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Referee's Report on the Doctoral Dissertation
Probing the nature of super-Eddington accretion in ultraluminous X-ray sources
submitted to the Nicolaus Copernicus Astronomical Center by mgr Samaresh Mondal

1 Introduction

Mgr Samaresh Mondal presents in his PhD dissertation the results of a research related to several aspects of the physics of ultraluminous X-ray sources. This class of accreting objects gathers a lot of attention among the astrophysicists community since several decades. First of all, the ULX apparent luminosity corresponds to the expected luminosity of systems with the missing black hole population of intermediate mass, in a range between $\approx$20 and 100000 solar masses. When in 1990-ties the ULX sources were confirmed to reside at positions far from the host galaxy nucleus, they became the best candidates for the intermediate mass black holes. On the other hand, if ULX are the stellar mass black holes or neutron stars, there should be a mechanism making them to shine at luminosity greatly exceeding the Eddington luminosity. This boosted the studies invoking various phenomena responsible for beaming of the emission. These studies were intensified after a discovery that several ULX host a pulsar. Finally, a detection of gravitational waves generated by merging stellar black holes revealed that the masses of merging objects are very often larger than the masses of confirmed Galactic stellar black holes. The ULX studies can help to explain an origin of such massive binary systems.

Since the ULX emission in the bands of energy lower than X-rays is weak and predominantly of the accretion disk origin, an unambiguous determination of the compact object mass is very difficult. Only for two sources it was possible to constrain that mass from the optical light curve of the companion star, but the limits are quite wide. Thus, except for the confirmed neutron star systems the masses of ULX are still unknown. In such a situation, until better optical data are provided, the research conducted in the X-ray band should be extended to various aspects of the system emission, among them the variability studies, discrete features spectroscopy and a detection at energies above 10 keV, enabled with the NuSTAR satellite.

A recent progress in the modelling of the neutron star accreting at a high rate demonstrated that many properties of ULX can be explained by that scenario, with several mechanisms proposed for a quenching of the pulsed emission. This may point towards the neutron star nature of large of even majority of ULX. On the other hand, there is also a growing evidence for a black hole nature of many ULX, based on the variability study and an examination of the high energy spectral cut-off. Compared to the neutron star scenario with a luminosity greatly exceeding the Eddington luminosity, the massive stellar black hole ULX would accrete slightly above or around the Eddington limit. This, in turn offers a possible connection between extragalactic ULX and Galactic ULX candidates, like SS 433 and the systems accreting near the Eddington limit, like V4641 Sgr, GRS 1915+105 and V404 Cygni. Nevertheless, there is a possibility that a fraction of ULX is related to the intermediate mass black holes, with the new candidates found by the recent ULX population studies. There is also a growing theoretical effort to connect these sources with the high mass stellar BH mergers observed by the gravitational wave observatories. All this shows that the ULX are one of the most intense astrophysics' fields explored currently.

2 Dissertation contents

The dissertation consists of 75 (36+39) pages. The contents is divided into five main chapters accompanied by a supplementary material. The main chapters are Introduction and the four chapters presenting the research results in a form of the four papers published by the Author and his collaborators:

- *An extreme ultraluminous X-ray source X-1 in NGC 5055*,
  S. Mondal, A. Różańska, E.V. Lai, and B. De Marco, A&A 642, A94, 2020 (1 citation);
- *Spectral state transitions in Circinus ULX5*,
  S. Mondal, A. Różańska, P. Bagińska, A. Markowitz, and B. De Marco, A&A 651, A54, 2021 (0 citations);
- *Evidence for Fe K_α line and soft X-ray lag in NGC 7456 ultraluminous X-ray source-1*,
  S. Mondal, A. Różańska, B. DeMarco, and A. Marcowitz, MNRAS 505, L106, 2021 (—).
- *The connection between merging double compact objects and the ultraluminous X-ray sources*,
  S. Mondal, K. Belczyński, G. Wiktorowicz, J.-P. Lasota, and A.R. King, MNRAS 491, 2747, 2020 (11 citations).

The main chapters are preceded by the Abstract (English and Polish versions), Acknowledgments, List of abbreviations, Table of symbols and List of contents. The list of references appears after the Introduction.

Introduction is divided into 6 sections. In the first section the Author presents basic facts about the ultraluminous X-ray sources. The second, widest section provides an information on the X-ray properties of the ULX sources. Then, the counterparts of ULX in other energy bands and ULX as possible predecessors of merging double compact objects are shortly introduced in the next two sections. A motivation of the thesis is given in section five. The last section are Concluding remarks. There are 7 figures presented in the Introduction. The list of references consists of 95 positions, cited in the Introduction and in the four papers included.

Chapter 2 is the original paper on the timing and spectral studies of the extreme ULX hosted by NGC 5055 galaxy. The Authors analyzed the Chandra and XMM-Newton spectra, concentrating on a comparison of the multicolour and slim disk models. In addition, correlations between several spectral parameters were studied. A broad-band analysis of data from the Suzaku, XMM-Newton and NuSTAR observations of Circinus ULX5 is presented in the second paper (chapter 3). Spectral states transitions over 17 years were studied by an application of several accretion models and the hardness-intensity diagram. The third paper (chapter 4) contains a report on the spectral and timing analysis of data collected by XMM-Newton for ULX-1 hosted by NGC 7456 galaxy. In this case, besides the spectral modelling revealing a presence of the iron fluorescence line, a quite comprehensive examination of the source variability was performed. Contrary to the first three papers, the fourth paper (chapter 5) presents the results of a theoretical study aiming at finding a connection between the ULX and merging double compact objects. The Authors explored various aspects of the isolated binary system evolution applying a population synthesis code to determine the ULX phase probability for merging DCOs.

3 Remarks

3.1 Major issues

Paper IV

Paper IV lacks a Discussion section. Although many details of the obtained results are commented in the Results section, it will be desired to compare some aspects of the analysis with the results obtained by other groups, e.g., Finke and Razzaque 2017, Marchant et al. 2017, Middleton and King 2017, Klencki and Nelemans 2018. This way the Authors can confront their conclusions with those derived based on different assumptions or with the use of other population codes.

3.2 Minor issues

Abstract, third paragraph, third sentence
The parameter constraining the line origin is just a width of the line, not its equivalent width.

Streszczenie, last but two sentence
The Polish translation does not correspond to the Abstract and the content of Paper IV where only the isolated binary evolution scenario was examined.

Sec. 1.1, first sentence of the second paragraph
Word “outskirts” seems not adequate here, some ULX are observed quite close to the galaxy centre.

Sec. 1.1.1, last but sentence of the first paragraph
Both ranges provided for the XRB luminosity are not quite correct. During the outburst the luminosity can reach level close to the Eddington limit (see next issue), whereas during the quiescence it can be well below the quoted value of 0.1%.

Sec. 1.1.1, last paragraph, first sentence
This is not true that the Galactic BH XRB never reach the Eddington luminosity. There are two outbursting sources, V4641 Sgr and V404 Cygni, and one persistent source, GRS 1915+105, for which for some periods the luminosity was very close or even above the Eddington luminosity, see e.g. M. Revnivtsev et al. A&A 391, 1013, 2002 (V4641 Sgr), K. Vierdayanti et al., PASJ 62, 239, 2010 (GRS 1915+105), S.E. Motta et al., MNRAS 468, 981, 2017 (V404 Cygni).

Sec. 1.1.2, last sentence
The statement about the spectral changes appears too strong. The Author should specify what type of the spectral variability was found by him for the first time. Spectral shape changes observed for ULX are discussed by P. Kaaret, H. Feng, and T.P. Roberts (ARA&A 55, 303, 2017), with many examples of the variability listed, in particular the transitions between the spectral states mentioned in the last paragraph of Sec. 2.5 of their review.

Sec. 1.2.2, diskbb model subsection
The diskbb model is not accurate for disk inner radii close to 6 R_g, due to a neglected condition of a torque-free boundary. A better solution is the diskpn model (Gierliński et al., MNRAS 309, 496, 1999).

Sec. 1.2.2, nthcomp subsection
The last two sentences seem to be somewhat unclear and incorrect. In the first of this sentences probably there should be word “which” added before “have energies”. The second sentence is improper because the nthcomp model offers a high-energy cut-off that is more steep than the exponential cut-off. This gives a better approximation of the true Comptonization, where the sharp cut-off comes from the two facts: the high-energy cut-off of the electron population and decreasing number of multiple scatterings on high-energy electrons. By the way, currently this model is superseded by a more accurate thcomp model (A.A. Zdziarski et al., MNRAS 492, 5234, 2020).

Sec. 1.2.2, end of the last paragraph
In practice, for a limited sample size (limited number of spectral channels), the Akaike information criterion should be replaced by the sample-size corected AIC (N. Sugiura, Comm. Statist. A7, 13, 1978).

Sec. 1.2.4, first paragraph and caption to Fig. 1.6
The statement that the high-energy cut-off in the XRB and AGN spectra appears at energies around 100 keV is oversimplified. When the spectra are fitted with the Comptonization models, there is a quite wide range of the plasma temperature observed, between $\approx$20 and $\approx$200 keV.

Bibliography
References are ordered as they appear in the Introduction. An alphabetical order or a numbered list would be a

better choice to allow the reader easier finding of a given reference.

Paper I, Abstract, Results
In the second sentence the Authors conclude that there is no spectral variability. Then, in the rest of that paragraph they state about quite tight correlations between some spectral parameters. That means that the spectral variability was statistically meaningful, wasn't it? Maybe it should be stated that there was a small spectral variability found within a given observation, whereas the spectral models obtained for different periods were substantially different?

Paper I, Table 2
It can be interesting to estimate the uncertainty for flux and luminosity. This can be done using the Xspec cflux model. How this ucertainty values compare with the differences of the fluxes for the three observations? How does taking it into account change the results of the luminosity-temperature dependence?

Paper II, Sec. 5.2, Table 3
As mentioned above, for Sec. 1.2.2. of Introduction, it can be interesting to check the model comparison with the sample-size corrected AIC test.

Paper III, Sec. 3.1
The iron line significance can be also checked using the sample-size corrected AIC test.

Paper III, Sec. 4
The Authors should comment very large value of the equivalent line width found for the iron line: e.g., what can be a possible origin of the line, is it correlated with the flux when compared with the M82 X-1 line?

It can be useful to comment here the significance of soft lags observed for other ULX.

3.3 Editorial corrections

The dissertation is written in English, the text is clear and concise. The only issue is the use of the conjunction "Whereas" starting many times a single depended clause instead of using it as a part of a compound sentence. There is a number of misprints, listed below.

Abstract, third paragraph, end of second sentence
"receptively" –> "respectively"

Abstract, third paragraph, fourth sentence
"1000 s–40 ks" –> "1–40 ks"

Abstract, third paragraph, fifth sentence
"Form" –> "From"

Abstract, fourth paragraph, first sentence
"advance LIGO/Virgo" –> "Advanced LIGO/Virgo"

Streszczenie, first word
"Ultra jasne" –> "Ultrajasne"

Streszczenie, second paragraph, first sentence
"alizę" –> "analizę"

Streszczenie, second paragraph, seventh sentence
"źródsło" –> "źródło"

Streszczenie, second paragraph, eighth sentence
"najmiej" –> "najmniej"

Streszczenie, second paragraph, last but one sentence
"wewnęrzne" –> "wewnętrzne"

Streszczenie, third paragraph, second sentence
"energi" –> "energii"

Streszczenie, third paragraph, third sentence
Word "równoważnej" should not appear here, see the first of Minor issues.

Streszczenie, third paragraph, fifth sentence
"analiza czasowa" –> "analiza zmienności"

Streszczenie, fourth paragraph, first sentence
"tworząć" –> "tworząc"

List of physical symbols, last position
"Fit statics" –> "Fit statistic"

Sec. 1.1.2, end of the first paragraph
"mass of a central" –> "mass of the central object"

Sec. 1.1.3, first sentence
"delectation" –> "detection"

Sec. 1.2.1, fourth paragraph, third sentence
The number of sources detected by ROSAT should be ≈ 150000, not ≈ 15000.

Sec. 1.2.1, Chandra subsection
"Advance CCD" –> "Advanced CCD"

Sec. 1.2.1, XMM-Newton subsection
"with of" –> "with a"
"optical mongering" –> "optical monitor"

Sec. 1.2.1, NuSTAR subsection
"up to 70 keV" –> "up to 79 keV"

Sec. 1.2.1, last paragraph
"was to used" –> "was to use"
"mutli-epoch" –> "multi-epoch"

Sec. 1.2.2, last paragraph, the fourth, fifth and eighth sentences
"statics" –> "statistic"

Sec. 1.2.3, second paragraph
"Feng and Kaaret (2009) studies" –> "Feng and Kaaret (2009) studied"

Sec. 1.4, first paragraph
"super-giant donor, named B9Ia" –> "supergiant donor of B9Ia classs"
"high enough" –> "high mass enough"

4 Conclusions

Mgr Samaresh Mondal presented in his PhD dissertation a set of valuable results obtained for several individual ULX as well as for the ULX population. The examination of the isolated binaries evolution using the StarTrack population code and based on numerous realistic assumptions demonstrated that nearly 50% of merging DCOs in the local Universe were preceded by the ULX phase. This is an important conclusion, connecting the two classes of objects, ULX and gravitational wave sources, intensively studied within the XXI century's astronomy. For the three selected ULX the Author explored the spectral and timing data collected by several modern observatories. In the case of extremely luminous NGC 5055 X-1 this diagnosis pointed towards a stellar mass accretor with a slim disk scenario and a strong beaming of the emission due to the optically thick wind. A stellar mass object was also found for the second extremely luminous Circinus ULX5, exhibiting an unusual spectral variability with the three distinct states identified. The hard excess seen above 10 keV was interpreted as a hint of a neutron star, despite the pulsed emission not observed. For the third studied source, NGC 7456 ULX-1, both an iron fluorescence line and soft band emission lag were found for the first time in a single ULX system. This work exposed some difficulties with the soft lag interpretation within the reverberation or wind reprocessing scenarios.

From the scientific point of view the thesis prepared by mgr Samaresh Mondal substantially contributes to the field of ultraluminous X-ray sources. Studying the evolution of double compact objects in the context of the ULX phase the Author proved his competence in performing a comprehensive population modelling with a number of various ingredients. On the other hand, examining properties of the three individual ULX the Author demonstrated an ability to reduce and analyze properly spectra and timing data from XMM-Newton, Suzaku, NuSTAR and Chandra satellites, using also his own software. Interpreting the results the Author performed various calculations, aiming at examination of the correlations between various parameters of the studied objects. The results were compared with those coming from other studies and discussed in a relation to various aspects.

Presentation of the results in the thesis is clear, with a convincing interpretation. Despite several minor issues related to some information given in Introduction and details of the statistical analysis the Author proved a high level of his expertise to carry on the research tasks. In conclusion, the PhD thesis of mgr Samaresh Mondal fully satisfies all the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defence.

Piotr Lubiński

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