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Review of the doctoral dissertation by José Ortuño-Macías, entitled
"Kinetic Numerical Simulations of Particle Acceleration Mechanisms in Relativistically Magnetized Jets"

The doctoral thesis of Mr. José Ortuño-Macías deals with the general problem of particle acceleration in astrophysical magnetised plasma, and, in particular, within relativistic jets launched from Active Galactic Nuclei (AGN), investigated by means of kinetic numerical simulations carried out under the supervision of dr hab. Krzysztof Nalewajko. The thesis consists of three chapters: a broad introduction (Chapter 1), a thematically consistent collection of two peer-review first-author papers published in the Monthly Notices of the Royal Astronomical Society in 2020 (Chapter 2), and in the Astrophysical Journal in 2022 (Chapter 3). The dissertation is written in English and, according to co-author statements, the share of Mr. José Ortuño-Macías contribution for Chapters 2 and 3 is estimated to be at the level of 70% and 60%, respectively. In my opinion, both of those papers provide a truly valuable and novel insight into the energy dissipation processes taking place in astrophysical outflows.

The first Sections 1.1-1.3 of Chapter 1, aim to provide the very basic, introductory information regarding AGN, relativistic jets in AGN, non-thermal emission processes in jet-dominated (blazar-type) sources, and finally particle acceleration processes that may be at play in relativistic plasma. This part of the thesis seems not well-organised, and in places even chaotic; a reader may even wonder if it is at all relevant or needed for the main part of the thesis (i.e., Chapters 2 and 3). Once the author decided to provide such a basic AGN review in the dissertation, however, more time should be devoted to make it more comprehensive and better written.

In particular, when talking about jetted AGN, one could mention also the other morphological classes expanding upon the Fanaroff-Riley type I and II dichotomy. Also, contradictory statements should be eliminated; for example, in one place the author says *"As the jet outflows from the launching region, it expands roughly conically"*, to clarify further below *"Jets are found to have a conical shape at large distances from their origin […] with a parabolic shape at sub-pc distances from the SMBH"*. The other example being *"Hence, even if the poloidal field is dominant at the onset of the jet, the toroidal field is likely to become dominant at some distance, as studies of the polarization of these objects have revealed"*, which is contradicted to some extent a few lines later by *"A recent study of the jet magnetic field structure of M87 […], has shown that a helical magnetic field structure is present at large distances from the launching source ~1 kpc"* (note that a large-scale helical magnetic field means that the poloidal component is roughy in equipartition with the toroidal component). Similarly, several repetitions, e.g., those regarding the problem of a conversion of AGN jets from Poynting flux-dominated to matter-dominated, should be avoided.

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More substantial remarks regarding this part of the thesis, are as follows:

- Equation 1.7 in Section 1.1.2, corresponds to a very general definition of the polarisation degree based on the Stokes parameters, not specific to any particular radiative process; for the synchrotron emission specifically, polarisation degree could be given as a combination of modified Bessel functions, analogous to the expression 1.5 for the synchrotron power spectral density (see equation 6.37 in the textbook "Radiative Processes in Astrophysics" by Rybicki & Lightman).
- When talking about Faraday rotation (equation 1.8 and above), the author should note that the lambda-square dependence in the rotation of the polarisation angle, is valid only for the case of an "external Faraday screen", i.e. when the Faraday rotation takes place *outside* of the emission region.
- Equation 1.9 should be introduced as "the pitch angle-averaged energy loss rate", and not simply "the averaged energy loss rate"; also here in this sub-section devoted to the inverse-Compton emission, reduction in the scattering cross section by quantum effects, i.e. the Klein-Nishina regime of the interaction, should be at least mentioned.
- In the following sub-section "Radiation reaction limit", it is stated that *"As the particle accelerates, the radiative losses increase until the moment when the acceleration and the radiation reaction force become equal."*, but this statement is confusing without clarifying before that the radiative losses timescale for the processes such as synchrotron, scales inversely with particle energy, while the acceleration timescales in astrophysics typically increase with increasing particle energies.
- Section 1.2.1. introduces the magnetization parameter sigma, defined as the ratio of the magnetic pressure to the particle thermal pressure *nkT*, while in the following paragraph it is stated that *"Due to the low density of these particle accelerating regions, collisions between particles are uncommon in comparison with their interactions with electromagnetic fields, hence, particles are unable to thermalize."*
- Equation 1.13 in Section 1.3.2 is in fact the momentum diffusion equation, obtained from the Fokker-Planck equation describing stochastic particle acceleration, under the assumption of particle isotropy and non-relativistic velocities of turbulent modes interacting resonantly with particles.

Section 1.3.4, devoted to the problem of instabilities of magnetized relativistic jets, is, on the other hand, very well written, providing many valuable information and references, particularly relevant in the context of Chapter 3. Sections 1.4–1.5 of the Introduction are similarly well organised; however here large parts of the text repeat those in the first Sections 2–3 of Chapter 2, in particular regarding the implementation of the radiation drag force following Cerutti et al. (2013) —- whose ZELTRON code (or, rather, a customized version of the code) was used by Mr. José Ortuño-Macías in his numerical analysis —- and the general simulation setups, and as such seem obsolete.

In Chapter 2 of the thesis, the author presents the result of kinetic (PIC) simulations of relativistic magnetic reconnection in electron–positron plasma, including the dynamical influence of the synchrotron radiation process. This chapter was published in 2020 as a two-author paper Ortuño-Macías & Nalewajko, in the international high-impact factor journal Monthly Notices of the Royal Astronomical Society; on the day of writing of this review, the paper was cited eight times according to the SAO/NASA Astrophysics Data System (ADS).

The simulations presented here follows the evolution of plasmoids, which are generated in the central region of a tearing mode-unstable Harris current layer. The main scientific results of the analysis were, in my opinion, (1) to demonstrate that

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large plasmoids, and even more precisely their cores, dominate the production of the synchrotron emission, exceeding the emissivity of the background plasma by orders of magnitude; (2) to show that relativistic "mini-jets" present within the gaps between plasmoids, contribute little to the overall radiative output of the simulated system, in contrast to some earlier theoretical speculations and models proposed; and (3) to reveal a significant stratification in the spatial distribution of particles within and around plasmoids, depending on particle energies; this stratification, together with the complex magnetic field topology of the reconnection sites, means that the integrated synchrotron continuum of the system may not reflect directly the overall particle energy distribution in a standard manner.

Important differences in the simulation setup with respect to some of the other analogous work presented in the literature, were (i) using open boundary conditions that allow outgoing particles to escape freely, instead of current layers contained in periodic domains, as the latter was shown to lead to the formation of artificially large single plasmoids, while the former provides a sustained steady-state reconnection process; and (ii) taking into account the effect of synchrotron radiation reaction on individual particles, which may effect the evolution of plasmoids.

In the Introduction of the paper, Section 1, the segment devoted to blazars and blazar jets, is very generic, however the part summarising briefly the previous research on particle acceleration in relativistic reconnection sites, is rather clear and informative, with basically all the relevant information and references provided. Sections 2 and 3 of the paper, Simulation Setup and Analysis Methods, are also very informative, and do help a reader to understand various challenges and subtleties of PIC simulations, in particular regarding the procedure of including the synchrotron radiation reaction in the simulations, or of the plasmoids identification. Sections 4–6 —- Results, Discussion, and Conclusions —- present an in-depth insight into the details of the evolution of the plasmoids, as well as of individual particles, and of their synchrotron emission, thanks to a number of well-designed plots enabling for a proper visualisation of complex evolutionary paths.

My remarks regarding this Chapter of the thesis, are more a list of questions and problems I wish the authors had commented in more detail in the text, namely:

- I do not see any big contrast in bulk Lorentz factors between the mini-jets and plasmoids (in particular, small plasmoids) identified in the simulations; if correct, isn't it to some extent surprising, keeping in mind the previous discussion of such structures in the blazar literature?
- Mini-jets appear to contribute little to the overall synchrotron radiative output of the simulated system, due to a combination of their low density and low magnetic fields; but this may not be true anymore for the inverse-Compton emission component, expected to be relevant in the high-energy segment of the electromagnetic spectrum of blazar sources, where in fact ultra-fast blazar variability has been observed; and while it is true that the authors do not follow the inverse-Compton emission of simulated particles, they nonetheless could comment on this issue.
- Individual particles seem to experience acceleration mainly due to the electric field in the current layer, coincidently with a formation of new plasmoids *"that trap the particles in the reconnection midplane"*, but not by means of stochastic, Fermi-type processes within merging plasmoids, or when scattering off the mini-jets, as discussed previously in the literature (Drake et al. 2006, Hoshino 2012); is this observation specific to the particular simulation setup by the authors, or is it a more general finding in the most recent literature reporting on PIC simulations of relativistic reconnection?
- The term "Speiser orbit" is used to describe trajectories of some individual particles in Section 4.6, but the Speiser motion is not explained or defined, or even mentioned any other time throughout the paper.

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- The authors claim in the Abstract and in the Conclusion section that *"Rapid flares of synchrotron radiation can be produced by tail-on mergers between small/fast plasmoids with large/slow targets"*, yet on the other hand they admit in Section 4.7 that *"Because of their very short duration, the contribution of these flares to the overall radiation fluence is rather insignificant."*; this may be confusing to a reader, and the authors could make it more clear if they believe that such rapid flaring signatures of merging plasmoids could be relevant/observable in the context of astrophysical AGN jets.

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In Chapter 3 of the thesis, the author presents the result of their kinetic simulations of current- and pressure-driven instabilities, and the related particle acceleration, in cylindrical magnetised jets. This chapter was published in 2022 as a multi-author paper Ortuño-Macías et al., in the international high-impact factor Astrophysical Journal.

It should be emphasized that, while the bulk of the stability analysis for relativistic astrophysical jets is typically approached in the framework of the MHD approximation, the authors here perform a series of 3D PIC simulations of collisionless pair plasma, assuming (i) ultra-relativistic equation of state for the jet particles, and (ii) a power-law scaling of the toroidal magnetic field with the distance from the jet axis, including the inner and outer cutoffs. This toroidal magnetic field is initially balanced by a combination of a gaseous pressure gradient, and the poloidal magnetic field component; the relative importance of the balancing forces changes from the force-free regime ("screw-pinch configuration"), up to magnetohydrostatic equilibrium with no poloidal field ("Z-pinch configuration"), and the authors transition smoothly between those two limits by means of the introduced mixing parameter f_{mix}. The main motivation of the study was the previous numerical work by Alves et al. (2018), who observed that during the nonlinear development of the instabilities, a large-scale induced coherent electric field appears in the axial direction, enabling for an efficient acceleration of the jet particles up to the Hillas limit.

The introduction Section 1 in the paper is, again, well written, with many relevant references and recent results summarized clearly. The list of references here could not be complete, of course, due to a large number of the papers published on the topic of the stability of relativistic magnetised jets. Similarly, the following Sections 2, Initial Configuration, is very informative and cohesive. My only remark on this subject is that, as it seems to me, in all the studied magnetohydrostatic equilibrium ($f_{mix} = 1$) configurations, the toroidal magnetic field component drops to zero at the jet boundary, while in general it doesn't have to be null at that point (in fact, in a well-defined class of jet models, toroidal magnetic field can be quite substantial at the very boundary of the outflow).

Sections 3–4 present the results of the analysis regarding instability modes. It is shown that in the $f_{mix} = 1$ case, short-wavelength modes appear quickly at the jet axis, and propagate radially outward, efficiently dissipating toroidal magnetic field to internal energies of the jet particles. The authors observe that the kink m=1 mode is the first to emerge, followed by the pinch m=0 mode, which is typically the fastest growing one, and then by the higher modes; the growth timescales increase with decreasing f_{mix} . What should be emphasized here, is the very clear presentation of the obtained results, with a number of various plots using colour coding and different curve/point shapes and styles, utilized to compare between different simulations performed when exploring the parameter space of the model. Such a careful presentation helps a reader a lot to get a proper insight into the jet structure and the growth of instabilities.

In Section 5 of the paper, the authors focus on particle acceleration processes. Here they show that the bulk of the acceleration takes place during the phase of a fast

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dissipation of the toroidal magnetic flux, followed by a slow magnetic dissipation phase. The fast magnetic dissipation phase involves a temporary spike of the axial electric field, and the most rapid increase in the maximum particle energies correspond indeed to the linear acceleration by this electric field along the jet axis. The maximum particles energies typically reach the Hillas limit at the end of the fast dissipation phase, and may even exceed it later on, depending on the toroidal magnetic profile and the mixing parameter f_{mix}. With more and more dynamically relevant poloidal magnetic field component, particle acceleration proceeds slower as slower, as the instability growth timescales gets longer and longer, and in general becomes more complex; in the limiting case $f_{\mathrm{mix}} = 0$, particle acceleration is rather limited, and after the fast magnetic dissipation phase the toroidal field flux basically saturates.
Finally, the authors also conclude that the magnetic X-points present in the simulations are not the sites of active magnetic reconnection, and there is in general no evidence for any efficient particle acceleration by parallel electric fields; this is most likely due to strong guide fields suppressing the efficiency of the magnetic reconnection process.

The Discussion and Conclusion Sections 6–7 summarize nicely the most important findings of the project, including particle acceleration beyond the Hillas limit, a role of the perpendicular and parallel electric fields in accelerating the jet particles, as well as astrophysical applications. In this context, let me comment that while I do see limitations in the authors' kinetic approach to the problem of a stability of magnetised relativistic jet (the scale problem!), I also appreciate the advantage of the method and the simulation setup, in particular regrading hot equation of state for the jet particles (ultrareletativistic pair plasma with $k_B T > 10^4 m_e c^2$), which is a more realistic approximation of astrophysical jets than cold plasma ($k_B T < m_e c^2$). However, I struggle to understand the simulated case of a force-free jet, $f_{\mathrm{mix}} = 0$, for which the magnetization parameter sigma is below unity for most of the jet radii, implying a completely uniform particle pressure across the outflow - how realistic such a configuration could be the first place?

All in all, I consider the doctoral thesis of Mr José Ortuño-Macías to be a truly valuable contribution to our understanding of particle acceleration in astrophysical magnetized plasma, and relativistic AGN jets in particular, and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Sincerely,

dr hab. Łukasz Filip Stawarz, prof. UJ

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