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Review of the Doctoral Dissertation by Bestin James, entitled *"Modeling Magnetized Jets from Accreting Black Holes"*

The doctoral thesis of Mr. Bestin James, completed under the supervision of Prof. Agnieszka Janiuk at the Center for Theoretical Physics, Polish Academy of Sciences, addresses the general problem of the launching of relativistic jets and outflows by highly magnetized accretion flows around spinning black holes. For his research, conducted by means of numerical simulations, the author uses the general-relativistic magneto-hydrodynamic (GRMHD) code High Accuracy Relativistic Magnetohydrodynamics (HARM), which was originally developed by Gammie, McKinney & Tóth (2003), and later customized and further developed by Prof. Janiuk and her group.

The simulation setup presented in the dissertation typically involves a pressure equilibrium torus surrounding a Kerr black hole or a Bondi-type accretion flow onto a Kerr black hole, with a poloidal magnetic field added either at the beginning or eventually only at later stages of the simulation runs. Through a detailed analysis of the output numerical data, the author investigates various general properties of the studied systems. The focus is particularly on the overall energetics of the inflow-outflow structure, including mass accretion rates, magnetic flux accumulated at the black hole horizon, and total jet power. Additionally, the author examines the internal structure of the jets, considering stratification in plasma magnetization or in the total energy—to—mass flux ratio across the outflow.

The thesis is composed in English and is founded on two peer-reviewed papers (Janiuk, James & Palit 2021, The Astrophysical Journal, v917, p102; James, Janiuk & Nouri 2021, The Astrophysical Journal, v935, p176), encompassing Chapters 3 and 4 of the dissertation; additionally, it includes preliminary findings from an ongoing work (James, Karas & Janiuk, in preparation), presented in Chapter 5.

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In the first chapter of the thesis, the author provides a summary of the astrophysical background of the research. This includes relevant information on topics such as astrophysical black holes, accretion processes in astrophysics, radiation mechanisms, relativistic jets, Gamma-ray Bursts (GRBs), and Active Galactic Nuclei (AGN). The second chapter delves further into the HARM code and typical simulation setups.

My primary observation regarding the initial two chapters of the dissertation is that the English could benefit from more meticulous revision. There exist several passages and sentences that are confusing or grammatically incorrect. Below are examples of such instances:

"Compact objects in astrophysics are either the resulting remnants of stellar evolution such as neutron stars and stellar mass black holes or their higher mass counterparts, supermassive black holes."

"The supermassive black holes on the other hand may have formed from the early cosmic times through still unclear formation mechanisms."

"After remaining many decades as just theoretical curiosities, the existence of black holes in nature was considered to explain the observed properties of quasars in the 1960s."

"Here we briefly describe them all in one place the way it is used in the HARM code and the assumptions made in the code"

Another observation is that, while some of the sections in the introductory chapters are quite detailed, offering an in-depth discussion on issues such as the efficiency of accretion onto a Kerr black hole (§1.2.1), spherical accretion (§1.2.3), and geometrically thin accretion disks (§1.2.4), other sections are exceedingly brief and condensed to the extent that they seem insubstantial and even unnecessary. This is particularly applicable to sections concerning radiation mechanisms (§1.3), relativistic jets (§1.6), and phenomenology of GRBs and AGN (§1.7–1.8).

Finally, the third major critique of the introductory chapters is that the set of MHD equations has not been adequately introduced or discussed, particularly concerning the induction equation for the magnetic field. For instance, the non-relativistic HD equations are initially introduced in §1.2.3 within the context of the Bondi accretion model. Only later, in §1.2.4, is the relativistic formulation of the local conservation laws for the stress-energy tensor and particle flux mentioned. What appears somewhat odd is that the magnetic component of the MHD equations only appears in §2.1.1, which is dedicated to the presentation of the HARM code. Even there, the magnetic induction equation is introduced suddenly (equation 2.8), with no mention of Ohm's law, the perfect conductivity limit, and so on. In my opinion, the dissertation would greatly benefit from a thorough summary and comprehensive discussion of the relativistic MHD equations.

The other, relatively minor, comments regarding the introductory chapters are outlined below:

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- In §1.1.1, equation 1.2 is introduced as *"the line element in the Schwarzchild metric in spherical coordinates"* yet it is, in fact, the line element in a flat Minkowski spacetime expressed in spherical coordinates; the Schwarzschild metric involves additional functions $a(M, r)$ and $b(M, r)$ alongside dt^2 and dr^2 terms.
- In the same §1.1.1, in the equation for the line element in the Kerr metric (equation 1.5), M stands for the gravitational radius, not the mass measured in, e.g., grams, and this leads to notation conflicts with previous equations (1.2–1.4); additionally, the angular momentum a in this equation cannot represent the dimensionless spin parameter, as stated by the author, but should instead be the angular momentum J expressed in units of length, namely $a = J/cM$. Notably, the notation conflict is most evident in equation 1.6, where M stands for the gravitational radius on the right-hand side while denoting mass (in units such as grams) on the left-hand side.
- In §1.2, the statement *"All the observations we conduct in astronomy except the newly developed paradigm of gravitational waves require the emission of energy in the form of electromagnetic radiation."* is incorrect, considering recent IceCube detections of high-energy neutrinos from astrophysical sources, and ultra-high energy cosmic rays observed by, for example, the Pierre Auger Observatory.
- In §1.2.1, the author provides a summary of the analysis of geodesic motion in the equatorial plane by solving the Euler-Lagrange equations in the Kerr metric (equations 1.14–1.16), subsequently identifying the photon orbits (equation 1.19) and the innermost stable circular orbits (1.21–1.23); however, it remains unclear to readers the distinction between the two types of orbits, and the author should clarify that this discussion pertains to either null geodesics for massless particles or timelike geodesics for massive ones.
- In §1.2.3, the author states *"The particles [...] may exchange energy between them through scattering, that is through Coulomb interactions. If these interactions are frequent, the matter in the flow can be characterized by its density, pressure and temperature or in other words, the hydrodynamical approximation, as a starting point."*, but this is incorrect, as even in the regime of a collisionless plasma where Coulomb collisions are extremely infrequent, a hydromagnetic approximation can still be applied due to the presence of a magnetic field, which imparts fluid-like characteristics to the plasma; in fact, astrophysical plasmas are typically collisionless.
- Also in §1.2.3, concerning the Bondi accretion model, the author mentions *"We have seen that the accretion flows must be transonic, that is they have to transition from a subsonic to supersonic velocity, in order to satisfy the boundary conditions near a black hole."*; in reality, there are two physically valid solutions to the Bondi problem: one transonic as discussed in this section, and the other subsonic, representing an accretion flow that remains subsonic at all radii.
- In §1.2.4, on page 20, *"The thick disk: These are geometrically thick and optically thin disks"* – shouldn't it read *"optically thick disks"* instead?
- In §1.6, the parameter κ in the provided expression for the Blandford-Znajek jet power (equation 1.105) is undefined; additionally, the provided formula appears to be applicable only for small black hole spins ($a \ll 1$).
- In §2.1.1, equation 2.1 is introduced as *"conservation of particle number"*, but it actually represents the local conservation law of matter current density (particle flux).
- Also in §2.1.1, the electromagnetic field's unit system should be clearly specified (Gaussian units with $c = 1$?). Moreover, instead of *"the strength of the magnetic field in the fluid frame"* the quantity B^2 should accurately be termed the rest-frame magnetic energy density.
- In §2.2, Figure 2.4 lacks a 512x512 B=0 curve (blue); is this omission due to it being identical to the 1024x1024 B=0 case? If so, this should be indicated.

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Chapter 3 of the dissertation encompasses the previously published peer-reviewed paper titled *"Variability studies of jets from accreting black hole sources at different mass scales"* by Janiuk, James & Palit (2021). This work is particularly captivating, as it endeavors to establish a connection between the outcomes of GRMHD axisymmetric simulations of jet launching from magnetized tori around spinning black holes and various observational findings concerning the variability of relativistic jets in GRBs or AGN. As stated in the introductory remark, all simulations and data analyses within this work were carried out by Bestin James, excluding the power density spectral data analysis. The core premise of this research lies in the assertion by the authors that the observed variability in the jet emission *"directly reflects"* the variability of the central engine, which is moreover shaped by the development of the magnetorotational instability (MRI) within the accretion flow.

While I've found the work to be engaging, I do identify three primary concerns within it. The initial issue, as I see it, pertains to the normalization of the poloidal magnetic field's initial distribution in the torus. This normalization appears to be unrealistically high, given the values of the plasma parameter β, which is significantly less than unity around the density maximum radius of approximately $16\,r_g$. The rationale behind this choice of initial conditions remains unexplained, and there is no mention of whether simulations with lower magnetization were explored to determine if they would yield qualitatively distinct outcomes concerning jet production.

The second concern pertains to the interpretation of the parameter μ, which stands for the total energy flux of the jet normalized to its mass flux. The authors appear to suggest, in particular, that the distribution of μ values across and along the jet, while still in proximity to the jet's launching point, could serve as an approximation for the bulk velocity pattern that develops further along the outflow. While it is accurate that the terminal bulk Lorentz factor of a gradually accelerating and collimating electromagnetic jet is determined by the overall ratio of the total energy flux (predominantly Poynting flux) to the mass flux at the jet's base, the local μ value at a specific location, such as a jet boundary near the launching site, does not directly correspond to the bulk Lorentz factor of that portion of fluid farther along the outflow. Instead, it signifies the radial profile of the jet's magnetic field and its evolution.

In this context, the authors' observation, *"We note highly inhomogeneous outflows, where larger values of μ are reached at the edges of the jets rather than at the z polar axis"*, can be readily comprehended. This is due to the fact that, for any reasonable configuration of a jet produced via the electromagnetic extraction of energy from the disk and black hole rotation, the jet's toroidal magnetic field vanishes at the jet axis while dominating over plasma inertia at the jet boundaries. Similarly, the authors' assertion, *"The jet structure is clearly nonuniform, and more energetic blobs are always located in the outer regions, while less energetic ones travel close to the axis"*, can be interpreted in the

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same manner. It's important to emphasize here that since the μ parameter is dimensionless, its elevated values do not necessarily denote the "more energetic" segment of the outflow, but rather signify sections with a "relatively lower mass flux".

And thirdly, my concern revolves around the "minimum variability timescale" (MTS), defined by the authors *"as the average of peak widths at their half maximum on the μ variability plot"*. As mentioned earlier, I hold the opinion that local values and fluctuations in the μ parameter do not correspond to the broader velocity pattern and cannot be directly correlated with the variability of the jet emission. The authors suggest, in this context, that *"the frequency of these [μ] changes, measured at the base of the jet, is related to the frequency of collisions between the shells transported downstream by the jet and is the source of observable gamma-ray pulses, produced in the internal-shock scenario"*. However, in the internal shock model, the jet plasma must be matter-dominated for shocks to form in the first place. Therefore, this model appears challenging to reconcile with the concept of Poynting-dominated outflows emerging from the Blandford-Znajek process, unless some additional mechanism is invoked to allow for an efficient dissipation of the jet magnetic field energy. Furthermore, there remains an open question regarding the extent to which MTS estimations are reliant on the resolution and dimension of the numerical simulations, given that *"the variability of the jet, assessed in terms of pulse durations, is driven by the MRI in the disk"*.

Chapter 4 of the dissertation incorporates the previously published peer-reviewed paper titled *"Modeling the Gamma-Ray Burst Jet Properties with 3D General Relativistic Simulations of Magnetically Arrested Accretion Flow"* by James, Janiuk & Nouri (2022). Here the authors introduce their 3D GRMHD simulations of jet launchings from two distinct types of tori. The initial tori configurations follow either Fishbone & Moncrief (1976) or Chakrabarti (1985), both augmented with a poloidal magnetic field. These two types of tori are anticipated to represent the central engine of long and short GRBs, respectively. The authors' primary objective is to pinpoint differences in various jet parameters and characteristics between these two scenarios. As stated, Bestin James conducted all simulations and data analyses outlined in this research.

As this work naturally extends the analysis presented in the preceding chapter, some of the concerns I raised earlier are relevant here as well. A notable advantage and improvement over the prior study is clearly the dimensional aspect of the simulations, as 3D modelling allows to capture more reliably the internal structure of the emerging jets. This is particularly evident in the power-spectral density of fluctuations in the μ parameter, which now closely resembles flickering noise (in contrast to being closer to uncorrelated white noise in the previous axisymmetric simulations). Therefore, I address only a relatively minor inquiry concerning the presented analysis results in this

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section: In §3.1, the authors describe how *"With time, the toroidal field develops also at the polar regions, where it is being wound-up by the rotation of the black hole."* Upon examining Figure 3, however, I struggle to comprehend how the toroidal magnetic field can be potent in the polar regions (i.e., $\theta = 0$), particularly in the torus description by Fishbone & Moncrief (1976). In contrast, in the Chakrabarti (1985) model, the field behaves in accordance with the general expectation, i.e., it vanishes at the jet axis.

Finally, Chapter 5 of the dissertation, titled *"Black hole outflows driven by accretion of large-scale magnetic fields"*, unveils initial outcomes from an ongoing collaborative effort with Prof. Vladimír Karas from the Astronomical Institute, Czech Academy of Sciences. In line with the provided statement, Bestin James undertook all numerical simulations and data analyses presented in this chapter.

This work deals with equatorial outflows that have the potential to develop within strongly magnetized accretion flows. The authors' simulations commence with a uniform density across the entire computational grid and a Kerr black hole at its center. As the process of accretion advances and attains a state of equilibrium, the authors introduce "an asymptotically uniform" magnetic field throughout the computational grid, employing the Wald (1974) solution. Subsequently, the authors observe the accumulation of magnetic flux at the black hole horizon, magnetic field lines undergoing reconnection during accretion onto the black hole, and the emergence of equatorial mass outflows. In my perspective, although preliminary, this work holds potential interest. However, similar to previous chapters, the simulation setup—which essentially involves Bondi spherical accretion combined with a sudden introduction of a very strong magnetic field, at plasma β parameter levels in the range of 0.1–1.0—lacks justification concerning its physical plausibility.

In conclusion, despite the earlier comments and critical assessments, I hold the view that Mr. Bestin James' doctoral thesis constitutes a highly valuable addition to our comprehension of relativistic jet formation through magnetized accretion flows around Kerr black holes, particularly in the regime of a strong magnetization. The core of this dissertation lies in the GRMHD simulations carried out by the PhD candidate, which undoubtedly showcase his adeptness in programming and his comprehensive grasp of accretion processes in astrophysics, alongside the broader context of a magnetohydrodynamical approximation of the astrophysical plasma. I eagerly anticipate delving into Mr. Bestin James' forthcoming research papers, with the hope that they will wield an even more substantial influence within the scientific community. Therefore, I strongly recommend the acceptance of this dissertation for a public defense.

Łukasz Stawarz

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