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Warsaw, 21 December 2021

Referee report for the PhD Thesis of mgr Marta Aleksandra Dziełak

The PhD Thesis of mgr Marta Dziełak titled "**Constraining the geometry of the accretion flow in black hole X-ray binaries**" prepared under the supervision of Dr. Barbara De Marco and Prof. Andrzej Zdziarski aims to address the long-standing issue whether, in the galactic X-ray binaries in their hard states, the cold disk extends down to the marginally stable orbit, or it is evaporated and replaced in the innermost part with the hot plasma flow. The author selected two representative sources with excellent data coverage to address this issue, and she used both spectral analysis and spectral-timing techniques to reach stronger conclusions.

Correspondingly, the Thesis consists of 4 major sections: the Introduction and the three sections presenting the published papers. All these papers are multi-author publications but in two of these papers mgr Dziełak is the first author (paper I and III), and in the second paper she is the second author so her contribution to these papers is essential. Declarations of co-authors confirm that.

Introduction

The first section reads well, the overview of black holes in nature is broad, the presentation of characteristic properties of the X-ray binary systems sets nicely the stage for the detailed analysis presented in the published papers. Introduction of accretion disk and the additional hot medium is well argued for. The author mentions also the non-thermal plasma which indeed may play some role. The introduction to the X-ray reflection/reprocessing is short but very good, even Auger de-excitation was mentioned. Mgr Dziełak also discuss in some detail the shape of the Kalpha line which serves as an excellent tool to study the flow geometry due to relativistic corrections to its shape. But there is a puzzling inaccuracy in the *Introduction*: a statement, that Sgr A* was already observed in X-ray in 1964 by the instrument Aerobee. To my knowledge, Sgr A* was first seen in X-rays in 2003, by Baganoff et al., using Chandra satellite. Some terms are not explained, e.g. tau which appears at page 11, although indeed the notations used is customary in the field. Second part of the Introduction is devoted to spectral-timing methods which reveal additional information about the flow geometry, and are used later in the Thesis. The third part contains well illustrated introduction to spectral states (hardness-intensity diagram for GX 339-4 is the ideal case), this subsection is also compact but competent, with very good choice of the most important information. Finally, mgr Dziełak introduces the problem of the physical conditions at the inner region of the accretion flow which she later addresses in her Thesis. This section well highlights the on-going discussion in the literature whether or not the disk in the hard state extends down to the ISCO, and this part contains numerous references to publications supporting each of these possibilities. Overall, the Introduction brings nice review of the topic of accreting black holes in binary systems.

Results contained in the Thesis

In paper I the author performs the comparison of spectral models for disc truncation in the hard state of GX 339–4 which is one of the best studied transient low-mass BH X-ray binaries. Mgr Dziełak analyzed the archival RXTE data from this source, covering a number of outbursts. She finally concentrated on the last outburst (years 2010/2011) since there the coverage of the onset of the outburst was the best. Only four brightest observations were finally selected for the data fitting, but the author tested 7 models, plus additional tests of their small modifications. The conclusion about the position of the cold disk inner radius depended on the adopted model but for the model no. 6, favored by mgr Dziełak, the inner disk radius was located at 49 Rg. The errors were unfortunately very large, so the location of the disk inner radius at the Innermost Stable Circular Orbit (ISCO) was ruled out at only 90 % confidence level. The parameters of the model 6 were physically justified, with moderate metallicity, reflection fraction rather large, as expected from the geometrical setup, and the viewing angle consistent with estimates of the inclination of the binary system. Data preparation, selection and finally data fitting required a lot of solid work. I am a little disappointed by the statement that only model 3 is actually self-consistent from the point of view of the fitted ionization parameter. Probably, forcing this self-consistency in model 6 by trying to use the higher density reflection models would give stronger arguments for the disk recession. In addition, the model 2 has a strange property to have highly ionized reflector as the distant one, and a neutral reflector close to the black hole which is rather unlikely.

The conclusion about the receding disk in the hard state was later supported by studies of Wang et al. (2020) for the same source at later epochs, using the NICER and NuSTAR data which allowed to see well the harder X-rays which implied the truncation of the cold disk at ~ 50 Rg at the onset of the outburst.

Paper II focuses on a brighter source, MAXI J1820+070, discovered only a few years ago. Mgr Dziełak in this work performs re-analysis of the data from NICER and NuSTAR with the aim to find a better model for the source evolution. Indeed, it was possible to fit the data with a truncated disk model, and such model is consistent with additional information from the satellite INTEGRAL in hard X-ray/gamma-ray band while the model without truncation over-predicts the gamma ray flux by a very large amount. As the author shows, when fitting only the X-ray data, both solutions are formally of comparable quality, and the two local minima are separated by a very high barrier, so there is no continues passage from one minimum to the other. Mgr Dziełak thus argues convincingly that the evolution in the source id due to the shrinking of the disk inner radius, instead of shrinking corona, as proposed by Kara et al. (2019). The data quality allows to firmly determine the stratification in the hot medium. The fitting procedure combines the model elements in a standard way so it does not depend on a specific geometry depicted in Figure 4 for illustrative purposes. In my personal opinion the picture most likely looks different, with the hard distant component actually coming from a vertically extended jet. Otherwise the proportions do not seem likely to me, with the height of the violet component of 500 Rg, and its radial extension down to 200 Rg only, or much less, if I understand correctly. In jet interpretation we would have the hard X-ray source also located as requested, downstream (as this would be an outflowing material) from the inner inflow.

In paper III mgr Dziełak extends her research of the same source with the goal to prove even more firmly the stratification of the hot flow. This time it is done using a complementary method, based on time analysis. The data used covers again the hard rising state as seen by NICER. Data selection for creating lightcurves was done carefully, removing the problematic or not working modules. This allowed to obtain the power spectrum density (PSD) and to decompose it into four Lorentzians.

Next the author, using the method of Axelsson, Hjalmarsdotter & Done (2013), constructs the rms spectra for each of the four individual Lorentzians. Their spectral shapes are very much different at energies below ~ 7 keV. Finally, the spectral shapes of these Lorentzians is fitted using the spectral models. The final model consists of a disk component (region I0, and two comptonization regions, softer (region II), and harder (region III), as in the previous paper. In the discussion part, the author compares the Lorentzian frequencies to the Keplerian frequencies, thus localizing the dominant radius. For the cold disk, this radius implies the position of the disk inner radius at ~ 45 Rg, supporting again the scenario of the truncated disk.

Summary

Summarizing, the Thesis contains a number of interesting results, based on extensive data fitting which required competence and patience. The error analysis was careful and competent. All papers contain a lot of references in their introductory parts, well covering the state of the field, and specifically the contradictory statements from the literature about the cold disk extension. However, I would be more happy to see additionally, in the Thesis summary, the broader context. For example, Paper I at the beginning lists nicely a lot of theoretical considerations about the disk evaporation, so it would be interesting to see if any of those can be actually ruled out by the observational results presented in the Thesis.

Conclusion

In summary, I consider the doctoral thesis of mgr Marta Aleksandra Dziełak to be a valuable contribution to the understanding of the state transitions in the Galactic black hole binaries, 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.

B Czerny

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