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To the Scientific Council of Nicolaus Copernicus Astronomical Center Polish Academy of Sciences
Bartycka 18, 00-716 Warsaw, Poland.

I, the undersigned, Dr. Ciro Pinto, selected member of the PhD committee and among the referee of the doctoral dissertation hereby report my review of the doctoral thesis by Samaresh Mondal. At first, I will provide a global assessment of the work from both a theoretical and an observational perspective. Then I will go into more detail regarding the various topics addressed in the thesis.

This thesis is focused on the understanding of an extreme and important phase in the lifetime of accreting binary stars. Such astronomical objects are characterised by a compact object such as a neutron star or a black hole accreting matter from a companion star like the sun or even more massive. Here the accreted matter forms a disc around the compact object which radiates a broad electromagnetic spectrum, by means of viscosity and friction, and often peaks in the X-ray energy band. Under particular circumstances the companion or donor star undergoes epochs of extremely high transfer of matter which enables the compact object to shine above a theoretical limit known as Eddington luminosity. Ultraluminous X-ray sources (ULXs) are the most luminous accreting binaries and provide the ideal workbench to study the super-Eddington accretion mechanism. After 20 years of important developments in this research field, several questions remain unanswered regarding the structure of these extreme accretion discs, the nature of the compact objects, their influence onto the surrounding medium (or feedback), and their role in the mergers of black holes and neutron stars that produce the gravitational wave signal that have been recently discovered.

The PhD candidate, Samaresh Mondal, has therefore attempted at tackling several issues regarding the nature of the compact objects, the structure of their super-Eddington accretion discs, the overall super-Eddington mechanism, and the ULX contribution to the coalescence of compact objects and the production of gravitational waves. The work presented in the dissertation is unambiguously of high standards thanks to the use of state-of-art techniques both in terms of data analysis and theoretical modelling. The student has shown a very good knowledge of the theoretical background in the research field of accreting compact objects and an appropriate use of the literature for the analysis and the discussion of the results. The ability to switch between rather different topics and techniques - which cross various aspects of data analysis and theoretical computations - implies that a good independence to conduct the scientific work has been reached over the years. Below I will briefly discuss the major achievements of this doctoral thesis and some minor issues.

In the 1st half of the thesis (Chapters 2 and 3, i.e. Paper I and Paper II) there is a detailed X-ray spectroscopic study of two ultraluminous X-ray sources, NGC 5055 ULX-1 and Circinus ULX-5. By taking advantage of the spectral variability of the two sources and multi-epoch observations obtained with different X-ray satellites (e.g. XMM-Newton, Chandra, Suzaku, and NUSTAR), the authors have tried to decompose the ULX X-ray spectra into the 2-3 main components and place strong constraints on the accretion regime. In particular, the trend between the luminosity and the temperature of the disc is not consistent with a standard thin disc model but rather suggests an expanding photosphere, which is typical of super-Eddington accretion disc and a wind photosphere. The variability could be due either to stochastic variability in the wind driven by changes in the accretion rate or to the system precession in which the winds variable optical depth exposes

different areas of the accretion disk. This was observed in several ULXs and on similar timescales (super-orbital periods of 2-3 months). It is rather surprising that the authors have not used Swift long-term and more regular monitoring to understand the overall source behaviour. The presence of a super-Eddington accretion mechanism favours a stellar-mass compact object (a neutron star or a black hole below 15 solar masses) over sub-Eddington accretion onto an intermediate-mass BH.

Chapter 4 (i.e. Paper III) reports an interesting study of spectral and timing properties in the bright and variable (on short, hours, timescales) ultraluminous X-ray source NGC 7456 ULX-1. The paper reports findings of interesting spectral and timing characteristics that could place constraints on the geometry and nature of the binary system. At first, the detection of a putative Fe K 6.4 keV line could reveal potential X-ray reprocessing in the outer part of the disc. Secondly, there is evidence for a time delay of 1 ks between the soft and hard X-ray band with the former lagging the latter. The large size of the lag could reveal multiple Compton down scattering in a dense wind which can only be possible in a super-Eddington accretion scenario, ultimately ruling out the presence of an intermediate mass black hole. Should these features be confirmed at a higher significance (>3σ) in deeper observations, they would be of great relevance for the understanding of the system geometry and accretion regime. Both Chapter 3 and 4 would have benefited from a discussion of the implications that these variable ULXs have on the rest of the ULX sample which (according to the authors) have insignificant variability (although see my comment below). In other words, it would need a sentence in which they explain why understanding these peculiarly variable sources would allow us to place constraints on the whole ULX population and the super-Eddington mechanism.

Chapter 5 (i.e. Paper IV) shows an outstanding attempt to understand the evolution of binary systems that undergo a ULX phase with particular focus on those who are able to produce mergers of compact objects. These two phenomena are crucial to understand the implications of super-Eddington accretion in the binary evolution and the origin of the gravitational waves that have been recently discovered and presumably produced by merging of compact objects such as neutron stars and black holes. The work is of high standards and very well described. The physics involved is well addressed within the synthesis of binary population and evolution. Among their results, I consider of great relevance the fact that around 50% of the merging compact objects (found by gravitational waves) have likely gone through a ULX phase before the merger occurred. Only about 5% of the ULXs currently known are expected to produce such events. The authors also place substantial constraints on the duration of the super-Eddington, ULX, phase between 10^4 and 10^6 years (depending on whether Roche-lobe overflow or wind-accretion is considered). This is of great interest as it would nicely explain the 10^5 years age of the superbubbles found around a large fraction of ULXs of which the authors do not seem to be aware. Finally, the number of NS-ULXs is estimated to account for > 10% of the total number of ULXs which agrees with the current estimates. The results are likely robust and of great astrophysical and cosmological interest. The work would have benefited from a discussion of the role and effects of advection onto the disc structure and binary evolution which is accounted for in their computations (see comments below).

There are some small issues that made me desist from requesting the conferment of the thesis with honours (or distinction). I will summarise them here. 1) In the overall discussion of the spectral and flux variability of ULXs, the candidate has often highlighted that most ULXs do not vary at all, which is incorrect as ULXs often show a remarkable variability on long timescales (of a few months) with flux modulation likely due to the orbit or the precession of the accretion disc. In fact, all the sources that the student has studied do show remarkable variability. A discussion of the timescales and the amplitude of flux variability is unfortunately missing. 2) Another issue is the general treatment of the super-Eddington accretion. The candidate often ignores the contribution of advection in the accretion disc which can increase the amount of the matter that is dragged onto the compact object with respect to that lost into the wind. This may have a significant effect onto the evolution of the accretion disc and the whole binary system. 3) The statements regarding accretion

in Galactic classical X-ray binaries (e.g. when mentioning that they never reach luminosity close to Eddington) is not fully correct as we are aware of several black hole binaries, such as GRS 1915, and even neutron star binaries that have surpassed in more epochs the luminosity of 10^39 erg/s. 4) There are other incorrect sentences in the introduction such as "ULXs are point-like sources located on the outskirts of galaxies", which is wrong as ULXs are located everywhere in the host galaxies, some of which are even in the central regions including the famous M 82 X-1 and X-2, the 1st pulsar ever discovered. 5) The increase of neutral column density (NH) cannot be used as an argument to test wind variability if it is correlated with the powerlaw (PL) slope because this is a well known artefact produced by the steeper spectrum which if modelled with a powerlaw – instead of a comptonisation – adds soft X-ray flux which in turns requires a higher column density. 7) The presence of the Fe K line in the spectrum of NGC 7456 ULX-1 is achieved by taking the risk of oversampling the spectral resolution and without checking the effects from the high instrumental background. The latter could have been done by decreasing the radius for the source region because the adopted value is rather large (40 arc seconds) and may include spurious background photons. It is also not clear whether the look-elsewhere effect has been taken into account.

These are however technicalities that do not jeopardise the great research work performed by the student, the significant improvement provided to the current understanding of the research field in matters of super-Eddington accretion, the nature of ultraluminous X-ray sources, and ultimately the origin and production of gravitational waves.

Summing up, I consider the doctoral thesis of Samaresh Mondal to be a valuable contribution to the research field 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. Ciro Pinto