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Modelling the accretion-ejection flow around the supermassive black hole at the centre of the Milky Way

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Abstract. Sagittarius A* (Sgr A*) - our galaxy's supermassive black hole - has been highlighted as a unique laboratory for relativistic astrophysics. The most recent development in the area is the 2022 *Event Horizon Telescope Collaboration* (EHT) reconstructed image of Sgr A*'s close environment, which allows for better constraints to be put on state-of-the-art models. The goal of my Master's thesis is to accurately reproduce the observed spectrum, image, and light polarization of Sgr A* (by the *EHT*), using the General Relativistic Ray-tracing code, GYOTO, to simulate new and more realistic models for the black hole jets and disk. We present our new *Thick disk + Parabolic jet* analytic model, which aims to reproduce both the non-thermal properties of the observed spectrum and the image observables from the EHT observations. With this work, we aim to derive new constraints on the accretion-ejection mechanism for Sgr A*.

1 Introduction

Sagittarius A* (Sgr A*) was first detected in 1974, by Bruce Balick and Robert Brown [1]. When this interferometry detection was made, it proved the existence of an extremely compact object (a **supermassive black hole - SMBH**) at the center of our own galaxy.

Since then, various observations have been conducted around Sgr A* on wavelengths from the radio to the X-ray (for more on these observational campaigns see [2] and references therein). These observations also showed that part of the spectrum comes from non-thermal synchrotron emission. In addition, another key step towards understanding these objects is the *Event Horizon Telescope* (EHT) collaboration's reconstructed images of both M87 [3] in 2019 and Sgr A* [4] in 2022. With these images, we can get measurements on fundamental astrophysical parameters of these objects' close environment and place new and strong constraints on our models.

Many studies have been conducted around this topic. Some of which assumed and/or explored the presence of relativistic jets ([5], [6], [7]). In particular, [6] shows how their analytical model of Sgr A* was able to nearly perfectly fit the observed spectrum data, achieving a $\chi^2 = 0.54$, including the radio frequencies, which are usually associated with the presence of jets (more in **section 2.1**). Moreover, while observing active galactic nuclei (AGNs), that are powered by the central SMBHs, jet formation, probably due to the *Blandford-Znayek* process, was observed ([8]). For all this, we too will include jets in our model (more in **section 2.1**).

To sum up, this project aims to create a new analytical model, using the relativistic ray-tracing code — GYOTO [9], by improving on *Vincent et. al. 2019*'s work [6]. Firstly, we aim to replicate their excellent fitting results and, secondly, to fit all the EHT data for a non-rotating black hole. Unfortunately, there will be no time to study how different spin parameters would impact the final fitted values or the synthetic images. So, we will focus on the $a = 0$ case and leave this study for future work. These improvements aim to build on the previous model, bringing new physical aspects/parameters that will enrich the simulations, while maintaining it analytical.

2 Old VS New Model

2.1 Conical Jets + Torus Disk

In 2019, before the EHT collaboration released their reconstructed images of Sgr A*, an attempt at fitting the observed spectrum with analytical models was made by *Vincent et. al.* [6]. In their work, they used conical-shaped relativistic jets together with a torus disk to simulate the close environment of Sgr A*, as seen in **Fig1** from [6]. In addition to this, a very high accurate fitting was made to the observed spectrum data available (**Fig3** from [6]). Despite having a very good fitting of the spectrum, there are a few key aspects that needed to be addressed.

Firstly, the ring like structure that comes from the *torus disk* rises from construction. Although it was a simple and purely analytical solution, an improvement was made in order to add a new layer of complexity to the disk, as well as, making it more realistic. Additionally, taking a look at Fig. 1, a quick comparison between different magnetic configurations for the *Torus Disk + Conical Jet Model* is made. A much more in depth study on the matter has been made in [5]. In summary, the author presents results on the conical jets model (**section 2**), as well as a table (**Table 2**) with intensity ratio (I_{sh}^{in}/I_{sh}^{out}) comparisons between the different magnetic configurations. The author then concludes that, based on current models with preferentially vertical magnetic field configurations around Sgr A* ([10]), the jet hypothesis should be a robust one. As such, will be the chosen configuration for this works' jets.

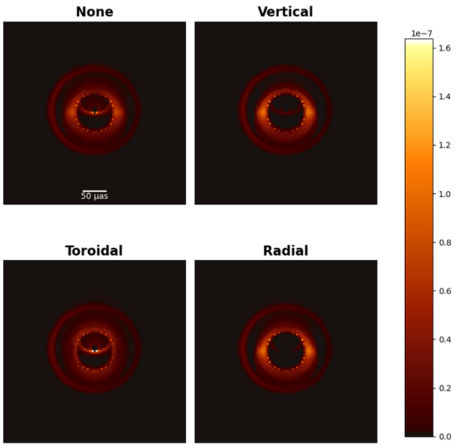

Figure 1: Illustration of jet's brightness under different magnetic configurations

Lastly, the jets' shape. Conical jets have a set aperture. Because of this, a distant observer will see the conical jet angular size increase as he observes it at a large distance from the black hole. To solve this, a more realistic parabolic shape should be used. This avoids the mentioned problem by creating a constant jet sheath that will not become apparently larger with its distance from the source. This is also consistent with both observations of M87* and with numerical GRMHD (General Relativistic Magnetohydrodynamics) simulations results, that favor the parabolic shape for jets formed around SMBHs [11], [12].

2.2 The new model

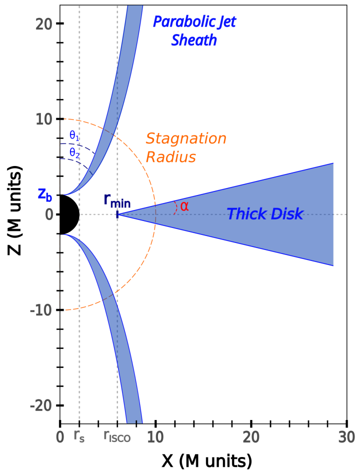

Figure 2: Sketch of the *Thick Disk + Parabolic Jets* model.

With all this into consideration, a **thick disk** with **parabolic** shaped **jets** has been implemented, as sketched in Fig. 2.

An example of such improved complexity is the addition of new physical parameters like the stagnation radius, that will heavily impact the final synthetic images. In Fig. 3, the combined effects of the stagnation radius - region where particles plummet into the black hole - with synchrotron beaming creates various orders of imaging in the final picture. In this figure, the primary image of the front jet is clear, as well as a gap where its base should be. Because particles are falling into the black hole, this region appears to have little to no emission. On the other hand, in the backward jet, we can see two distinct regions. In this case, the in-falling particles are falling towards the observer. Because of this, the secondary image in region **B** appears brighter and closer to the center of the image than the primary image **C**.

As for the disk, the main changes come from its shape and how it is defined within GYOTO's code. On the one hand, the *torus disk*, as mentioned, was a simple and analytical solution, based only on the disk's central enthalpy and central temperature. It had its shape set by default, which meant that it would always behave as if it had a tangled and averaged magnetic configuration [13]. On the other hand, the new *thick disk* allows, firstly, for a more costume use, as it has a wider variety of available inputs like inner radius, disk aperture, plasma density, etc.. For the thesis's project most of the disk's parameters will, ideally, be left free to be fitted. Secondly, the *thick disk* also respects other GRMHD results on the accretion mechanism around SMBHs. On top of this, the new observable data of the EHT images will be used to place constraints on our model in post-process analysis.

All in all, the model's updates come to bridge a gap between numerical GRHMD simulations that favor certain physics (like the jet's parabolic shape) and other analytical models and studies that try present the most accurate and simple solutions possible to highly complex problems. With this, an updated model on our galaxy's SMBH is presented and tested for future studies.

3 Accretion-Ejection Flow Study with GYOTO

Studying how different physical parameters impact the output's spectrum and synthetic images is crucial in understanding what parameters should be at study and how each needs to change in order to obtain the best results. Particularly, some physical parameters impact the spectrum very similarly and, thus, are degenerate with each other. In the same way, keeping a close eye on how each parameter impacts the resulting synthetic images may also lead to identifying degeneracies or giving new ways of distinguishing their impact on the spectrum or on the final images during post-process analysis.

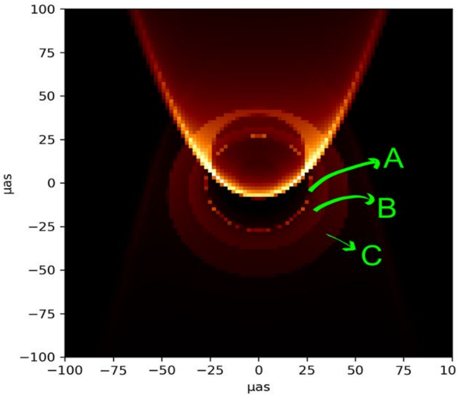

Figure 3: Synthetic image of the parabolic jets. Highlighted region **A** corresponds to the photon ring. Regions **C** and **B** refer the 1^{st} and 2^{nd} order images of the backward jet.

3.1 *Spectrum Variability*

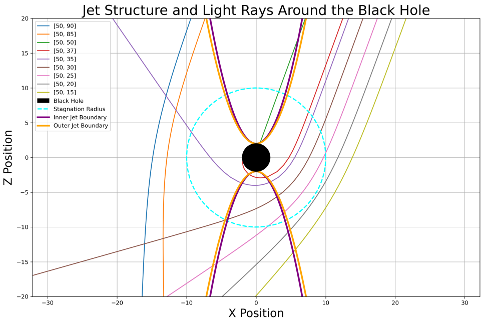

Figure 4: Plotting of the null geodesics for a Schwarzschild black hole with mass equal to Sgr A*. Dashed blue line represents the stagnation radius.

The fitting of the chosen analytical model to the observed spectrum is the first step in achieving the best-fitted values. GYOTO's capabilities as a simulator allows for a accurate and in-depth understanding of which variables are the most important to study and vary in a grid search, for example.

Another important aspect to notice when simulating the overall spectrum is how each frequency region behaves for different inputs. For instance, low frequencies may vary less with certain parameters. This is the optically thick region of the spectrum. In it, simulated light-rays only reach the outer most layers of the plasma from the jets and/or disk. On the other hand, higher frequencies allow light to travel through the plasma and thus both the simulated spectrum results and observed images may vary a lot more in this region. Finally, understanding this becomes evidently necessary as the EHT frequency ($230GHz$) is found in the transition region between optically thin and thick.

3.2 *Synthetic Images*

As mentioned, one of the main goals of this Master's thesis is to accurately replicate the EHT reconstructed images of Sgr A*. As such, an in depth analysis of how to get a ring like shape with the chosen parameters must be made. The first step to do so is to study the null geodesics, and how they curve around the black hole (Fig. 4), as well as different relativistic effects that might occur. Such relativistic effects regard, for example, the beaming effect of plasma [14], and should be studied for the entirety of the relevant spectrum range including the optically thick and thin regions of the spectrum ([15], [16], [17]). Having done this, an even greater understanding of the importance and impact of the physical parameters, like the previously mentioned stagnation radius, on the generated images will be.

4 Conclusions and Future Work

To sum up, with the improvement of numerical models, there is the possibility to better understand the accretion-flow physics around black holes. Furthermore, the recent EHT collaboration data of Sgr A* brings new observational constraints for our model. Thanks to GYOTO, we can make analytical models of Sgr A*'s close environment, that will, in turn, aim to fit all of its observational data, including EHT image, spectra and polarization quantities (Q and U Stokes parameters) to produce the best "quiescent" model with spin parameter $a = 0$. At the time of writing this article, no fitting results could be presented yet. As such, follow up work will be focused on making a fitting to the observed spectrum.

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References

[1] Bruce Balick and Robert H. Sanders. "Radio Fine Structure in the Galactic Center". In: *Astrophysical Journal* 192 (Sept. 1974), pp. 325–336. DOI: `10.1086/153062`.

[2] Reinhard Genzel, Frank Eisenhauer, and Stefan Gillessen. "The Galactic Center massive black hole and nuclear star cluster". In: *Reviews of Modern Physics* 82.4 (Dec. 2010), pp. 3121–3195. ISSN: 1539-0756. DOI: `10.1103/revmodphys.82.3121`. URL: `http://dx.doi.org/10.1103/RevModPhys.82.3121`.

[3] Event Horizon Telescope Collaboration et al. "First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole". In: *The Astrophysical Journal* 875.1, L4 (Apr. 2019), p. L4. DOI: `10.3847/2041-8213/ab0e85`. arXiv: `1906.11241 [astro-ph.GA]`.

[4] The Event Horizon Telescope Collaboration et al. "First Sagittarius A* Event Horizon Telescope Results. VII. Polarization of the Ring". In: *The Astrophysical Journal Letters* 964.2 (Mar. 2024), p. L25. DOI: `10.3847/2041-8213/ad2df0`. URL: `https://dx.doi.org/10.3847/2041-8213/ad2df0`.

[5] Paloma Thevenet. "Mock observables of the accretion and ejection flow around the black hole at the center of the Galaxy". MA thesis. LESIA Observatoire de Paris, 2024.

[6] Vincent, F. H. et al. "Multi-wavelength torus–jet model for Sagittarius A*". In: *A&A* 624 (2019), A52. DOI: `10.1051/0004-6361/201834946`. URL: `https://doi.org/10.1051/0004-6361/201834946`.

[7] N Aimar et al. "GYOTO 2.0: a polarized relativistic ray-tracing code". In: *Classical and Quantum Gravity* 41.9 (Apr. 2024), p. 095010. DOI: `10.1088/1361-6382/ad351d`. URL: `https://dx.doi.org/10.1088/1361-6382/ad351d`.

[8] R. D. Blandford and R. L. Znajek. "Electromagnetic extraction of energy from Kerr black holes." In: *Monthly Notices of the Royal Astronomical Society* 179 (May 1977), pp. 433–456. DOI: `10.1093/mnras/179.3.433`.

[9] F H Vincent et al. "GYOTO: a new general relativistic ray-tracing code". In: *Classical and Quantum Gravity* 28.22 (Oct. 2011), p. 225011. DOI: `10.1088/0264-9381/28/22/225011`. URL: `https://dx.doi.org/10.1088/0264-9381/28/22/225011`.

[10] M. Wielgus et al. "Orbital motion near Sagittarius A*: Constraints from polarimetric ALMA observations". In: *Astronomy & Astrophysics* 665 (Sept. 2022), p. L6. ISSN: 1432-0746. DOI: `10.1051/0004-6361/202244493`. URL: `http://dx.doi.org/10.1051/0004-6361/202244493`.

[11] Masanori Nakamura et al. "Parabolic Jets from the Spinning Black Hole in M87". In: *The Astrophysical Journal* 868.2, 146 (Dec. 2018), p. 146. DOI: `10.3847/1538-4357/aaeb2d`. arXiv: `1810.09963 [astro-ph.HE]`.

[12] Hung-Yi Pu et al. "STEADY GENERAL RELATIVISTIC MAGNETOHYDRODYNAMIC INFLOW/OUTFLOW SOLUTION ALONG LARGE-SCALE MAGNETIC FIELDS THAT THREAD A ROTATING BLACK HOLE". In: *The Astrophysical Journal* 801.1 (Mar. 2015), p. 56. ISSN: 1538-4357. DOI: `10.1088/0004-637x/801/1/56`. URL: `http://dx.doi.org/10.1088/0004-637X/801/1/56`.

[13] F. H. Vincent et al. "Astrophysical imaging of Kerr black holes with scalar hair". In: *Physical Review D* 94.8, 084045 (Oct. 2016), p. 084045. DOI: `10.1103/PhysRevD.94.084045`. arXiv: `1606.04246 [gr-qc]`.

[14] Amardeep Bharti and Navdeep Goyal. "Fundamental of Synchrotron Radiations". In: *Synchrotron Radiation*. Ed. by Daisy Joseph. Rijeka: IntechOpen, 2019. Chap. 2. DOI: `10.5772/intechopen.82202`. URL: `https://doi.org/10.5772/intechopen.82202`.

[15] R H Tourin. “OPTICALLY THICK PLASMAS”. In: *J. Quant. Spectry. Radiative Transfer* Vol: 3 (Dec. 1962). DOI: `10.1016/0022-4073(63)90009-8`. URL: `https://www.osti.gov/biblio/4694621`.

[16] V.L. Ginzburg. *The Propagation Of Electromagnetic Waves In Plasmas*. Oxford: Pergamon Press, 1970.

[17] T.J.M. Boyd and J.J. Sanderson. *An Introduction to the Atomic and Radiation Physics of Plasmas*. Chapter 6: Opacity. Cambridge: Cambridge University Press, 2018. Chap. 6.