Constraining the horizon scale magnetic fields of Sgr A* using Chandra's and EHT observations

Samik Mitra[1], Michal Zajacek[2], Bozena Czerny[3]

[1]International Centre for Theoretical Sciences, India, [2]Masaryk University, Brno, Czechia, [3]Centre for Theoretical Physics, Warsaw, Poland

Introduction

The accretion dynamics around Sgr A* remains a fundamental mystery. While General Relativistic Magnetohydrodynamic (GRMHD) simulations are the standard for interpreting Event Horizon Telescope (EHT) data, they face two critical tensions:

- The Jet Paradox: Models utilizing the Magnetically Arrested Disk (MAD) state predict strong jet activity, yet observations of the Galactic Center show no evidence of a relativistic jet.
- The Variability Gap: These simulations consistently overestimate the X-ray light-curve variability observed by the Chandra X-ray Observatory.

This discrepancy suggests that current magnetic field configurations in simulations do not accurately reflect the physical environment of the Galactic Center (GC). This study utilizes multi-wavelength constraints from Chandra and EHT to narrow the parameter space.

Accretion model for Sgr A*

Matter accretion onto Sgr A* is driven by stellar winds from orbiting Wolf-Rayet stars. Consequently, the flow is modelled as a low-angular momentum (sub-Keplerian), quasi-spherical in nature (Moscibrodzka et al. 2006; Czerny et al. 2008; Mitra et al. 2022, 2024). We model only the inner, low-angular-momentum tail of the wind-fed flow, where the mass accretion rate becomes approximately constant.

Model Assumptions:

- Flow Profile: Steady ($\partial_t \to 0$), axisymmetric ($\partial_\phi \to 0$), and magnetized.
- Ideal MHD: Magnetic fields (b^μ) are "frozen" into the plasma, ($u_\mu b^\mu = 0$). We consider only b^r and b^ϕ to be present for simplicity we keep $b^\theta \sim 0$.
- Vertical equilibrium: Fluid variables depend solely on radial distance (r), with negligible off-equatorial motion ($u^\theta \sim 0$ and $\partial_\theta \to 0$).
- Thermodynamics: A radially varying adiabatic index, $\Gamma(r)$, is utilized

$$\left.\begin{aligned} \partial_r(\sqrt{-g}\rho u^r) &= 0 \\ \partial_r(\sqrt{-g}T^r_\nu \xi^\nu) &= 0 \\ \partial_r(\sqrt{-g}\,{}^*F^r_\nu) &= 0 \end{aligned}\right\}$$

Conserved GRMHD equations

$$\begin{cases} T^\mu_\nu = T^\mu_\nu|_{\rm Fluid} + T^\mu_\nu|_{\rm Mag} \\ \xi^\nu \equiv (-1,0,0,1) \end{cases}$$

$\nu = t$

Radial magnetic flux, $\Phi = \sqrt{-g}(u^r b^t - u^t b^r)$

$\nu = \phi$

Iso-rotation parameter, $\mathcal{J} = \sqrt{-g}(u^r b^\phi - u^\phi b^r)$

$$b^r = -\frac{\gamma_\phi^2(\Phi + \mathcal{J}\lambda)}{u^t(v^2-1)} \qquad b^\phi = \frac{\mathcal{J}v^2 - \gamma_\phi^2(\mathcal{J} + \Phi\lambda)}{u^t(v^2-1)}$$

$\dot{M}-$paradox & Influence from wind-fed simulations

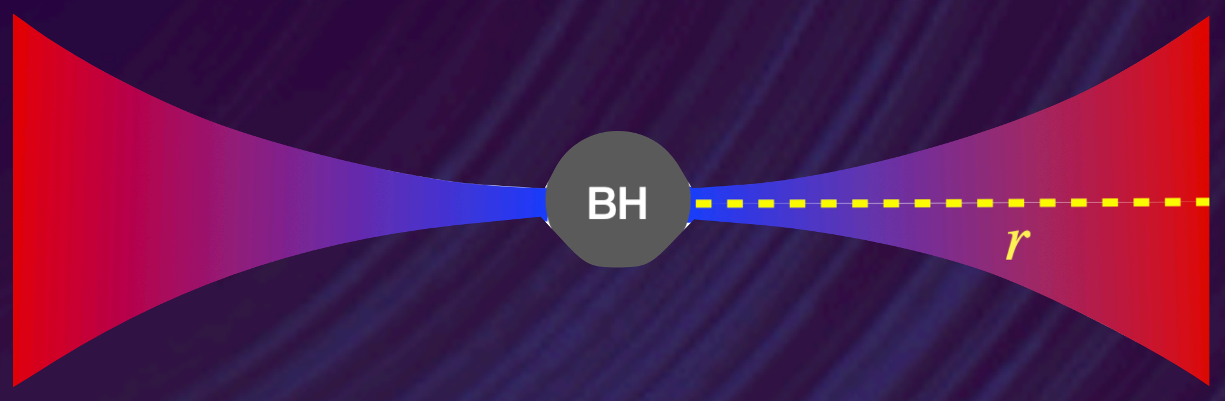
Chandra observations (Baganoff et al. 2003) at the Bondi radius ($r \sim 10^5 r_g$) suggest a capture rate of $\sim 10^{-6} M_\odot$ yr^{-1}, yet horizon-scale measurements indicate $\dot{M} \leq 10^{-8} M_\odot$ yr^{-1}. This two-order-of-magnitude discrepancy implies that most gas captured at large scales never reaches the central black hole.

In this context, the wind-fed simulation of Ressler et al. (2018, 2023) confirmed that only the low-angular momentum tail of the stellar winds can accrete, which results in $\dot{M} \propto \sqrt{r}$, effectively bridging the gap between the Bondi scale and the horizon.

Note that, the motion of the stellar winds actually deviates the accretion flow structure around GC from Bondi flows significantly.

Parameter	Value at $r = 740 r_g$
$\dot{M}\,(M_\odot\,{\rm yr}^{-1})$	$\sim 10^{-7} - 10^{-8}$
Angular momentum (λ)	$\sim 0.5 - 0.6\,\lambda_{\rm Kep}$
Flow temperature ($T_{\rm gas}$)	$\sim 10^8 - 10^9 K$
Number density (n_e)	$\sim 10^5 - 10^6\,{\rm cm}^{-3}$
Radial velocity (v)	$\sim 0.03 - 0.05\,c$

Rather than employing arbitrary boundary conditions—as illustrated by the cyan curve in Fig. 1—our semi-analytical model is initialized using the constraints detailed in the table above. By adopting these parameters, we ensure that our horizon-scale magnetic field analysis remains physically consistent with Chandra's multi-wavelength observations and wind-fed simulations of the GC.

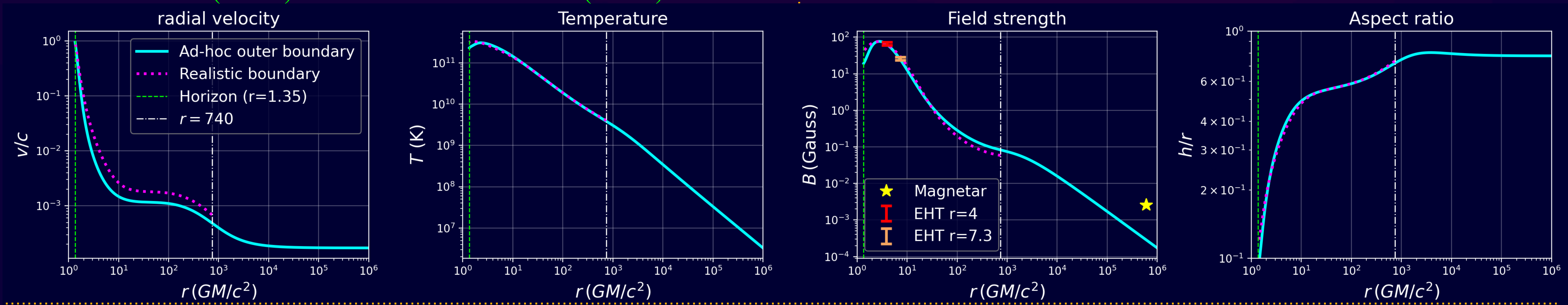


EHT-constrained magnetic-field profile

Initially, randomly oriented magnetic fields are associated with the stellar winds. As material accretes and angular momentum is transported, differential rotation develops a strong toroidal (b^ϕ) component while the inflow preserves a poloidal (radial b^r and polar b^θ) component.

To address the Jet Paradox, we focus on the b^r and b^ϕ components. The suppression of a coherent b^θ prevents the unphysical launching of a relativistic jet, maintaining consistency with the quiescent state observed in EHT and Chandra data for Sgr A*.

We require the magnetic-field profile to satisfy the EHT 2024 constraints: $r = 4 r_g$: 67^{+8}_{-9} G and $r = 7.3\, r_g$: 26^{+3}_{-4}G.



Contact: Dr. Samik Mitra, Postdoctoral Scholar, ICTS-TIFR, Bengaluru, India, Email: samik.mitra@icts.res.in

Thanks to the "Sujata and Tatineni Prem Kumar Travel Grant Fund" grant support from ICTS-TIFR and the IAU grant support.