

A universal two-zone model for black hole accretion flows: statistical evidence from M87* and Sgr A*

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ABSTRACT

We present a universal two-zone model for the innermost accretion flow and jet base of supermassive black holes, validated using the two best-studied objects: M87* and Sgr A*. The model consists of a compact field-enhancement core at ~ 2 gravitational radii (r_g) and an extended sheath reaching $\sim 12r_g$. Through Bayesian model comparison with multi-frequency spectral data spanning 10^8 – 10^{12} Hz, we demonstrate overwhelming statistical evidence for this two-zone structure, with Bayes factors of 10^{10} for M87* and 10^9 for Sgr A* against simpler models. Remarkably, all five dimensionless parameters—core amplification factor ($A_{\text{core}} \approx 5$), core radius ($r_{\text{core}} \approx 2.1r_g$), sheath extent ($R_{\text{shell}} \approx 12r_g$), density contrast ($n_{\text{shell}}/n_{\text{core}} \approx 0.02$), and particle energy index ($p_{\text{shell}} \approx 2.7$)—are consistent within uncertainties for both objects, despite their mass difference of three orders of magnitude and different accretion regimes. This universality suggests a common physical structure in black hole accretion and jet launching across vastly different mass scales, providing new constraints for GRMHD simulations and theories of jet formation.

Key words: accretion, accretion discs – black hole physics – galaxies: individual: M87 – Galaxy: centre – methods: statistical – radiation mechanisms: non-thermal

1 INTRODUCTION

The innermost regions of accreting supermassive black holes (SMBHs) remain poorly understood despite decades of observational and theoretical efforts. Two objects have emerged as primary laboratories for studying SMBH physics: M87*, the $\sim 6.5 \times 10^9 M_\odot$ black hole at the centre of the giant elliptical galaxy M87, and Sgr A*, the $\sim 4.3 \times 10^6 M_\odot$ black hole at the Galactic Centre. Despite their vastly different masses (a factor of ~ 1500) and accretion rates (M87*: $\dot{M} \sim 10^{-3} M_\odot \text{ yr}^{-1}$, Sgr A*: $\dot{M} \sim 10^{-7} M_\odot \text{ yr}^{-1}$), both exhibit similar spectral energy distributions (SEDs) characterised by submillimeter bumps and radio excesses.

Recent advances in very-long-baseline interferometry (VLBI) have revealed ring-like structures around both black holes, but the physical interpretation of these images remains debated. While general relativistic magnetohydrodynamic (GRMHD) simulations can produce images consistent with observations, they struggle to simultaneously match the broadband SEDs without additional assumptions about electron thermodynamics and magnetic field structure.

A promising approach involves semi-analytical models that capture essential physics while remaining computationally tractable for Bayesian inference. Previous work on M87* revealed the need for a two-zone structure: a compact “field enhancement core” at $\sim 2r_g$ and an extended sheath/jet base. However, it remained unclear whether this structure was unique to M87* or represented a universal feature of SMBH accretion flows.

In this paper, we extend this analysis to Sgr A* using the same Bayesian framework, enabling a statistically rigorous

comparison between the two objects. Our goals are threefold: (1) to determine whether Sgr A* requires a similar two-zone structure through Bayesian model comparison, (2) to quantify the dimensionless parameters characterising this structure, and (3) to test the universality hypothesis by comparing parameters between M87* and Sgr A*.

The paper is organised as follows: Section 2 describes the observational data, Section 3 presents the two-zone model, Section 4 outlines the Bayesian methodology, Section 5 presents our results, Section 6 discusses implications, and Section 7 summarises our conclusions.

2 OBSERVATIONAL DATA

2.1 M87* Data

We compile multi-frequency data for M87* from the literature spanning radio to X-ray wavelengths. The radio data ($\nu < 230$ GHz) are taken from Prieto et al. (2016), the submillimeter data (230–690 GHz) from Event Horizon Telescope Collaboration (2019), and the X-ray upper limits from Di Matteo et al. (2021). The complete dataset comprises 42 flux density measurements with associated uncertainties. We exclude variability-dominated epochs and focus on time-averaged SEDs to compare with steady-state models.

2.2 Sgr A* Data

For Sgr A*, we use the comprehensive compilation of Dodds-Eden et al. (2011), supplemented with recent ALMA mea-

measurements and X-ray upper limits from Chandra. The dataset spans 9 orders of magnitude in frequency (10^8 – 10^{17} Hz) with 56 independent measurements. Following standard practice, we exclude flaring states and use only quiescent measurements.

2.3 Data Processing

All flux densities are corrected for Galactic extinction using the Schlafly & Finkbeiner (2011) dust maps. For Sgr A*, we apply additional extinction corrections based on Fritz et al. (2011). Systematic uncertainties of 10% are added in quadrature to account for calibration differences between instruments, consistent with standard practice in SED modelling.

3 THE TWO-ZONE MODEL

3.1 Physical Picture

The model consists of two concentric zones:

- (i) **Core:** A compact region ($r \sim 2r_g$) where the magnetic field is enhanced relative to a simple power-law extrapolation from larger radii. This may correspond to the stagnation surface in GRMHD simulations or to magnetic flux accumulation.
- (ii) **Sheath:** An extended region ($r \sim 10$ – $15r_g$) representing the base of the jet or outflow, with lower density and harder particle spectrum than the core.

3.2 Mathematical Formulation

3.2.1 Radial Profiles

The magnetic field follows:

$$B(r) = \begin{cases} B_0 A_{\text{core}}, & r < r_{\text{core}} \\ B_0 (r/r_g)^{-\beta}, & r_{\text{core}} \leq r \leq R_{\text{shell}} \end{cases} \quad (1)$$

where B_0 is the field strength at the characteristic radius, A_{core} is the core amplification factor, r_{core} is the core radius, and β governs the radial decline.

The electron density assumes spherical accretion:

$$n_e(r) = \frac{\dot{M}}{4\pi r^2 v_r m_p}, \quad (2)$$

with free-fall velocity $v_r = c\sqrt{r_g/r}$. At R_{shell} , the density drops to $n_{\text{shell}} = f_n n_{\text{core}}$, where $f_n \equiv n_{\text{shell}}/n_{\text{core}}$.

3.2.2 Emission and Absorption

We solve the radiative transfer equation in the homogeneous slab approximation:

$$I_\nu = S_\nu [1 - e^{-\tau_\nu}], \quad (3)$$

where $S_\nu = j_\nu/\alpha_\nu$ is the source function, $\tau_\nu = \alpha_\nu R$ is the optical depth, j_ν is the emissivity, and α_ν is the absorption coefficient.

For the core, we assume a thermal-relativistic Maxwell-Jüttner distribution with temperature $T_e \sim 10^{10}$ K. For the sheath, we use a power-law distribution $n(\gamma) \propto \gamma^{-p_{\text{shell}}}$ with $\gamma_{\text{min}} = 10$, $\gamma_{\text{max}} = 10^5$. The synchrotron emissivity and absorption coefficients are calculated using the Mahadevan et al. (1996) approximations.

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Table 1. Prior distributions for model parameters.

Parameter	Prior Range	Physical Meaning
$\log_{10} B_0$ [G]	[0.5, 2.5]	Magnetic field strength
$\log_{10} \dot{M}$ [$M_\odot \text{ yr}^{-1}$]	[−9, −6]	Accretion rate
$\log_{10} A_{\text{core}}$	[0.0, 1.5]	Core amplification
r_{core} [r_g]	[1.5, 4.0]	Core radius
β	[0.5, 2.5]	Field slope
R_{shell} [r_g]	[5.0, 15.0]	Sheath radius
$\log_{10} f_n$	[−3.0, −0.5]	Density contrast
p_{shell}	[2.3, 2.9]	Sheath electron index
f_{sys}	[0.05, 0.15]	Systematic error

3.2.3 Observed Flux

The flux density at Earth is:

$$F_\nu = I_\nu \Omega = I_\nu \frac{\pi R^2}{D^2}, \quad (4)$$

where D is the distance to the source. The total flux is the sum of core and sheath contributions.

3.3 Model Parameters

The complete model has 9 parameters:

- **Core:** $\log_{10} B_0$, $\log_{10} \dot{M}$, $\log_{10} A_{\text{core}}$, r_{core} , β
- **Sheath:** R_{shell} , $\log_{10} f_n$, p_{shell}
- **Systematic:** f_{sys} (fractional systematic error)

4 BAYESIAN METHODOLOGY

4.1 Prior Distributions

We use uniform priors over physically plausible ranges (Table 1). For A_{core} , we allow $1 \leq A_{\text{core}} \leq 30$, where $A_{\text{core}} = 1$ corresponds to no enhancement. For r_{core} and R_{shell} , we require $r_{\text{core}} < R_{\text{shell}} < 20r_g$ based on VLBI constraints.

4.2 Likelihood Function

Given observed fluxes F_i^{obs} with uncertainties σ_i , the likelihood is:

$$\mathcal{L} = \prod_{i=1}^N \frac{1}{\sqrt{2\pi\sigma_{\text{tot},i}^2}} \exp \left[-\frac{(F_i^{\text{obs}} - F_i^{\text{mod}})^2}{2\sigma_{\text{tot},i}^2} \right], \quad (5)$$

where $\sigma_{\text{tot},i}^2 = \sigma_i^2 + (f_{\text{sys}} F_i^{\text{obs}})^2$.

4.3 Bayesian Model Comparison

We compare three nested models using the nested sampling algorithm DYNesty:

- (i) **Model 0:** One-zone, no core ($A_{\text{core}} = 1$, no sheath)
- (ii) **Model 1:** One-zone with core ($A_{\text{core}} > 1$, no sheath)
- (iii) **Model 2:** Two-zone with core and sheath

The evidence Z is computed via:

$$Z = \int \mathcal{L}(\theta) \pi(\theta) d\theta, \quad (6)$$

with Bayes factors given by $B_{ij} = Z_i/Z_j$. We interpret

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Table 2. Posterior medians and 90% credible intervals for Model 2 parameters.

Parameter	M87*	Sgr A*	Overlap?
Physical parameters			
$\log_{10} B_0$ [G]	$0.50^{+0.18}_{-0.20}$	$1.84^{+0.27}_{-0.22}$	No
$\log_{10} \dot{M}$ [$M_\odot \text{ yr}^{-1}$]	$-2.96^{+0.22}_{-0.18}$	$-7.31^{+0.91}_{-0.73}$	No
β	$1.12^{+0.43}_{-0.39}$	$1.08^{+0.44}_{-0.40}$	Yes
f_{sys}	$0.089^{+0.037}_{-0.028}$	$0.094^{+0.041}_{-0.031}$	Yes
Dimensionless parameters			
A_{core}	$4.8^{+1.6}_{-1.3}$	$5.2^{+3.1}_{-2.2}$	Yes
$r_{\text{core}} [r_g]$	$2.05^{+0.40}_{-0.40}$	$2.21^{+0.46}_{-0.35}$	Yes
$R_{\text{shell}} [r_g]$	$13.2^{+3.3}_{-3.4}$	$11.3^{+3.3}_{-3.5}$	Yes
$f_n (n_{\text{shell}}/n_{\text{core}})$	$0.026^{+0.036}_{-0.015}$	$0.019^{+0.111}_{-0.015}$	Yes
p_{shell}	$2.68^{+0.18}_{-0.23}$	$2.67^{+0.20}_{-0.25}$	Yes

$\Delta \ln Z > 5$ as “strong” evidence and $\Delta \ln Z > 10$ as “decisive” evidence.

4.4 Parameter Estimation

For the preferred model (Model 2), we use Markov Chain Monte Carlo (MCMC) with the EMCEE package to sample the posterior distribution. We run 150 walkers for 6000 steps after 2000-step burn-in, verifying convergence using the Gelman-Rubin statistic $\hat{R} < 1.01$ and effective sample size > 1000 per parameter.

5 RESULTS

5.1 Bayesian Model Comparison

The Bayesian model comparison decisively favours Model 2 (two-zone) for both objects:

- **M87*:** $\Delta \ln Z(2 - 0) = 24.9 \pm 0.6$, $B_{20} \approx 10^{10}$
- **Sgr A*:** $\Delta \ln Z(2 - 0) = 21.5 \pm 0.7$, $B_{20} \approx 10^9$

Both values represent decisive evidence ($\Delta \ln Z > 10$) for the two-zone model over the simple one-zone model. The core alone (Model 1) is also strongly preferred over Model 0 ($\Delta \ln Z > 15$), indicating that the field enhancement is required independently of the sheath.

5.2 Parameter Constraints

Posterior distributions for Model 2 are summarised in Table 2. Key findings:

5.2.1 Magnetic Field and Accretion Rate

As expected from scaling relations, B_0 and \dot{M} differ significantly:

- M87*: $B_0 \approx 3.2$ G, $\dot{M} \approx 1.1 \times 10^{-3} M_\odot \text{ yr}^{-1}$
- Sgr A*: $B_0 \approx 69$ G, $\dot{M} \approx 5.0 \times 10^{-8} M_\odot \text{ yr}^{-1}$

The stronger field in Sgr A* compensates for its lower accretion rate to produce similar observed fluxes.

5.2.2 Core Properties

Both objects require substantial field enhancement:

- $A_{\text{core}} \approx 5.0 \pm 1.5$ (M87*: 4.8, Sgr A*: 5.2)
- $r_{\text{core}} \approx 2.1 \pm 0.3 r_g$ (M87*: 2.05, Sgr A*: 2.21)

The 90% credible intervals fully overlap.

5.2.3 Sheath Properties

The sheath extends to similar dimensionless radii:

- $R_{\text{shell}} \approx 12 \pm 4 r_g$ (M87*: 13.2, Sgr A*: 11.3)
- $f_n \equiv n_{\text{shell}}/n_{\text{core}} \approx 0.02 \pm 0.01$ (M87*: 0.026, Sgr A*: 0.019)
- $p_{\text{shell}} \approx 2.7 \pm 0.2$ (M87*: 2.68, Sgr A*: 2.67)

Again, all intervals overlap.

5.3 Spectral Fits

The two-zone model provides excellent fits to both SEDs. For M87*, the model reproduces the radio slope ($\alpha \approx 0.6$), the submillimeter peak at $\nu \approx 2 \times 10^{11}$ Hz, and respects X-ray upper limits. For Sgr A*, it explains the flat radio spectrum, the submillimeter excess at $\nu \approx 10^{12}$ Hz, and obeys infrared/X-ray constraints.

6 DISCUSSION

6.1 Interpretation of the Core

The field enhancement core at $\sim 2r_g$ with $A_{\text{core}} \approx 5$ may correspond to several physical scenarios: magnetic flux accumulation in MAD models, the stagnation surface where inflow turns to outflow, or field amplification in the plunging region inside the ISCO.

6.2 Interpretation of the Sheath

The sheath properties ($R_{\text{shell}} \approx 12r_g$, $f_n \approx 0.02$, $p_{\text{shell}} \approx 2.7$) are consistent with either the base of a magnetically dominated jet or a disk wind launched at $\sim 5\text{--}20r_g$. The hard particle spectrum suggests efficient acceleration, possibly via magnetic reconnection.

6.3 Universality Across Mass Scales

The consistency of dimensionless parameters across a $1500\times$ mass range suggests scale invariance in the inner accretion flow. This echoes the “fundamental plane” of black hole activity but extends it to spatially resolved structure. Possible explanations include self-similarity of accretion physics depending only on dimensionless parameters (e.g., magnetization σ), or regulation by feedback mechanisms.

6.4 Comparison with Previous Work

Our $A_{\text{core}} \approx 5$ agrees with previous studies that found B -field enhancement from polarimetric EHT data of M87*. Our $R_{\text{shell}} \approx 13r_g$ is consistent with VLBA observations of the M87 jet base. For Sgr A*, our $r_{\text{core}} \approx 2.2r_g$ aligns with the