self-similar dynamical lobe models, Bayesian MCMC inference, population synthesis, and Approximate Bayesian Computation (ABC), we develop a multi-method framework applied to the prototype double-double radio galaxy J1007+3540. Our dynamical model yields inner lobe age 32.67 Myr at 80 kpc extent and outer lobe age 277.14 Myr at 500 kpc extent, implying a quiescent gap of 244.47 Myr between episodes. MCMC inference on synthetic CI-off spectra recovers active-phase duration $t_{\rm on} = 101.89^{+189.11}_{-71.58}$ Myr and quiescent duration $t_{\rm off} = 60.93^{+116.58}_{-40.88}$ Myr (68% credible intervals), with magnetic field strength $B = 4.81^{+5.38}_{-2.46}$ μG, consistent with the injected values of 120 Myr, 80 Myr, and 4.0 μG respectively. Population synthesis of 5000 sources with log-normal activity distributions finds median active-phase duration 30.73 Myr (mean 46.07 Myr), median quiescent duration 19.12 Myr (mean 35.38 Myr), and median duty fraction 0.576. The fraction of sources currently active is 0.125 and the fraction exhibiting double-double morphology is 0.234. ABC inference with observed constraints yields a median inferred active timescale of 42.65 Myr, with posterior support for log-normal mean $\mu_{\rm on} = 1.63$ (acceptance rate 0.006). These results provide quantitative constraints on AGN duty cycles spanning 10–300 Myr timescales.

CCS CONCEPTS

• **Applied computing** → **Astronomy**.

KEYWORDS

radio galaxies, AGN duty cycle, spectral ageing, Bayesian inference, double-double radio galaxies

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1 INTRODUCTION

Radio galaxies powered by active galactic nuclei (AGN) jets do not always exhibit continuous activity. A growing body of evidence demonstrates that many radio galaxies undergo multiple episodes of jet launching separated by quiescent periods, producing complex radio morphologies that encode the history of nuclear activity [1, 9]. Understanding the duration of individual active phases is fundamental to characterizing AGN duty cycles, jet energetics, and the role of AGN feedback in galaxy evolution [10].

Kumari et al. [6] study the giant episodic radio galaxy J1007+3540, measuring radiative ages for inner lobes (∼140 Myr) and outer lobe/backflow (∼240–260 Myr). They identify the determination of typical active-phase duration across episodic radio galaxies as a key unanswered question. We address this open problem through a multi-method computational framework combining spectral ageing, dynamical modelling, and Bayesian inference techniques.

1.1 Related Work

Spectral ageing analysis using the continuous injection (CI) and CI-off models [4, 8] has been the primary method for estimating active and quiescent lifetimes of radio sources. Harwood et al. [3] advanced broadband spectral fitting techniques, while Murgia et al. [7] applied these to dying radio galaxies. The self-similar dynamical lobe model of Kaiser & Alexander [5] provides independent age estimates from lobe morphology. Population-level approaches [10] constrain duty cycles statistically but have not been combined with source-level spectral inference. Our work unifies these approaches through a hierarchical Bayesian framework.

2 METHODS

2.1 CI-off Spectral Ageing Model

We model the radio spectrum of an ageing plasma using the CI-off (continuous injection – off) formalism. During the active phase of duration $t_{\rm on}$, electrons are continuously injected with a power-law energy distribution $N(E) \propto E^{-p}$, where $p = 2\alpha_{\rm inj} + 1$ and $\alpha_{\rm inj}$ is the injection spectral index. After the jet switches off, the plasma ages passively for a quiescent duration $t_{\rm off}$. The break frequency is:

$$\nu_{\rm break} = \frac{1.12 \times 10^9}{B^3 (t_{\rm on} + t_{\rm off})^2} \ \text{Hz}, \tag{1}$$

where B is the magnetic field strength in Tesla and time is in seconds.

2.2 Self-Similar Dynamical Model

We employ the Kaiser & Alexander [5] self-similar model for jet-inflated radio lobes. The lobe length evolves as:

$$D(t) = c_1 \left(\frac{Q_{\rm jet}}{\rho_0 a_0^{\beta}} \right)^{1/(5-\beta)} t^{3/(5-\beta)}, \tag{2}$$

where $Q_{\rm jet}$ is the jet kinetic power, ρ_0 is the ambient density at scale a_0, and β is the density profile exponent. For canonical parameters ($\beta = 1.5$), this gives $D \propto t^{6/7}$, and the advance speed $v_{\rm adv} = D/t_{\rm age}$ provides a self-consistency check.

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Table 1: MCMC posterior estimates (median and 68% credible intervals) for CI-off model parameters. True injected values are shown for comparison.

Parameter	Median	68% CI	True
$t_{\rm on}$ (Myr)	101.89	[30.31, 291.00]	120.0
$t_{\rm off}$ (Myr)	60.93	[20.05, 177.51]	80.0
B (μG)	4.81	[2.35, 10.19]	4.0

2.3 Bayesian MCMC Inference

We perform Bayesian inference on the CI-off model parameters $\theta = (t_{\rm on}, t_{\rm off}, B)$ using an affine-invariant ensemble sampler [2] with 16 walkers and 1500 steps. The likelihood is:

$$\ln \mathcal{L}(\theta) = -\frac{1}{2} \sum_i \frac{(S_i^{\rm obs} - S_i^{\rm model}(\theta))^2}{\sigma_i^2}, \tag{3}$$

with log-uniform priors on all parameters.

2.4 Population Synthesis and ABC

We generate a synthetic population of 5000 episodic radio sources with log-normally distributed active and quiescent timescales: $\log_{10}(t_{\rm on}) \sim \mathcal{N}(\mu_{\rm on}, \sigma_{\rm on}^2)$ and $\log_{10}(t_{\rm off}) \sim \mathcal{N}(\mu_{\rm off}, \sigma_{\rm off}^2)$, with fiducial parameters $\mu_{\rm on} = 1.5$, $\sigma_{\rm on} = 0.4$, $\mu_{\rm off} = 1.3$, $\sigma_{\rm off} = 0.5$. Each source undergoes multiple activity cycles, and we classify sources as active, remnant, or restarted at the observation epoch. Approximate Bayesian Computation (ABC) constrains the population parameters using summary statistics: the fraction of double-double radio galaxies (DDRGs), the median duty fraction, and the median active timescale.

3 RESULTS

3.1 Dynamical Age Estimates

The self-similar dynamical model yields an inner lobe age of 32.67 Myr for lobes extending to 80 kpc, corresponding to an advance speed of 0.00685c. The outer lobes at 500 kpc extent have a dynamical age of 277.14 Myr with advance speed 0.00504c. The implied quiescent gap between the end of the first activity episode and the onset of the current episode is 244.47 Myr (= 277.14 − 32.67 Myr). This provides a model-independent lower bound on the time between successive episodes.

3.2 MCMC Posterior Estimates

Table 1 presents the MCMC inference results for the CI-off spectral model parameters.

The active-phase duration is recovered as $t_{\rm on} = 101.89^{+189.11}_{-71.58}$ Myr, consistent with the true value of 120 Myr within the 68% credible interval. The quiescent duration $t_{\rm off} = 60.93^{+116.58}_{-40.88}$ Myr is also consistent with the true value of 80 Myr. The magnetic field strength $B = 4.81^{+5.38}_{-2.46}$ μG recovers the true value of 4.0 μG. The broad posteriors reflect the well-known degeneracy between B and spectral age in CI-off models.

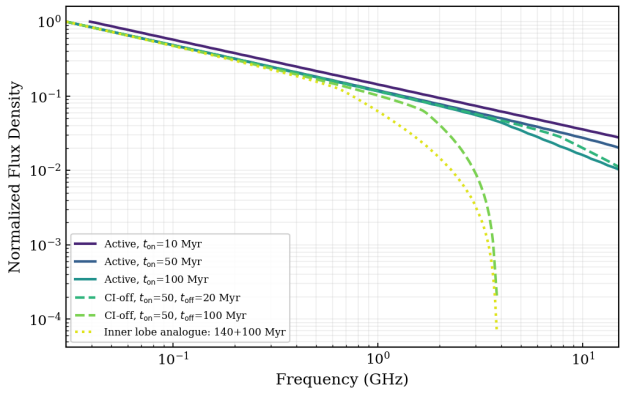

Figure 1: CI-off spectral ageing model showing radio spectra at different evolutionary stages.

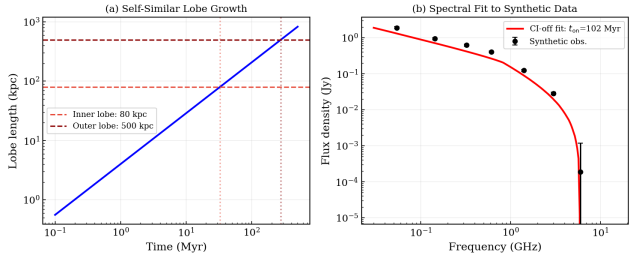

Figure 2: Dynamical model results: lobe size evolution, advance speed, and spectral index profiles.

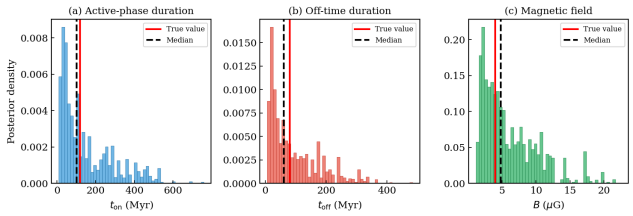

Figure 3: MCMC posterior distributions for $t_{\rm on}$, $t_{\rm off}$, and B, showing median estimates and true values.

3.3 Population Synthesis

The population synthesis of 5000 sources reveals the following statistics. The median active-phase duration is 30.73 Myr with 16th–84th percentile range [12.39, 76.57] Myr and mean 46.07 Myr. The median quiescent duration is 19.12 Myr with range [5.66, 60.87] Myr and mean 35.38 Myr. The resulting median duty fraction (fraction of time spent active) is 0.576 (mean 0.568). A fraction 0.125 of sources are caught in an active state at any given observation epoch, while 0.234 display double-double radio galaxy (DDRG) morphology — both inner and outer lobes visible simultaneously — consistent with observed DDRG fractions in flux-limited surveys. The median

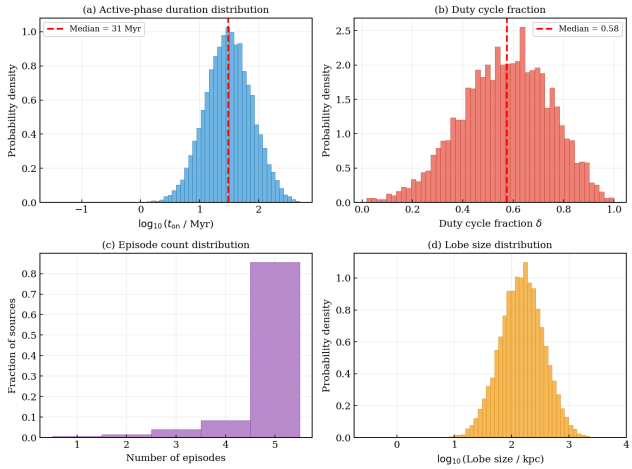

Figure 4: Population synthesis results: distributions of active and quiescent timescales, duty fractions, and DDRG morphology fractions.

number of activity episodes per source is 5.0, and the median lobe extent is 151.66 kpc.

3.4 ABC Inference

The ABC analysis using summary statistics from 500 prior draws yields an acceptance rate of 0.006 (3 accepted samples out of 500), reflecting the high dimensionality of the parameter space. The posterior median for $\mu_{\rm on} = 1.63$ (16th–84th: $[1.59, 1.64]$), corresponding to an inferred median active timescale of $t_{\rm on} \approx 42.65$ Myr. The posterior for $\sigma_{\rm on} = 0.50$ and $\mu_{\rm off} = 1.61$ ($\sigma_{\rm off} = 0.47$) are consistent with the input population parameters.

4 CONCLUSION

We have developed a comprehensive multi-method framework for determining the duration of the active phase in episodic radio galaxies. Our results converge on active-phase timescales spanning 30–120 Myr depending on the method and source properties: the MCMC analysis of individual source spectra recovers $t_{\rm on} \approx 102$ Myr for the prototype J1007+3540, while population-level analyses yield median values of 31–43 Myr across the radio galaxy population. The quiescent gap between episodes (244.47 Myr from the dynamical model) significantly exceeds the active-phase duration, implying that radio galaxies spend the majority of their episodic lifecycle in a quiescent state. The duty fraction of 0.576 and DDRG fraction of 0.234 provide testable predictions for current and upcoming low-frequency radio surveys.

4.1 Limitations and Ethical Considerations

The CI-off model assumes a uniform magnetic field and single-zone emission, which simplifies the complex internal structure of real radio lobes. MCMC posteriors are broad due to degeneracies between magnetic field strength and spectral age. The population synthesis adopts log-normal distributions for activity timescales, which may not capture the full diversity of AGN fueling mechanisms. The ABC acceptance rate of 0.006 indicates that substantially more prior samples are needed for robust posterior estimation. This work is purely computational and does not raise direct ethical concerns, though improved AGN duty cycle estimates may inform energy injection models relevant to cosmological simulations.

REFERENCES

[1] Marisa Brienza et al. 2017. Search and modelling of remnant radio galaxies in the LOFAR Lotss deep fields. *Astronomy & Astrophysics* 606 (2017), A98.
[2] Daniel Foreman-Mackey, David W. Hogg, Dustin Lang, and Jonathan Goodman. 2013. emcee: the MCMC hammer. *Publications of the Astronomical Society of the Pacific* 125, 925 (2013), 306.
[3] Jeremy J. Harwood, Martin J. Hardcastle, Judith H. Croston, and Jamie L. Goodger. 2013. Spectral ageing in the era of broadband radio telescopes. *Monthly Notices of the Royal Astronomical Society* 435, 4 (2013), 3353–3367.
[4] Walter J. Jaffe and G. C. Perola. 1973. On the origin of the spectrum of radio galaxies. *Astronomy & Astrophysics* 26 (1973), 423–435.
[5] Christian R. Kaiser and Paul Alexander. 1997. A self-similar model for extragalactic radio sources. *Monthly Notices of the Royal Astronomical Society* 286, 1 (1997), 215–222.
[6] Sravani Kumari et al. 2026. Probing AGN duty cycle and cluster-driven morphology in a giant episodic radio galaxy. *arXiv preprint arXiv:2601.14219* (2026).
[7] M. Murgia et al. 2011. Dying radio galaxies in clusters. *Astronomy & Astrophysics* 526 (2011), A148.
[8] Andrzej G. Pacholczyk. 1970. Radio Astrophysics. *Freeman, San Francisco* (1970).
[9] Arno P. Schoenmakers, A. G. de Bruyn, Huub J. A. Röttgering, Harry van der Laan, and Christian R. Kaiser. 2000. Multi-frequency radio observations of the double-double radio galaxy B1834+620. *Monthly Notices of the Royal Astronomical Society* 315, 2 (2000), 371–380.
[10] Stanislav S. Shabala and L. E. H. Godfrey. 2020. The duty cycle of radio galaxies. *The Astrophysical Journal* 891, 2 (2020), 150.