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Examiner's report on the Doctoral thesis of Kateřina Klimovičová

This thesis deals with the high-frequency quasi-periodic oscillations (QPOs) revealed in X-rays coming from low mass X-ray binaries (LMXBs) – systems consisting of a compact object (a stellar-mass black hole or neutron star) in a binary orbit together with an ordinary star of lower mass which has been evolving more slowly and has just reached the stage where it expands following the end of its core hydrogen-burning phase and spills matter towards its compact companion. The accreted matter typically forms a rotating disc around the compact object, with viscous stresses in the disc then causing sufficient heating to produce emission of the X-rays. The high frequency spectrum of the radiation often displays a prominent pair of peaks with frequencies in a simple number ratio (most notably 3:2). Bearing in mind the high frequency (in the region of a kilohertz), this has been taken as evidence of them being caused by resonant phenomena occurring in the innermost part of the disc. Various models have been developed over the years to explain the origin of these peaks but it still remains an open issue. This thesis focusses on cases where the compact object is a neutron star, surveying the situation for the existing models, assessing their possible validity and also advancing a number of new ideas. The work presented for evaluation consists of reprints of eight papers (Part 2), prefaced by a systematic extended introduction (Part 1), which puts the work in context and also adds some additional material. Seven of these papers have already been published in refereed journals and the eighth has recently been submitted for publication. The candidate has also been an author on nine other articles published in refereed journals (and first author on two of them).

Part 1 starts with a review of the properties of LMXBs (Chapter 1) and of the essential features of different classes of pre-existing models for the QPOs (Chapter 2) - prominent among these are the Relativistic Precession (RP) model (in a number of variants but the basic version of which involves resonance between the periastron precession frequency and orbital frequency for hot blobs of matter in the inner parts of the accretion disc), and the Epicyclic Resonance (ER) model (which involves resonant axisymmetric oscillation modes of essentially free particles in the inner parts of the disc). Also appearing in the thesis work, are the rather different Resonant Switch (RS) models (involving a combination of two of the more basic models with switching in between them). Then the presentation moves on to a brief overview of the basic features of the new models coming from the current work: the Cusp Torus (CT) model, where the accretion flow is considered to be in a toroidal configuration rather than a completely thin disc, and analytic approximations depending on either one and two parameters. In my view, the presentation in Chapters 1 and 2 is admirably succinct and to the point.

Chapter 3 contains comments on the attached papers 1-2 and 4-8, dealing directly with the properties of the QPO models being studied and fitting them to the observational data for the frequencies of the two peaks. Much of the work in those papers focusses heavily on two representative LMXBs (4U 1636-53 and Circinus X-1), because there is good frequency data available for each of them and because they are good representatives of the classes of high- and low-frequency twin peak QPO sources respectively. Also, there is particular emphasis on the RP classes of QPO models. The candidate has been concerned about the extent of concentration on just certain objects and models, and at the beginning of Chapter 3 presents an extensive range of frequency data and QPO model fits also for a range of the other sources and models, prepared specially for the thesis. The rest of Chapter 3 then contains discussion of Papers 1-2 and 4-8. Chapter 4 contains discussion of Paper 3 which deals with the situation when an oscillating torus is responsible for the QPOs, looking at how it would appear to a distant observer using a sophisticated relativistic ray-tracing code. Some new results are included here beyond those in the paper and indications are given about future work. The figures are particularly nicely presented. Chapter 5 contains the conclusion.

I now move on to comments on the attached papers forming Part 2 of the thesis.

Paper 1: *Mass-Angular-momentum Relations Implied by Models of Twin Peak Quasi-periodic Oscillations.* This paper follows on from earlier work concerned with fitting QPO data from a group of sources with low QPO frequencies to the RP model, using the Kerr geometry as an acceptable approximation for the space-time outside neutron stars with masses close to the maximum (as is the case for many of those involved with LMXBs due to the continuing accretion flow). There, it was found that the fitting gives a relation between the neutron-star mass M and angular momentum j rather than giving particular values for each of them separately. In Paper 1, this treatment was extended to sources with high QPO frequencies and using also other QPO models, finding similar behaviours with the relation between M and j. The focus is on 4U 1636-53 and Circinus X-1 as mentioned above. In the case of 4U 1636-53 the neutron-star spin frequency is independently known to be ~ 580 Hz from X-ray burst observations and approximate values for M and j compatible with that QPO model can then be calculated (unless there are no such values). This is returned to later, in Paper 5. When making the fits of the data to the RP QPO models, it is found that while this works well for Circinus X-1, the quality of the fit for 4U 1636-53 (with higher frequencies) is extremely poor, with a value of χ^2 ~ 16 dof (in comparison with ~ 1.3 for Circinus X-1). It is suggested that if the RP models are indeed correct ones for that case, there must be some unknown systematic uncertainty involved. Similar behaviour is noted for some other QPO models tested and this leads on to the considerations in Paper 2.

Paper 2: *Test of the Resonant Switch Model by Fitting the Data of Twin-Peak QPOs in the Atoll Source 4U 1636-53.* As mentioned earlier, the RS models involve two different QPO prescriptions operating at different radii with a switch from one to the other at a resonant point as one moves inwards through the disc. This worked much better for giving a satisfactory solution for 4U 1636-53. The best fit (χ^2 ~ 2.6 dof) involved two RP variants, and there was also a plausible explanation for why the switch between them should occur. The RS fitting procedure also gives alternative estimates for M and j, but the choice between them is refined later in Paper 4.

Paper 3: *Twin peak high-frequency quasi-periodic oscillations as a spectral imprint of dual oscillation modes of accretion tori.* As mentioned previously, this paper deals with the possibility that an oscillating torus is responsible for the QPOs (see Paper 6), and investigates how it would appear to a distant observer using a sophisticated relativistic ray-tracing code. It is somewhat off the main line of the thesis but is a valuable adjunct to it and is a very impressive paper in its own right. In the larger view of LMXB studies it forms an important part of the picture and is likely to be important for future developments.

Paper 4: *Equations of State in the Hartle-Thorne Model of Neutron Stars Selecting Acceptable Variants of the Resonant Switch Model of Twin QPOs in the Atoll Source 4U 1636-53.* This paper is a sequel to Paper 2, and checks on whether the alternative solutions obtained for 4U 1636-53 using the Kerr approximation for the space-time, can match with values of M and j calculated by the Hartle-Thorne method using realistic equations of state and the 580 Hz rotation frequency. A self-consistency check is also performed between the Kerr and Hartle-Thorne results before arriving at a main solution for M and j.

Paper 5: *Constraining Models of Twin-Peak Quasi-periodic Oscillations with Realistic Neutron Star Equations of State.* This follows on from Paper 1 and deals with determining specific values for M and j from the M versus j relation found there. Again this is done for the case of 4U 1636-53 using the Hartle-Thorne method together with a range of equations of state and the rotation frequency of 580 Hz. It is found that there are no viable matches for the Tidal Disruption and Warped Disc QPO models but that there *are* matches for all of the RP ones although there are doubts about them because of the frequency fitting to the QPO models being so bad. Formulae for the epicyclic and Keplerian frequencies are also calculated with the Hartle-Thorne approach and the fits obtained from them are found to be consistent with the Kerr ones, validating the approximation.

Paper 6: *Twin peak quasi-periodic oscillations as signature of oscillating cusp torus.* This paper introduced the Cusp Torus (CT) QPO model where the accretion flow is considered to be in a toroidal configuration rather than a completely thin disc. This turns out to be extremely successful giving $\chi^2 = 2.3$ dof when tested with 4U 1636-53 (as compared with 16.4 for RP) and it seems now to be a plausible model of choice although it needs wider testing. Having oscillations of a toroidal structure rather than just free particle motion seems very reasonable.

Paper 7: *On one-parametric formula relating the frequencies of twin-peak quasi-periodic oscillations.* This paper introduces and investigates a simple one-parameter formula which reproduces the frequency behaviour of a number of sources on which it has been tested although for some others a second parameter also needs to be introduced. The QPO frequencies are here calculated in Schwarzschild spacetime which is said to be a good approximation for this purpose.

Paper 8: *Simple analytic formula relating the mass and spin of accreting compact objects to their rapid X-ray variability.* This paper follows on after Paper 7, extending the treatment to rotating compact objects using Kerr and Hartle-Thorne spacetimes. I still have to study this article in detail.

In summary, I think that this thesis contains some very interesting work and makes a very significant contribution to the subject area of high frequency QPOs in LMXBs. My main caveats are that (i) Part 1 would benefit from including a short comprehensive overview of the subject matter; this is something that I missed as a reader; (ii) it would have been good to have some focussed discussion of the use of Kerr as an approximation for high-mass neutron-star spacetimes; that was alarming to me at first; (iii) there are really a lot of errors, some of which were quite disconcerting, particularly (iv) The ongoing confusion about the use of the dimensionless quadrupole symbol q, sometimes as q = QM/J^2 (= 1 for Kerr) and sometimes as q = Q/M^3 (= j^2 for Kerr). I think the actual calculations are OK but I found this business very disturbing! I would particularly recommend very carefully checking Paper 8 (the one which has just been submitted).

However, having said this, let me repeat that I like the thesis and think that it makes a very significant contribution which certainly merits award of the Doctorate.

John Miller

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