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Review of the doctoral dissertation:

Kinetic Numerical Simulations of Particle Acceleration Mechanisms in Relativistically Magnetized Jets

by José Ortuño-Macías

The doctoral thesis of Mr. José Ortuño-Macías treats on the magnetic field dissipation and particle acceleration in astrophysical magnetized relativistic jets, such as those found in active galactic nuclei (AGN) or gamma-ray bursts (GRBs). These objects are powerful sources of high-energy particles and radiation. Despite many decades of research on astrophysical jets solutions to many basic questions are still pending. Among them are non-thermal particle generation mechanisms, their efficiency, location within the jet, and the radiation emission signatures. The PhD thesis by Mr. Ortuño-Macías addresses these questions and studies particle acceleration resulting from two types of physical phenomena: 1) steady-state magnetic reconnection and 2) instabilities that build up within jets of cylindrical geometry. The studies are performed in the regime of strongly magnetized relativistic plasma that pertains to the jet launching phase, in which the energy in the form of the Poynting flux is dissipated and transferred to particles and radiation. The research is performed with state-of-the-art particle-in-cell (PIC) kinetic numerical simulations. Scientific investigations are timely and of current great interest in high-energy astrophysics, as solving a long-standing question about the origin of accelerated particles has become more pressing in recent years with the inflow of high-quality data of multi-wavelength and multi-messenger observations.

The doctoral dissertation is written in English and submitted in the form of a collection of two thematically related scientific articles that are preceded with the introduction, as required. The first article by Ortuño-Macías and Nalewajko (2020), *Radiative kinetic simulations of steady-state relativistic plasmoid magnetic reconnection,* is published in Monthly Notices of the Royal Astronomical Society (497, 1365–1381). The second paper by Ortuño-Macías et al. (2022), *Kinetic Simulations of Instabilities and Particle Acceleration in Cylindrical Magnetized Relativistic Jets*, is published in the Astrophysical Journal (931:137, 22pp).

The comprehensive introduction contains 7 sections. The first section introduces basic characteristics of AGN jets and radiative processes. The second section describes observed properties of blazars and shortly other high-energy astrophysical relativistic objects. Non-thermal particle acceleration mechanisms are presented in the third section with an extended review of current state of research on relativistic magnetic reconnection and instabilities in magnetized jets – an introduction to the topics addressed in the thesis. The fourth section presents the method of kinetic PIC simulations, selected numerical algorithms, and features of the PIC code Zeltron. Some details of the simulation setups used in the studies are given in the fifth section. Section 6 describes motivations and the thesis overview, and the seventh section contains discussion of the future prospects.

Relativistic magnetic reconnection has been extensively studied in recent years with PIC simulations by many international teams. The novelty of the approach presented in the work by Ortuño-Macías and Nalewajko (2020) is to include different levels of strong radiative energy losses due to the synchrotron radiation reaction and calculate synchrotron emission light curves directly from simulations. The approach assumes open-boundaries to ensure steady-state system evolution. Very large-scale and long-time 2D simulations have been performed for electron-positron plasma. The paper presents very detailed, sophisticated and involved analysis of magnetic reconnection in the range of particle cooling lengths, as given by a combination of plasma magnetization and temperature. Tracing the properties of individual plasmoids and particle acceleration histories allows the Authors to get detailed insight into the microphysical processes involved. Their work contains several important new results. They first confirm the general features of steady-state magnetic reconnection known from earlier works. They further find that the main sites of synchrotron emission are the cores of large plasmoids, in which particle densities are significantly enhanced due to efficient radiative cooling. They demonstrate that rapid bright flares result from tail-on mergers of small/fast and large/slow plasmoids. They also show that minijets that are relativistic outflows between the plasmoids do not significantly contribute to the observed radiation due to low particle densities in these structures. These results are discussed in a broad context of observational and other theoretical findings.

The second paper by Ortuño-Macías et al. (2022) studies cylindrical static relativistic magnetized jets in pair plasmas with 3D large-scale PIC simulations. A novel approach in this work is to design a new radial profile of toroidal magnetic field, for which the contributions of forces due to the axial magnetic field and the gas pressure that provide the initial equilibrium are controlled with a single parameter. This allows a transition between configurations that have been earlier investigated by others and restricted to either purely gas pressure-balanced or the axial field-balanced configurations. The Authors also investigate the effects of the power-law index of the radial profile of the toroidal magnetic field. They show that all configurations under study are unstable. The kink mode is dominant except the case of the toroidal magnetic stress being balanced entirely by the gas pressure, for which the growth rate of the kink mode is comparable to that of the pinch mode. These instabilities lead to dissipation of the toroidal magnetic field and particle acceleration. It is found that magnetic dissipation proceeds through the fast and slow phase, and only in the fast phase particles are efficiently accelerated. The acceleration is provided mainly by the induced coherent axial electric field. The energy of accelerated particles is limited by finite duration of the fast magnetic field dissipation phase.

The results briefly summarized above and presented and discussed in full in the thesis concern current and highly-debated problems in high-energy astrophysics. State-of-the-art research methods are used to deliver original important solutions to two related, though quite distinct research topics. The results are published in high-rank scientific journals. The Candidate declares that his contribution to both publications was to prepare the setup of PIC simulations, perform most of the numerical experiments and the analysis of the results including their graphical presentation, and to write most of the body of the manuscripts. He estimates the percentage of his contribution to 70% in the first paper and 60% in the second paper. This is compatible with declarations of the coauthors. In particular, the supervisor of the thesis, dr. hab. Krzysztof Nalewajko, estimates his contribution to 30% in both works. Beside designing and directing the project, he also executed some of the simulations, performed some of the data analysis and wrote parts of the manuscripts. Though it seems not typical that the execution of simulations and data analysis is not performed solely by a PhD student, it is fully justified in this specific case by the wide range of the simulations and the comprehensive scope of the data analysis that both are time-consuming. One should also note, that contributions of other coauthors of the second paper were restricted to provide comments on the results and the manuscript or an advice on the direction of the project. Therefore, in my opinion the Candidate's contribution to the dissertation is well adequate.

Scientific publications included in the thesis are of the highest quality, are very well organized and written. In comparison, the introduction to the thesis falls a little shorter in quality. Apart from some typos and editorial mistakes, there are few inconsistencies in notation (e.g., ρ in Eq. 1.14 on p. 20 denotes the mass density, in the footnote of the same page the resistivity, and on p. 25 the charge density), lack of definitions of variables (e.g., $\lambda(x)$ in Eq. 1.40), improper use of some terminology (e.g., the word "phenomena" is often used instead of "object" in relation to objects, such as, e.g., the Crab Nebula, pulsar wind nebulae, jets), or inconsistent information (e.g., the text suggests that Boris pusher is used in Zeltron code, whereas a more advanced Vay pusher is implemented, as noted in publications). In my opinion, the introduction could have also been extended with information that is not given in the papers. This might have contained the results of tests of numerical convergence that is typically presented in dissertations that use numerical methods. It might have also provided a more extended justification for the use of the specific parameter ranges. As an example, I could not find in the papers a justification for the use of chosen values of magnetizations and plasma temperatures, that would quote specific observations.

These shortcomings of the dissertation do not in any way reduce my very high assessment of the presented research. The content of the dissertation, both of the introduction and the research papers and including the adequate literature review, shows that the PhD candidate has a well-established and comprehensive general knowledge in his field of research and scientific discipline astronomy. I expect a high impact of the publications contained in this thesis on the follow-up research and the discipline. I am certain that Mr. José Ortuño-Macías will be able to independently conduct scientific work in the future.

In summary, I consider the doctoral thesis of Mr. José Ortuño-Macías to be a valuable contribution and to meet the criteria prescribed by law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Jacek Niemiec