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Review of a thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Astronomy by Fatemeh Kayanikhoo

Summary of the thesis.

Fatemeh performs numerical simulation of ultraluminous X-ray sources(ULXs), astrophysical systems containing accreting neutron stars (NSs) with moderately strong magnetic fields, and accreting at super-Eddington rates. The origin of ULXs is a hotly debated topic, especially after discovery of coherent pulsation, suggesting that in some cases the accretor is a NS.

The work is composed of two main parts: (i) a more technical comparison of PLUTO and KORAL MHD codes; (ii) more practically-oriented study of super-Eddington accretion onto neutron stars. In the submitted form, sections of part (ii) are separated into a separate chapter/preprint

First the author conducts comparative tests of two major codes, Koral and Pluto.

Major part of the work includes simulations of NS accretion for different surface magnetic fields and different mass accretion rates.

It was found that the weaker dipole simulation results in higher apparent luminosity. For example, in simulations with 10^{10} G magnetic field, the apparent luminosity about 120 Eddington was observed, while for stronger fields of 10^{11} gauss the resulting luminosity drooped to approximately 40 times Eddington. The apparent luminosity increases with the increase of the accretion rate.

The major conclusion is that independently of the strength of the surface magnetic field, for accretion rates beyond 300 Eddington, apparent luminosity is exceeding $\sim$ 100 Eddington was observed, compatible with observations of ULX.

General relativistic radiative magnetohydrodynamic code

Aims and results of each project

Chapter 2: Energy distribution and substructure formation in astrophysical MHD simulations

The authors assess the reliability of the state-of-the-art numerical codes, PLUTO and KORAL by quantifying and discussing the impact of dimensionality, resolution, and code accuracy on magnetic energy dissipation, reconnection rate, and substructure formation. Results obtained with relativistic and non-relativistic, resistive and non-resistive, as well as two- and three-dimensional set-ups performing the Orszag-Tang test problem are compared. It is found that sufficient resolution in each model, for which numerical error is negligible and the resolution does not significantly affect the magnetic energy dissipation and reconnection rate. Non-relativistic simulations show that at sufficient resolution, magnetic and kinetic energies convert to internal energy and heat the plasma. In the relativistic system, energy components undergo mutual conversion during the simulation time, which leads to a substantial increase in magnetic energy at 20 per cent and 90 per cent of the total simulation time of 10 light-crossing times the magnetic field is amplified by a factor of 5 due to relativistic shocks. It is demonstrated that in KORAL simulations more substructures are captured than in PLUTO simulations.

Chapter 3 and Chapter 4. The two Chapters are closely related, but are separated into two papers to be published separately.

Chapter 3 describes studies of Super-Eddington accretion onto neutron stars with moderate magnetic field. Numerical simulations of super-Eddington accretion onto neutron stars with various surface magnetic fields are performed. Different accretion rates are considered. The outflows propagate to angles close to the polar axis resulting in the cone-like optically thin region through which radiation flux escape towards the observer. This cone-like region widens with increasing dipole strength. Thus the radiation is more collimated in the weaker dipole in comparison to the stronger dipole.

It is also found that magnetospheric radii are consistently smaller than predicted by basic analytical models.

It is concluded that the ULXs are likely accreting neutron stars with dipole magnetic fields of the order of 1010 G which they accrete beyond 300 L_{Edd}.. A caveat is that even with long simulations performed, they reach about one-quarter of the pulsation period detected in PULXs. Thus the results are not suitable for the study of PULXs. Additionally, the thick outflows depending on the viewing angle may obscure the pulsation.

Paper 2: Moderately magnetized accreting neutron stars as ULXs with strong outflows

Here authors concentrate on the particular part of Paper 1, and perform perform radiative magnetohydrodynamics simulations in general relativity (GRRMHD) of super- Eddington accretion disk onto neutron stars endowed with a magnetic dipole corresponding to surface strengths not exceeding 100 GigaGauss. Accretion is found to power strong outflows which collimate the emergent radiation of the accretion columns, leading to apparent radiative luminosities of 100 Eddington, when the true luminosity is a few Eddington units. Surprisingly, the collimation cone/angle widens with increasing magnetic field. Thus, in the simulations the apparent luminosity of the neutron star is substantially larger for weaker magnetic fields (10^{10} G) than for the stronger ones (10^{11} G).

Impact on the field

The thesis present the results of fundamental, and numerically very challenging, simulations of relativistic accreting sources, that includes effects of general relativistic, plasma physics, and - most difficult and challenging - radiation transfers. The work includes both numerically oriented parts (comparison of different codes), and astrophysical applications to accreting Ultra Luminous X-ray sources.

Limitations of the approach, as well as plans to address them in future works are clearly stated, eg future use of the HEROIC code that is capable of computing the radiation fields and spectra.

Overall summary

The thesis summarizes the work with one paper published, two more are ready for submission. The work demonstrates both the proficiency, knowledge of the fields and methods, as well as critical analysis and clear ways to improve the work/future goals.

I consider that

- the doctoral dissertation constitutes an original solution to a scientific problem,
- the dissertation demonstrates the candidate's general theoretical knowledge in a given scientific discipline,
- the dissertation demonstrates the candidate's ability to independently conduct scientific work

Summing up, I consider the doctoral thesis of Fatemeh Kayanikhoo to be a valuable contribution 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.

Best regards,

Maxim Lyutikov,