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Simulation of Black Hole Inner Accretion Disk-Corona and Optimization of the Hard X-ray Polarimeter, X-Calibur

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Simulation of Black Hole Inner Accretion Disk-Corona and Optimization of the Hard X-ray Polarimeter, X-Calibur

by

Banafsheh Beheshipour

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The Graduate School
of Washington University in
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Mass accreting stellar mass and supermassive black holes are strong sources of X-rays. The X-ray observations enable studies of the process of black hole accretion and give us information about the spacetime background. In the framework of my thesis work, I have continued the development of a general-relativistic ray-tracing code enabling the simulation of the Comptonization of photons in the hot accretion disk corona. I use the code to investigate the impact of various approximation schemes for modeling the Comptonization finding that a fully relativistic treatment is needed for accurate predictions in the soft and hard X-ray regimes (0.1-100 keV). I use the code to study the impact of the 3-D geometry of the corona on the observed X-ray flux and polarization energy spectra. Furthermore, I study the observational signatures of accretion disk hotspots orbiting the black holes. Such orbiting hotspots have been invoked to explain the presence of high-frequency quasi-periodic oscillations (HFQPOs) in the X-ray light curves from several accreting stellar-mass black holes.
holes. I use the newly developed numerical tools to model the properties of one supermassive black hole (Mrk 335) and one stellar mass black hole (GRS 1915+105). I conclude with a discussion of the scientific potential of spectral, timing, and polarimetric studies of black holes with missions such as the Imaging X-ray Polarimetry Explorer (IXPE) and the enhanced X-ray Timing and Polarimetry Mission (eXTP). As a graduate student, I played an active role in preparing the X-Calibur hard X-ray polarization mission for a long duration balloon flight from McMurdo in December 2018. My work aimed at reducing the readout noise of the polarimeter’s Cadmium Zinc Telluride (CZT) detectors. My work contributed to a substantially lower energy threshold and thus a substantially improved sensitivity of X-Calibur.
Chapter 1

Introduction

1.1 Motivation

Whereas observations test general relativity (GR) in the regime of weak gravitational fields and slow motion (see Misner et al. [109] and Will [171] for details of the experiments), GR has not yet been tested exhaustively in the regime of strong fields [131, 174]. The black hole (BH) region of an asymptotically flat spacetime is defined as a region from which no future pointing null geodesics can reach future null infinity and the event horizon is the boundary of that region [8]. BH metrics are solutions of Einstein’s vacuum equations. According to GR’s no-hair theorem, astrophysical (largely electrically neutral) black holes can be described as a function of their spins and masses alone.

Due to the strong gravitational attraction from BHs, matter accretes onto BHs in a disk-shaped geometry. The disk emits photons in the UV to X-ray wavelength range. Analytical accretion disk models commonly assume that the disk is truncated at the radius of the innermost stable circular orbit (ISCO). Inside the ISCO, the accreting material quickly plunges on unstable orbits into the black hole. The matter is thus rather tenuous inside
the ISCO, and contributes little (< 10%) to the overall emission of the accreting black hole. The structure and behavior of the disk depends on the spacetime background, and X-ray observations thus present the opportunity to test GR predictions in the strong gravity regime. The accretion disk of stellar-mass BHs and the coronas of supermassive BHs mostly emit in the X-ray band, making X-ray observation a preferred channel for BH studies.

In the past decades, the advancements in spectral and timing X-ray observations have shed light on the inner workings of BHs (e.g. [65]) and fundamental physics. Although the fitting of X-ray observations with the current state-of-the-art models gives BH spin and inclination values, there is still some disagreement between the results obtained with different methods. X-ray polarimetry adds to new observables to X-ray spectral and timing studies. The X-ray polarimetric observations promise to deliver key insights into the emission mechanisms and the structure of accretion flows, and will give us additional handles on the black hole spin and inclination.

This thesis is focused on polarization studies of the X-ray emission from the inner region of the accretion flow. It presents X-ray polarization simulation for various accretion disk and corona configurations. The results show the capability of future polarimetry missions to constrain the geometry of black hole accretion flows. My thesis work included the optimization of the X-Calibur hard X-ray polarimeter for the long duration balloon (LDB) flight in December 2018. My work focused on a very successful program to reduce the readout noise of the Cadmium Zinc Telluride (CZT) detectors.
1.2 Black Holes

As mentioned in the previous section, BHs are massive objects with strong gravitational fields, so they are an ideal laboratory to test fundamental physics, the hypotheses of BH theories and star formation. In GR, BHs can potentially have any mass but in astrophysics only a certain range of BH masses have been observed. Thus, BHs are divided into three classes; stellar mass, supermassive, and intermediate mass BHs.

Stellar mass BHs usually have masses between $3 - 100 M_\odot$. It is believed that they are created from the final stage of heavy star evolution. It is expected that about one billion stellar mass BHs exist in our galaxy [6, 66, 156]. Supermassive BHs have masses in the range of $10^5 - 10^{10} M_\odot$ and their exact origin is not known yet. They have been observed at the center of a large number of galaxies and it is believed that they have major impacts on star formation in galaxies. The intermediate mass BHs, as it is clear from their name, have masses between the range of stellar and supermassive BHs, $10^2 - 10^4 M_\odot$. There is no dynamical measurements of the mass of these objects and their natures are still elusive [6].

Studying BHs, we pursue understanding the physics of the accretion, the jet and wind formation, and their connection with the accretion pattern. Recent high and low energy observations with missions such as and NuSTAR (Nuclear Spectroscopic Telescope Array) [64], XMM-Newton [93], RXTE (Rossi X-ray Timing Explorer) [90] gave us information about the population of BHs in our galaxies and other galaxies, BHs’ spin rate, the extremely luminous AGNs, etc. Cyg X-1 (e.g. [40, 43]), GRO J1655-40 (e.g. [122, 123]), GRS 1915+105 (e.g. [46, 47]), 1H0419-577 (e.g. [162]) are some of the well studied BHs (in spin and mass measurements) with these missions observations. Their observations also enlightened some of the unknowns about BHs such as; the accretion disk, jet, and corona properties. With all
of the sensitive X-ray and Gamma-ray spectral observations now available, astrophysicists are more focused to improve the theoretical study of BHs including more detailed simulation of jets, accretion, magnetic field, etc. The improvement in simulations together with current and future observations can help us to investigate the BHs in more detail.

1.3 Outline of Models

1.3.1 Accretion Disk Models

Shakura & Sunyaev [146] and Lynden-Bell & Pringle [94] presented the first models of geometrically thin accretion disks around BHs. The accretion disk will be geometrically thin when the accretion flow radiates efficiently, so that the disk temperature drops well below the local virial temperature [112]. Novikov & Thorne [119] developed the fully general relativistic version of the thin disk model. These models assume an optically thick accretion disk photosphere locally emitting thermal Bremsstrahlung emission. Novikov & Thorne also assume that the disk is truncated at the ISCO and that the shear stress vanishes at that radius. In my thesis, I used the analytical results of Novikov and Thorne (1973) to simulate the emission from geometrically thin and optically thick accretion disks. The model will be called the thermal disk model in the following.

As mentioned above, the efficient radiative cooling of the disk leads to a disk temperature well below the virial temperature and to a geometrically thin accretion disk. If the gas cannot cool efficiently, we expect the accretion flow to be geometrically thick. For very small accretion rates, the accreting plasma does not radiate efficiently, the optical depth for photons is small, and a geometrically thick flow may form. Conversely, for very high accretion
rates, the optical depth is very high, photons are diffusively trapped in the accretion flow, and are accreted along with the matter into the black hole. In both cases, the radiative emission does not balance the viscous energy generated by the accretion flow, and a fraction of the accretion energy is stored as entropy rather than being radiated away [112]. The corresponding accretion flow model is called advection-dominated accretion flow (ADAF) and was first studied by Ichimaru [71]. Narayan & Yi [112] solved the energy and momentum conservation equations in this case and predicted several properties of the ADAF disks. The accreting gas temperature is close to the virial temperature, and the flow is quasi spherical with the disk vertical thickness being comparable to the disk radius. This model can explain many phenomena in low-luminosity and supper-Eddington accreting BHs (for more details see Narayan & Popham [111] and Abramowicz et al. [1]).

Later, Narayan et al. [113], improved the ADAF model by studying the impact of convective turbulence on the accretion flow properties. They consider inward and outward convective angular momentum transport. In the case of outward angular momentum transport, they recover the ADAF solutions. For the inward angular momentum transport, depending on the viscosity, they can recover an ADAF solution or a non-accreting solution. They refer to the non-accreting solution as a convection-dominated accretion flow, CDAF. Xu & Chen [172] and Das [32] studied “disk-wind solutions” in which only a fraction of the matter accretes onto the BH and most of the matter leaves the system as a wind. Based on this model, Blandford & Begelman [18] developed an adiabatic inflow-outflow accretion flow solution (ADIOS) which may describe the accretion flows onto neutron stars.

It is possible to convert some of the rotational energy of a black hole into electromagnetic energy. The Blandford-Znajek process describes the prediction that a black hole immersed in a magnetic field can loose some of its mass/energy and angular momentum by driving
a Poynting flux [17]. This Poynting flux may play a central role for the formation of the relativistic jets of accreting black hole systems.

Over the last decades, numerical simulations of accretion flows based on magnetohydrodynamic (MHD), general relativistic magnetohydrodynamic (GRMHD) and general relativistic radiation magnetohydrodynamic (GRRMHD) simulations have emerged as a powerful tool to study the physics of accretion [50,104,115,139]. The numerical models have largely confirmed the predictions of the analytical models in the case of low to intermediate accretion luminosities $\dot{M}c^2$ ($\dot{M}$ being the accretion rate) between a few percent and a few ten percent of the Eddington luminosity. The Eddington luminosity $L_{\text{Edd}}$ is the limiting luminosity at which the radiation force on accreting protons equals the gravitational attraction. The numerical simulations show that the luminosity within the ISCO is indeed only a few percent of the total luminosity and that the radial brightness profile agrees well with that predicted by Novikov and Thorne [87,114,180].

1.3.2 Corona Models

In the so-called hard state, the energy spectra of stellar mass BHs include a thermal component peaking at about 1 keV and a power law component extending to high energies of $\sim 100$ keV or higher which may sometimes have a break or exponential cutoff at high energy. The thermal component is known to be generated by photons from the accretion disk. The power law component, is believed to be generated in the corona, a cloud of hot, yet mostly thermal, plasma Comptonizing the photons (e.g. [62]). The low energy photons, which originate in the thermal disk, Compton scatter inside the corona. Repeated energy gains in subsequent Compton scattering processes result in a power law energy spectrum. Over the
last 40 years, many different models of the corona geometry have been discussed. The simplest model assumes a lamppost geometry [36, 102]. In this model, the corona is a compact point source isotropically emitting high-energy photons in its rest frame (Fig. 1.1a). The point source is located close to the rotation axis of the BH at a certain height and irradiates the accretion disk. The offset of the source from the rotational axis and its height affect the energy spectrum and radial dependence of the light hitting the accretion disk (e.g. [166]). The lamppost corona may be associated with the base of a jet or the accumulation of hot gas in the low density regions above and below the BH [69]. Although this is a simple model, it describes the observations quite satisfactorily [26, 102]. Various authors studied variants of the model featuring spatially extended coronas of various shapes, e.g. cone-shaped or cylinder-shaped coronas close to rotation axis (e.g. [98, 150]). Blandford & Begelman [19] and Miller [108] discussed that a hot wind leaving the accretion disk may produce the steep power law emission observed from accreting stellar mass BHs.

Alternative corona models assume wedge or sandwich geometries (Fig. 1.1b) that cover the disk [178]. Such geometries can arise from a geometrically thin, optically thick accretion disk forming an optically thin corona of hot gas buoyantly rising to the surface of the accretion disk. Such a flow could be uniform or clumpy. The latter case is commonly referred to as a clumpy corona (Fig. 1.1d) and could result from magnetic flares ejecting clumps of hot, high magnetic field, low density plasma Haardt et al. [63]. A spherical corona could result from thermal instabilities of the inner disk where the thin flow puffs up and forms a spherical entity resembling an ADAF (Fig. 1.1c).

The geometries of the corona and its plasma component affect the hard state spectrum and the break/cutoff energy. Although several papers (e.g. [144, 150, 166]) have studied the observational signatures of different corona geometries and use comparisons with data to
Figure 1.1: Schematic diagrams of different corona models.
constrain the corona geometry, no consensus about the shape and location of the corona has emerged yet. The reflection spectroscopy of X-ray reverberation is a way to constrain corona properties. Although it is not easy to simulate the reverberation of the extended corona models, this has been studied for the lamppost model and is able to constrain its height and size [38, 54]. Also, there is evidence that coronae are evolving with time as the observed X-ray emissions are variable. This has been observed for two sources Mrk 335 [169] and 4U 1630-47 [28] with NuSTAR observations. Also, recently, Dallilar et al. [35] determined the magnetic field around the BH, mainly in the plasma of corona, for binary system V404 Cygni. They studied the different wavelength observations, from infrared to X-ray, during the source outburst and compared the flux decay at each wavelength to constrain the corona region and find the magnetic field. In this thesis, I am investigating if the polarization of the X-rays can be used to distinguish between the different corona models. I improved on earlier studies of the polarization of the coronal emission (e.g. [37, 144]) by combining for the first time a fully relativistic scattering treatment with a 3D simulation of the corona (see chapter 2).

1.3.3 Quasi Periodic Oscillations Models

Quasi Periodic Oscillations (QPOs) have been observed in the power spectra of several X-ray sources [132]. As the observations showed, these features can be divided into two categories: high frequency QPOs (HFQPOs) and low frequency QPOs (LFQPOs). Several QPO frequencies might be associated with fundamental frequencies of test particle orbits. If this is true, QPOs might be a powerful tool to measure black hole spins and to test GR in the strong gravity regime [142]. A number of models have been developed to explain
the observed QPOs in different frequency ranges. Since the focus of this thesis is on high frequencies, I review some of these models here.

Stella & Vietri [148] explain the HFQPOs in Low Mass X-ray Binaries (LMXBs) as the general relativistic Lens-Thirring precession of the innermost disk region. Abramowicz & Kluzniak [2] proposed that HFQPOs can be created as a resonance of the orbital and epicyclic motion of the accreting matter. The torus model, first presented by Rezzolla et al. [134], posits that p-mode oscillations of an accretion torus cause the HFQPOs. Bursa et al. [25] study the flux variability induced by radial torus oscillations for a Schwarzschild BH. Their calculations indicate that the high-frequency modulation of the X-ray flux could result from light bending in the strongly curved BH spacetime. The resonance model of Petri [129] describes HFQPOs as resulting from the resonance of a spiral wave in the inner part of an accretion disk with vertical epicyclic oscillations. Recently, Dexter & Blaes [34] proposed that local and vertical epicyclic and acoustic breathing modes could lead to observing HFQPOs in the steep power law spectral state. Wagoner et al. [161] and Kato [80] explain HFQPO with the adiabatic perturbations of the relativistic accretion disk. Last but not least, Tagger & Varniere [153] and Fukumura & Kazanas [49] also describe the HFQPOs as the observational signature of magnetohydrodynamic Rossby wave instabilities (RWI) and as the light echo, respectively.

In this thesis, we study observational signatures of HFQPOs predicted by the hotspot (HS) model [140]. This model assumes an accretion disk with a bright HS orbiting the BH that creates a time varying X-ray signal. The model is motivated by the similarity between the HFQPO and the coordinate frequency near the ISCO. Furthermore, following the work of Merloni et al. [106], the resonance between the azimuthal and radial oscillations may explain the observed integer commensurabilities between different HFQPO frequencies [140].
Recently, Li & Bambi [91] argued that the HS model can distinguish BHs and wormholes based on infrared observations. Sec. 2.4 describes our HS model in more detail. Some studies have shown the limitations of the HS model to explain some observations. For example, Markovic & Lamb [101] have presented that the HS model is not a physically viable explanation for HFQPOs observed in neutron star binaries. They claimed that the coordinate frequencies and the relative power of these frequencies do not agree with the observations. In our simulation for stellar-mass BHs, we chose the HS model presented in Schnittman [142] since it addresses the limitations pointed out in previous studies.

### 1.4 X-Ray Observations

As neutron stars, stellar mass and supermassive black holes emit a large fraction of their bolometric luminosity in the X-ray band, X-ray studies present one of the best observational channels to study these extreme objects. X-ray timing and spectral studies with satellites such as *Ginga* [96], *RXTE* [90], *Chandra* [164], and *NuSTAR* [64] have shaped our understanding of BHs (e.g. [65]). Simulations show that X-ray polarimetry can deliver key insights into the physics and emission mechanisms of these objects. Sections 1.4.2 and 1.4.4 summarize the X-ray polarimetric observations of BH obtained so far, and describe future balloon and satellite borne missions that will measure the polarization of the X-rays from compact sources.
1.4.1 Spectral Observations

The energy spectra of mass accreting stellar mass and supermassive BHs exhibit thermal and non-thermal components as well as absorption and reflection lines and components. Several methods have been developed to measure the spins of the BHs. One of the best studied methods for stellar mass black holes involves the fitting of the X-ray energy spectra observed in the “thermal state”, a state in which the \( \sim \) keV energy spectrum is dominated by the thermal Bremsstrahlung of the geometrically thin, optically thick accretion disk. The method requires the independent measurement of the BH mass \( M \) and the inclination of the binary, both from IR/optical or other observations of the orbital properties of the binary system, and is based on the assumption that the black hole and accretion disk spin axes are aligned. Fitting of the observed energy spectra with the thermal disk model gives the radius of the inner edge of the disk, which in this model is assumed to coincide with the radius \( r_{ISCO} \) of the ISCO. Since \( r_{ISCO} \) is a function of the black hole mass \( M \) and spin parameter \( a \) alone, the spin parameter can be inferred. Kulkarni et al. [87] used GRMHD simulations to study the systematic errors resulting from using the analytical thin disk model predictions in the fit (which neglect the emission from within the ISCO), and found them to be small compared to the uncertainties of the BH mass, the distance of the system from us, and the BH inclination.

As mentioned above, the power law component observed between a few keV and the hard X-ray/gamma-ray regimes is thought to originate in the corona. The spectrum is characterized by the spectral index \( \Gamma \), and it is proportional to \( dN/dE \propto E^{-\Gamma-1} \). In the case of mass accreting supermassive black holes in Active Galactic Nuclei (AGNs), the accretion disk mainly emits at energies around UV or infrared while in mass accreting black holes in X-ray
binaries (binary black holes or BBHs) the accretion disk emission peaks at around 1 keV. The power law thus dominates the entire X-ray energy range in AGNs and dominates above a few keV in BBHs. The power law properties constrain certain physical properties of the corona, in particular the optical depth of the corona.

When the accretion disk is illuminated with photons, the photons may reflect off the disk and create a reflection spectrum. This spectrum consists of fluorescent lines and the Compton hump. The most prominent fluorescent line in the X-ray regime are Fe K-\(\alpha\) lines at ionization state dependent rest frame energies between 6.4-6.97 keV. In 1995, the first relativistically broadened iron line was detected from an AGN with the ASCA satellite [154, 158]. The observed Fe K-\(\alpha\) line shapes are very broad owing to Doppler and gravitational frequency shifts [41]. The modeling of the Fe K-\(\alpha\) line shape makes it possible to constrain the BH spin, BH inclination, and the physical properties of the corona [53, 55].

1.4.2 Timing Observation

Timing observations give us additional ways to probe the properties of BHs and accretion flows. Particularly powerful techniques include the observations of QPOs, and the observations of time lags between the direct and reflected corona emission, a technique referred to as BH reverberation. As mention in Sec. 1.3.3, several observation have shown the presence of QPOs in power spectra of BHs. RXTE revealed High Frequency (>40 Hz) QPOs in a number of BBHs [132]. In the seven systems that the HFQPOs have been found, three were detected with a single frequency, and four with multiple frequencies. For example, the binaries GRO J1655-40 and possibly GRS1915+105 exhibit pairs of HFQPOs with frequencies at a 3:2 frequency ratio [132].
The technique of reverberation mapping is well known from optical studies of AGNs and has been used to measure the mass of the supermassive black holes of AGNs [26, 128]. Photons originating close to the BH illuminate a cloud of gas further out (inside the broad line region) and generate secondary scattered photons. The original emission and the scattered emission reach an observer with light travel time lags referred to as reverberation time lags. Combining the information about the size of the system (from the time lag) with the information about the depth of the gravitational well (from the line widths) enables us to estimate the black hole mass. In a very similar way, hard X-rays from the corona reach the observer directly and illuminate the disk, creating fluorescent lines and the Compton hump emission. The time lag is the time difference between the direct emission and the reflected emission. X-ray reverberation studies require long observations. First results were published by Reynolds et al. [133] and Young & Reynolds [173]. Whereas the time lags observed for BBHs (e.g. [110]) cannot consistently be explained as reverberation time lags (e.g. the time delay goes both ways, contradicting the reverberation origin of the lag), X-ray observations of AGNs seem to give clear reverberation detections. The first robust time lag detection was reported for the Seyfert I galaxy 1H0707-495. The source showed that the reflected soft and hard emission lagged the direct power law emission. The dependence of the time lags on frequency and energy encodes information about the corona geometry, the accretion disk properties, and the background spacetime. The reverberation observations are commonly interpreted assuming a lamppost corona geometry (e.g. [26, 170]). Zoghbi et al. [181] and Kara et al. [79] reported the detection of time lags between the direct emission and the Compton hump emission. The observations indicated a long delay for high-energy photons indicating scattering at the outer regions of the disk. The interpretation of the data with extended corona models faces the uncertainty of where in the corona the flare originate and how they propagate through the corona. Wilkins et al. [170] studied the observational signatures of extended disk-shaped
Figure 1.2: Polarization fraction (left panel) and angle (right panel) of a thermal disk for different spins (a) of a BH with inclination of 75°.

coronatas above the accretion disk assuming the flares originate close to the black holes and propagate outwards.

1.4.3 Polarization Observation

X-ray polarimetry will give us two new observables, polarization fraction and angle. The propagation of photons through the curved spacetime of a BH affects the net polarization as the polarization vector is parallel transported along the geodesic of a photon. Thus, the polarization plane will rotate as the light propagates through curved spacetime [109]. The measurement of the polarization angle and fraction as function of energy will provide novel ways to measure the spin and inclination of the BH [92, 132]. An example of the effect of the BH spin on the polarization energy spectrum is shown in Fig. 1.2 from my simulation of the thermal accretion disk. The left panel shows the polarization fraction of a thermal
disk and the right panel shows polarization angle, when varying the BH spin. Another effect that changes polarization is scattering. Chandrasekhar [29] studied polarization signatures of thermal photons originated from an optically thick atmosphere, such as the accretion disk of a BH, and the ones that scatter off this atmosphere. His analytical results for indefinitely thick electron scattering atmospheres are commonly used to calculate the polarization of the thermal photons emitted by the accretion disk plasma and to calculate how the polarization changes when photons scatter off the accretion disk [85, 86, 92, 143, 145]. Ingram et al. [73] studied the polarization signatures of the Lense-Thirring precession of the inner accretion flow. In this thesis, I investigate the polarization properties of the coronal emission and the HFQPO emission based on numerical simulations for a broad range of different accretion disk and corona geometries (see the details in Chapters 3 and 4).

1.4.4 Future Polarization Missions

The measurement of polarization energy spectra is technically challenging. Early detectors made use of the polarization dependence of the Bragg reflection of X-rays. The narrow bandpass of the technique resulted in limited overall sensitivities. The first polarimetry satellite OSO-8, launched in 1978, measured the polarization of the Crab pulsar and nebula [163]. Later, several stratospheric balloon experiments were flown to measure the polarization of the X-rays from BHs. PoGo+, a balloon borne polarimeter launched in 2016, published results for the Crab nebula in the 20-160 keV energy range. X-Calibur is another balloon X-ray polarimeter that will measure the polarization of the 15-60 keV emission from pulsars, BBHs, and other X-ray binaries. The mission is scheduled to be flown in 2018 from McMurdo (antarctic). NASA has recently started the implementation of the Imaging X-ray Polarimeter Explorer (IXPE) mission [165]. IXPE is scheduled for a launch in 2021 and will observe the
2-8 keV polarization from bright galactic sources and a few extragalactic sources. *IXPE* will achieve a minimum detectable polarization (MDP) of 1% in for more than 33 LMXBs and 7 HMXBs (high mass X-ray binaries). While the MDP for the Crab nebula and pulsar of *OSO-8* was 3%, *IXPE* should get an <1% MDP in several independent energy bins.

1.5 Thesis Structure

This thesis describes my studies of the inner accretion flows of BHs and my investigations of different HFQPO and corona models using polarization simulations. Chapter 2 describes the ray-tracing simulations of BHs and their surroundings, including the details of the thermal disk, corona, and HS model simulations. The chapter also explains the different scattering models that I use in the corona simulations. In Chapter 3, I present my results concerning the polarization of the emission from coronas with different geometries and physical properties. Chapter 4 describes the results from my studies of the polarization of HSs and compares the HS model with other competing models. Chapter 5 describes the work I have done in preparation of the *X-Calibur* flight, including the calibration of the *X-Calibur* detectors, truss deflection tests, and the thermal analysis from the test flight in 2016. I close in Chapter 6 with a summary of the results and with a discussion of several possibilities for future investigations and caveats that need to be addressed in future. Throughout this thesis, all distances are in units of gravitational radius \( r_g = GM/c^2 \), and we set \( G = c = \hbar = 1 \).
Chapter 2

Ray-Tracing Simulation of a Black Hole and its Surroundings

2.1 Introduction

This chapter introduces aspects of GR relevant for my thesis work and the methodology of ray tracing simulations that I used to study the X-ray emission from black holes. The ray tracing simulations are based on a code originally developed by Krawczynski [85] to study the impact of the spacetime on the properties of the thermal accretion disk emission. Follow-up studies of the impact of the assumed metric on the spectral, timing, and polarization properties of the thermal, power law, and reflected emission were carried through by Hoormann [69, 70]. I improved this code by adding the capability of simulating the Comptonization of photons in accretion disk coronas of arbitrary shapes. The first section introduces the GR ray-tracing code and the GR concepts that are used in the code. Next this chapter explains the simulation of the thermal accretion disk emission, the HS model, and BH coronas. The section includes material published in my journal papers [9, 10].
2.2 General Relativistic Ray-Tracing Simulation

The ray-tracing code tracks photons from their origin to the observer in Boyer Lindquist coordinates. The code simulates the emissions and propagates the photon trajectories forward in time using the geodesic equations:

$$\frac{d^2x^\mu}{d\lambda'^2} = -\Gamma^\mu_{\sigma\nu} \frac{dx^\sigma}{d\lambda'} \frac{dx^\nu}{d\lambda'},$$

with $\lambda'$ being an affine parameter and $\Gamma^\mu_{\sigma\nu}$ the Christoffel symbols. The photons are tracked until they reach the observer at a fixed global coordinate, $r = 10,000 \ r_g$, where $r_g$ is the gravitational radius defined as $GM/c^2$. The code uses the fourth order Runge-Kutta method or the Cash-Karp method to parallel transport the photon’s wave vector (4-momentum) and polarization vector. The zero component of the wavevector tracks the gravitational and Doppler frequency shifts between the emission and the absorption. Energy spectra are generated by superimposing thermal energy spectra with the frequency shifts and statistical weighting factors from the raytracing simulations. The photons are tracked until they come too close to the event horizon ($r < r_H + 0.02$), or until the radial coordinate $r$ exceeds 10,000 $r_g$. If the latter happens, the trajectory is back-tracked to $r = 10,000r_g$.

2.2.1 Tetrad

In 3-dimension Euclidean spacetime, we describe a vector with a particular coordinate basis. The magnitude and direction of a vector are independent of the chosen coordinate basis. In GR, we can use the same concept by introducing tetrad vectors. Einstein equivalence principles state that we can define a local inertial frame at any point of spacetime. A tetrad
is an orthonormal basis of tangent vectors with one vector being the four velocity of the reference frame. We can define a tetrad at any point in spacetime and convert from the global coordinate system to the local coordinate system with an appropriate transformation. While in GR the basis vectors of the global coordinate system do not have to be orthogonal to each other or normalized, a tetrad is chosen to be orthonormal. In the local inertial frame, the physics are the same as in the absence of a gravitational field.

In the simulations, we use multiple local frames: the rest frame associated with the accretion disk plasma (used when calculating emission, absorption and scattering off the disk), the rest frame of the coronal plasma (used when calculating scatterings in the corona), and the observer frame. In this section, I define each of these frames' tetrad and the transformation matrix to transform a vector from the global Boyer-Lindquist (BL) frame to that local reference frame. In the BL frame the Kerr metric is written in the form:

$$ds^2 = -(1 - \frac{2Mr}{\rho^2})dt^2 - \frac{4aMr\sin^2\theta}{\rho^2}dt d\phi + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\phi^2 + \sin^2\theta(r^2 + a^2 + \frac{2a^2Mr\sin^2\theta}{\rho^2})d\phi^2$$

(2.2)

with $\rho^2 = r^2 + a^2\cos^2\theta$ and $\Delta = r^2 - 2Mr + a^2$. When a photon scatters off the disk, the photon wave vector and polarization vector are transformed from global BL coordinates into the disk frame coordinates (marked with a hat symbol) making us of the following tetrad:

$$e_\hat{t} = p^t e_t + p^\phi e_\phi,$$

$$e_\hat{r} = \frac{e_r}{\sqrt{g_{rr}}},$$

$$e_\hat{\theta} = \frac{e_\theta}{\sqrt{g_{\theta\theta}}},$$

$$e_\hat{\phi} = ae_t + be_\phi,$$

(2.3)
where “a” and “b” are constant defined by using normalization of \( e_\phi \) and its orthogonality to \( e_t \) \( (e_t.e_\phi = 0 \) and \( e_\phi.e_\phi = 1) \). Thus, the transformation matrix \( e_\mu^\nu \) between the two coordinates can be found with \( e_\nu = e_\mu^\nu e_\mu \).

In this thesis it is assumed that the corona is rotating with the ZAMO (zero angular momentum) frame at an angular velocity of \( v_\phi = -g_{\phi t}/g_{\phi\phi} \) with \( g_{\phi\phi} \) and \( g_{\phi t} \) being components of the Kerr metric. Thus, we use the ZAMO tetrad (indicated with a tilde symbol) for the corona frame:

\[
e_t = 1/\alpha e_t + \omega/\alpha e_\phi,
\]
\[
e_\tau = \sqrt{\frac{\Delta}{\rho^2}} e_r,
\]
\[
e_\theta = \sqrt{\frac{1}{\rho^2}} e_\theta,
\]
\[
e_\phi = \sqrt{\frac{1}{\psi}} e_\phi,
\]

where \( \omega, \alpha, \) and \( \psi \) are defined with:

\[
\alpha^2 = \frac{\rho^2 \Delta}{\rho^2 \Delta + 2Mr(a^2 + r^2)},
\]
\[
\omega = \frac{2Mr \alpha}{\rho^2 \Delta + 2Mr(a^2 + r^2)},
\]
\[
\psi = \frac{\rho^2 \Delta + 2Mr(a^2 + r^2)}{\rho^2 \sin^2 \theta}.
\]
Finally, to measure the photon’s momentum and polarization at the observer frame (indicated with a bar symbol) we define the following tetrad:

\[
\begin{align*}
e_{\bar{t}} &= \frac{e_t}{\sqrt{g_{tt}}}, \\
e_{\bar{r}} &= \frac{e_r}{\sqrt{g_{rr}}}, \\
e_{\bar{\theta}} &= \frac{e_r}{\sqrt{g_{\theta\theta}}}, \\
e_{\bar{\phi}} &= a^' e_t + b^' e_{\phi},
\end{align*}
\]  

(2.6)

where \(a^\prime\) and \(b^\prime\) are constants defined by using the normalization of the \(e_{\bar{\phi}}\) and its orthogonality to \(e_{\bar{t}}\).

### 2.2.2 Polarization Simulation

Our simulation code uses Table XXIV of Chandrasekhar [29] to calculate the initial polarization of the photon and the statistical weight for its emission direction. The polarization of each photon is defined based on the Stokes parameters, \(I, Q, U,\) and \(V\). Because we can only measure linear X-ray polarization, we neglect the circular polarization, so in our simulations, \(V = 0\). Using the Stokes parameters polarization fraction and angle are defined with:

\[
\begin{align*}
\Pi &= \frac{\sqrt{Q^2 + U^2}}{I}, \\
\chi &= \frac{1}{2} \tan^{-1} \frac{U}{Q}
\end{align*}
\]  

(2.7)
To track the photons’ polarization, we describe the polarization direction with a vector. The polarization vector \( \mathbf{f} \) is normalized and perpendicular to the photon’s wave vector \( \mathbf{k} \). It is transported parallel to the wave vector following the geodesic equation:

\[
\frac{df^\mu}{d\lambda} = -\Gamma^\mu_{\sigma\nu} f^\sigma \frac{dx^\nu}{d\lambda}. \tag{2.8}
\]

In the local inertial frame, the Stokes parameters are calculated from the polarization vector with the help of certain basis vectors. We select the direction of \( \mathbf{k} \) as one of our basis vectors and the other two basis vectors, \( e_1 \) and \( e_2 \), are chosen to be normal to the \( \mathbf{k} \) direction. Thus, we can write the 4-vector of \( \mathbf{f} \) as \( \mathbf{f} = (0, \cos \chi e_1 + \sin \chi e_2) \) and thus \( Q = \Pi I \cos 2\chi \) and \( U = \Pi I \sin 2\chi \).

When a photon hits the accretion disk, it is scattered into a random direction with equal probability per solid angle and with a statistical weight determined from Table XXIV of Chandrasekhar [29]. To calculate the scattered Stokes parameters, we express the initial photon’s Stokes parameters in terms of Chandrasekhar’s parameters: \( I_\perp \), \( I_\parallel \), and \( U \), to be able to use his Table XXIV. \( I_\perp \) and \( I_\parallel \) are the intensity in the direction perpendicular and parallel to the meridian plain and are defined by:

\[
I_\perp = \frac{1}{2}(I - Q), \\
I_\parallel = \frac{1}{2}(I + Q). \tag{2.9}
\]

In Corona scattering, the scattered Stokes parameters are calculated using the scattering matrix. The details of this process are explained in Sec. 2.5.1.
2.3 Thermal Disk Photons

In the simulations the BH accretion disk extends from the radius $r_1$ to $r_2$ with $r_2 > r_1 \geq r_{ISCO}$. The disk emits thermally with a brightness distribution $F(r)$ based on the result of Page & Thorne [125]. The latter authors used the conservation of mass, angular momentum, and energy to derive

$$F(r) = \frac{-\dot{M}}{4\pi} e^{-(\nu+\psi+\mu)} \int_{r_{ISCO}}^{r} \frac{p_{\phi,r} dr}{p_{\phi}}$$

(2.10)

where $\dot{M}$ is the accretion rate for a stationary, axially symmetric metric given by the functions $\nu$, $\psi$, and $\mu$, and $p^\mu$ is the four-momentum of the disk material and "\" denotes the ordinary partial differentiation (see Bardeen [7] and Page & Thorne [125] for the nomenclature). Photon packages are assumed to be emitted with a Blackbody energy spectrum with the temperature

$$T_{eff} = \left(\frac{F(r)}{\sigma_{SB}}\right)^{\frac{1}{4}}$$

(2.11)

with $\sigma_{SB}$ being the Stefan-Boltzmann constant. Recent GR Magnetohydrodynamic (GRMHD) simulations show that the Novikov-Thorne results are a good approximation of the more detailed results [118, 126, 127].

We divide the accretion disk in 10,000 radial bins spaced equally in the logarithm of the Boyer Lindquist coordinate $r$. For the radially symmetric accretion disk emission, the code makes use of the azimuthal symmetry of the problem: all photons are launched at an azimuthal angle $\phi = 0$. When they leave the simulation sphere, we infer that the probability to find them in the azimuth angle interval from $\phi$ to $\phi + \Delta\phi$ equals $\Delta\phi/2\pi$. Photons are created in the plasma frame with a limb darkening function from Chandrasekhar [29].
Figure 2.1: Image of the steady emission from the accretion disk of a Schwarzschild BH (left image) and a Kerr BH with the spin of 0.9 (right image).

Figure 2.1 shows a 2D images of an accreting Schwarzschild BH at an inclination of 75°, and the accreting Kerr BH with the spin of 0.9 seen at the same inclination for 2-15 keV energy band. The lengths and orientations of the bars in the image show the polarization fractions and angles, respectively. The image clearly shows the relativistic beaming and de-beaming of the emission from the disk resulting in pronounced brightness variations across the disk (see also [143]).

2.4 Hotspot Model

Stella & Vietri [148, 149] introduced the HS model to explain the observations of QPOs with frequencies comparable to the orbital frequencies of matter orbiting BHs and neutron stars close to the ISCO. The HS model can explain not only the detection of HFQPO at one frequency but also twin HFQPOs with integer frequency ratios resulting from non-linear resonances occurring near geodesic orbits [2, 3].
The HS model posits that a region with a temperature exceeding that of the ambient material orbits the BH. We assume that all the matter orbits the BH on a nearly circular orbit with the angular frequency \( \nu_\phi \) given by [7]:

\[
\Omega_\phi = 2\pi \nu_\phi = \frac{\pm \sqrt{M}}{r^{3/2} \pm a\sqrt{M}}.
\] (2.12)

For a prograde (retrograde) orbit, the upper (lower) sign applies. Typically, we consider a HS with a radius of around 0.25 – 0.5 \( r_g \). It has been argued that a larger HS will not survive a long time because of the viscous shearing of the disk [101]. Schnittman & Bertschinger [140] have shown that the light curve and the HFQPO power spectrum are independent of the HS’s size and shape. They also tried to explain the 3:2 commensurability for twin peaks in some X-ray binary systems with the idea of a noncircular orbit of the HS and its different coordinate frequencies. This idea leads to some beat frequency in the light curve and they believe that one of the peaks is at the azimuthal frequency and the other is at beat modes, \( \nu_\phi \pm \nu_r \). Fig. 2.2 shows the simulated HS in the two different phase of its orbit around a Kerr BH.
2.5 Comptonization in the Corona

I simulated both isothermal wedge and spherical coronae of hot electrons. As we track individual photons originating from the accretion disk, we check for each integration step if the photon is inside the corona. If so, we transform the start and end point of the integration step into the rest frame of the corona plasma, and determine the optical depth between these two points. The optical depth is then used to determine the probability for the scattering, \( p = e^{-d\tau} \), where \( \tau \) is the optical depth and \( d\tau \) is defined with:

\[
d\tau(r, z) = \kappa \rho(r, z) dl,
\]

where \( dl \) is the distance that the photon travels between the two integration step, \( \kappa \) is the opacity to electron scattering and is 0.4 cm\(^2\)/g, and \( \rho(r, z) \) is the density of the coronal plasma at radius \( r \) and height \( z \). Since the total optical depth is a function of the worldline, we characterize the density with the scattering coefficient (the optical depth per proper length) \( \sigma = d\tau/dl \).

The wedge coronae lie above and below the accretion disk and with a constant opening angle (see Figure 2.3 (a)). For the wedge corona, we assume the coronal gas density depends on radius and height with (Equation (6) of Schnittman & Krolik [144]):

\[
\rho(r, z) = \rho_0(r) \exp\left(-\frac{z}{H(r)}\right),
\]

where \( \rho_0(r) = \tau_0/\kappa H(r) \) and with the adjustable parameter \( \tau_0 \). We quote \( \sigma \) in the wedge corona for the mean height and the mean radius of the disk. In the wedge corona, all seed photons are thermally emitted accretion disk photons.
Figure 2.3: Sketch of the wedge and spherical corona geometries. (a) The wedge corona extends above and below the accretion disk with an opening angle of $\theta_c = \tan^{-1} \frac{H}{R}$. (b) The spherical corona extends from the BH horizon to $R_{\text{edge}}$. The disk is truncated at $R_{\text{edge}}$. 
The spherical corona extends from $r_{ISCO}$ to $R_{\text{edge}}$. In this geometry, the accretion disk is truncated at the outer edge of the corona at $R_{\text{edge}}$ (Fig. 2.3 (b)). The optical depth is chosen to be a linear function of radius, $\tau(r) = (\tau_0/R_c)r$, where $R_c = R_{\text{edge}} - r_{ISCO}$ is the radius of the corona and the $\sigma$ is $\tau_0/R_c$. Since the disk of the spherical corona model is truncated at the edge of the corona, it is assumed that the corona has a seed photon luminosity and energy spectrum both as a function of the radial coordinate $r$, the same as the wedge corona, and that the corona launches the photons with a random polar angle $\theta$ with a flat $\cos(\theta)$ distribution.

To determine if a photon scatters, a random number is drawn. If it scatters, its wave vector and polarization vector are transformed first to the rest frame of the coronal plasma (described in Sec. 2.2.1). We then draw a random direction of the scattering electron in the comoving plasma rest frame, transform the wave vector of the photon from the plasma rest frame into the rest frame of the electron, and determine the photon wave vector after scattering. Transformation to the rest frame of an electron is a Lorentz boost with the matrix components of:

$$\Lambda_{\mu'}^\nu = \begin{pmatrix} \gamma & 0 & 0 & -\beta \gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta \gamma & 0 & 0 & \gamma \end{pmatrix} \quad (2.15)$$

where the prime symbol shows the electron rest frame, $\gamma$ is the electron Lorentz factor, and $\beta$ is electron’s velocity in units of the speed of light in the corona rest frame. In the electron rest frame the new scattering energy and polarization vector are calculated. The next section describes the wave vector and polarization vector calculation in the electron-photon scattering. After the scattering, the photon wave vector and polarization vector are
transformed back, first into the coronal rest frame and then into the global Boyer-Lindquist frame, where the tracking continues.

2.5.1 Scattering Models

We simulate photon-electron scatterings using the Thomson approximation and the full K-N cross section. In both cases, we transform the wave vector and polarization vector of the photon first from the global BL coordinates into the corona frame coordinates, and subsequently into the rest frame of one of the scattering electrons (assumed to be isotropic in the corona frame). We randomly draw the direction of the scattered photon in the electron rest frame. In the Thomson approximation the scattering does not change the photon energy. More accurately, the photon loses energy according to the Compton equation:

\[ \epsilon_1 = \frac{\epsilon_0}{1 + x(1 - \cos \theta)}, \]  

(2.16)

where \( \epsilon_1 \) and \( \epsilon_0 \) are the energy of the photon after and before scattering, respectively, \( x \) is the photon energy in units of the electron rest mass, and \( \theta \) is the scattering angle.

We use the Stokes parameters and the non-relativistic Raleigh and relativistic FANO scattering matrices to calculate the statistical weight of the scattering and polarization fraction of the scattered photon. The Stokes parameters are calculated with the help of two sets of basis vectors (see Figure 2.4). The projection of the polarization vector onto the first set of basis vectors allows us to calculate the polarization angle \( \chi_0 \), and the Stokes parameters \( Q_0 = \Pi_0 I \cos 2\chi_0 \), and \( U_0 = \Pi_0 I \sin 2\chi_0 \), with \( \Pi_0 \) being the polarization fraction of the incoming photon.
Figure 2.4: Basis vectors used for determining the Stokes parameters for a Compton scattering process in the electron rest frame before (non-primed indices) and after (primed indices) the scattering. \( \mathbf{b}_3 \) points in the direction of the initial photon wave vector, \( \mathbf{b}_2 \) lies in the scattering plane, and \( \mathbf{b}_1 \) is normal to that plane. The vector \( \mathbf{b}_3' \) points into the direction of the scattered photon, \( \mathbf{b}_1' = \mathbf{b}_1 \), and \( \mathbf{b}_2' \) is perpendicular to the plane of \( \mathbf{b}_1' \) and \( \mathbf{b}_3' \).

The Stokes parameters before and after scattering (subscripts 0 and 1, respectively) are related via:

\[
\begin{pmatrix}
I_1 \\
Q_1 \\
U_1
\end{pmatrix} = \mathbf{T}_{R/K-N} \begin{pmatrix}
I_0 \\
Q_0 \\
U_0
\end{pmatrix}.
\]  

(2.17)

The Raleigh scattering matrix (\( \mathbf{T}_R \)) is given by [29]:

\[
\mathbf{T}_R = \frac{1}{2} r_0^2 \begin{pmatrix}
1 + \cos^2 \theta & \sin^2 \theta & 0 \\
\sin^2 \theta & 1 + \cos^2 \theta & 0 \\
0 & 0 & 2 \cos \theta
\end{pmatrix}
\]  

(2.18)
and the expression for the Fano scattering matrix ($T_{k-N}$) reads [45,105]:

$$
T_{k-N} = \frac{1}{2} r_0^2 \left( \frac{\epsilon_1}{\epsilon_0} \right)^2 \begin{pmatrix}
1 + \cos^2\theta + \frac{1}{m_e c^2} (\epsilon_0 - \epsilon_1) (1 - \cos\theta) & \sin^2\theta & 0 \\
\sin^2\theta & 1 + \cos^2\theta & 0 \\
0 & 0 & 2\cos\theta
\end{pmatrix}.
$$

(2.19)

The Stokes parameters give us the polarization fraction $\Pi_1$ and angle $\chi_1$ after scattering according to Equation (2.7) and we use $\chi_1$ to calculate the polarization vector $f'$ of the outgoing photon. We transform the wave vector and polarization vector back into the corona frame and the global BL coordinates.

### 2.5.2 Scattering Likelihood

For each scattering, we multiply the statistical weight of the photon with a factor $w_1 = I_1/I_0$, encoding the physics of the scattering process in the rest frame of the scattering electron, and with the kinematical factor $w_2 = (1 - \beta \cos(\theta_0))$, with $\theta_0$ being the angle between the photon’s and electron’s momentum vectors in the coronal rest frame. The factor $w_2$ reflects the higher likelihood of photon-electron head-on collisions compared to photon-electron tail-on collisions. As the factor is frequently omitted in simulations of Compton interactions, we briefly justify it based on the derivation of the rate of Compton scatterings of electrons immersed in an isotropic bath of photons [16,20,177]. In the rest frame of a scattering electron, the number of scatterings is given by:

$$
\frac{dN'}{dT'} = c \sigma_T \int f(p') d^3 p'
$$

(2.20)
with \( c \) being the speed of light, \( \sigma_T \) the Thomson cross section, \( \mathbf{p}' \) the momentum of the scattered photons, and \( f'(\mathbf{p})' \) the number density of photons per momentum volume element \( d^3p' \). The scattering rate can be transformed into the rest frame of the coronal plasma (undashed variables) noting that \( dN \) and \( f(\mathbf{p}) \) are Lorentz scalars, \( dt' = 1/\gamma dt \), and \( d^3p' = \gamma(1 - \cos(\theta)) d^3p \). Assuming isotropic photons in the rest frame of the coronal plasma \( f(\mathbf{p}) = f(p) \), the scattering rate is:

\[
\frac{dN}{dt} = c\sigma_T \int (1 - \beta \cos(\theta)) f(p) d^3p
\]  

(2.21)

demonstrating that scatterings with pitch angles \( \theta \) contribute with a weight proportional to \( 1 - \beta \cos(\theta) \).
Chapter 3

Simulations of Photons

Comptonization in Extended Coronae

This chapter presents the paper that I published [10] under the supervision of my advisor, Henric Krawczynski, and great comments and suggestions of Dr. Malzac.

3.1 Introduction

AGNs are powerful sources of X-rays. Their spectrum is dominated by a power law continuum presumably emitted by hot and possibly partially non-thermal plasma of particles, known as a corona. Repeated inverse Compton processes in the corona energize optical/UV photons originating from an accretion disk emitting in the IR/optical/UV. Even though the first accretion disk and corona models were developed in the seventies (e.g. [119, 146]) and refined over the last 40 years (e.g. [39, 61, 120]), the geometry of the corona, i.e. its location and spatial extent, is still a matter of intense debate [59].
Recent X-ray reverberation observations (e.g. [42, 167]) and future X-ray polarization observations offer a new way of constraining the corona geometry that is complementary to the more traditional constraints X-ray spectroscopy. Polarimetric observations with the Imaging X-ray Polarimetry Explorer (IXPE) and Small Explorer (SMEX) mission [165] promise to provide geometrical information about the corona and the inner structure of accretion disks. The polarization of X-ray emission from the accretion disk of a stellar-mass BH is predicted to be linear polarized with the polarization fraction being a function of inclination of the disk [92, and references there in]. In the case of AGNs, X-rays are emitting from a hot corona in the vicinity of the accretion disk. The polarization of this emission depends on the scattering off the accretion disk and on the scattering processes in the corona. This dependency of the polarization on the scattering makes polarization studies a promising way to distinguish between different corona geometries.

Schnittman & Krolik [144] showed that in stellar-mass BH, the corona geometry has a major impact on the predicted energy spectra of the polarization fraction and the polarization angle. Dovciak et al. [37] studied the polarization of unpolarized corona X-rays scattering off the accretion disk of AGNs. In this chapter, we study for the first time the impact of the Klein-Nishina (K-N, Klein & Nishina [84]) cross section on the polarization of the coronal emission. Furthermore, we study how non-thermal electrons in the coronal plasma and polarized synchrotron and cyclotron seed photons affect the observable polarization properties.

Our studies are based on a general relativistic ray-tracing code that simulates the individual scattering processes accounting for the energy dependent K-N cross section in the framework of a general relativistic ray tracing code. The code assumes that the 3-D corona plasma orbits the black hole with the angular velocity of a ZAMO (Zero Angular Momentum Observer).
The seed photons are polarized with an initial polarization given by the classical results of Chandrasekhar (1960). The code tracks photons forward in time, making it possible to study repeated scatterings in the corona and off the accretion disk.

Although simple models assume a single-temperature corona, the coronal plasma may have a distribution of temperatures and/or an admixture of non-thermal plasma (e.g. from magnetic reconnection in the corona). The Atacama Large Millimeter/Submillimeter Array (ALMA) may be able to reveal the presence of non-thermal plasma in AGN coronae [74]. The energy spectra of black holes in X-ray binaries show clear evidence for non-thermal particles (e.g. [30, 58, 99, 130, 136]). In Cyg X-1, the non-thermal component was detected to be strongly polarized [77, 88], and this was taken as evidence that it is formed as synchrotron emission in the jet rather than as inverse Compton emission in the corona. Further below, we will use our code to evaluate the possibility that non-thermal electrons in the corona produce high polarization fractions at high energies.

The structure and strength of the magnetic fields in AGN accretion disks is still a matter of debate (e.g. [15, 17]). Cyclotron or synchrotron (cyclo-synchrotron) photons are naturally expected from the energetic electrons radiating in the ambient coronal magnetic field (see e.g. [97, 159]). In this chapter, we will evaluate if X-ray polarization could contribute to clarifying the situation if a fraction of the seed photons are highly polarized cyclotron or synchrotron photons.

We described the ray-tracing code, the corona geometries, and the Compton scattering of photon inside the corona in Sect. 2.2.2 and 2.5. We report on the results of the studies of the impact of the K-N cross section, non-thermal electrons in Sect. 3.2. In Sect. 3.3 we model the NuSTAR observations of Mrk 335, and use the modeling to predict the polarization fraction and angle energy spectra. Sect. 3.4 and 3.5 present the effect of having cyclotron
Figure 3.1: Energy spectrum of the 4 treatments in the coronal scattering. Model (I) is Thomson approximation, (II) is same as (I) but adding the \((1 - \beta \cos \theta)\) factor, (III) is same as (II) but considering the energy loss of photons, (IV) is same as (III) but using Fano scattering matrix.

and synchrotron seed photons on the polarization results. We summarize our results in Sect. 3.6. The mass of AGN is \(10^8 M_\odot\) unless otherwise specified. The inclination is \(i = 0^\circ\) for an observer viewing the disk face-on and \(i = 90^\circ\) for an observer viewing the disk edge-on.

### 3.2 Polarization Signatures of Corona Geometries

I simulated two extended corona geometries, wedge and spherical coronae (Fig. 2.3). The wedge coronae lie above and below the accretion disk and is chosen to have a constant opening angle of \(8^\circ\). The spherical corona extends from \(R_{ISCO}\) out to \(R_{edge} = 15r_g\). The definition of optical depth and scattering coefficient \((\sigma)\) for these coronae are presented in Sec. 2.5. Here we show the spectral and polarization result of these two corona.
As mentioned in Chapter 2, our simulation improved the previous coronae simulations by including a complete relativistic scattering and the likelihood of this scattering in the corona. Figure 3.1 shows the effect of these different scattering models on the energy spectra obtained for simulating a spherical corona with \( \tau_0 = 3 \) with four different treatments: (i) in the Thomson approximation (the photon energy does not change in the rest frame of the scattering electrons), using the Raleigh scattering matrix and omitting the weighting factor \( 1 - \beta \cos(\theta) \); (ii) same as (i) but including the weighting factor \( 1 - \beta \cos(\theta) \); (iii) as (ii) but accounting for the energy loss of the photon in the rest frame of the scattering electrons, (iv) as (iii) but using the Fano scattering matrix. We see that the weighting factor scattering likelihood makes a noticeable difference and changes the 1-10 keV photon index by \( \Delta \Gamma \approx 0.1 \). Replacing the Raleigh scattering matrix by the Fano scattering matrix does not noticeably impact the energy spectrum in 1-10 keV; while at higher energies it changes the photon index by \( \Delta \Gamma \approx 0.4 \).

Figure 3.2 compares the polarization fraction energy spectra for treatments (iii) and (iv) and shows that using the proper K-N cross section instead of the Thomson cross section neither impacts the polarization properties of the keV photons. Interestingly, the K-N cross section shows a difference when increasing the energy of the seed photons by a factor of 50 (adequate for the accretion disks of accreting stellar-mass black holes), see Fig. 3.3. In these plots corona densities (\( \sigma \)) are set to give same spectral index for both treatments (iii) and (iv) in 2-10 keV. For such high seed photon energies, photons scatter fewer times to get into the X-ray band, increasing the importance of each individual scattering. The polarization differences are larger for the wedge corona compared to the spherical corona as the former scatterings are generally more important as the corona covers a larger fraction of the inner accretion disk area. Based on Equ. 2.16 we expect more pronounced K-N effects at the highest energies. However, the results reveal significant differences at <10 keV energies. As the K-N
Figure 3.2: Comparison of the polarization fraction energy spectra for the spherical corona (a) and wedge corona (b) calculated with the Thomson cross section, model (iii), (solid line) and the K-N cross section, model (iv), (dashed line) for a black hole inclination of 75°. The different panels show the results for different optical depths; left side (spherical corona) from top to bottom: $\tau_0 = 1.5/\sigma = 0.12$, $\tau_0 = 3/\sigma = 0.24$, $\tau_0 = 5/\sigma = 0.39$; right side (wedge corona) from top to bottom: $\tau_0 = 0.9/\sigma = 0.16$, $\tau_0 = 2.3/\sigma = 0.41$, $\tau_0 = 4.3/\sigma = 0.76$. 
Figure 3.3: Polarization fraction and angle spectra for the Thomson cross section (solid line) and the KN cross section (dashed line) of the hot accretion disk of a stellar-mass black hole seen at an inclination of $75^\circ$. In each panel the optical depths have been chosen to produce the same spectral index in 2-10 keV. (a) and (c): Spherical corona with $\tau_0 = 3, \sigma = 0.24$ for Thomson and $\tau_0 = 2.2, \sigma = 0.17$ for KN with $\Gamma \approx 1$. (b) and (d): Wedge corona with $\tau_0 = 4., \sigma = 0.71$ for Thomson and $\tau_0 = 1.7, \sigma = 0.3$ for KN with $\Gamma \approx 1.2$. 
cross section leads to a reduced scattering rate at higher energies, more photons end up in the <10 keV band. The higher polarization fraction in K-N scatterings explains the higher polarization of the <10 keV photons.

Figure 3.4 shows the polarization fraction for the same spectral index of the two geometries for different scattering coefficients (σ). We choose corona densities (σ) giving the same net 2-10 keV spectral index of the Comptonized emission for the two geometries. This reveals that at Γ > 1.1, lower τ0/σ, the wedge corona is more polarized than the spherical corona; while at Γ = 1.1, the two geometries almost have the same polarization fraction; and at steeper spectrum the spherical corona is more polarized at certain bins. This result shows that the difference between the geometries becomes even somewhat more significant for smaller
Figure 3.5: Comparison of the polarization fractions of the wedge corona rotating with ZAMO frame (solid line) and co-rotate with underlying disk (dashed line) for model (iv) at the inclination of $75^\circ$.

$\Gamma$-values. The polarization angle of the two models are almost the same at higher energies, while at lower energies for all spectra the two geometry shows opposite polarization direction, Fig. 3.4 (b). In the wedge corona photons are influenced by two types of scattering, scattering in the corona and scattering off the disk, while in the spherical corona photons that scatter off the accretion disk are much less than in the wedge corona, so the scattering is dominant by the corona scattering. The angle of polarization for the photons scattered off the disk are in opposite direction of the coronal scattering [144]. At lower energies, the two corona shows opposite polarization angle because of the difference in the dominant scattering in the two geometries. While at higher energies mostly coronal scattering is dominated in the two geometries, the polarization angle of the two models are almost the same. In practice, it is hard to distinguish models based on the polarization direction alone, because the orientation of the spin axis of the accretion disk is not well constrained observationally.
As mentioned above, the simulations assume that the wedge corona orbits the black hole with the angular frequency of a ZAMO. As a consequence, the photons originating in the disk will experience Compton scatterings owing to the bulk motion of the coronal plasma relative to the accretion disk. We studied the effect of this bulk motion by running additional simulations with a corona co-rotating with the underlying disk (called Keplerian corona in the following). Fig. 3.5 compares the polarization fraction of the ZAMO and Keplerian coronas - all other parameters being equal. The results show that ZAMO coronas give higher polarization fractions than Keplerian coronas, owing to the bulk motion of the former. At higher energies, the effect is not noticeable because the large number of scatterings reduce the impact of the first few scatterings on the net polarization signal.

It is important to note that the two coronae cover different portions of the accretion disk with different thermal photon properties. To assess the impact of this point, we performed the same analysis using only seed photons coming from the same portion of the accretion disk for both models. The results was the same as in Fig. 3.4. In our result, the increase in the polarization fraction when increasing the optical depth/scattering coefficient is not as clear as Schnittman & Krolik [144], Fig. 6 and 15. They increased $\tau$ and adjusted the corona temperature to maintain the same Compton $y$ parameter. Thus, they compare different corona scattering coefficients for the same energy flux. But in our case, the temperature of the corona is constant and we are comparing polarization for different spectral energies.

### 3.3 Simulation of Seyfert I Galaxy Mrk 335

This section we present the results of our code when used to model the NuSTAR observations of the Seyfert I galaxy Mrk 335 [81]. The source harbors a supermassive BH with a mass of
Figure 3.6: Simulated (solid line) and observed (data points with error bars) spectrum of Mrk 335. The simulations assume a spherical corona with $R_{\text{edge}} = 15 \, r_g$.

$M = 2.6 \times 10^7 M_\odot$ accreting at a rate of $\dot{M} = 0.2 \dot{M}_{\text{edd}}$ [168]. Fitting the NuSTAR energy spectrum gives a 2-10 keV photon index of $\Gamma \approx 1.9$, and the fit of the Fe-Kα line suggests a black hole spin of $a = 0.89$ in geometric units and a black hole inclination of $\sim 70^\circ$. For AGNs, the accretion disk inclination can be inferred from fitting the Fe-Kα line, or from a combined fit of the flux and polarization energy spectra.

For each corona geometry, we choose three different corona sizes, and adjust the optical depth to recover the observed spectral index. Figure 3.6 shows the observed and simulated energy spectra, Figure 3.7 shows the polarization fraction, and Table 4.1 lists the model parameters. The shaded area in the plots show the energy band that IXPE and XIPE can measure in the near future. In this energy range, there is a clear difference between the two corona geometries, while it is hard to constrain the size. The average polarization fraction
Figure 3.7: Simulated polarization fractions Mrk 335 for coronae of different sizes: (a) Spherical corona, (b) Wedge corona. The shaded area shows the energy range of IXPE.

of Mrk 335 in the energy of 2-10 keV, The IXPE energy band, as a function of inclination is shown in Fig. 3.8. In the wedge corona one can clearly see the polarization difference between the inclinations, while it is hard to compare in the spherical. The difference between the two geometries is also clear in different inclinations. Mrk 335 is a faint source with the flux of about $10^{-11}$ erg/cm$^2$/s which will need 2-3 days of IXPE observation for an MDP of 10%. For brighter sources, e.g. NGC 4151 with one order of magnitude higher fluxes (e.g. Marin et al. [100]), IXPE will achieve an MDP of 10% in less than two hours and an MDP of 3% in one day.
3.4 Spectral and Polarization Signatures of Non-Thermal Corona

In this section assess the impact of a non-thermal power law component of the coronal electron plasma on the observed polarization properties. The energy spectra of AGNs and stellar-mass black holes in X-ray binaries often exhibit evidence for the presence of such a component (see [31, 74, 76, 97] and references therein). We assume that the energy spectrum of the thermal electron component is described by the Maxwell-Juttner distribution:

\[
\frac{dN}{d\gamma} = \frac{\gamma^2 \beta}{\theta K_2(\frac{1}{\theta})} \exp\left(-\frac{\gamma}{\theta}\right),
\]  

(3.1)
Figure 3.9: Comparison of the polarization predicted for fully thermalized coronal electrons (dot-dashed line) and a thermal plus non-thermal hybrid electron distribution (solid line) for a spherical corona with $\tau_0 = 3$ and $\sigma = 0.24$ (a) and a wedge corona with $\tau_0 = 1.9$ and $\sigma = 0.34$ (b).

where $\gamma$ is the Lorentz factor of the electrons, $\theta = kT_e/m_e c^2$ is the electron temperature in units of the electron rest mass, and $\beta = v_e/c$ is the electron velocity in units of the speed of light. The Maxwell-Juttner distribution describes plasmas with temperatures exceeding 100 keV. At lower temperatures, the distribution resembles the non-relativistic Maxwell distribution. The non-thermal electron component is given by $dN/d\gamma = \xi \gamma^{-p}$ with the normalization constant $\xi$ and the power law index $p$. (Oriented Scintillation Spectrometer Experiment) observations of NGC 4151, Johnson et al. [76] estimated that $\sim 8\%$ but less than 15\% of the source power is in the non-thermal electron component. The results agree with those of Fabian et al. [44] who studied several NuSTAR AGN observations and estimate that the non-thermal component carries 10\%-30\% of the source power. In the following, we assume a non-thermal energy population with $\gamma$-factors between 1 and 1000 carrying 15\% of the total energy of the coronal electrons.
Figure 3.10: Polarization fractions of different subsets of the photons shown in Fig. 3.9 (a), i.e. for photons scattering only off non-thermal electrons (red line), thermal electrons (blue line), the mixture of thermal and non-thermal electrons (black line), and for all photons (green line).

Figure 3.9 shows the impact of the non-thermal component on the observed polarization signatures. We assume $p = 3$ and a rather low temperature of the thermal component of 50 keV so that we can see the impact of the non-thermal electrons at the high-energy end of the observed energy spectra. For both corona geometries, the addition of a non-thermal electron component carrying 15% of the energy barely changes the polarization properties.

Fig. 3.10 shows additional details for the spherical corona model. Photons scattering only off non-thermal electrons are highly polarized as a small number of scatterings results in a high polarization fraction. Photons scattering only off thermal, and off thermal and non-thermal electrons exhibit very similar polarization properties.

Fig. 3.11 shows the polarization of photons as function of their arrival direction. Fig. 3.11(a) shows photons only scattering off non-thermal photons with a high polarization fraction
Figure 3.11: Images of the 1-10 keV photons from Fig. 3.10 with the color scale showing the intensity in logarithmic scale, the length of the black bars is the polarization fraction, and the orientation of the black bars is the direction of the preferred electric field of the photons (inclination 75°). (a) shows photons that scattered only off non-thermal electrons, (b) shows photons that scattered only off thermal electrons, (c) shows photons that scattered off two electrons, and (d) shows all photons.
(encoded by the length of the black bars) when they originate from the inner part of the accretion flow ($< 15 r_g$). Fig. 3.11(b) shows the much smaller polarization of photons scattering only off thermal electrons, and Fig. 3.11(c) shows that the polarization of all photons very much resembles the results of Fig. 3.11(b). The polarization angle for all images of photons coming from the corona is very comparable and the patterns are very similar. However, the polarization fractions are higher for image (a) explaining the larger bars. Outside of the corona, photons scatter off the disk, so they are more vertically polarized. Inside the corona, the spherical symmetry of the corona and the axial symmetry of the background metric and accretion disk lead to a spherical polarization pattern.

Ghisellini et al. [57] argue that the coronal plasma may not have sufficient time to thermalize. Figure 3.12 compares a thermal model with $T_e = 171$ keV with a non-thermal model with $p = 2$ for $1 < \gamma < 3$. We choose the same corona temperature and power law index as in Ghisellini et al. [57], giving the same spectral index in 2-10 keV. The two models produce almost identical polarization energy spectra with the difference being most pronounced at photon energies exceeding 500 keV.

### 3.5 Effects of Cyclo-Synchrotron Seed photons on Polarization Signatures

Depending on the magnetic field strength, the electrons may loose a good fraction of their energy by emitting cyclo-synchrotron photons. In this section, we explore the impact on the X-ray polarization energy spectra. We assume an ordered magnetic field of strength $B$ oriented either perpendicular to the disk along the $z$-axis, or parallel to the disk in the $x$ and $y$
Figure 3.12: Comparison of the polarization of a fully thermal and a fully non-thermal electron energy distribution for the spherical (a) and wedge (b) corona geometries.

The cyclo-synchrotron photons are partially circularly and partially linearly polarized. Since X-ray polarimeters can only measure the linear polarization, we neglect the circular polarization in the following. As above, we assume the presence of a power law electron component with $dN/d\gamma = \xi \gamma^{-p}$ for electrons emitting cyclo-synchrotron photons. The synchrotron photons are polarized perpendicular to the magnetic field with a polarization fraction of $[137]$

$$\Pi_0 = \frac{(p+1)}{(p+7/3)}.$$  \hspace{1cm} (3.2)

Non-relativistic electron emit cyclotron photons with a polarization fraction of

$$\Pi_0 = \frac{1 - \cos^2(\theta)}{1 + \cos^2(\theta)},$$  \hspace{1cm} (3.3)

where $\theta$ is the angle between the magnetic field and the line of sight [137]. In the following, we consider a scenario in which 50% of the seed photons are thermal photons from the accretion disk (polarized according to Chandrasekhar’s equation), and 50% are synchrotron photons.
Figure 3.13: Polarization fractions of the X-ray photons from different seed photons for a spherical corona seen at an inclination of 75°. The overall polarization is completely dominated by the photons from thermal seed photons. The solid line has large error bars because of the very small number of synchrotron photons being scattered into the 0.1-100 keV energy range.

from an electron power law distribution with $p = 3$ for which Equ. 3.2 gives a polarization fraction of 75%.

Fig 3.13 shows the polarization energy spectra for the spherical corona geometry and the magnetic field parallel to the accretion disk. The red line shows the polarization fraction of the synchrotron photons. As the synchrotron photons are emitted in the infrared band and only a tiny fraction makes it into the X-ray band via a large number of Compton scatterings, the error bars on the polarization fraction and direction are rather large. Accordingly, the X-ray emission is strongly dominated by the thermal seed photons even if a substantial fraction of the seed photon energy goes into the synchrotron component. We obtain the same results for the magnetic field being perpendicular to the accretion disk. Accounting for
the effect of synchrotron self-absorption reduces the overall impact of the synchrotron seed photons on the observed energy spectra even more. As cyclotron photons are less energetic and exhibit lower polarization fractions than synchrotron photons, we expect that they have a similarly negligible impact on the observed polarization energy spectra. Our result of a negligible impact of the synchrotron seed photons on the emitted energy spectra agrees with the earlier findings of [145].

3.6 Summary and Discussion

The results presented in this chapter can be summarized as follows: the simulated X-ray polarization and energy spectra depend strongly on the proper treatment of the kinematic effects (change of the photon energy in the rest frame of the scattering electrons, and relative probability for head on and tail on collisions) and the use of the relativistic cross section. Using the K-N cross section rather than the Thomson cross section increases the 1-10 keV polarization fractions by as much as $\sim 3\%$ for the wedge corona of the hot accretion disk of a stellar-mass BH. For the colder accretion disks of AGNs, the cross section does not impact the predicted polarization properties noticeably. The difference between the different corona geometries depends on the optical depth of the coronal plasma, or, conversely, on the energy spectrum of the observed emission. For high optical depths and hard energy spectra, the spherical corona emission is more polarized than the wedge corona emission in the 2-20 keV energy band. For small optical depths and soft energy spectra, the wedge corona emission exhibits a 1-2% higher polarization than the spherical corona over the entire 1-100 keV energy range. The different polarization fractions are accompanied by differences in the polarization direction.
We presented simulations for the Seyfert I galaxy Mrk 335. We predicted the polarization for the two corona geometries and three different corona sizes. Keeping the energy spectrum fixed, the different corona models predict different polarization fractions and angles. We anticipate that the upcoming IXPE mission will add valuable observables for constraining the properties of the inner engine of AGNs - in particular if several complimentary techniques including spectral, timing, and polarization analyses can all be used for one and the same object.

Finally, we find that a non-thermal electron component with about 15% of the internal electron energy has a negligible impact on the observed polarization properties. Even a completely non-thermal corona with a small optical depth producing the same energy spectrum as a thermal corona shows similar polarization properties as a fully thermalized corona. Similarly, cyclotron and synchrotron photons do not impact the polarization energy spectra strongly – even when they carry a substantial fraction of the seed photons’ luminosity. The reason is that these cyclo-synchrotron photons are expected to have too long wavelengths so that only a small fraction is scattered into the X-ray energy range. Synchrotron photons could have an impact if generated with much shorter wavelengths, e.g. as a consequence of magnetic reconnection events in the corona.
Chapter 4

Spectral and Polarization Signatures of High Frequency Quasi-Periodic Oscillations

This chapter presents the paper I published [9] under the supervision of my advisor, Henric Krawczynski, and comments of my colleague, Dr. Hoormann.

4.1 Introduction

The X-ray observations of accreting neutron stars and BHs of the last one and a half decade have revealed new avenues for testing GR in the strong gravity regime [131, 140]. The RXTE revealed High Frequency (>40 Hz) QPOs in a number of accreting BHs in X-ray binaries [132]. Altogether, HFQPOs have been found in seven systems, three with a detection at a single frequency, and four with a detection at multiple frequencies. As presented in Sect. 1.3.3, a number of models have been developed to explain the observed HFQPOs in
different frequency ranges. In this chapter we investigate the HFQPOs using the HS model. We summarized the HS model and describe our simulations in Sect. 2.4. This chapter presents our results on the spectral and spectropolarimetric observational signatures of the HS model.

A timing and spectroscopy mission like LOFT is ideally suited to detect HFQPOs [21, 48, 160] and to measure QPO-phase-resolved energy spectra. Spectroscopic X-ray polarimetry observations (see e.g. [13, 85, 89, 92, 107, 143]), offering three times as much information as purely spectroscopic observations (i.e. the Stokes parameters I, Q and U rather than I alone as function of energy) would offer additional handles to distinguish between HFQPO models. As some X-rays scatter before leaving the accretion disk, even the thermal emission is polarized (e.g. Li et al. [92] and references therein). The polarization angle changes as the X-rays propagate through the strongly curved spacetime of the BH. Additional photon scattering off the accretion disk or in the accretion disk corona modifies the polarization fraction and angle. Zamaninasab et al. [175, 176] studied the polarization of HSs orbiting supermassive BHs at infrared wavelengths and used infrared observations of the supermassive BH Sgr A* to constrain its mass and spin.

We use the ray-tracing code developed by Krawczynski [85] to model the X-ray emission from HSs orbiting Schwarzschild and Kerr stellar-mass BHs in X-ray binaries. Although our studies are generic in nature, our Kerr BH calculations adopt parameters chosen to describe the 166 Hz QPO of the galactic BH GRS 1915+105. HFQPOs has been observed in steep power law state (SPL) of BHs. The SPL state commonly attributed to a corona of hotter gas which reprocesses the accretion disk photons and gives rise to a power law emission spectrum (e.g. [132]). Since the geometry and physical properties of a corona are not fully understood, a wide range of coronal models have been proposed (e.g. [39, 61, 103, 120, 144]).
In this chapter we model a geometrically thin, optically thick accretion disk with an orbiting HS with and without a sandwich corona. The corona properties have been chosen to give the power law energy spectrum of GRS 1915+105 in the SPL state.

In a somewhat related study Ingram et al. [73] have studied the polarization properties of low frequency QPOs assuming that they originate from the Lense-Thirring precession of the inner accreting flow. They find polarization fraction variations on the order of 1% which could be detected and studied by an X-ray polarimeter with hard X-ray sensitivity such as the proposed PolSTAR mission.

The rest of the chapter is structured as follows. Section 4.2 and 4.3 presents the results for Schwarzschild and Kerr BHs, including a discussion of the observational signatures as function of the HS parameters. In Sect. 4.4 we summarize the results and discuss the expected energy spectra and polarization signatures of competing HS models in thermal and power law emission, respectively.

### 4.2 Thermal Simulation for Hot Spot

We assume that the HS is a disk segment emitting with a temperature five times higher than the surrounding material. This temperature gives (for the adopted HS size) HFQPO rms amplitudes comparable to the observed ones. The effects of the HS size on the observable signatures are discussed in the result section. The HS of the Schwarzschild BH extends from the innermost stable circular orbit ($r_{\text{ISCO}} = 6$) to $r = r_{\text{ISCO}} + 2\Delta r$, where $\Delta r = 0.5$ and from $\phi$ to $\phi + \Delta \phi$, where $\Delta \phi = 0.08\pi$. The HS of the Kerr BH is centered at the radial coordinate $r = 5 + \Delta r$ to model the 166 Hz QPO of GRS 1915+105.
We use the general relativistic ray-tracing code of Krawczynski [85]. Photons are tracked forward in time from their emission site to the observer, including, if applicable, one or several scatterings off the accretion disk. The HS is treated in the same way as the accretion disk (explained in Sect. 2.3), except that the effective temperature and thus the brightness and the statistical weight is higher for this segment. For simplicity we do not reduce the temperature of the adjacent parts of the accretion disk which would be required in a self-consistent steady-state solution. The slight temperature reduction of the adjacent material would enlarge the contrast between the HS and the disk and would thus enlarge the observational signatures.

Fig. 4.1 shows the phase-resolved energy spectra of the accretion disk and HS emission of GRS 1915+105. We divided the orbit into 5 phase bins and each line in the figure shows the energy spectra of the HS for the specific phase bins. Note that the phase also characterizes the azimuthal position of the HS. At phase = 0 (0.5) the HS is closest to (furthest away from) the observer. The energy spectra exhibit well defined flux peaks. The corresponding energy to these peaks, i.e. peak energies, for the total emission (HS plus accretion disk) are shown in Fig. 4.2 as function of phase for both simulated BHs. The peak energies are higher for the Kerr BH as its HS is closer to the BH (the HS center is at 5.5 $r_g$ for the Kerr BH and 6.5 $r_g$ for Schwarzschild BH) allowing for bright emission from the inner regions of the accretion disk.

The integral flux, intensity, drops in the last phase bin even though the energy spectrum still hardens (Fig 4.1), owing to the Doppler shift from the relativistic motion of the accretion disk plasma. This can be understood as follows: Photons returning to the disk and scattering off the disk have a very broad energy spectrum owing to the energy gains/losses incurred during the scattering process. These scattered photons come a bit later than the unscattered
Figure 4.1: Phase-resolved energy spectra of a HS orbiting GRS 1915+105 for HS emission (upper panel) and total emission (lower panel).
Figure 4.2: Intensity (i.e., average 2-30 keV photon flux) (upper panel) and peak energy (lower panel) of the total X-ray emission from the Schwarzschild and Kerr BHs. The intensity is normalized to 1 when integrated over all phases.
photons, giving rise to the hard spectrum at the end of the peak. Interestingly, the flux peak leads the peak of the spectral hardness by $\sim 0.2$ in phase.

Figure 4.3 and 4.4 show the normalized intensity, polarization fraction and angle for the Schwarzschild and Kerr BHs. The intensity is normalized to 1 when integrated over all phases. Comparing these figures one can see the effect of the BH spin on the polarization of the observed emission. Interestingly, the HS model predicts that the peak of the emission (dominated by direct HS emission relativistically beamed towards the observer) is accompanied by a drop in polarization fraction and a large swing of the polarization direction.

As shown below, the polarization properties result from the competition of the direct HS emission and the HS emission reflecting off the accretion disk. Also, the effect of including the emission of both the disk and HS on the polarization fraction and angle is shown in figure 4.5. The total polarization is lower due to the disk emission being less polarized.

Figures 4.6 and 4.7 show (for the Schwarzschild BH) the light curve and polarization angle of an orbiting HS together with snapshot of images of the emission made with direct (non-scattered photons) and returning (scattered photons) radiation, respectively. In the top middle snapshot in Fig. 4.6 the bottom ring is observable due to the extreme curvature of the spacetime close to the BH.

The light curve in figure 4.6 demonstrates the HS is brightest in the $0.7T - 0.9T$ phase bin (with $T$ being the orbital period of the HS). The apparent brightness distribution results from the combined effect of relativistic boosting and light travel time effects. The spot appears to orbit faster during the first half of its orbit. The same result is seen for GRS 1915+105.

Figures 4.7 show the effect of scattering on the polarization. Approximately between 10 – 40% of photons scatter off the disk depending on the phase of the HS. These scattered
Figure 4.3: Intensity, polarization fraction, and polarization angle of the HS emission for a Schwarzschild BH, viewed at an inclination of $75^\circ$. The emission is polarized with a maximum polarization fraction of $\approx 8.5\%$. The polarization angle exhibits a full $180^\circ$ swing in one orbit. A polarization angle of $0^\circ$ corresponds to emission with an electric field vector perpendicular to the spin axis of the accretion disk.
Figure 4.4: The same as Fig. 4.3 for a HS orbiting the Kerr BH. The emission is highly polarized with a maximum polarization fraction of $\approx 10\%$. The polarization angle swings by $90^\circ$ during one orbit.
Figure 4.5: Polarization fraction and angle of the HS plus disk emission for the Kerr BH. This is polarized with a maximum polarization fraction of $\approx 1.2\%$. 
Figure 4.6: Light curve, polarization fraction and angle, and images of the direct emission from a HS orbiting the Schwarzschild BH viewed at 75° inclination (relative to the spin axis of the accretion disk). The images show the HS in five phase bins. For instance, the first image (top left) shows the emission of the phase bin from $t = 0$ to $t = 0.2T$, $T$ being the HS period. The axis label and scale for the images are the same as in Fig. 2.1. The intensity is normalized to 1 when integrated over all phases.
photons are highly polarized and thus strongly impact the net polarization of the signal (Fig 4.7). The importance of the scattered photons on the polarization angle can be seen from the intensities (Fig 4.8). For direct photons the polarization vector is mostly parallel (±90°). The scattered photons acquire a 90° rotated polarization angle. In the 0.1 T – 0.7 T phase bin, the returning radiation intensity becomes higher, so the observed polarization angle is dominated by returning radiation which is strongly polarized, thus it is around 0°/180°. For phases over 0.8 T the direct intensity with a 90 degree rotated polarization angle dominates. Furthermore, the change of the polarization angle is larger for the Kerr BH than for the Schwarzschild BH owing to the stronger curved spacetime of the Kerr BH and the larger fraction of photons returning to the accretion disk for a Kerr BH with a smaller ISCO.

All polarization plots show an anti-correlation between the intensity and the polarization fraction of the HS. For example, in Fig. 4.4, we see that the high fluxes in the second half of the orbit are polarized to a low degree. The effect is smaller for the Schwarzschild BH which shows higher polarization fractions than the Kerr BH at the end of the orbit. The effect of photons returning to the accretion disk on the polarization fraction owing to the curved spacetime is shown in Fig. 4.7. Not only does the figure emphasize that scattering leads to a strong polarization of the returning radiation, but also it confirms the anti-correlation of intensity and polarization fraction. The same result is seen for GRS 1915+105.

It is instructive to compare our results with those of Broderick & Loeb [23] who modeled the polarized emission of a HS orbiting a BH. While the emission of the HSs in Figs. 5 and 6 depolarizes when the intensity peaks, the hot spot emission of Broderick & Loeb depolarizes briefly before the intensity peaks. We explain the different results by three main reasons: (i) Our code assumes that the initial polarization of the emission is given by Chandrasekhar’s
Figure 4.7: The same as Fig. 4.6 for the emission returning to the accretion disk and being scattered at least once.
Figure 4.8: Intensity and polarization angle of the direct, and the returning radiation, and the sum of these (observed). The results show that the polarization angle is dominated by the returning radiation for the central phase bins.
classical results for the emission of an optically thick atmosphere [29]: the polarization fraction increases from zero close to the zenith to a few percent close to the horizon (where “zenit” and “horizon” refer to an observer in the disk frame) and the polarization direction is perpendicular to the plane of the zenith and the emission direction. In contrast, Broderick & Loeb assume a constant polarization fraction, always orthogonal to the spin axis of the BH. 

(ii) Whereas we modeled the X-ray emission returning to and scattering off the accretion disk (strongly impacting the observed net-polarization), Broderick & Loeb do not do so. (iii) Broderick and Loeb assumed a different HS geometry and size and the predicted results are to some extent dependent on them.

A single pronounced HS produces cleaner observational signatures than a combination of several HSs. We studied the observational appearance of multiple HSs by simulating an accretion disk with 10 identical HSs. We assume that the HSs orbit the BH at the same distance but with a random phase. Figure 4.9 shows the light curve and polarization signature of this simulation for the Kerr BH. Similar to the results for a single HS, we see that the polarization fraction anti-correlates with the flux. The polarization variation is smaller than for a single HS in the same way as a bigger HS leads to smaller polarization variations as the polarization of different parts of the HS do not add up coherently.

Furthermore, we investigate the change in polarization by changing inclination of the BH and size of the HS. Figure 4.10 shows that the polarization fraction increases with BH inclination. Note that in the simulation of Schnittman & Bertschinger [140] the HFQPO amplitude exhibits a similar behavior with increasing inclination. For polarization angle, there is no simple behavior but generally it decreases by increasing inclination as a result of the lower polarization of photons leaving the emitting plasma in its reference frame closer to the surface normal. Larger HSs are less polarized than
Figure 4.9: Intensity, polarization fraction, and polarization angle of the emission from 10 identical HSs for the Kerr BH, viewed at an inclination of $66^\circ$. The emission is polarized with a maximum polarization fraction of $\approx 2.2\%$. 
Figure 4.10: Polarization fraction versus inclination for GRS 1915+105. Different lines show different phase bins. The polarization fractions increase with increasing inclination.
smaller HSs as averaging over different polarization directions reduces the polarization fraction. The HS polarization also gets smaller when increasing the distance of the HS from the BH as the fraction of returning radiation decreases. We see the same result for polarization angle by enlarging the HS. Our results show that the effect of inclination and HS size on the polarization are stronger for the Kerr BH than the Schwarzschild BH. Also, in this chapter we assumed that the HS temperature is $5T_{\text{eff}}$ to produce the realistic modulation in flux. Whereas the polarization of the HS is independent of its temperature, the peak energy of the emission is not. A larger HS can have a lower temperature and still produce the same flux modulation. Such a larger HS would emit less polarized emission due to averaging different polarization directions over a larger area.

4.3 Corona Simulation for Hot Spot

We simulate a wedge corona geometry to study the effect of coronal Comptonization on the observed HFQPO polarization. The vertical optical depth of this corona is set to a constant, $\tau_0 = 0.2$ and the temperature of the hot electrons in the corona is set to $T_{\text{corona}} = 30$ keV. These parameters reproduce the observed photon index for GRS 1915+105 in the SPL state [14]. The opening angle of the wedge is set to $2^\circ$. A larger opening angle would result in longer light travel times inside the corona and would result in a wider X-Ray pulse from the HS. Here we use the algorithm for Thomson scatterings inside the corona (see the discussion of [144] for a justification). A more detailed description of the modeling of the Comptonization of the photons in the corona is given in Sect. 2.5.

Figure 4.11 shows the power law tail of the observed flux for the HS and coronal emission. The simulation gives a photon index close to the one observed For GRS 1915+105 by Belloni
Figure 4.11: Observed energy flux per logarithmic energy interval $E^2 dN/dE$ from the accretion disk with a sandwich geometry for GRS 1915+105. The Comptonized spectrum has a photon index of $\approx 2.7$.

et al. [14] in the SPL state. The phase-resolved energy spectra of the HS and the accretion disk are shown in Figure 4.12.

The HS emission can clearly be recognized by the hard emission at the highest energies. Overall, the results look similar to the ones discussed in the absence of a corona (Fig. 4.1). Figure 4.13 shows the normalized intensity, polarization fraction and polarization angle for the same model. Although the polarization signatures are somewhat less pronounced when accounting for the Comptonization of the emission in the corona (because of the associated light travel delays and loss of phase information), the intensity and polarization fraction still show an anticorrelation as discussed for the model without a corona. In Fig. 4.13 the polarization peaks around the phase $0.2 T$ where the photons scattered in the corona are more dominant.
Figure 4.12: Phase-resolved energy spectra of a HS emission (upper panel) and total emission (lower panel) for GRS 1915+105 with a sandwich corona geometry.
Figure 4.13: Intensity, polarization fraction, and polarization angle of the HS coronal emission for GRS 1915+105. The emission is polarized with a maximum polarization fraction of $\approx 6\%$. 
4.4 Summary and Discussion

This chapter shows results from simulating HSs orbiting accreting Schwarzschild and Kerr BHs in X-ray binaries. The HS flux shows a pronounced peak accompanied by a hardening energy spectrum, with the hardness peak trailing the flux peak by 0.2 in phase. This specific signature could be observed by an instrument like LOFT. The mission would detect GRS 1915+105 with a detection rate exceeding 100,000 counts/s [152]. Using Fourier filter techniques of Tomsick & Kaaret [157] with the light curves with > 30 detected photons during each period of the 166 Hz QPO with an rms of 6% would make it possible to determine a phase for each detected photon. The phase-resolved light curve would distinguish the HS model (predicting a sharp peak in the light curve) from competing models that predict more sinusoidal variations of the flux (see the discussion below). Phase-binning the data would make it possible to determine the peak energy of the energy spectra as a function of QPO phase as shown in Fig. 4.2.

We carried through a detailed simulation and analysis to evaluate the detectability of the phase-resolved spectral variations with LOFT. We used the methods of Timmer & Koenig [155] to simulate the time-variable emission from the accretion disk with a realistic power spectral density (Fig. 4.14, top panel).

We then used the methods of Ingram & van der Klis [72] to simulate quasi-periodic oscillations based on the phase-resolved HS intensity from Fig. 4.4. Subsequently, we added statistical fluctuations to the total signal, taking the LOFT sensitivity into account. The bottom panel of Fig. 4.14 shows the resulting light curve for a 1 s LOFT observation. Although the long-term flux evolution is dominated by the low-frequency flux variability of the accretion disk emission, the HFQPOs with a period of ≈ 0.006s can clearly be recognized.
Figure 4.14: Examples of simulated disk emission (upper panel) and disk plus HS emission (lower panel).
Figure 4.15: The observed light curve predicted for *LOFT* (Fig. 4.14) after bandpass filtering. Subsequently, we applied the frequency filtering method of Tomsick & Kaaret [157] selecting on frequencies within ±20% of the HFQPO. The filtered light curve is shown in Fig. 4.15.

The filtered flux curve is subsequently used to determine the *reconstructed phase*. We find that the difference between the reconstructed and true phases is approximately normally distributed with a sigma of ≈ 0.08 for a 5 minutes observation of *LOFT*. The phase tagging becomes more accurate as we increase the observation time. Using the reconstructed phases, we can reconstruct phase-resolved energy spectra. The lower (upper) panel of Fig. 4.16 shows the phase-resolved energy spectrum measured based on the basis of the true (reconstructed) phase information. The phase reconstruction does reduce the differences between the phase-binned energy spectra, but not catastrophically. Although we show the results here only for the HS of the thermal accretion disk, it is clear that a similar analysis could be carried through for the corona HS. A mission like *LOFT* would thus make it possible to test the
Figure 4.16: The folded phase-resolved energy spectra for the simulation of the LOFT observation (upper panel) and the phase-resolved energy spectra of the thermal model for total emission (lower panel). The orbital period is divided into six equally spaced bins, each line representing the energy spectrum observed in one of these bins.
predictions of the HS in a good detail. The high statistical accuracy of the data would even enable the parameters of the HS (e.g. its size) to be constrained.

The HS thermal emission (direct and reflected) is polarized to between $\sim 1\%$ and $\sim 10\%$ and exhibits large-amplitude polarization swings (see Table 4.1). According to our simulation, the HS contributes a fraction of $f \approx 9\%$ to the total emission; the HS model thus predicts that the overall polarization fraction varies by $\sim \pm f(\Pi_{\text{max}} - \Pi_{\text{min}})/2 \approx 0.4\%$ as a function of HS phase where $\Pi$ is the polarization fraction. This prediction for HS in coronal emission with the higher $f$ but the lower variation in polarization is $0.3\%$. A specific prediction of the HS model is an anticorrelation of the polarization fraction as a function of the HS flux. The variations in polarization fraction of the competing HFQPO models are most likely much smaller. In the resonance model, e.g. Abramowicz & Kluzniak [2] and Abramowicz et al. [4], a perturbation excites oscillatory modes close to the ISCO. Petri [129] models the HFQPOs of GRS 1915+105 by assuming that a spiral wave in the inner part of the accretion disk is in resonance with vertical epicyclic oscillations. In this model, the brightening disk portion is a ring segment rather than a more localized HS. The polarization of the emission from the bright ring segment will be more similar to that of the HS averaging over all phases. The averaging process reduced the expected polarization by a factor of a few. In the torus model [134] HFQPOs are the result of p-mode (pressure mode) oscillations of an accretion torus orbiting the BH close to the ISCO. The model assumes a non-Keplerian geometrically thick disk resembling a torus rather than a disk. The HFQPOs are thought to arise from hydrodynamic or magnetohydrodynamic instabilities [134]. The authors set an upper limit on the radius $r_t$ of the torus of GRS 1915+105 of $r_t < 2.7r_g$ because in the absence of stabilizing magnetic fields, a larger torus would be susceptible to non-axisymmetric perturbations. We estimated the polarization of the emission from such a torus by considering the emission from a ring at a radial coordinate of $r_t = 2.7 \ r_g$. The ring is optically thick, and for simplicity
Table 4.1: Polarization properties of the Schwarzschild and Kerr BHs

<table>
<thead>
<tr>
<th>Black Hole</th>
<th>HS Min pol. frac.</th>
<th>HS Max pol. frac.</th>
<th>Disk pol. frac.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarzschild (spin= 0)</td>
<td>0.17 %</td>
<td>8.4 %</td>
<td>3.2 %</td>
</tr>
<tr>
<td>Kerr (spin= 0.95)</td>
<td>0.21 %</td>
<td>9.5 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>

Table 4.2: Polarization properties of different HFQPO models

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>Average pol. frac.</th>
<th>Max pol. frac. variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS model</td>
<td>Schnittman &amp; Bertschinger [140]</td>
<td>4.86 %</td>
<td>4.6 %</td>
</tr>
<tr>
<td>Resonance model</td>
<td>Petri [129]</td>
<td>0.78 %</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>Torus model</td>
<td>Rezzolla et al. [134]</td>
<td>2.97 %</td>
<td>&lt; 0.1 %</td>
</tr>
</tbody>
</table>

we assume that its flux changes sinusoidally with a frequency equal to the HFQPO and a maximum flux exceeding the minimum flux by a factor of 5. The torus model predicts variations in polarization of ≪1%. Furthermore, the minute peaks of the polarization fraction are in phase with the brightness peaks. The results described in this paragraph are summarized in Table 4.2.

Could a next-generation space-borne X-ray polarimeter like PolSTAR (a space-borne version of the balloon-borne X-Calibur experiment [11,12,60] with excellent sensitivity in the 3–50 keV energy band), PRAXYS [75], or IXPE [165] detect the polarization variation predicted by the HS model? We considered two methods to search for the polarization variations: (i) the analysis of Fourier transformed Stokes parameters and derived quantities, and (ii) the analysis of the polarization fraction and angle as function of QPO phase. We evaluated the first method based on the Stokes parameters $I_i, Q_i$ and $U_i$ for each detected X-ray photon, as defined in [82]. We calculated the polarization fraction $\pi_k$ of the $k^{th}$ time bin with the standard equation: $\pi_k = \sqrt{\sum_{i_k} Q^2_{i_k} + U^2_{i_k}} / \sum_{i_k} I_{i_k}$. However, the Fourier transform of $\pi_k$ did not show pronounced peaks near the QPO frequency, indicating that quantities other than $\pi_k$ should be used to search for quasi-periodic variations of the polarization fraction. The second method requires us to determine a phase for each individual detected event, enabling
the determination of phase-binned polarization fractions and polarization angles. As the
detection rate of first-generation polarimeters for GRS 1915+105 would be $\sim 100$ counts $s^{-1}$, they would detect less than one photon during each HFQPO cycle (and an even smaller fraction of HS photons). Such a low rate would not enable the assignment of a QPO phase.

The study of the polarization properties of HFQPOs would thus require the concurrent operation of a first-generation X-ray polarimeter with a LOFT-type timing mission. The latter instrument would supply the information for phase-binning the data from the polarimeter mission. Whereas the systematic errors on measurements of absolute polarization fraction with a polarimeter like PolSTAR are of the order of 0.25%, the systematic errors on short-term variations in polarization fraction are much smaller. We conclude that the detection of the HS polarization signatures would be challenging but not entirely impossible.

In this chapter we simulated the simple thermal disk and a wedge corona geometry with a HS to model spectral and polarization signatures of a HS. Other disk models such as ADAF can produce a very hot gas in the innermost region of the disk, making the HS with a temperature higher than 5 keV, which can produce seed photons that are already in high energy bands, with a moderate upscattering in the small coronal region [142]. Also it will be exciting to do similar studies based on GRRMHD codes that evolve the accretion disk and a HS self-consistently.
Chapter 5

X-Calibur, Hard X-ray Polarimeter

X-Calibur is a hard X-ray polarimeter which flew for a test flight from Ft. Sumner, NM on a stratospheric balloon in September 2016. It is scheduled for a 30 day long duration balloon (LDB) flight from McMurdo, Antarctica in December 2018. X-Calibur measures the linear polarization of 20-60 keV X-rays. It includes a grazing incidence mirror which works as a light collector [121], a scattering polarimeter, and an arc-second pointing system (developed by the Wallops Arc Second Pointer (WASP) team [151]). For the 2018 flight, the main targets of X-Calibur will be neutron stars. For these targets, X-Calibur observations can help to distinguish between the two main types of their beam, the pencil-like and fan-like beam, which will provide us with the evidence to infer the geometry of the X-ray emission region. Also with X-Calibur observations, we can measure the magnetic field strength and the angle of dipole axis by measuring the polarization swing and the rotation of polarization angle. In the framework of my thesis work, I contributed to (i) the optimization of the detector/ASIC (Application Specific Integrated Circuit) packages, (ii) tests of the deformation of the truss structure, and (iii) the analysis of the thermal results from the test flight in 2016.
5.1 X-Calibur Polarimeter

This section describes the design and working principle of the X-Calibur polarimeter. The polarimeter includes a scattering element which is surrounded by four boards of Cd(Zn)Te (CZT) detectors (Fig. 5.1 and 5.2). It measures polarization using the fact that linearly polarized X-rays preferentially Compton scatter in a direction perpendicular to their electric field vector. This results in a sinusoidal modulation in the distribution of the scattering azimuthal angles. The amplitude of the modulation determines the polarization fraction and its phase determines the polarization angle. X-Calibur uses an X-ray mirror focusing photons onto the scattering element to achieve a high photon detection rate. The scattering element is chosen to maximize the scattering probability and minimize the photo-absorption probability in the X-Calibur energy band. A large fraction of the scattered photons strike a CZT detector and are photo-absorbed there. The charge signal is read out by custom developed Application Specific Integrated Circuits (ASICs) connected to the CZT detectors. The signals from triggered ASICs are subsequently digitized and transferred to the computer via Field Programmable Gate Array (FPGA) boards. The scattering and detection process is shown in Fig 5.1.

Primary and secondary charged and neutral high-energy particles in Earth’s atmosphere create background for the polarimeter. This background and the associated count rate fluctuations limit the sensitivity of X-Calibur and may cause a spurious polarization signal. To reduce the background, the polarimeter and front-end readout electronics are surrounded by an active CsI(Na) shield. The particles interact with the shield and produce scintillation lights which are readout by four (2016 configuration) or eight (2018/2019 configuration) Photomultiplier Tubes (PMTs). For the 2016 flight, a partially active/partially passive shield
Figure 5.1: Schematic showing the detection of photons with the X-Calibur polarimeter. The cosmic X-ray photons are focused with the X-ray mirror onto the scattering element. Some of the photons scatter in the element and are subsequently detected by the surrounding CZT detectors. Some photons may pass through the element without scattering. These photons are detected by the tail-end CZT detector and are used for monitoring the pointing of the telescope and the mirror-detector alignment.

was used (Fig 5.2). The 2018/2019 flight will use a fully active shield. The polarimeter/shield assembly is rotated around the optical axis to reduce the impact of a non-uniform detector response.

5.2 ASICs and CZT detector

Customized ASICs are widely used in high-energy astrophysics instruments. ASICs can achieve much better energy resolutions and fulfill the requirement of a high packaging density. ASICs are used to read out hybrid silicon detectors and CZT detectors [56]. The latter are well-suited for hard X-rays in ranges of 5 keV to a few MeV. When a photon strikes a CZT detector it deposits its energy in the detector and produces a photoelectron. The photoelectron propagates through the CZT and deposits its energy by creating electron-hole pairs and some phonons. Sometimes, the photoelectron emits a Bremsstrahlung-photon.
Figure 5.2: A sketch of polarimeter (left) and the shield (right). Left panel: Exploded view of polarimeter. The scattering element is surrounded by 4 rings of CZT detectors with an additional CZT detector at the tail-end. Right panel: For the 2018/2019 flight the polarimeter is inside a fully active CsI(Na) shield read out by 8 PMTs.

which is photo-absorbed and creates another photo-electron or sometimes escapes. The detector is biased with a high voltage (HV) which causes the electrons to drift to the detector anode and the holes to drift to the cathode. The electrical charge induced on the detector pixels is amplified by the ASICs. The self-triggering ASICs prompt the amplitude to digital conversion and the transfer of the digitized pulse heights (proportional to the observed charge) to the computers. X-Calibur uses pixelated 2mm thick and $2 \times 2\text{cm}^2$ footprint CZT detectors to insure that $>99\%$ of the scattered X-rays are absorbed.

5.2.1 ASIC Requirements for X-Calibur

The X-Calibur CZT/ASIC packages need to detect X-rays in the 20-60 keV energy range. The measurement of the azimuthal scattering angles requires the detectors to have a good
spatial resolution. In the case of X-Calibur, the spatial resolution is given by the pixel pitch of 2.5 mm and enables the measurement of the azimuthal scattering angle with an accuracy of \(360^\circ / (4 \times 8) = 11.25^\circ\). The data acquisition needs to be sufficiently fast to cope with (background dominated) trigger rates of a few kHz without loosing a substantial fraction of the photons to deadtime. Last but not least, the detectors should achieve a low-energy trigger threshold of \(<20\) keV and an energy resolution of a few keV Full Width Half Maximum (FWHM) to enable the detection of 20-60 keV photons. I worked on the optimization of the readout electronics to suppress electronic noise and to achieve a low energy threshold \(E_{th}\). I tested all ASICs and all CZTs of X-Calibur to select ASIC/CZT combinations satisfying the requirements of \(>90\%\) of fully functional channels with a \(<20\) keV energy threshold. Sec. 5.2.3 present the details of this work.

### 5.2.2 Different ASIC Designs

Each X-Calibur detector has 64 pixels that are read out by two 32-channel ASICs. The ASIC has been developed by G. De Geronimo at Brookhaven National Lab. The ASIC is fabricated in 0.25 \(\mu\)m CMOS (Complementary Metal Oxide Semiconductor) technology and requires a total of 166 mW power. Each ASIC has 32 front-end channels with a built-in capacitor that allows one to inject charge into individual channels for testing purposes. Table 5.1 compares the X-Calibur ASICs with other ASICs that have been proposed or used in other high-energy astrophysics missions.
Table 5.1: Comparison of the state-of-the-art readout ASICs.

<table>
<thead>
<tr>
<th>Property</th>
<th>NCI2 (X-Calibur)</th>
<th>NuSTAR</th>
<th>HEXITEC</th>
<th>HPLH (H3D)</th>
<th>HEXID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad Pitch (µm)</td>
<td>220</td>
<td>600</td>
<td>250</td>
<td>116.16 (Min)</td>
<td>200</td>
</tr>
<tr>
<td>Channels</td>
<td>32</td>
<td>1,024</td>
<td>350</td>
<td>128</td>
<td>11,600</td>
</tr>
<tr>
<td>CMOS Technology (µm)</td>
<td>0.25</td>
<td>0.35</td>
<td>0.25</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Power per Channel (mW)</td>
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<td>0.05</td>
<td>High (not published)</td>
<td>2.3</td>
<td>0.6</td>
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<td>Y</td>
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<tr>
<td>Temp. Sensor</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
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</tr>
</tbody>
</table>

5.2.3 Optimization and Calibration of CZT/ASIC Packages

To achieve a low energy threshold and excellent energy resolutions for the X-Calibur flight, we tested all the CZT/ASIC packages with an X-ray source, optimized their threshold, and calibrated the energy spectra. I used Eu-152 and an Ba-133 radioactive sources as calibration sources. These two sources were chosen because of their high intensity X-ray lines in the 5-200 keV energy range covering the X-Calibur 20-60 keV energy range. Eu-152 has strong X-ray lines at 40.12 keV and 122.78 keV, and Ba-133 has strong lines at 30.6-30.9 keV, 80.99 keV, and 356.01 keV.

The test set up for testing and calibrating all the CZT/ASIC pairs is shown in Fig. 5.3. The CZT/ASIC pairs are plugged into an FPGA board and the board is kept inside a copper box to shield against the ambient electromagnetic noise. The X-ray source is taped to the copper box lid above the detectors. A digitized energy spectrum is shown in Fig. 5.6. The ASICs threshold levels are set manually by screening each channel’s spectrum until the optimized energy thresholds are found.

To quantify the characteristics of each channel and calibrate them, the lines are fitted with a Gaussian line profile. The FWHM of the peak shows the energy resolution of the channel.
Figure 5.3: Test setup for optimization and verification of the CZT/ASIC packages. Left image: The CZT HV board is inside a shield copper box. A black cloth covers the copper box to reduce light contamination. Right image: The inside of the copper box. CZT/ASIC pairs are connected to the FPGA board and the data acquisition computer via a ribbon cable. The board is covered with a grounded copper shields to shield against digital noise from the readout electronics.
Figure 5.4: Distribution of $E_{th}$ for the X-Calibur 2016 test flight. The mean energy of the distribution is 24.4 keV. Energy thresholds above 25 keV will result in the loss of signal and a lower X-Calibur sensitivity.

The data are calibrated using the fact that there is a linear dependence between the deposited energy and the measured pulse height. The linearity has been quantified with the help of the internal test pulse generator of the ASIC. The calibration equation is written as

$$E = (PH - Ped)/\alpha,$$  \hspace{1cm} (5.1)

where $PH$ is the pulse height of the signal, $Ped$ is the channel pedestal, and $\alpha$ is the gain of each channel. The parameters $Ped$ and $\alpha$ can be fitted based on energy spectra with two lines at known energies.

After the X-Calibur test flight in 2016, we improved the readout electronics. During the test flight, the ASICs were operated at a medium gain of 28.5 mV/fC and their energy thresholds were higher than required. Fig 5.4 shows the distribution of the $E_{th}$ for all ASICs used for the test flight. Following the flight, we worked on the readout electronics to reach lower
energy thresholds. With the help of the ASIC designer G. De Geronimo and our electrical engineer P. Dowkontt, we changed the HV biasing scheme, the grounding of all components, and the FPGA readout sequence, enabling to run the ASIC with the highest gain setting of 57 mV/fC. We redesigned the HV filter circuit, and added the ground connections. Some of the tests were performed with the ASICs only, with the ASICs hooked up to CZT detectors, and with biased CZT detectors. Some of the tests used the ASIC analog output connected to a scope. ASICs exhibited an average noise of 1.5 mV RMS and a narrow test pulse peak (Fig. 5.5). Fig. 5.6 compares the spectra of an ASIC before and after the improvements. The changes improved the energy threshold by a factor of 5.

The CZTs and ASICs for the flight are chosen based on the observed energy thresholds, energy resolutions, and number of good channels. We prepared four boards of CZT/ASIC pairs and integrated them as shown in Fig. 5.2. Fig. 5.7 shows the energy resolution and the energy threshold distribution for the complete system.
Figure 5.6: Calibrated spectra taken with a Eu-152 source before and after the modifications described in the text. The X-ray lines are at 40 keV, 45 keV, and 121 keV can be recognized. The energy threshold improved from 22 keV (Fig. 5.4) to 5 keV FWHM.

5.3 Truss deflection

X-Calibur has an 8 m long truss consisting of two halves which are connected to a gimbal frame. Some portion of the flight equipment is mounted on the truss. The X-Calibur measurements require a high degree of thermal and mechanical stability so that the focal spot of the mirror is centered onto the detector with a deviation of less than 3 mm (corresponds to an angle of 77°).

I tested the stiffness of each truss half by measuring the deformation of it under the simulated flight load. The deflections are monitored with an Al testing structure holding one half of the truss at a time. A camera is mounted on one end of the truss element and images a LED ring mounted on the other end of the truss element (Fig. 5.8). We measured the change of the position of the LED ring in the camera image as function of the test mass mounted on the truss. Fig. 5.9a shows the measured deformations before and after the test flight in
Figure 5.7: (a) Distribution of $E_{th}$ for the upcoming X-Calibur flight in 2018-2019. The mean of the distribution is at 12.7 keV. (b) The energy resolution of the 40 keV peak of Eu-152 with X-Calibur.

2016. The results showed that the truss did not sustain structural damages during the flight and the landing and exhibited very similar bending behavior before and after the flight. As Fig. 5.9a shows, the max deformation under a 1G flight load is about ±2mm both before and after the test flight. The elasticity of the deformations was assessed by loading and unloading each half of the truss with a 1G flight load and checking if the truss returned to the same positions. The same camera/LED ring monitoring system was used during the flight (see Fig. 5.9).

### 5.4 Analysis of Thermal Measurements from Test Flight 2016

This section reports on thermal measurements of some important X-Calibur components during the test flight in 2016. Some components, i.e. the mirror and the polarimeter, need
Figure 5.8: Truss assembly for the truss deflection test. A truss half is mounted to the Al support structure (right side) and the weights are loaded onto the other side (left side).

Figure 5.9: (a) Truss deformation as a function of load before and after the 2016 test flight for each truss element. The points show the vertical deformation of the center of the LED ring. The truss performance stays well within the required range. The two lines show the predicted deformation based on a finite element analysis of the truss. (b) Offset of the mirror focal spot during the test flight. The large circle shows the diameter of the scattering element and the red dot shows the center of scintillation. The blue dots are the measured position of the focal spot during the flight. The focal spot offset was maintained at <1 mm during the test flight.
to be kept within certain temperature ranges. We installed several temperature sensors on X-Calibur to monitor the temperature of these parts. Temperature sensors and heaters installed on each Al joint of the truss allow us to monitor and correct for thermal deformations of the truss. The analysis of the thermal deformations, the temperature predictions, and the required power for the heaters were calculated by J.K. Hoormann [70] and S. Cannon. They showed that, in the worst case in Ft. Sumner (NM), we will have a difference of 40 °C between the temperatures of the different joints. During the test flight, the joint temperature did not vary much between the individual joints and we did not use the heaters.

Electronic boards heat up while working and very hot temperatures can damage them. The heat must be conducted from inside the polarimeter to the outside. We attached brass plates to the electronic boards for this purpose. To monitor the temperatures of the electronics we placed two temperature sensors inside the CsI shield. Fig. 5.10a shows that the temperature of the polarimeter stayed within the acceptable range (-20 - 25°C) during the flight.
In order to prohibit any damage to the X-ray mirror, it has to be kept at temperatures below 40°. We turned on the mirror heaters for a few hours during the night and after sunrise to keep the mirror at > −10C. Recent tests of the mirror by T. Okajima at the GSFC showed that the mirror performs well within 0 and 20 °C (Fig. 5.10b).

## 5.5 LDB Flight

X-Calibur is scheduled for an LDB flight in Dec. 2018 from McMurdo (Antarctica). We implemented several modifications to improve the sensitivity of the polarimeter. We improved the ASIC readout system to exhibit less noise and achieve lower energy thresholds as discussed in Sec. 5.2.3. In addition, the new system will use a beryllium scattering element in place of a plastic scattering (scintillator) element. The beryllium scattering element has a lower atomic number and higher density than the plastic scattering element making it an ideal polarization analyzer in the X-Calibur energy range from 20 to 60 keV [83]. As the background rate in McMurdo is a factor of 3-10 times higher than in Ft. Sumner, we are improving the shielding to suppress the background rate (a detailed analysis for X-Calibur was described by Amini [5]). The use of a fully active rather than partially active shield (shown in Fig.5.2) is expected to reduce the residual background rate by a factor three. Last but not least, we added a tail-end CZT detector to the polarimeter. The detector (Fig. 5.2) observes the X-ray source and allows us to monitor the alignment of the mirror and the detector during the flight. The tail-end detector can furthermore be used to monitor the background rate.
Chapter 6

Discussion and Outlook

6.1 Summary of Results

In the framework of my thesis, I have studied the polarization of the X-ray emission from the inner accretion flow of stellar-mass and supermassive BHs based on a general relativistic ray tracing code. Furthermore, I contributed to the preparation of the 2018-2019 LDB flight of the X-Calibur, a hard X-ray polarimetry mission.

In Chapters 2-4, I report on the results of simulating HFQPOs resulting from a HS in the accretion disk, and the results of simulating the thermal and power law emission from the accretion disk and corona of spinning BHs. As part of my thesis work, I extended the ray tracing code developed by Krawczynski [85] enabling the simulation of the step-wise energization of photons in the accretion disk corona (Chapter 2). In Chapter 3, summarizing the results published in [10], I investigate the polarization signatures predicted with the fully relativistic treatment of the scattering processes and various approximations. Furthermore, I describe how X-ray polarization observations of AGNs with missions like IXPE will constrain
the corona geometries. My results show that the approximate treatments and the fully relativistic treatment give significantly different X-ray flux and polarization energy spectra for all energies higher than 30 keV. Interestingly, the fully relativistic treatment predicts higher polarization fractions than the approximate treatments. My studies show furthermore that non-thermal electrons and cyclo-synchrotron photons have a minor impact on the predicted polarization energy spectra. My simulations ignored the effect of the magnetic field on the predicted polarization signatures which can cause inhomogeneous distribution of electrons in the corona and change the pattern of electron-photon scattering.

Chapter 4, summarizing Beheshtipour et al. [9], examines the HS model for HFQPOs. I studied the observed polarization of a HS creating a 166 Hz QPO for GRS 1915+105 and compared it with two competing models. I found that different HFQPO models give very similar results, making it hard to distinguish between the models based on the polarization signatures. Furthermore, I used a phase-finding method to phase-resolve energy spectra and showed that this method is more sensitive than an analysis based on the Fourier transformation of the Stokes parameters. A future mission with a large effective area would make it possible to assign a QPO phase to each photon, enabling the study of the QPO-phase-resolved flux and polarization energy spectra and the correlation of these with the flux level. Owing to the short periods of the HFQPOs, the IXPE mission would not be able to assign a QPO phase to each photon. However, concurrent observations of a source with IXPE and a high-throughput mission like LOFT or the eXTP [179] would enable us to use the light curves of the latter missions to phase tag the photons observed with IXPE, and thus to study the phase dependence of the polarization properties.

In this thesis, the ray-racing code was used for the simple model of disk and corona. A more realistic simulation can be done using GRMHD simulations which the geometry of
disk/corona and the jet can be derived self-consistently. Implementing the GR ray-tracing to GRRMHD simulations will make a major advancement in the studies of the inner accretion flow and jet formation. These improved simulations together with the current and upcoming observations will enlighten the ambiguities about BHs.

In the experimental part of my PhD research (Chapter 5), I contributed to the preparation of the X-Calibur LDB flight. Chapter 5 summarizes improvements of the detector system, telescope truss tests, and thermal results from the first test flight. My work contributed to lowering the energy threshold of the X-Calibur detectors from 35 keV to 15 keV. Analyzing the data from the X-Calibur test flight in 2016 showed that the truss performed well and the temperature of the payload stayed in the desired temperature ranges.

The X-Calibur observations in 2018 and the IXPE observations in 2021 will provide novel information about compact sources. These observations would allow us to obtain geometrical information about the corona and the inner part of the accretion disk which are too small to image directly, to find the magnitude and structure of the magnetic fields around BHs, and to measure the BH’s spin. These observations together with the current and future spectral and timing missions, such as NuSTAR and NICER, will provide enriched information about BHs and GR in a strong gravity regime. Also the Athena (Advanced Telescope for High ENergy Astrophysics) mission [124], launching in 2028, has the capability for sensitive high spacial resolution imaging and sensitive spatially resolved spectroscopy that can help to find the structure of galaxies and AGNs, their chemical abundances, and the kinematics of their gases. Athena can probe jet physics over the whole expected range of time scale to understand creation of jets, wind outflow velocity and column densities, wind ionization state, and the connection between the jet-wind and the accretion disk. Also, the sensitive
reflection and reverberation measurements with Athena can help to constrain the corona properties [38].

6.2 Shortcomings of the Simulations

6.2.1 Faraday Rotation

In the presence of an external magnetic field and a non-vanishing plasma density close to the BH, the polarization direction changes depending on the relative direction of the photon and the magnetic field. This effect is called Faraday rotation. While photons propagate along the magnetic field, the plane of the photon polarization rotates which causes a change in the polarization angle of the photon. Photons traveling along different trajectories experience different changes of the polarization direction tending to reduce the net polarization when averaging over the polarization of many photons. Davis et al. [33] computed the impact of Faraday rotation on the observed polarization of BHs. They assumed a strong enough magnetic field to produce a significant Faraday rotation. They used the fact that the polarization plane rotates according to the equation:

$$\chi_f = \frac{3\lambda^2 \tau_T}{16\pi^2 e} B \cdot k,$$  \hspace{1cm} (6.1)

where $B$ is the magnetic field, $\tau_T$ is the optical depth of the plasma, $\lambda$ is the photon wavelength and $k$ is the direction of photon’s wave vector. Since the angle depends on $\lambda^2$, for the short wavelength photons such as hard X-rays, the Faraday effect is not very significant unless with large magnetic field ($> 10^5$ G). Strong magnetic fields have been observed in AGNs and magnetars.
For low energy photons, a small difference in the trajectories of a photon will cause a large
difference in polarization angle, thus reducing the net polarization when averaging over dif-
ferent trajectories. So, the depolarization effect is large for low energy photons and negligible
for high energy ones. Thus, X-ray polarimetry provides a new way to constrain the magnetic
field strength and uniformity in accretion disks.

Since Faraday rotation only impacts lower energy photons, we ignore this effect. In the
corona simulations, because of the Compton scattering and the power law spectrum, we are
more interested in energies > 10 keV. As shown in Davis et al. [33], the Faraday rotation has
a negligible effect even for strong magnetic fields of $10^5$–$10^6$ G. In contrast, we are simulating
X-rays with energies 1-10 keV in our hotspot simulations. We expect that Faraday rotation
strongly impacts the polarization at energies below 2 keV. Improved simulations should
model the effect of Faraday rotation.

6.2.2 Absorption

Disk reflectivity is an important factor when photons scatter off the disk. Several ob-
servations have shown that absorption impacts the spectrum of AGNs and binary BHs
(e.g. [14, 135]). In our simulation, we assume that the disk is 100% reflective and we ignore
photon absorption in the disk. This assumption justifies the use of Chandrasekhar’s formal-
ism for describing the scattering. Chandrasekhar solved the photon transfer equation for
isotropic scattering with an albedo of $w_0 \leq 1$, where $w_0 = 1$ describes the perfect scattering
case. For polarized radiation, he considered the case of $w_0 = 1$. Due to the nonlinearity of
the integrals and the complexity of the equations, he did not derive results for the case of
non-perfect scattering with $w_0 < 1$. Absorption processes are most important for simulating
the reflection spectrum. The absorption depends on the atomic structure and the ionization state and density of the accretion disk plasma. García et al. [51, 52] presented detailed studies of the properties of the reflected emission as a function of the metallicity of the disk and the ionization state. Studies of the impact of the plasma density on the reflected energy spectra are ongoing.

In addition to the absorption effects in the accretion disk photosphere, the spectrum is also affected by absorbing materials in the BH’s and disk’s surrounding. The absorbing medium can be located along the line of sight, partially covering the disk and the X-ray source. Marin et al. [95] studied the impact of absorption on the polarization of the observed photons. They investigated the properties of the red wing of the Fe-Kα emission line for two cases. In the relativistic reflection scenario, the red wing is explained entirely by GR effects close to the black hole. Alternatively, the red wing may be created by absorbing material. They compared these two possible scenarios by simulating the resulting polarization and showed that there is a maximum difference of 10% between the two models at < 50 keV energies.

6.2.3 Quantum Electro Dynamic Effects

One of the predictions of the theory of Quantum Electro Dynamics (QED) is that light travels with different speeds through a magnetic field in a vacuum depending on its polarization. This effect is known as vacuum birefringence. The effect has not yet been observed in the laboratory because of the very small velocity differences even at the strongest magnetic fields attainable in the laboratory, and due to the limitations of the sensitivity of the instruments. So astrophysical objects with strong magnetic field are the best laboratories to search for QED effects [27]. The effect has be studied with polarization observations. Heyl & Caiazzo
[67] showed that due to this effect the polarization angle of the photons follow the magnetic field direction out to a certain radius, called a polarization limiting radius. This radius depends on the magnetic field strength and direction. They found that, for a magnetar, the effect of the vacuum polarization changed the observed polarization fraction by a factor of 5.

The QED effect and the vacuum polarization can also affect the X-ray flux. Ho & Lai [68] studied this effect on the atmospheric structure of the energy spectra from neutron stars. Using modified parameters due to the vacuum polarization effect, they solved the radiative transfer equation and thus found that this effect causes a broad suppression of the X-ray flux at energies between a few keV to a few tens of keV. The effect is expected to soften the high energy tail of thermal spectrum of neutron stars.

### 6.2.4 Scattering (Wind and Halo)

The observed X-ray can scatter off the wind or halo found in binary systems like High Mass X-ray Binaries (HMXBs). HMXBs are binary systems with a compact object in orbit with an early-type star. In HMXBs the X-rays interact with both, the accretion flow and the stellar wind which cause scattering and thus affect the photon polarization. The wind scattering is usually described as a simple Compton scattering off free electrons. The wind is expected to be ionized in most of the region between the two stars, and exhibits polarized resonance lines. This effect is expected to be strongest for HMXBs. The impact of the wind and resonance line scattering on the polarization was studied by Kallman et al. [78]. Their results show that the maximum of the observed polarization fraction scales with the optical depth of the
wind. They found furthermore that the wind scattering can increase the polarization during eclipse, and can cause the resonance lines to be highly polarized.
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