Durham University

Department of Physics

Science Laboratories,
South Road
Durham DH1 3LE
Tel: 0191 334 361
Email Chris.Done@durham.ac.uk

28/11/2023

Report on thesis of Jakub Podgorny

X-ray polarization of radiation from black hole accretion flows is undergoing a renaissance with the launch of NASAs IXPE satellite giving the first data capable of observationally testing the models. This thesis work on studying how the geometry and physical conditions in the accretion flow can affect the X-ray polarization is then very timely and important.

The thesis starts with an introduction to polarization, and it is defined via Stokes parameters, and then gives a review of the polarization properties of various radiation mechanisms, most importantly electron/Compton scattering. This is the major process expected to give rise to polarization, both in the intrinsic X-ray radiation and from reflection/scattering from surrounding material. The chapter reviews the general relativistic effects close to a black hole, and their effect on polarisation as well as energy and intensity. There is a short discussion of how polarisation is measured, with a focus on IXPE, and then a review of the accretion flow in both stellar and supermassive black holes, and the wider nuclear structures in which this is embedded in Active galaxies (AGN) and Quasars, together with their expected polarisation. The chapter ends with a discussion of the codes used in the thesis to calculate the spectral and polarisation properties.

Chapter 2 introduces new work calculating the intrinsic polarisation properties of an accretion disc which is partially ionised rather than completely ionised as assumed in standard models of its polarisation. They use a constant density slab to approximate the surface of the disc, and it is nice to see a short discussion about how this differs from the expected hydrostatic equilibrium (or constant pressure) results. The reflection of coronal X-rays from this slab is well studied in the literature, but what is new here is the calculation of its polarisation. The dominance of bremsstrahlung and emission lines from the X-ray heated upper layer at soft X-ray energies depolarises compared to electron scattering reflection, and there is an interesting note that this could give a test of ionised reflection models for the soft X-ray excess seen in AGN, but there are no current instruments which can measure this. The effect of partial ionisation on the disc emission itself is also studies, with transmission of blackbody radiation through the slab. Here there are a number of assumptions which have to be made in the codes, some of which do not appear well motivated (photoionisation rather that collisional, vertical temperature structure). In particular, having optical depth as a free parameter, as the blackbody emission incident on the base of the slab is assumed intrinsically unpolarised, so it cannot reach the electron scattering limit unless tau>1. At these optical depths the results appear quite physical, and there is a nice discussion on how absorption can enhance polarisation above the pure scattering limit. It would have been nice to have a summary section concluding this chapter, as there were multiple results.

Chapter 3 again shows new work in integrating the results from chapter 2 on reflection from a single density partially ionised slab into a full accretion disc reflection model with lamppost X-ray reflection and full general relativistic ray tracing. The lamppost geometry sets the reflected fraction, so the contribution of reflection to the full spectrum is fixed in the model for a given disc inner radius. This should also set the ionisation state of the photoionisation but since the density is also unknown, and for comparison to previous work, the ionisation state is assumed constant, as is the disc density. These are tabulated and publically available to the community. There is also a short section on reflection in the sandwich geometry, but it seems physically inconsistent to include reflection from underneath the corona as this X-ray source has optical depth so will intercept the reflected emission and Compton scatter it again, reducing the reflected normalisation. It would have been nice to include a discussion of this point.

Chapter 4 switches topic from exploring the close vicinity of the black hole, to much more distant material in AGN. There should have been a little more discussion on the motivation for having column separated from electron scattering optical depth, as it is not really a proxy for partial ionisation since the absorption crosssections are neutral, but this is only used for understanding different torus geometry effects. The full reflection tables are then used, but these do assume optically thick columns, whereas the torus is likely optically thin, especially along lines of sight which only intersect part of this structure. The discussion here is sometimes confusing as there are many examples given, and the plots could do with a small sketch geometry on the top to better indicate which results are given. A full torus plus wind geometry is then explored, though the choice of neutral material for the wind seems unphysical if this is physically associated with the warm absorber (wind from the torus) but could be more realistic for the wind on the inner edge of the broad line region revealed by reverberation studies.

Chapter 5 reviews the new IXPE results. There is a brief discussion of the hard state of Cyg X-1. There are clear issues with understanding soft state polarisation, so it seems premature to have much confidence in the results for the one object which is possible to fit with standard models (high spin in 4U1957+115: Marra et al 2023). There is a very nice direct comparison of the reflection models in Chapter 3 with the Cyg X-1 hard state data, though it would have been nice to include a reflection dominated fit, where the lamppost enhances the reflected fraction via lightbending (though the dominant effect is a gravitational blueshift). Presumably this would require a very small source height, so general relativistic effects would depolarise the resulting reflection. The soft state of 4U1630 is also compared in detail to the models in Chapter 2, but here the blackbody temperature used for the atmosphere is significantly lower than that seen, which appears inconsistent. Cyg X-3 is fit with the AGN models of Chapter 4, as it is dominated by scattering as in Seyfert 2s, though it would be interesting to explore if the very different density makes a difference. The Seyfert 1 AGN (NGC4151, MCG-5-23-16 and IC4329A) all have X-ray spectra which are quite hard, so their similarity to the hard state Cyg X-1 is quite natural, while the Seyfert 2 Cir Galaxy is similar to Cyg X-3. The chapter concludes with prospects for detecting polarisation in Seyfert 1 and 2 AGN.

The thesis ends with a summary and future outlook.

In general the thesis is well written, and well structured. Much of the work is computational, using a variety of complex codes which in general were developed by others, but these were clearly not just used as black boxes. There is frequent cross-comparison between codes (which resulted in finding several errors) as well as most importantly, checking by assessing the physicality of the results.

In summary, this is a very impressive thesis, and clearly meets the requirements for PhD in terms of contributing to research in the field, with substantial new work as evidenced by six first author papers published in the refereed literature. I look forward to discussing the results at the viva.

Yours faithfully

Prof Chris Done