X-ray Polarization from Black Holes:
*GEMS Scientific White Paper*

Jeremy Schnittman\(^1\), Lorella Angelini\(^1\), Matthew Baring\(^2\), Wayne Baumgartner\(^1\), Kevin Black\(^1\), Jessie Dotson\(^3\), Pranab Ghosh\(^4\), Alice Harding\(^1\), Joanne Hill\(^1\), Keith Jahoda\(^1\), Phillip Kaaret\(^5\), Tim Kallman\(^1\), Henric Krawczynski\(^6\), Julian Krolik\(^7\), Dong Lai\(^8\), Craig Markwardt\(^1\), Herman Marshall\(^9\), Jeffrey Martoff\(^10\), Robin Morris\(^3\), Takashi Okajima\(^1\), Robert Petre\(^1\), Juri Poutanen\(^11\), Stephen Reynolds\(^12\), Jeffrey Scargle\(^3\), Peter Serlemitsos\(^1\), Yang Soong\(^1\), Tod Strohmayer\(^1\), Jean Swank\(^1\), Yuzuru Tawara\(^13\), and Toru Tamagawa\(^14\)

**ABSTRACT**

We present here a summary of the scientific goals behind the Gravity and Extreme Magnetism SMEX (*GEMS*) X-ray polarimetry mission’s black hole (BH) observing program. The primary targets can be divided into two classes: stellar-mass galactic BHs in accreting binaries, and super-massive BHs in the centers of active galactic nuclei (AGN). The stellar-mass BHs can in turn be divided into various X-ray spectral states: thermal-dominant (disk), hard (radio jet), and steep power-law (hot corona). These different spectral states are thought

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\(^1\)NASA/GSFC
\(^2\)Department of Physics and Astronomy, Rice Univ.
\(^3\)NASA/ARC
\(^4\)Department of Astronomy and Astrophysics, TIFR, Mumbai, India
\(^5\)Department of Physics and Astronomy, University of Iowa
\(^6\)Department of Physics, Washington U.
\(^7\)Department of Physics and Astronomy, Johns Hopkins University
\(^8\)Department of Astronomy, Cornell University
\(^9\)Center for Space Research, MIT
\(^10\)Department of Physics, Temple U.
\(^11\)U. Oulu, Finland
\(^12\)Department of Physics and Astronomy, North Carolina State University
\(^13\)Nagoya University, Japan
\(^14\)Riken University, Japan
to be generated by different accretion geometries and emission mechanisms. X-ray polarization is an ideal tool for probing the geometry around these BHs and revealing the specific properties of the accreting gas.

1. INTRODUCTION

The first positive detection of polarized X-rays from an astronomical source was made with a sounding rocket experiment in 1971 \cite{Novick1972}. The last positive detection of polarized X-rays from an astronomical source was made with the Orbiting Solar Observatory (OSO-8) in 1976 \cite{Weisskopf1976}. Both observations were of the Crab nebula, one of the brightest X-ray sources in the sky, and quite highly polarized at a level of $\sim 20\%$. As most polarization detectors are fundamentally limited by counting statistics, it would take orders of magnitude more photons to reach a sensitivity of a few percent, the level of polarization expected from many classes of astrophysical sources. It is quite likely that, in the era of OSO-8, no other source on the sky would have given even a marginal detection.

Now, after more than thirty years since that last successful observation, we are on the brink of a new era of discovery with X-ray polarization. A recent flurry of new mission proposals has renewed interest in theoretical modeling of X-ray polarization from a variety of astrophysical sources. The Gravity and Extreme Magnetism SMEX (GEMS) mission\cite{GEMS}, with an expected launch date of April 2014, will provide broad-band spectropolarimetry with high sensitivity in the 2–10 keV band \cite{Black2003, Bellazzini2006, Swank2009}. GEMS should be able to detect polarization from a large number of galactic and extragalactic sources at the $\delta \sim 1\%$ level, including stellar-mass black holes (BHs), magnetars, pulsar wind nebulae, and active galactic nuclei (AGN). Altogether, there are a few dozen known X-ray sources that are expected to have polarization and flux levels great enough to be reliably detected by GEMS. This document outlines the primary science questions regarding X-ray polarization in accreting BHs, both the stellar-mass BHs that are found in galactic X-ray binaries, and also the supermassive BHs that power quasars and AGN at the centers of distant galaxies.

A black hole is the quintessential compact object. Even the supermassive BH in the center of our galaxy only subtends an angle of $\sim 2 \times 10^{-5}$ arcsec. While radio interferometry

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\begin{itemize}
  \item More recently, there has been evidence of polarized hard X-rays and $\gamma$-rays from INTEGRAL and Fermi, but not in the 2-10 keV band that GEMS will probe.
  \item \url{heasarc.gsfc.nasa.gov/docs/gems}
\end{itemize}
is just now beginning to achieve this level of angular resolution, X-ray telescopes are orders of magnitude away, and unlikely to reach it in the foreseeable future. Thus, to observe the detailed geometry of the X-ray emitting regions of the accretion flow around a BH, we have to rely on indirect measurements such as spectroscopy and timing, interpreted through theoretical models for the source. Polarization will provide a new, powerful tool for probing the geometry of BH accretion. At the most basic level, polarization measures symmetry. A source with rotational symmetry around the line of sight (e.g., an accretion disk viewed face-on) will necessarily give zero net polarization. A source with reflection symmetry across a plane (e.g., a non-relativistic disk viewed at some angle) will be polarized either parallel or perpendicular to that symmetry plane. In general, highly symmetric objects will produce more highly-polarized signals than disordered or turbulent systems.

For extremely relativistic systems like BHs, the geometry of the accretion flow is intimately mixed up with the geometry of the curved space-time surrounding the BH. The effects of relativistic beaming, gravitational lensing, and gravito-magnetic frame-dragging can break the symmetry of even an ideal steady-state disk, and give a non-trivial net rotation to the integrated polarization vector. Because the temperature in an accretion disk should increase closer to the BH, where these relativistic effects are strongest, it was predicted long ago that the observed angle and degree of polarization of thermal disk emission should depend on photon energy (Stark & Connors 1977; Connors & Stark 1977; Connors et al. 1980). The emissivity in the disk is itself a function of the space-time geometry, since the spin of the BH strongly affects the efficiency of angular momentum transfer and thus accretion, particularly in the inner disk where temperatures are highest.

To complicate the matter further, many X-ray binaries and AGN exhibit strong non-thermal radiation, strongly suggesting the presence of a hot corona. The physical mechanism that produces this corona is not currently well-understood, but is almost certainly magnetic in origin. Additionally, many BHs produce strong relativistic jets of similarly unknown origin. We hope that X-ray polarization will help us constrain the many various models to explain these exotic systems. To a large extent, the questions we want to answer are the same as those that drive more established BH observations like spectroscopy and timing analysis, but from the more geometric perspective of polarization.

2. BLACK HOLE STATES

Galactic BHs are known to exhibit remarkable variability in their flux and spectral properties, on time scales from milliseconds to years. Remillard & McClintock (2006) identify four distinct states, based on well-defined observational characteristics: Quiescent, Thermal
Dominant, Steep Power Law, and Hard. Since polarization measurements require large numbers of photons, there is not much hope that we will be able to observe sources in quiescence. The other three states are likely associated with distinct accretion geometries, as described below.

2.1 Thermal Disk State

The simplest state is the Thermal Dominant state. This is defined by a strong thermal peak in the spectrum, peaking around $1 - 3$ keV, with little or no hard flux above $\sim 10$ keV. There is very little variability, and no significant quasi-periodic oscillations (QPOs). The physical model usually employed is that of a geometrically thin, optically thick, steady-state accretion disk, aligned with the BH spin axis. In the analytic “alpha-disk” model (Shakura & Sunyaev 1973; Novikov & Thorne 1973), the gas orbits the BH on circular geodesic orbits and then plunges abruptly into the BH at the inner-most stable circular orbit (ISCO). Since the ISCO is a strong function of BH spin, any observable that depends on its location provides a potential method for measuring spin.

In recent years, a number of different groups have studied the detailed properties of this plunging region using 3-D, fully relativistic magneto-hydrodynamic (MHD) simulations. The results have not been entirely conclusive. Noble et al. (2008, 2010) find significant dissipation from gas near the ISCO, while Reynolds & Fabian (2008) and Shafee et al. (2008); Penna et al. (2010) find a more abrupt cutoff, similar to the idealized case of Novikov & Thorne (1973), with the peak flux coming from somewhat outside the ISCO, and little or no emission coming from the plunging region. In either case, the inner edge for any single source appears to be fixed over a range of luminosities (Gierliński & Done 2004). If we wish to measure BH spin with X-ray observations, whether by using continuum fitting, broad iron lines, or polarization, it is critical to understand the detailed behavior of the gas near the ISCO.

As shown in Schnittman & Krolik (2009), spectropolarization observations of stellar-mass BHs in the thermal state may provide a way to break the degeneracy between spin and magnetic torques inside the ISCO. Polarization is particularly dependent on the emissivity and orbital dynamics in the inner disk because of the strong relativistic effects there. As originally pointed out in Agol & Krolik (2000), photons emitted very close to the BH get strongly deflected by gravitational lensing, and can actually pass over the BH and intersect with the far side of the disk, a process known as “returning radiation” (Cunningham 1976). For highly ionized accretion disks (as expected for the $\sim 1$ keV temperatures in typical X-ray binaries), the returning radiation can scatter off the disk at large angles, which naturally leads to high polarization. If even 5% of the total flux returns to the disk, it can dominate the polarization signal (Schnittman & Krolik 2009). Because the accretion disk opacity is expected to be dominated by electron scattering, the seed polarization should be emitted
with modest polarization of a few percent, oriented parallel to the disk surface in the local fluid frame (Chandrasekhar 1960). The scattered radiation, on the other hand, will be highly polarized and perpendicular to the disk surface, especially for observers at high inclination angles. Figure 1 shows polarization images of a 10\(M_\odot\) BH in the thermal disk state, including only the direct radiation (left), and the total flux, including the returning radiation (right).

![Polarization images](image)

Fig. 1.— Ray-traced image of direct radiation from a thermal disk (left). The observer is located at an inclination of 75° relative to the BH and disk rotation axis, with the gas on the left side of the disk moving towards the observer, which causes the characteristic increase in intensity due to relativistic beaming. The black hole has spin \(a/M = 0.9\), mass \(M = 10M_\odot\), and is accreting at 10% of the Eddington limit with a Novikov-Thorne emissivity profile, giving peak temperatures around 1 keV. The observed intensity is color-coded on a logarithmic scale and the energy-integrated polarization vectors are projected onto the image plane with lengths proportional to the degree of polarization. The (right) image, includes the returning radiation, made up of photons emitted from the inner disk, deflected by the BH and scattered off the opposite side of the disk towards the distant observer. [reproduced from Schnittman & Krolik (2009)]

Since the radiation emitted closest to the BH, where the disk is hottest, is most likely to get deflected by the BH as returning radiation, the high-energy flux tends to be polarized parallel to the disk’s rotation axis (“vertical” in our convention, with \(\psi = \pm 90^\circ\)), while the low-energy flux from the outer disk is oriented perpendicular to the disk axis, as projected on the sky (“horizontal,” with \(\psi = 0^\circ\)). The location and shape of this polarization transition is a direct probe of the emissivity profile near the ISCO. Figure 2 shows the polarization expected from a 10\(M_\odot\) BH in the thermal state, with a Novikov-Thorne emissivity profile that goes to zero at the ISCO, for a range of spin parameters yet holding \(L = 0.1L_{\text{Edd}}\) fixed. As the spin increases, more of the flux originates closer to the horizon, and return radiation becomes more important, leading to a larger fraction of observed radiation in the vertical
Aside from potentially measuring the BH spin, this return radiation can be used to probe the space-time as close to the horizon as possible and still allow the photons to escape. In this context, the polarization swing from horizontal to vertical might even be used to constrain alternative theories of gravity, e.g., testing the no-hair theorem of general relativity (Johannsen & Psaltis 2010a,b; Krawczynski 2012b).

**Fig. 2.**—Polarization degree and angle for a range of BH spin parameters. All systems have inclination $i = 75^\circ$, BH mass $10M_\odot$, luminosity $L/L_{\text{Edd}} = 0.1$, and Novikov-Thorne radial emission profiles. [reproduced from Schnittman & Krolik (2009)]

*Schnittman & Krolik (2009)* also allowed for emission inside of the ISCO by including a simple power-law parameterization that connected smoothly with the Novikov-Thorne emissivity profile in the inner disk. Thus the spectropolarization signal from any disk could be completely described by only a few parameters: BH mass, spin, luminosity, distance, inclination, and the additional power-law parameter for emission inside the ISCO.

Even if such a simple model were a perfect description of the BH source, there still exist fundamental degeneracies among the parameters, in particular the mass, luminosity, and distance. These degeneracies may be broken by observations at other wavelengths, e.g. optical absorption lines in the companion star that could be used to make radial velocity measurements, in turn giving the binary mass function. Other observational techniques, such as the continuum fitting method, require *a priori* knowledge of the disk inclination (Shafee et al. 2006), while interpreting measurements of the broad iron Kα line typically is based on some assumption of the ionizing flux distribution, and requires some knowledge of both the emission and reflection edges of the accretion disk (Krolik & Hawley 2002). X-ray polarization promises to be quite complementary to these more established techniques. For
example, the polarization below $\sim 1$ keV should probe the Chandrasekhar regime of the disk, and thus provide a good estimate of the inclination, especially in cases where the inner disk is tilted with respect to the orbit of the binary system (Li et al. 2008). Additionally, if the orientation of the disk axis can be determined, we will be able to compare it with observations of radio jets from the same source (Reid et al. 2011). In Schnittman & Krolik (2009) a simple data analysis method was used to estimate our ability to recover the model parameters of a hypothetical BH source with an idealized detector response function. As expected, there was some degeneracy between the BH spin and emissivity parameters, but with sufficient signal-to-noise, these parameters may both be determined independently. Similar calculations must be repeated with the specific GEMS response function.

Despite these theoretical uncertainties, the thermal disk state is still arguably the most well-understood state for BH binaries, and promises to give the most fundamental physical measurements, allowing us to probe strong-field general relativity with a relatively small uncertainty on the astrophysical factors that often plague such investigations. The central questions we hope to address are:

- What is the emissivity profile of optically thick, magnetized accretion disks near the BH, and to what extend will X-ray polarization be able to measure this profile?
  - How does this profile depend on BH spin, and how accurately can we measure the spin by using polarization measurements?
  - Is the radiation generated in the inner disk and plunging region thermalized?
  - Where is the inner edge of the disk, as defined by emission?
- What is the polarization of seed photons in a turbulent, magnetic (yet still thermal-dominated) accretion disk?
- Can spectropolarization give definitive evidence for strong gravitational lensing? How well can we use the light bending of return radiation to probe strong-field gravity and test general relativity?

### 2.2 Hot Corona State

The brightest BH transients usually fall into the category of the “Very High” or “Steep Power Law” (SPL) state, characterized by a power-law spectrum with $I_\nu \sim \nu^{-\alpha}$, ($\alpha \gtrsim 1.4$) in addition to a weaker thermal peak. The SPL state is also where we find most of the high-frequency quasi-periodic oscillations (QPOs), which appear strongest in the non-thermal part of the X-ray spectrum (Remillard & McClintock 2006). One popular physical picture behind the SPL state is one of a relatively cool thermal accretion disk surrounded by a geometrically thick corona of hot electrons with temperature $\gtrsim 50$ keV (Zdziarski & Gierliński 2004; Zdziarski et al. 2005). From the slope of the power-law spectrum, the Compton $y$-parameter
for the corona is thought to be of order unity, thus implying an optical depth of \( \tau \sim 1 - 2 \) (Rybicki & Lightman 1979). Other suggested models include bulk Comptonization from a converging accretion flow (Titarchuk & Shrader 2002; Turolla et al. 2002).

As evidenced by the plethora of models for the SPL, X-ray spectroscopic observations have not been able to constrain the detailed geometry of the corona very well in galactic BHs. Is it clumpy or homogeneous? Is it centrally concentrated or diffuse? What is the scale height? The answers to these questions should in turn provide important clues about the physical origin of the corona. Is it magnetically dominated like the solar corona? Is it gravitationally bound to the BH? A better understanding of the coronal properties will also lead to improved modeling of the broad iron emission line, which is likely excited by the high-energy photons originating in the corona.

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\text{Fig. 3.— Degree and angle of polarization for a sandwich corona, varying the optical depth and electron temperature, maintaining a roughly constant Compton-y parameter. [reproduced from Schnittman & Krolik (2010)]}
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Schnittman & Krolik (2010) considered a few different simple geometries for the corona and used a Monte Carlo ray-tracing code to calculate the expected polarization signature for each case. Figure 3 shows one example of how polarization may provide additional information about the properties of the corona. The geometry considered here is a smooth sandwich with constant opening angle of \( H/R = 0.1 \), and vertically-integrated optical depth constant across the entire disk. The same qualitative behavior is found as in the thermal disk, with the polarization swinging from horizontal at low energies to vertical at high energies. However, unlike the thermal state where the transition is due to the global geometry of return radiation, in the coronal state, the polarization transition can be explained by more
local effects. When the optical depth of the hot corona is of order unity and the scale height is relatively small ($H/R \lesssim 0.1$), photons that scatter multiple times are constrained to move in a plane parallel to the disk, and thus are preferentially polarized in the vertical direction. The more scattering events, the stronger the degree of polarization (Sunyaev & Titarchuk 1985; Matt et al. 1993; Poutanen & Svensson 1996). Since each scattering event in the hot corona increases the photon energy by an average fractional amount, those photons that scatter more will have larger polarization and higher energy.

The sandwich models shown in Figure 3 were chosen to all have the same Compton $y$-parameter and thus produce nearly identical broad-band spectra. Yet the polarization signals clearly distinguish between them. The reason is simple enough: to reach a certain energy, the same seed photon would have to scatter more times in a warm corona ($T_c \approx 50$ keV) than in a hot corona ($T_c \approx 200$ keV). More scattering requires a more constrained geometry, which in turn naturally leads to higher polarization.

In addition to the planar sandwich geometry, Schnittman & Krolik (2010) also considered toy models such as a spherical central corona surrounded by a truncated thermal disk, and a clumpy corona with a finite number of hot blobs orbiting above the disk. In all cases, the characteristic transition from horizontal to vertical polarization was present, suggesting that low-resolution measurements made with the first generation of X-ray polarimeters may not be able to distinguish between these simple models. On the other hand, if we do not see such a swing, or if the polarization is below $\sim 1 - 2\%$ across the entire band, then whole families of coronal models could be ruled out.

In conjunction with more traditional X-ray observations like spectroscopy and timing, polarization will help to address these questions:

- What are the physical properties of the corona: density, temperature, scale height, magnetization, homogeneity?
- What is the physical origin of the hot corona?
- How does the hot corona interact with the cool disk; what is the nature of the boundary between these different regions?
- What is the profile of ionizing flux that generates iron fluorescent lines; does it originate from the corona or disk or jet?
- Where is the inner edge of the disk, as measured by reflection opacity?

For particularly bright galactic sources such as GRS 1915+105, even first-generation instruments like GEMS should be able to make some time-dependent observations of variable polarization. As one example, we plan to model the time-varying polarization from
the large amplitude low-frequency (∼ 1 – 10 Hz) QPOs often seen in the SPL state. One possible physical model for these QPOs is that of an inclined disk or torus precessing around the spinning BH at the Lense-Thirring frequency, modulating the flux and spectrum \cite{Schnittman06, Ingram09}, and the polarization as well. Since the inclination of the inner disk is changing with the flux, polarization is an ideal tool for either confirming or challenging this model. In GRS 1915+105, the ∼ 1 Hz QPOs are strong enough to resolve and add in phase over many periods \cite{Miller05}.

2.3 Hard State

\cite{Remillard06} define the Hard State as one where the spectrum is dominated by a flat power-law with (0.4 ≤ \(\alpha\) ≤ 1.1) and no significant contribution from a thermal disk. There are often strong QPOs in the 1–10 Hz frequency range, and also radio jets are quite common \cite{Fender04}. As in the coronal SPL state discussed above, there remain sizable uncertainties about the nature and geometry of the hard X-ray emitting region. Popular models for the hard state of stellar-mass BHs include a cool disk truncated at large radius (∼ 100 \(GM/c^2\)) surrounding a hot, radiatively inefficient flow \cite{Gierlinski97, McClintock01, Esin01, Done09}, or alternatively a more extended disk surrounded by an optically thick hot corona, possibly in the form of a hot wind \cite{Blandford04, Miller06, Reis09}. While the geometry of the corona could be as simple as a uniform slab in the SPL state \cite{Zdziarski05}, the hard state of galactic BH binaries, as well as the X-ray emission from AGN, are more likely caused by clumpy, inhomogeneous coronas, possibly caused by magnetic flares \cite{Haardt94, Poutanen99}. Even in the cases where radio jets are seen coincident with the X-ray observations (in either AGN or galactic BHs), it is not clear if the hard X-rays are coming predominantly from the jet \cite{Markoff03, Russell10}, from the corona \cite{Begelman87, Malzac09}, or from some combination of the two \cite{Maitra09}.

Models for coronae and truncated disks will be similar to those used above for the SPL state. More theoretical work will need to be carried out to develop comparable models for simulating the polarization from jets. Some work in this area already exists in the AGN context \cite{Begelman87, Poutanen94} and for one specific stellar-mass BH picture \cite{McNamara09}; we need to generalize these models to a wider range of galactic black holes in the hard state. Jets are known to produce highly polarized flux in other wavelengths, generally attributed to synchrotron radiation of hot electrons in a coherent magnetic field. These hot electrons can produce synchrotron self-Compton radiation in the X-ray band, also strongly polarized \cite{Poutanen94}. The jet can also serve as a source for hard X-rays that can get polarized by scattering off the accretion disk/corona (the “lamp post”
model; Dovciak et al. (2004)). Additionally, low-energy seed photons from the disk may get upscattered in the jet, further adding to the polarization signal (“external Comptonization;” McNamara et al. 2009)). In either case, the total flux from the jet may be relatively small, but highly polarized. With new models for X-ray polarization from BH jets, we may be able to distinguish between the coronal and jet models for the physical nature of the low hard state.

We have learned a great deal from polarization measurements of jets in the radio, IR, and optical bands, but because they can probe different length and energy scales, we expect X-ray polarization measurements to significantly improve our understanding of BH jets, helping to answer the central questions: What is the magnetic field structure of the jet? What are the basic physical properties of the jet: density, composition (baryons vs pairs), Lorentz factor, electron temperature? How is the jet generated near the BH? What role does BH spin play in jet production and strength? What is the source of the seed photons for inverse Compton processes?

As we have seen with the coronal models, by adding more model parameters, it often becomes more difficult to constrain any one of them with observations. Thus it will be critical to provide quantitative estimates of the confidence limits achievable by polarization observations of real astrophysical sources. At the very least, we expect that X-ray polarization detections (or even upper limits) will be able to rule out entire classes of jet models. Here multi-wavelength observations will be particularly valuable, using radio observations to confirm the presence of a jet and possibly its orientation (Fender et al. 2004).

3. ACTIVE GALACTIC NUCLEI

It has long been known that a significant fraction of the flux from AGN is emitted in the X-ray band (Elvis et al. 1978). As in stellar-mass BHs, this high-energy flux likely comes from lower-energy seed photons inverse-Compton scattered in a corona of hot electrons with $T_e \sim 100$ keV. Similar to the stellar-mass case, this leads to a relatively hard power-law spectrum with index $\alpha \sim 0.5 - 1$ (Nandra et al. 1991; Mushotzky et al. 1993). However, unlike the stellar-mass case, the temperature of the inner disk for an AGN will be well below a keV, leading to a thermal peak in the UV band. Furthermore, even when the disk is dominated by radiation pressure and electron scattering opacity, there should still be a substantial fraction of metals that are not fully ionized, producing a large opacity for absorption above $\sim 1$ keV.

Both of these AGN features—lower energy seed photons and an X-ray absorbing disk—
lead to important differences in the polarization signature as compared to the stellar-mass case. Because the seed photons start off with lower energies, they must scatter more times in the corona in order to reach the $\sim 1 - 10$ keV band. For a thin sandwich corona, this means that the scattering geometry is even more constrained than in the stellar-mass case, forcing the photons to move in a plane parallel to the disk surface, leading to a stronger vertical polarization \cite{PoutanenSvensson1996}. The AGN disk absorbs much of the incident X-ray flux from the corona, so the Compton $y$-parameter is effectively smaller than that of a stellar-mass system with the same coronal properties because scattering sequences are halted once a photon strikes the disk, thereby reducing the average path length of the photons that escape to infinity. An absorbing disk boundary condition with a sandwich corona therefore leads to an even higher degree of X-ray polarization because the photons are forced to scatter in a more constrained geometry before escaping the corona.

As shown in \cite{SchnittmanKrolik2010}, polarization correlates closely with covering fraction of the corona. In Figure 4, we show the polarization from an AGN with central mass $M = 10^7 M_\odot$, spin parameter $a/M = 0.9$, thermal luminosity $L_{\text{therm}} = 0.1 L_{\text{Edd}}$, and observer inclination angle $i = 45^\circ$. Four different corona models are considered: a homogeneous wedge with $H/R = 0.1$, $\tau_0 = 1$, and $T_c = 100$ keV, and three clumpy models with the same scale height, mean optical depth, and temperature, but with partial covering fractions of $f_c = 0.25$, 0.15, and 0.05. In the clumpy coronas, the density was chosen so that the total flux in $2 - 10$ keV was approximately the same in all cases. Again, the polarization transitions from horizontal to vertical near the thermal peak, here around 100 eV. Clearly,
the more uniform coronas lead to higher polarization, again showing that polarization is fundamentally a measure of symmetry.

Like their stellar-mass counterparts, many AGN produce powerful relativistic jets. In particular, the blazar class of AGN have their jet axes pointing towards the observer, which leads to intense beaming of radiation and rapid variability (see Krawczynski et al. (2012) for a detailed discussion of blazar science with GEMS). Blazar spectra are typically characterized by two peaks: a synchrotron peak in the UV/optical/mid-IR, and a secondary peak in the X-ray/gamma-ray band, likely caused by the inverse-Compton scattering of either the synchrotron flux (Poutanen 1994; Ghisellini et al. 1998) or possibly photons from the disk (McNamara et al. 2009). As mentioned above, polarization is most sensitive to the scattering geometry, and thus is an ideal tool to distinguish between internal and external inverse-Compton seeds (Krawczynski 2012a). Since hot electrons generally cool faster via synchrotron radiation than cool electrons, they will sample a smaller and thus more coherent portion of the jet’s magnetic field. It is therefore quite likely that X-rays created directly in the jet may be even more highly polarized than the optical flux observed in many blazars (Marscher et al. 2008). However, in the synchrotron self-Compton picture, it is the same electron population producing both the optical and X-ray flux, so it is not obvious how the polarization will scale with energy in those sources.

The open questions regarding AGN corona and jets may be addressed with X-ray polarization in much the same way as the galactic BHs, with the noted differences mentioned above, namely the lower-energy seeds require more scatterings to reach the 2 – 10 keV band, and the importance of absorption of X-rays by partially ionized metals in the disk atmosphere. On the practical level of connecting theory with observation, and planning of new scientific missions, one must also note that AGN are typically orders of magnitude less bright than galactic sources, and are also more likely to be seen at lower inclination angles where obscuration from surrounding dusk is lowest, giving lower polarization amplitude for most models. On the other hand, the persistence of even the most variable AGN makes them more reliable targets than the transient galactic sources. Furthermore, many of the bright nearby AGN also have an enormous wealth of previous deep observations across the spectrum, including polarization measurements in the radio, IR, and optical, all of which bring valuable independent insight into the geometry of these sources, and provide powerful constraints for many theoretical models.
4. GEMS TARGETS

There are currently about 30 known galactic BHs and BH candidates (Remillard & McClintock 2006). The majority of these objects spend most of their time in the quiescent state, but when they do go into outburst, they are some of the brightest X-ray sources in the sky, and thus ideal targets for photon-limited measurements like polarization. Many of the simple models discussed above predict polarization signatures that are strongly dependent on parameters like the accretion disk inclination, mass accretion rate, BH mass, and the distance to the source. All of these parameters could in principle be determined with complementary observation in other wavelengths. Thus it will be critical when trying to model real sources that we are able to incorporate as much prior information as possible, in order to maximize the relative value added by the polarization measurement.

Here we present a list of potential GEMS targets with a brief summary of the observational properties of each source, and the primary science questions that may be answered by each object. We also include some suggestions for multi-wavelength observations, either contemporaneous or in some cases, simultaneous. These targets are summarized in Table I.

4.1. Galactic BH binaries

Cyg X-1: The first stellar-mass black hole discovered, and one of the nearest and brightest in the galaxy. Recent observations have provided exquisite measurements of its mass, distance, and inclination (Reid et al. 2011; Orosz et al. 2011), which will make it even more valuable for using polarization to measure spin. However, the relatively low inclination suggests that we should expect low inherent polarization.

GX 339-4: A relatively nearby source with numerous observations of the iron line. The small mass leads to higher thermal temperatures, which is useful for observing the thermal state with GEMS’ 2-10 keV bandpass. The moderate yet uncertain inclination may make it difficult to generate a high degree of polarization.

LMC X-3: Despite its distance, and thus low flux, this is a high-priority source due to its high duty cycle in the thermal state, and relatively high inclination. With enough integration time, we should be able to observe directly the effects of spin and strong gravity on the polarization from a thin disk.

LMC X-1: Similar to LMC X-3, but lower inclination, so lower expected degree of polarization.

GRS 1915+105: This is an extremely bright, persistent source that is highly variable
and undergoes multiple state transitions, predominantly in the hard and steep power low states, and exhibits a rich selection of QPOs. It is a prime candidate for using time-resolved polarization to study the accretion geometry of the system. The large inclination makes high polarization likely.

\textit{4U 1957+11}: A relatively faint source that may be in the galactic halo. Mass and distance are not well-constrained, but thermal spectrum is consistent with very rapidly spinning BH \cite{Nowak2011}. Inclination not well known, but likely high, so this is a potentially promising source for testing thin disk models with extreme spins.

\subsection{Active galactic nuclei}

\textit{MCG 6-30-15}: The paradigmatic Seyfert-1 source for strong, relativistically broadened iron line emitted from the inner disk. The relatively high 2-10 keV flux makes it feasible for polarization measurements, and the inclination is well-constrained by the blue-shifted edge of the iron line. While this inclination is small (\(\sim 30\) degrees), the AGN corona models described in \cite{Schnittman2010} predict at least a few percent polarization in this case.

\textit{NGC 1068}: A nearby Type-2 Seyfert galaxy with an edge-on disk, the X-ray flux could potentially come from reflection of the central compact source off of the surrounding hot wind, which would lead to a very high degree of polarization \cite{Antonucci1985}. The low flux will make it difficult to measure anything but the highest polarization.

\textit{Cen A}: Nearby bright FR I radio galaxy with large scale relativistic jets. Galactic disk nearly edge-on, dominated by dust, gas, and star formation. Good source for studying jets; central engine heavily obscured below \(\sim 5\) keV \cite{Markowitz2007}. There is a strong narrow Fe line and the continuum is modestly variable.

\textit{NGC 4151}: A nearby Type-1 Seyfert with relatively large absorption column \cite{Weaver1994}. Recent observations suggest a time lag between the continuum and a broad iron line, with the continuum leading by \(2000\) s \cite{Zoghbi2012}. Combined with X-ray polarization, this promises to be a powerful probe of the illumination geometry of the inner disk.

\textit{NGC 5548}: A Sy 1.5 galaxy with estimated inclination \(\sim 30\) deg, but evidence for a disk truncated at large radius, as inferred from the lack of a broad Fe line \cite{Bremmeman2012}. Could be an excellent source for testing the spherical corona model for a radiatively inefficient accretion flow.
Table 1: *GEMS* target list of galactic BHs and AGN. The fluxes are in the 2-10 keV band. The hard/steep power law states are designated “H/SPL,” and “TD/VH” represents the thermal-dominant/very high state. The duty cycles and fluxes come from the all-sky monitor on *RXTE*.

| Source         | Mass ($M_\odot$) | Distance (kpc) | Inclination (deg) | State  | Flux (mCrab) | Duty Cycle (%) |
|----------------|------------------|----------------|-----------------|--------|-------------|----------------|
| GX 339-4       | 7±0.2            | 8±1            | 46±8            | H/SPL  | 58          | 32             |
|                |                  |                |                 | TD/VH  | 290         | 25             |
| GRS 1915+105   | 14±4             | 11–12          | 66±2            | H/SPL  | 750         | 95             |
|                |                  |                |                 | TD/VH  | 360         | 5              |
| Cyg X-1        | 14.8±1           | 1.9±0.1        | 27±1            | H/SPL  | 360         | 90             |
|                |                  |                |                 | TD/VH  | 880         | 10             |
| LMC X-1        | 10.9±1.5         | 48±2           | 36±2            | H/SPL  | 21          | 30             |
|                |                  |                |                 | TD/VH  | 21          | 68             |
| LMC X-3        | 11.5±2           | 48±2           | 60±10           | H/SPL  | 17          | 28             |
|                |                  |                |                 | TD/VH  | 25          | 65             |
| 4U 1957+11     | >3               | >10            | <75             | H/SPL  | 32          | 28             |
|                |                  |                |                 | TD/VH  | 31          | 70             |
| MCG 6-30-15    | 5×10^6           | 30,000         | 30              | SPL?   | 2–3         | 100            |
| NGC 1068       | 1.7×10^7         | 14,000         | >70             | ?      | <1          | 100            |
| Cen A          | 2×10^8           | 3,500          | ~60             | hard?  | 15          | 100            |
| NGC 4151       | 4.5×10^7         | 14,000         | 45              | SPL?   | 13          | 100            |
| NGC 5548       | 6.7×10^7         | 72,000         | 30              | hard   | 3           | 100            |
5. EPILOGUE

*GEMS* was proposed in response to the NASA SMEX announcement of opportunity in December 2008, was selected for phase A development in 2009 and selected for phase B in 2010. A technically successful Preliminary Design Review was held in Feb 2012. NASA Science Mission Directorate (SMD) indicated their intention to non-confirm (or cancel) in May 2012; the SMD decision was based on concerns that the eventual cost would be too high.
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