Postprint: Active Galactic Nucleus Jet Model for the Sgr A Lobes at the Galactic Center

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Abstract

The Sgr A lobes in the Galactic Center are a pair of bubble structures perpendicular to the Galactic disk and symmetric about the Galactic Center, with a height of approximately 15 pc. X-ray observations indicate that these bubbles possess well-defined boundaries and were likely formed by a shock wave from some energetic outburst phenomenon sweeping through the gas medium near the Galactic Center. Outflows generated by activity of the Galactic Center black hole constitute a viable mechanism for the formation of these bubbles; consequently, the formation history of these bubbles holds significant importance for understanding the evolution of the Galactic Center and high-energy astrophysical processes. Through hydrodynamic simulations, we investigate a model in which short-timescale active galactic nucleus (AGN) jets act as the cause of the bubbles. Numerical simulation results demonstrate that a jet lasting 500 years can satisfactorily reproduce the morphology, density, temperature, X-ray emission, and other properties of these bubbles. Based on current results, alternative bubble formation models cannot be ruled out, such as the outflow model produced by tidal disruption events. Future multi-wavelength observations will be capable of imposing more stringent constraints on the cause of the bubbles.

Full Text

Preamble

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An AGN Jet Model for the Sgr A Lobes at the Galactic Center

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Abstract

The Sgr A lobes are a pair of bubble-like structures perpendicular to the Galactic plane and symmetric about the Galactic center, with a height of approximately 15 pc. X-ray observations reveal that these bubbles have sharp boundaries, likely formed by shocks from an energetic explosion sweeping through the gas medium near the Galactic center. Outflows produced by activity of the central supermassive black hole represent a viable mechanism for bubble formation, making the formation history of these structures crucial for understanding the evolution and high-energy astrophysical processes at the Galactic center. We investigate a model where short-timescale active galactic nucleus (AGN) jets produce these bubbles through hydrodynamic simulations. Our numerical results demonstrate that a single jet episode lasting 500 years can satisfactorily reproduce the observed morphology, density, temperature, and X-ray emission properties of the bubbles. However, based on current results, we cannot exclude alternative formation models, such as outflows from tidal disruption events. Future multi-wavelength observations will provide more stringent constraints on the bubble origin.

Keywords: active galactic nucleus; jets and outflows; bubbles; interstellar medium

1 Introduction

Multiple lines of observational evidence indicate the presence of a supermassive black hole of approximately $4\times10^6 M_\odot$ at the Galactic center (Sgr A*) [**?**, **?**]. The evolution of supermassive black holes involves numerous extreme high-energy physical processes, likely including outflow phenomena that inject substantial mass and energy into their surroundings. Although recent observations suggest that Sgr A* currently resides in a relatively quiescent state, its past active phases may have significantly influenced the gas distribution in the Galaxy across various temporal and spatial scales. A prominent example is the Fermi Bubbles, which extend to heights of approximately 10 kpc and may have formed from AGN-driven outflows propagating through the Galactic circumgalactic medium millions of years ago [**?**].

On smaller spatial scales, recent X-ray and radio observations have discovered a pair of 15 pc-tall elliptical bubbles [**?**], commonly referred to as the Sgr A lobes.

Both Chandra and XMM-Newton telescopes have detected X-ray emission from hot gas within these bubbles, revealing temperatures of $0.7 \sim 1.0$ keV [?]. The X-ray surface brightness and thermal pressure of the bubble gas decrease with Galactic latitude, indicating that the outflowing gas is moving away from the Galactic plane. The bubbles exhibit remarkably sharp boundaries, suggesting they are enclosed by shocks generated by an outflow. Their orientation perpendicular to the Galactic plane and symmetry about the Galactic center further implicate outflows from the immediate vicinity of the central black hole as a plausible formation mechanism.

Potential outflow phenomena capable of producing such bubble structures fall into two categories: quasi-steady outflows, including stellar winds from stars near the Galactic center black hole and past AGN jets; and intermittent explosive events, including tidal disruption events (TDEs) of the central black hole and supernova explosions of individual stars in the Galactic center region [?]. Hydrodynamic simulations of supernova explosions in the Galactic center environment have provided some analysis [?, ?]. While a single supernova can inject sufficient energy to create a \$ \$15 pc bubble, the near-spherical symmetry of supernova energy injection makes it difficult to explain the highly symmetric, dual-lobed morphology of the Sgr A lobes, even when constrained by other stellar winds or gas disks. Since the timescale for stellar wind presence in the Galactic center far exceeds the age of the Sgr A lobes, models involving continuous energy injection from stellar winds also face challenges. TDEs can generate powerful winds and/or jets, injecting enough energy in a short period to form the Sgr A lobes, making them a viable formation mechanism [?]. However, no specific studies have yet examined an AGN jet model for these bubbles. Therefore, we investigate a model where shocks from jets launched by the Galactic center black hole produce the bubbles, similar to models proposed for the Fermi Bubbles [?].

X-ray observations indicate that the internal energy of the Sgr A lobes is on the order of 10^{43} J [?, ?]. The exact outflow velocity remains unknown, preventing precise age determination, but assuming bubble growth at the sound speed $c_s \approx 500$ km s^{-1} yields an age of approximately 3×10^4 years [?], providing an upper limit for model parameter constraints. Theoretical studies typically find AGN jet durations on million-year timescales, yet explaining the Sgr A lobes requires only a few hundred years—substantially shorter than conventional values. Recent observational evidence, however, suggests that AGNs can indeed produce short-timescale, low-energy jet phenomena [?]. X-ray observations of molecular clouds toward the Galactic center indicate that X-ray photons from these clouds may originate from the black hole region, reaching Earth after reflection off molecular clouds. This implies that the Galactic center black hole may have experienced a high-activity phase recently, with X-ray luminosity variability timescales far shorter than a million years [?, ?]. X-ray observations have also identified jet structure candidates near the Galactic center black hole [?, ?]. These observational lines of evidence collectively suggest that AGNs can produce the short-duration jets required by our model.

Another consideration for the AGN jet model' s viability is the fueling of the accretion disk. The numerous Wolf-Rayet stars in the Galactic center region represent a potential mass source. These stars undergo phases of extremely strong stellar winds lasting typically 10^5 years. Studies of Wolf-Rayet stellar winds suggest they could have played important roles in past activities of the Galactic center black hole and influenced the hot gas distribution within the central parsec [**?**]. Additionally, supermassive black holes can capture material from molecular clouds or massive stars to form accretion disks. In this work, we assume such an accretion disk exists without delving into the specific mass supply mechanisms.

We employ hydrodynamic numerical simulations to investigate the evolution of short-timescale AGN jets in the Galactic center environment and assess whether they can serve as the formation mechanism for the Sgr A lobes. We compare simulated bubble properties with observations, including temperature, density, morphology, and X-ray surface brightness distribution. Section 2 describes our numerical simulation setup, Section 3 compares simulation results with observations, and Section 4 summarizes and discusses issues related to the AGN jet model.

2.1 Simulation Setup

We assume axisymmetry for our simulation system and solve the hydrodynamic equations in two-dimensional spherical coordinates using the ZEUS-MP code [**?**]:

$$\begin{cases} \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0 \\ \frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla\cdot(\rho\mathbf{v}\mathbf{v}) = -\nabla P - \rho\nabla\Phi + \nabla\cdot\mathbf{T} \\ \frac{\partial e}{\partial t} + \nabla\cdot(e\mathbf{v}) = -P\nabla\cdot\mathbf{v} + \Gamma - \Lambda \end{cases}$$

where ρ, $\mathbf{v}$, P, Φ, e, and t represent density, velocity, pressure, gravitational potential, internal energy density, and time, respectively. Since the Sgr A lobes are oriented perpendicular to the Galactic plane and symmetric about the Galactic center, we assume the AGN jet injection is symmetric about the Galactic rotation axis. Given the density and temperature ranges of hot gas in the Galactic center and bubble regions, the radiative cooling timescale far exceeds the bubble age, so we neglect the radiative cooling term in the energy equation. We further assume all gas behaves as an ideal gas satisfying $P = k_B T\rho/(\mu m_u) = k_B T n$, where k_B is the Boltzmann constant, m_u is the atomic mass unit, $\mu = 0.61$ is the mean molecular weight per particle, and T and n represent gas temperature and number density, respectively.

We construct 600 exponentially growing grids in the r-direction and 400 uniform grids in the θ-direction. In the r-direction, we place the Galactic center black hole Sgr A* at the coordinate origin, with an inner boundary at 0.1 pc and an outer boundary at 30 pc, where $\Delta r_{i+1}/\Delta r_i = 1.007$, meaning each radial grid width is 0.7% larger than the previous one. During jet injection, we implement inflow boundary conditions at the inner radial boundary, switching to outflow conditions (matching the outer boundary) after jet cessation. Due to system symmetry, we simulate only one side of the jet evolution, setting the θ-direction grid from $0^\circ \sim 90^\circ$ with reflective boundary conditions at both boundaries.

2.2 Gravitational Potential and Initial Gas Distribution

Observations indicate the Sgr A lobes have a height of approximately 15 pc. Within 20 pc of the black hole, the gravitational potential is dominated by the black hole itself and the nuclear stellar cluster, so we adopt a constant gravitational field composed of these two components. For the black hole potential, we use the Newtonian gravitational field produced by a point mass of $M_{\rm BH} = 4 \times 10^6 M_\odot$. For the nuclear stellar cluster, we employ the potential model from reference [**?**]:

$$\Phi = \frac{1}{2} v_0^2 \ln\left(R_c^2 + r^2\right)$$

where $v_0 = 98.6$ km s^{-1}, $R_c = 2$ pc, and r denotes the radial coordinate.

In the Galactic center environment, pre-existing diffuse gas and material from stellar winds in the nuclear cluster collectively constitute the circumnuclear medium (CNM) assumed to exist before jet injection. Current observations cannot constrain the CNM distribution prior to bubble formation. For simplicity, we assume this medium was in hydrostatic equilibrium before jet injection, with density following an exponential distribution:

$$n(r) = n_0 \left(\frac{r}{r_0}\right)^{-0.7}$$

where $n_0 = 50$ cm^{-3} and $r_0 = 0.1$ pc. When solving for hydrostatic equilibrium, we assume a gas temperature of 5×10^6 K at $r = 50$ pc. This density distribution and the resulting temperature distribution are consistent with X-ray observations and Wolf-Rayet wind simulations in the region within 1 pc [**?**, **?**, **?**]. We note that the exponent in equation (2) lacks strong observational constraints; the initial density distribution directly affects the simulated bubble density and radiation intensity, consequently altering the required jet parameters. In the $0.1 \sim 1.0$ pc range, steady-state solutions assuming Wolf-Rayet stellar winds yield an exponent of approximately -2. We adopt -0.7 in this work to ensure the simulated bubble gas density matches observational values, representing a weak constraint on the gas density in our simulation region. If we retained the -2 exponent, the bubble density would be significantly lower than observed, and its radiation would correspondingly fall well below observational values. Therefore, we select the parameter combination in equation (2) such that the hot gas density matches observational or wind-solution values in the inner region while providing sufficient material beyond 1 pc to yield bubble densities and radiation comparable to observations. More stringent constraints on the initial density and temperature distribution require further investigation.

2.3 Jet Configuration

We implement jet injection using the inflow boundary condition in ZEUS-MP. During the jet duration, we set the inner radial boundary condition to inflow and specify jet density, energy density, and velocity in virtual grid cells within the jet half-opening angle. After jet cessation, we switch the inner boundary condition to outflow.

In our primary AGN simulation, we assume the jet direction is perpendicular to the Galactic plane. While black hole jets are related to black hole spin, the spin orientation of the Galactic center black hole remains uncertain, which may pose a challenge for the AGN jet model. We set the jet duration to 500 years and the jet half-opening angle to 10°. Within the $0^\circ \sim 10^\circ$ grid region, we specify jet material density $\rho = 5 \times 10^{-24}$ g cm^{-3}, temperature 10^8 K, and constant radial velocity 1.1×10^{10} cm s^{-1}. These jet parameters are chosen primarily to satisfy the observed properties of the Sgr A lobes. Under this configuration, the total jet mass is $4 \times 10^{-3} M_\odot$ and the total energy is 4.8×10^{43} J.

3.1 Bubble Evolution

Figure 1 [Figure 1: see original paper] shows the density and temperature distributions during the early and middle simulation stages. Following jet injection, a distinct shock surface forms, with its outer boundary corresponding to the bubble boundary in our simulation. During the jet injection period, the jet material undergoes multiple episodes of backflow, creating several recollimation shocks. At $t = 600$ years, the shock height in the z-direction exceeds 10 pc, and the shock surface exhibits a slightly wider base with an overall elongated shape, consistent with most jet simulation results. Without subsequent energy injection, the jet material velocity decreases substantially, gradually concentrating at the shock apex, while continuous backflow persists toward the bubble base. By $t = 1500$ years, a complex low-density region appears in the lower bubble portion, formed by multiple intricate backflow episodes. Although the shock surface height increases only modestly during this period, the proportion of energy allocated to lateral expansion grows because jet material accumulates at the apex accompanied by backflow and thermalization. Consequently, the shock surface width increases noticeably, and the overall morphology gradually approaches the elliptical shape observed for the Sgr A lobes.

When the jet evolution reaches $t = 3500$ years, the shock surface attains a height of 15 pc, and the overall morphology closely resembles the observed bubble shape. Figure 2 [Figure 2: see original paper] displays the density and temperature distributions at this epoch. The high-density region at the bubble' s outer boundary represents a dense shell formed by shock-compressed CNM gas, while the bubble interior develops a hot, low-density cavity. Some differences remain between the simulated bubble outline and actual observations, likely arising from uncertainties in jet parameters, as the shock surface width depends on multiple factors. For instance, our parameter survey reveals that jets with greater mass and lower velocity decelerate and thermalize at higher altitudes, producing enhanced backflow that broadens the shock surface. Studies of large-scale AGN jets also demonstrate that variations in jet power can alter shock surface widths [**?**].

3.2 Comparison with X-Ray Observations

In this section, we calculate the thermal X-ray emission from our simulated bubbles and compare the resulting X-ray surface brightness with observational values to assess the viability of the AGN jet model. We assume the hot gas in our simulations is optically thin and in collisional ionization equilibrium, using the Astrophysical Plasma Emission Code (APEC) to retrieve X-ray emission coefficients for plasma in the $2 \sim 4.5$ keV energy range [**?**]. The X-ray surface brightness is calculated as:

$$I(x,z) = \int n_e n_H \epsilon(T,Z)\,dy$$

where n_e and n_H are electron and hydrogen ion number densities, respectively, and ϵ is the emissivity obtained from APEC as a function of temperature T and metallicity Z (here taken as solar abundance). To compute the surface brightness, we select a spatial range of $-10 \sim 10$ pc in the y-direction, project fluid densities onto a uniform Cartesian grid with 0.05 pc width, and integrate along the y-axis as the line-of-sight direction. To compare with XMM-Newton observations, we convert the X-ray radiation units to "5×10^{-5} s^{-1} pixel^{-1}" . In this conversion, we adopt XMM-Newton telescope parameters: a pixel angular area of $4'' \times 4''$ and an effective area of approximately 1000 cm^2 for the $2 \sim 4.5$ keV range. Since neutral hydrogen along the line of sight absorbs most X-ray photons, we assume 75% of photons are absorbed. This absorption fraction corresponds to a neutral hydrogen column density range of $N_{\rm HI} = (5 \sim 7) \times 10^{22}$ cm^{-2} [**?**], similar to the values used in XMM-Newton observations ($N_{\rm HI} = (6.3 \sim 8.0) \times 10^{22}$ cm^{-2}) [**?**]. Different observational methods yield varying estimates for the neutral hydrogen column density; our adopted value is slightly lower than that estimated from dust by Ponti et al. [**?**].

Figure 3 [Figure 3: see original paper] presents our calculated two-dimensional X-ray surface brightness distribution, with white contours marking the Sgr A lobes observed by Chandra. The radiation computed from our simulations is comparable to XMM-Newton observations, and the bubble outline agrees well with observations. Following the analysis method of Heard & Warwick [**?**], we average the emission data within a 20° half-opening angle around the z-axis to obtain the surface brightness variation along the z-direction and compare it with XMM-Newton observations (Figure 4 [Figure 4: see original paper]). The simulated surface brightness decline along z matches observational results. The higher observed values in the innermost region likely arise because the extreme Galactic center environment hosts multiple X-ray emission mechanisms in addition to the Sgr A lobes. The lower simulated values beyond 12 pc may result from environmental gas contributions in XMM-Newton observations, where the measured values represent superposition of emission from the bubble apex and ambient gas.

From our calculated emission, we derive radiation-weighted average temperature and density of the bubbles: $T_{\mathrm{ave}} = 1.02$ keV and $n_{\mathrm{ave}} = 6.23\ \mathrm{cm}^{-3}$, both consistent with X-ray observational results [**?**, **?**].

4 Summary and Outlook

In this work, we have used hydrodynamic numerical simulations to analyze the possibility that AGN jets constitute the formation mechanism for the Sgr A lobes at the Galactic center. A single AGN jet episode lasting 500 years produces a shock front that, by 3500 years of evolution, can reproduce the observed bubble properties in terms of morphology, temperature, density, and X-ray surface brightness distribution. Based on current observational information, the AGN jet model stands as a viable candidate mechanism for the formation of the Sgr A lobes.

However, our simulation results alone cannot definitively prove that the Sgr A lobes originated from shock evolution driven by AGN jets. On one hand, TDE outflows also possess the capability to produce bubbles on the scale of the Sgr A lobes. On the other hand, X-ray observations reveal several bright spot structures within the bubbles that are approximately symmetrically distributed about the Galactic center. The specific origins of these emission features require further detailed analysis that cannot be explained by our thermal X-ray emission model alone. Additionally, the short-timescale AGN jet model faces a significant challenge: the required 500-year jet duration in our model is substantially shorter than timescales inferred from most AGN observations. While some observations suggest the Galactic center black hole may have experienced a rapidly varying active phase recently, this remains insufficient to demonstrate that Sgr A* produced a jet lasting only 500 years in the past.

The mass supply for the black hole accretion disk that generates jets could originate from various sources, such as winds from the series of Wolf-Rayet stars in the Galactic center or material stripped from massive stars captured by the black hole. Assuming a 10% energy conversion efficiency—where 10% of the accreted mass energy converts to jet kinetic energy—the required black hole accretion rate is approximately $10^{-5} M_{\odot}\ \mathrm{yr}^{-1}$, corresponding to an Eddington ratio of 10^{-4}. Wind simulations of Wolf-Rayet stars indicate that the Wolf-Rayet phase typically lasts $\sim 10^{5}$ years, and this stellar wind material may have participated in past activities of the Galactic center black hole [**?**]. Nevertheless, based on current observational evidence, we cannot determine the specific origin of the accretion disk.

References

[1] Genzel R, Eisenhauer F, Gillessen S. Reviews of Modern Physics, 2010, 82: 3121
[2] Morris M, Baganoff F, Muno M, et al. Astronomische Nachrichten Supplement, 2003, 324: 167
[3] Su M, Slatyer T R, Finkbeiner D P. ApJ, 2010, 724: 1044
[4] Guo F, Mathews W G. ApJ, 2012, 756: 181
[5] Mou G, Yuan F, Bu D, et al. ApJ, 2014, 790: 109
[6] Zhang R, Guo F. ApJ, 2020, 894: 117
[7] Yang H Y K, Ruszkowski M, Zweibel E G. Nature Astronomy, 2022, 6: 584
[8] Heard V, Warwick R S. MNRAS, 2013, 434: 1339
[9] Ponti G, Morris M R, Terrier R, et al. MNRAS, 2015, 453: 172
[10] Ponti G, Hofmann F, Churazov E, et al. Nature, 2019, 567: 347
[11] Zhao J H, Morris M R, Goss W M. ApJ, 2016, 817: 171
[12] Markoff S. Proceedings of the National Academy of Science, 2010, 107: 7196
[13] Yalinewich A, Piran T, Sari R. ApJ, 2017, 838: 12
[14] Ehlerová S, Palouš J, Morris M R, et al. A&A, 2022, 668: A124
[15] Li S, Guo F. https://ui.adsabs.harvard.edu/abs/2024arXiv240410205L, 2024
[16] Yang X, Yao S, Gallo L C, et al. ApJ, 2024, 966: 151
[17] Churazov E, Khabibullin I, Ponti G, et al. MNRAS, 2017, 468: 165
[18] Terrier R, Clavel M, Soldi S, et al. A&A, 2018, 612: A102
[19] Li Z, Morris M R, Baganoff F K. ApJ, 2013, 779: 154
[20] Zhu Z, Li Z, Morris M R, et al. ApJ, 2019, 875: 44
[21] Quataert E. ApJ, 2004, 613: 322
[22] Ressler S M, Quataert E, Stone J M. MNRAS, 2018, 478: 3544
[23] Calderón D, Cuadra J, Schartmann M, et al. ApJL, 2020, 888: L2
[24] Hayes J C, Norman M L, Fiedler R A, et al. ApJS, 2006, 165: 188
[25] Stolte A, Ghez A M, Morris M, et al. ApJ, 2008, 675: 1278
[26] Baganoff F K, Maeda Y, Morris M, et al. ApJ, 2003, 591: 891
[27] Whitehead H W, Matthews J H. MNRAS, 2023, 523: 2478
[28] Smith R K, Brickhouse N S, Liedahl D A, et al. ApJL, 2001, 556: L91

Note: Figure translations are in progress. See original paper for figures.