Astronomický ústav AV ČR

Michal Dovčiak
Tel.: (+420) 226 258 425
Fax: (+420) 226 258 499
dovciak@asu.cas.cz

Astronomical Institute of the Czech Academy of Sciences, Boční II 1401, CZ-14100, Praha 4, Czech Republic

REPORT ON PHD THESIS
by SUPERVISOR

Title: **Polarisation properties of X-ray emission from accreting supermassive black holes**

Author: **Jakub Podgorný**

Institution: **Faculty of Mathematics and Physics, Charles University, Prague**
École Doctorale de Physique et Chimie-Physique, Université de Strasbourg

Supervisors: **Michal Dovčiak, Frédéric Marin**

The main topic of the thesis is modelling polarisation properties of X-ray radiation coming from centers of active galaxies hosting super-massive black holes (Active Galactic Nuclei, AGN) and from accreting Galactic stellar-mass black holes forming a binary system with a donor star (X-ray binaries, XRBs).

Jakub first gives an overview of the subject in Chapter 1, where he summarises i) basic processes that induce polarisation of X-ray radiation, ii) relativistic effects changing radiation properties including polarisation as the light propagates from close vicinity of the black hole towards a distant observer, iii) X-ray polarisation detection methods including overview of past, present and future not only polarimetric X-ray missions, iv) properties of the two main object classes that are studied in his thesis, AGN and XRBs, and v) numerical codes used in his thesis for computation of radiative transfer in close vicinity of black holes including computation of polarisation properties (TITAN, STOKES, KY). This introductory Chapter not only nicely sets up the stage for the main part of the thesis but also shows the whole breadth of this research field that Jakub needed to master to be able to contribute with his own work. Vast list of references given shows that Jakub wrote this part with meticulous survey of available literature.

In the following chapters, Jakub presents his contributions to the field. The Chapter 2 contains his research of accretion disc emission in two scenarios. In the first scenario he studies the polarisation properties of re-processed disc emission that is illuminated by X-ray corona from above which emission is approximated by a power law with cut-offs. This part is a direct continuation of his work on his master thesis, here, the full set of reflection tables was re-computed for a given set of power-law indices with the same grid in ionisation parameter assuming a constant density slab. These tables are publicly available and can be used to predict or interpret polarisation properties of (mainly) AGN observed e.g. by IXPE, the recently launched NASA/ASI mission (launched in December 2021). This work has resulted in his first first-author publication [1]. In the second scenario Jakub computed the polarisation expected from accretion disc around black holes in XRBs in their thermal state. This part was directly motivated by IXPE observation of the transient XRB, 4U 1630-47, which shows unexpectedly high polarisation degree that cannot be explained to be induced in the Chandrasekhar purely electron scattering atmosphere that was usually used to predict polarisation properties of the accretion-disc thermal emission. Jakub studied the polarisation that is induced by photon transmission through a highly ionised constant density slab including absorption effects. Jakub has computed polarisation of such a slab for various ionisation states given by its density and temperature. Although Jakub has found these solutions do predict the observed polarisation degree rise with energy, they still fail to fully explain the observed high polarisation degree in this source. This work contributes to the IXPE collaboration discovery paper on this source, [2], co-authored by Jakub, which is currently in the reviewing process. In both of these scenarios, Jakub used available tools, TITAN and STOKES, that he had to learn to use and understand various small details (e.g. how the normalization of the resultant spectra are defined). To this respect, Jakub was in communication with prof. Agatha Różańska (TITAN) and dr. René Goosmann (creator of the STOKES code).

In Chapter 3 Jakub uses the results from Chapter 2 to predict the polarisation of accretion-disc re-processed emission due to illumination, integrating the local tables over the full accretion disc including all relativistic

effects. To this purpose he uses the code developed by him during his master thesis, KYNSTOKES, to fully exploit it in the two toy model corona geometries – lamp post (point-like) corona on the system axis and extended corona close above the disc (in the equatorial plane). Jakub shows the predicted polarisation in different scenarios for differently spinning black holes, different heights and radial intensities of the corona and different ionisation of the accretion disc. Part of this work (in lamp-post geometry) is published in his second first-author paper [3].

In Chapter 4 Jakub explores the polarisation that is induced by re-processing of emission from the central engine of AGN in its distant circumnuclear components. First he uses a more physical approach applying Monte Carlo code STOKES assuming wedge and torus geometries, then he continues with a simplified approach. He integrates tables computed in Chapter 2 in two specific geometries, distant torus and far-away disc, creating new tables and XSPEC models for these cases. Finally, Jakub computes a complete picture – the polarisation for both type-1 and type-2 AGN using the simulation of polarised radiation from inner central region to illuminate the distant components. While this part is based on older works of the two supervisors, new tools created by Jakub are used to produce more physically correct picture, even finding error in the past work for the type-2 case. The first and last parts of this chapter are already published in [4] and [5], the second part (new XSPEC models) is currently under a review ([6]). All three publications are with Jakub as the leading author.

In Chapter 5 Jakub summarises all polarimetric observations of XRBs and AGN performed by IXPE at the time of the thesis writing. There are also all Jakub's research contributions to the IXPE discovery papers summarised. Except already mentioned modelling for 4U 1630-47 in [2] (under review) and [7] (published), Jakub has actively contributed with modelling and interpretation of several other XRBs, Cyg X-1 in [8] (published), Cyg X-3 in [9] (under review), 4U 1957+115 in [10] (under review), LMC X-3 in [11] (accepted) and he even very efficiently lead the IXPE collaboration observation of LMC X-1 in [12] (published with Jakub as the first author). All Jakub's contributions in these publications are applications of his modelling work described in previous chapters. With respect to AGN, except already mentioned publication of [5], Jakub participated in the team working on several IXPE observations of AGN, MCG-05-23-16 published in [13] and [14], Circinus galaxy published in [15], NGC 4151 published in [16] and IC 4329A published in [17].

Jakub concludes his work with conclusions and future prospects, where his work based on his thesis could continue, in the last chapter (Chapter 6).

As one of the two co-supervisors, I most value Jakub's truely scientific approach to all his work – he always seeks to understand the computed results and to find reasons for their particular behaviours as well as he carefully assesses range of their validity and performs comparisons with the results of other existing codes, simulations or approximations. During his work on the thesis he deepened his knowledge of general tools (as language C, Python) as well as dedicated tools (as XSPEC, TITAN, STOKES, IXPEOBSSIM) that is a necessity in this field of research. During his PhD studies he established several international collaborations, above all he became a very active and productive participant of IXPE collaboration with his modelling work and even leading one of the observations. During his PhD studies, he has published 5 first-author papers and he has actively contributed to several more published papers as a co-author. He has already presented his work on several conferences and workshops.

I am persuaded that the research work done by Jakub Podgorný that has lead to the publication of this thesis and five first-author research papers already published in Monthly Notices of the Royal Astronomical Society, as well as the thesis itself demonstrate his capability of independent scientific research. I recommend the presented work to be accepted as a PhD thesis after its successful defence.

Date: 11. 12. 2023

Michal Dovčiak

[1] **Podgorný J** et al. (2022)
Spectral and polarization properties of reflected X-ray emission from black hole accretion discs
MNRAS, 510, pp. 4723-4735, DOI: 10.1093/mnras/stab3714

[2] Ratheesh A et al. including **Podgorný J** (2023)
The high polarisation of the X-rays from the Black Hole X-ray Binary 4U 1630-47 challenges standard thin accretion disc scenario
under review in ApJ, arXiv:2304.12752.

[3] **Podgorný J** et al. (2023)
Spectral and polarization properties of reflected X-ray emission from black-hole accretion discs for a distant observer: the lamp-post model
MNRAS, 524, Issue 3, pp.3853-3876, DOI: 10.1093/mnras/stad2169

[4] **Podgorný J**, Marin F & Dovčiak M (2023)
X-ray polarization properties of partially ionized equatorial obscurers around accreting compact objects
MNRAS, 526, pp. 4929-4951, DOI: 10.1093/mnras/stad3085

[5] **Podgorný J** et al. (2024)
X-ray polarization from parsec-scale components of active galactic nuclei: observational prospects
MNRAS, 527, pp. 1114-1134, DOI: 10.1093/mnras/stad3266

[6] **Podgorný J**, Dovčiak M & Marin F (2023)
Simple numerical X-ray polarization models of reflecting axially symmetric structures around accreting compact objects
under review in MNRAS, arXiv:2310.15647

[7] Rodriguez Cavero N et al. including **Podgorný J** (2023)
The First X-Ray Polarization Observation of the Black Hole X-Ray Binary 4U 1630-47 in the Steep Power-law State
ApJL, 958, L8, DOI: 10.3847/2041-8213/acfd2c

[8] Krawczynski H et al. including **Podgorný J** (2022)
Science, 378, pp. 650-654, DOI: 10.1126/science.add5399

[9] Veledina S et al. including **Podgorný J**
Astronomical puzzle Cyg X-3 is a hidden Galactic ultraluminous X-ray source
under review in Nature Astronomy, arXiv:2303.01174

[10] Marra L et al. including **Podgorný J**
IXPE observation confirms a high spin value in the accreting black hole 4U 1957+115
under review in A&A, arXiv:2310.11125

[11] Svoboda J et al. including **Podgorný J**
First X-ray polarization measurement confirms the low black-hole spin in LMC X-3
accepted by ApJ, arXiv:2309.10813

[12] **Podgorný J** et al. (2023)
The first X-ray polarimetric observation of the black hole binary LMC X-1
MNRAS, 526, pp. 5964-5975, DOI: 10.1093/mnras/stad3103

[13] Marinucci L et al. including **Podgorný J** (2022)
Polarization constraints on the X-ray corona in Seyfert Galaxies: MCG-05-23-16
MNRAS, 516, pp. 5907-5913, DOI: 10.1093/mnras/stac2634

[14] Tagliacozzo D et al. including **Podgorný J** (2023)
The geometry of the hot corona in MCG-05-23-16 constrained by X-ray polarimetry
MNRAS, 525, pp. 4735-4743, DOI: 10.1093/mnras/stad2627

[15] Marra L et al. including **Podgorný J** (2023)
Mapping the circumnuclear regions of the Circinus galaxy with the Imaging X-ray Polarimetry Explorer
MNRAS, 519, Issue 1, pp.50-58, DOI: 10.1093/mnras/stac3189

[16] Gianolli V E et al. including **Podgorný J** (2023)
Uncovering the geometry of the hot X-ray corona in the Seyfert galaxy NGC 4151 with IXPE
MNRAS, 523, pp. 4468-4476, DOI: 10.1093/mnras/stad1697

[17] Ingram A et al. including **Podgorný J** (2023)
The X-ray polarization of the Seyfert 1 galaxy IC 4329A
MNRAS, 525, pp. 5437-5449, DOI: 10.1093/mnras/stad2625