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Doctoral Thesis: **Probing the nature of super-Eddington accretion in ultraluminous X-ray sources**

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Referee's report:

The subject of the submitted Thesis by Samaresh Mondal is Probing the nature of the super-Eddington accretion in Ultraluminous X-ray sources (ULXs). ULXs represent an interesting class of astronomical objects on the X-ray sky. Their luminosity is higher than the usual luminosity of X-ray Binaries (XRBs). XRBs are binary-star systems, in which matter from one star accretes on a compact object, which can be a white dwarf, neutron star or a black hole. The high X-ray luminosity of ULXs led to two major hypotheses of their nature – either, there is much more matter that accretes on the compact object than expected, or the compact object must have a substantially larger mass. The second hypothesis led to a speculation that ULXs represent a not-yet revealed class of intermediate-mass black holes which can be the results of stellar interactions in globular clusters. A prototypical candidate for such an intermediate-mass black hole has been HLX-1, which remains the only solid candidate for this interpretation. For other sources, a breakthrough discovery was made by Bachetti et al. (2014) who discovered periodic pulsations in some ULXs with the short period hardly to be explained by a relatively large compact object. The period best corresponded to a rotational period of magnetized neutron stars. Therefore, most ULXs are now believed to be highly accreting neutron stars or stellar-mass black holes. Their accretion luminosity, however, exceeds the Eddington limit, for which the radiation pressure balances the gravitational attraction. Thus, these systems represent unique laboratories to study the super-Eddington accretion at work.

Samaresh Mondal has studied three ULXs and performed an original spectral and timing analysis of their X-ray observations using various X-ray satellites, including Chandra, XMM-Newton, Suzaku and NuSTAR space telescopes. His analysis led to

publication of three papers in highly-ranked astronomical journal, in which Samaresh is the first author, confirming his primary role in the research investigation. The performed spectral-timing analysis led to a better understanding of the role of different components responsible for the observed X-ray emission. In NGC 5055 X-1, the authors found an anti-correlation between the luminosity and the inner disc temperature, confirming the accretion exceeding the Eddington limit. In Circinus ULX5, the authors found subtle division of accretion states during the evolution of X-ray flux. In NGC 7456 ULX-1, they found for the first time the evidence of both an iron line and soft X-ray time lag.

Finally, the presented 4th paper (first chronologically) discusses the connection between the merging double compact objects and ULXs. It is an interesting theoretical work addressing a question whether the merging compact sources, being detected via gravitational waves, can go through ULX phase. Their work predicts that about 50% of double black holes evolve through an ULX phase. Similarly to previous three papers, also this paper is published in a highly-ranked refereed journal.

The Thesis is written as a collection of these four papers with a general introduction, in which the ULX problematics is well explained and also the student's contribution to the achieved work is described there. The Thesis contains original scientific results, as also approved by four publications published in highly-ranked reviewed journals. The results thus already went through a detailed review process and were found to be original scientific results.

Regarding the results, I would have a few questions that can be discussed during the Thesis defense:

1) It has not been ruled out that the studied ULXs can have a neutron star as the highly-accreting compact object, but the thermal black body of the neutron-star surface was not included in the spectral model for X-ray data fitting. Could such a component have any effects on the achieved results, namely on the inner accretion disc temperature measurements, and thus also on the found anti-correlation with the luminosity in NGC 5055 X-1?
2) In Paper II, different spectral states are identified in the ULX Circinus ULX5, and in Discussion of that paper, the state evolution is compared to q-shaped state diagram of XRBs. Why shall we expect spectral transitions of ULXs to follow the XRBs diagram where the accretion rate varies by several orders of magnitude between the low/hard and high/soft state. Shouldn't ULXs represent the upper extension of such diagrams rather than to be compared to all XRB's states?
3) Based on the found percentage of BH-BH progenitors that probably go through the ULX phase, could you predict how many BH-BH merging events should be observed by LIGO based on the known ULX population in local Universe, or the uncertainties (both in modelling and observations) prevail and such analysis would not be yet much conclusive?

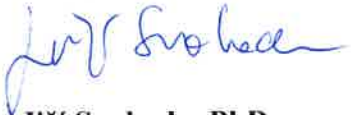
Some minor comments:

- on page 3, the XRB outburst is described as a sudden luminosity increase by order of magnitudes, but is estimated to reach only 1-5% of the Eddington luminosity, while the quiescence is estimated to be at 0.1-0.5% of the Eddington luminosity. The difference between those two ranges is not "order of magnitudes", but it is mainly that the outburst can reach much higher luminosity and quiescence is usually meant to be at much lower luminosity
- the Thesis structure in the Introduction could be improved – the description of the Thesis structure starts with "In the following section 1.2" but it appears before the start of the sub-section 1.1.1, and there are four other subsections before the Section 1.2. Some subsections in the Introduction (1.1, 1.1.1, 1.1.2) are finalised by a paragraph describing the motivation or the work that was done by the author. While it gives a good idea how the work is related to each part of these Introduction subsections, a clearer structure would be with a standalone section on Motivation and keep the Introduction to describe the basic facts about ULXs and X-ray data reduction.
- some references should be added in the Introduction, e.g., in Sect. 1.3 when the author describes that "Compact radio emission was detected from a couple of ULXs.", there is no reference to that. Also in Sect. 1.4 "The XLF of ULXs indicates that they belong to the high mass XRB category.", some more explanation or reference to this statement would be useful.
- When the references are not numbered, I believe the Bibliography should be sorted according to the alphabet for easier search in the literature

These minor remarks should, however, not affect my overall very good impression of the achieved high-quality scientific results and carefully written text of the submitted Thesis. I also appreciate brief and clear conclusions in the last Section of Introduction, clearly describing the author's contribution to the ULX research.

Summing up, I consider the doctoral thesis of Samaresh Mondal 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.

In Prague, on 12th of October 2021



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