Prospect of polarization measurements from black hole binaries in their thermal state with a scattering polarimeter

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\textbf{ABSTRACT}
X-ray polarization measurement is a unique tool which may provide crucial information regarding the emission mechanism and the geometry of various astrophysical sources, such as neutron stars, accreting black holes, pulsar wind nebulae, active galactic nuclei, supernova remnants etc., and can help us to probe matter under extreme magnetic fields and extreme gravitational fields. Although the three other domains of X-ray astronomy, i.e. timing, spectral and imaging are well developed, there has been very little progress in X-ray polarimetry with only one definitive polarization measurement and a few upper limits available so far. Radiation from accreting black holes in their thermal-dominated (high soft) state is expected to be polarized due to scattering in the plane-parallel atmosphere of the disc. Furthermore, special and general relativistic effects in the innermost parts of the disc predict energy-dependent rotation in the plane of polarization and some distinct signatures which can be used as a probe for measuring the parameters of the black hole, like its spin, emissivity profile and the angle of inclination of the system. We present the results from an analysis of expected minimum detectable polarization from some of the galactic black hole binaries, GRO J1655\textminus40, GX 339\textminus4, H1743\textminus322, Cygnus X-1 and XTE J1817\textminus330, in their thermal-dominated state with a proposed Thomson X-ray polarimeter. A proposal for a scattering polarimeter has been submitted to the Indian Space Research Organization for a dedicated small satellite mission and a laboratory unit has been built. Along with the measurement of the degree of polarization, the polarization angle measurement is also important, hence the error in the polarization angle measurement for a range of detection significance is also obtained.

\textbf{Key words:} accretion, accretion discs – instrumentation: detectors – instrumentation: polarimeters – X-rays: binaries.

\section{1 INTRODUCTION}
Since the birth of X-ray astronomy, sensitivity/capability of timing, spectral and spatial observations of the X-ray sources have improved by several orders of magnitude and has provided us with a wealth of information regarding the X-ray sky. X-ray polarimetry, however, continues to remain a fairly unexplored domain with only one definitive polarization measurement available made with OSO 8 in 1976 (Weisskopf et al. 1976) of the Crab nebula ($P = 19 \pm 1.0\text{ per cent}$) thus proving the synchrotron nature of the radiation. It also provided upper limits of $-13.5$ and $60\text{ per cent}$ for the pulse phase averaged degree of polarization in two X-ray accretion powered pulsars Cen X-3 and Her X-1, respectively (Silver et al. 1979). Although radio and optical astronomers extensively use polarimetry to probe into the radiation mechanism and geometry of sources, X-ray astronomy is still behind them in this regard which would provide some crucial information regarding the radiation mechanism, source geometry, inclination and magnetic fields, etc. Sensitive X-ray polarimetry could also be used as a probe for fundamental physics since it gives information on matter under extreme gravitation or magnetic fields. It could also solve degeneracy between different theoretical models which cannot be solved by timing and spectroscopy studies alone. Various emission mechanisms, such as synchrotron, non-thermal bremsstrahlung, etc., give rise to high degree of polarization. Other emission processes for polarization could be scattering of initially unpolarized radiation in asymmetric plasmas or discs. Vacuum birefringence through extreme magnetic fields or the phenomenon of Compton dragging can also give rise to polarization. The potential sources of X-ray polarization are accretion and rotation powered pulsars, thermal or reflected emission from the accretion disc. Cosmic acceleration sites such as supernova remnants (SNRs) and jets in active galactic nuclei or microquasars are also sources of polarization. In recent
times there has been significant development in X-ray polarization measurement techniques (Costa et al. 2001, 2008; Bellazzini et al. 2006). Various X-ray polarimetry missions are under development. Out of them the most significant one is the approved GEMS mission (Swank, Kallman & Jahoda 2008) which is based on photoelectron polarimeter technique. Recently a proposal has been submitted to the Indian Space Research Organization (ISRO) for a dedicated small satellite experiment for measuring X-ray polarization in the 5–30 keV range. This will be based on the principle of polarization measurement by anisotropic Thomson scattering of X-rays and will be sensitive to the bright X-ray sources. A laboratory unit has been built for the same (Rishin et al. 2009). Here we calculate the minimum detectable polarization (MDP) that we would get with the X-ray polarimeter experiment for the thermal emission from the accretion disc for some of the galactic black hole sources during their thermal-dominated spectral states. Apart from the MDP, the error in measurement of the angle of polarization for particular detection significance limits is also calculated. This analysis is important due to the following reasons.

(i) Sources with strong X-ray polarization, such as accretion powered pulsars or reflection-dominated emission from the accretion disc etc., are expected to have a fairly high degree of polarization and are sources of hard X-rays which are most suited for observation by the Thomson X-ray polarimeter. Galactic black hole binaries, however, have a soft spectrum in their thermally dominated state and typically peak at 1–3 keV. There is also expected to be very little flux above ~10 keV. The radiation itself is also not polarized to a high degree except in the innermost parts of the accretion disc in some cases. This makes its detection by the Thomson polarimeter difficult.

(ii) Black hole binaries have different spectral states and display state transitions in which either the thermal or the non-thermal component dominates the X-ray flux. They are also mostly transient sources which go into outburst once in a while during which they make their transition to the thermally dominated soft state. Therefore, detection of polarization from the black hole binaries in their thermal state would also be constrained by the condition of one of the sources going into outburst/state transition during the lifetime of the mission.

2 PROPOSED EXPERIMENT

2.1 Objective

A Thomson scattering X-ray polarimeter has been developed and a small satellite mission with a similar payload is under consideration by ISRO. It is based on the principle of anisotropic Thomson scattering of X-ray photons working in the 5–30 keV (with lithium scatterer) and 8–30 keV (with beryllium scatterer). It has a sensitivity of 2–3 per cent MDP in a 50–100 mCrab source for an exposure of 1 Ms (Rishin et al. 2009). The proposed experiment will be useful in measuring the degree and direction of X-ray polarization of a few (≥50) bright cosmic X-ray sources including accretion powered binary X-ray pulsars, galactic black hole candidates, rotation powered pulsars and magnetars, SNRs and active galactic nuclei.

2.2 Design and polarization measurement technique

Though the most sensitive polarization measurement devices are based on photoelectron track imaging, they require to be coupled with high throughput X-ray mirrors due to a small detector size. They also cover a softer energy range. The proposed scattering experiment is based on the well-established technique of X-ray polarization measurement using Thomson scattering which has moderate sensitivity over a relatively large bandwidth suited in the energy band of our interest. The experiment configuration consists of a central low Z (lithium, lithium hydride or beryllium) scatterer surrounded by xenon filled X-ray proportional counters as X-ray detectors which collects the scattered X-ray photons. The instrument is rotated along the viewing axis leading to the measurement of the azimuthal distribution of the scattered X-ray photons which gives information on polarization. The sensitivity of this experiment is dependent on (a) collecting area, (b) scattering and detection efficiency, (c) detector background and (d) modulation factor of the instrument.

2.2.1 Sensitivity and minimum detectable polarization of the Thomson scattering X-ray polarimeter

The experiment is based on the principle that the differential Thomson scattering cross-section for polarized radiation has an azimuthal dependence. The expression for differential cross-section is given by

\[ d\sigma = r^2(1 - \sin^2\theta\cos^2\phi)\,d\theta\,d\phi, \]

where \( \theta \) is the angle between the direction of the incident and scattered photon, \( \phi \) is the angle between the scattering plane defined by the direction and the electric field vector of the incident photon and \( r \) is the classical electron radius. The resultant azimuthal distribution follows the integral of the differential cross-section and is given by

\[ C(\phi) = B + A\sin(2\phi - P), \]

where \( A \) and \( B \) are constants, \( \phi \) is the azimuthal coordinate and \( P \) the angle of polarization of the incident radiation.

The modulation factor \( \mu \) for the pattern is expressed as

\[ \mu = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}}. \]

The degree of polarization for the incident beam is defined as

\[ P_{\text{pol}} = \frac{\mu_{\text{pol}}}{\mu_{100}}, \]

where \( \mu_{\text{pol}} \) is the observed modulation factor and \( \mu_{100} \) is the modulation factor of the instrument in the absence of background for a 100 per cent polarized radiation.

MDP of the measurement for 99 per cent confidence level is given as (Weisskopf, Elsner & O’Dell 2010)

\[ \text{MDP}_{99} = \frac{4.29}{\mu_{100}} \sqrt{\frac{(S + B)}{T}}, \]

where \( S \) is the total source counts in the units of counts s\(^{-1}\) given as

\[ S = R_{\text{esc}}A_e; \]

\( R_{\text{esc}} \) being the rate of incident photons per unit area, \( e \) is the overall detection efficiency and \( A_e \) the collecting area. \( B \) is the total background counts in the same unit given as \( B = R_{\text{bg}}A_s \); \( R_{\text{bg}} \) being the total rate of background photons per unit area and \( A_s \) the total detector area. \( T \) is the integration time. Following Weisskopf et al. (2010), for a required detection significance of \( \sigma = 3 \) (99.73 per cent confidence level) and 5 (99.99994 per cent confidence level) the MDP is calculated to be

\[ \text{MDP}_{99} = \frac{4.86}{\mu_{100}} \sqrt{\frac{(S + B)}{T}}, \]

(6)
and

$$\text{MDP}_{\sigma} = \frac{7.57}{\mu_{100} S} \sqrt{\frac{(S + B)}{T}}. \quad (7)$$

So for a given observation of particular $S$ and $B$ and the parameter $T$ determines the MDP at $\sigma$ level.

This is the expression for the MDP that we get for 1 d of observations for T seconds integration time. To improve our polarization detectability we should integrate it for more number of days. The net MDP obtained for $n$ days of observation each of $T$ seconds for a $\sigma$ detection significance is given by

$$\text{MDP}_{\text{net}} = \frac{7.57}{\mu_{100} S_{\text{net}}} \sqrt{\frac{(S_{\text{net}} + B_{\text{net}})}{T}}. \quad (8)$$

where $S_{\text{net}}$ and $B_{\text{net}}$ are the net source and background counts obtained by integration over $n$ days given by

$$S_{\text{net}} = \sum_{i=1}^{n} S_i \quad \text{and} \quad B_{\text{net}} = \sum_{i=1}^{n} B_i. \quad (9)$$

3 EXPECTED POLARIZATION FROM ACCRETING BLACK HOLES IN THEIR THERMAL STATE

One of the earliest work on the expected polarization properties of thermal emission from the accretion disc was done by Rees (1975). It predicted linear polarization with the electric field vector lying in the plane of the disc due to electron scattering in its plane-parallel atmosphere. This was predicted according to Chandrasekhar (1960) calculations for plane scattering atmosphere where polarization degree depends on the angle of inclination of the system, the maximum value being $\pm 12$ per cent for edge on systems. Sunyaev & Titarchuk (1985) showed that the polarization of the disc photons depends on the optical thickness of the disc. Connors, Piran & Stark (1980) computed X-ray polarization features from the standard accretion disc using general relativistic treatment which predicted energy-dependent rotation in the plane of polarization in the inner parts of the accretion disc closer to the black hole. Dovciak et al. (2008) extended this work by including the effect of optical depth and scattering atmosphere on the expected polarization signal. Li, Narayan & McClintock (2008) showed the use of polarization information obtained of the thermal emission from the accretion disc to infer the inclination of the inner region of the disc. Schnittman & Krolik (2009) computed X-ray polarization from accreting black holes in their thermally dominated state using a Monte Carlo ray tracing code in general relativity. For direct radiation from the disc it reproduces Chandrasekhar’s results for the outer part of the disc. There is a decrease in the degree of polarization and energy-dependent rotation in the plane of polarization in the innermost regions due to general relativistic effects. However, for the returning radiation there would be a rotation in the plane of polarization by $90^\circ$ at a transition radius, and an enhancement in polarization which can provide a good estimate of the black hole spin and also map the temperature of the inner accretion disc and its emissivity profile.

4 ANALYSIS AND RESULTS

We have calculated the expected MDP from five galactic black hole candidates during their transition to the soft spectral state in the three energy bands of 6–9, 9–11 and 11–15 keV. MDP was computed during the days when the blackbody temperature was highest (hence the source most thermally dominated) during the outbursts/state transitions of the sources. Equations (7) and (8) is used to calculate the MDP and MDPnet in the case of a $\sigma$ detection. The MDP_{net} value is also calculated for a $\sigma$ statistical detection given by equation (6) only in the 11–15 keV range, since it may not be detected for a $\sigma$ detection in all cases in this band.

The values of the parameters used for the calculation are as follow: $\sigma = 5$, modulation factor for 100 per cent polarization for our experiment, $\mu = 0.4$ and integration time $T = 43 \pm 200$ s (assuming a duty cycle of 50 per cent in a low altitude near equatorial orbit).

The source counts $S$ and background counts $B$ are obtained from spectral fitting of the Rossi X-ray Timing Explorer (RXTE)/Proportional Counter Array (PCA; Zhang et al. 1993; Jahoda et al. 1996) spectra in the 3–30 keV range during the designated period of the outburst/state transition of the source. The PCA has five xenon filled proportional counter detectors, sensitive in the range of 2–60 keV, and has an effective area of 6500 cm$^2$ at 6 keV. The RXTE/PCA spectral data were fitted using XSPEC to a model consisting of interstellar absorption (Morrison & McCammon 1983) plus a multicolour blackbody accretion disc ( Mitsuda et al. 1984; Makishima et al. 1986) and a power-law component. In addition, an iron line and a Fe absorption edge were applied to some data sets. A systematic error of 0.5 per cent was also added in quadrature with the error. For the source counts $S = R_{\text{in}} A_\epsilon$, $R_{\text{in}}$ is obtained from the blackbody count rate obtained by the spectral fitting of the data. $A_\epsilon = 1017$ cm$^2$ (collecting area for our experiment). Following Cowan et al. (2009), the energy-dependent efficiency $\epsilon$ is calculated for both lithium and beryllium scatterer assuming a disc-shaped scattering element with an optical depth of unity for Thomson scattering. The values obtained in the three energy bands of interest for both the materials of the scatterer are tabulated in Table 1.

The background consists of the detector internal background $B_1$. The power-law non-thermal component of the flux $B_2$ could also be polarized to a significant fraction having an energy dependence and could provide crucial information on the physics and geometry of the power-law photon-emitting regions and also on the properties of the black hole (Schnittman & Krolik 2010). However, in this work we have considered this component of the flux as a background due to the following reasons.

(i) Black hole binaries in their low hard states would give us information on the polarization of the power-law photon-emitting regions, i.e. the corona and also on the black hole parameters. This is, however, expected to differ significantly from the polarization obtained from the thermal photons in the inner parts of the accretion discs obtained in the high soft states. Therefore, a difference in the polarization information obtained in the two states would clearly distinguish between the two components. The power-law photons are likely to have only small energy dependence, and, in particular, a continuous change of the polarization angle with the energy is typical of the GR effects near the black hole.

Table 1. Energy-dependent efficiency for Li and Be scatterer.

| Energy range (keV) | Efficiency (Li) | Efficiency (Be) |
|-------------------|----------------|----------------|
| 6–9               | 9.4 per cent   | 4.0 per cent   |
| 9–11              | 16.1 per cent  | 8.5 per cent   |
| 11–15             | 21.7 per cent  | 14.4 per cent  |
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Figure 1. 1 d averaged long-term ASM light curve of GRO J1655 −40 showing the 2005 outburst of GRO J1655 −40.

(ii) Moreover in the thermal-dominated (high soft) spectral states of the black hole binaries, the emission from the disc dominates over the power-law photon-emitting regions and hence the polarization signal can be thought to come predominantly from the accretion disc of the source. There is, however, a possibility of some dilution of the polarization signal in the thermal states due to the non-thermal power-law component.

Therefore, $B = B_1 + B_2$. $B_1$ is calculated from the background obtained from the spectral fitting of the PCA spectra with the area scaled for the polarimeter detector. Hence

$$B_2 = \frac{\text{Counts}_{\text{AscPCA}}(\text{counts s}^{-1})}{\text{A}_{\text{PCA} \text{Total}}} \times \text{A}_{\text{off} \text{Total}}.$$

$$S_{\text{net}} = \sum_{i=1}^{n} S_i \quad \text{and} \quad B_{\text{net}} = \sum_{i=1}^{n} B_{1i} + B_{2} \ast n. \quad (10)$$

This gives us an estimate of best MDP that we could have achieved by integration during that particular outburst/transition of the source using the X-ray polarimeter. Calculating the MDP in the three energy bands of interest also enables us to do spectropolarimetry that would be crucial to map the energy-dependent rotation in the plane of polarization in the inner parts of the accretion disc and possibly the transition radius where there would be a 90° rotation in the plane of polarization. This would be essential to calculate the parameter space of the black holes and give an estimate of its spin and emissivity profile.

We have also calculated the maximum error on determination of the angle of polarization for a given $n\sigma$ value (statistical detection limit).

Results for the five black hole candidates for which the MDP is calculated are given below.

4.1 GRO J1655 −40

GRO J1655 −40 in an X-ray transient which was first discovered in 1994 July when it went into an outburst and was detected by the Burst and Transient Source Experiment (BATSE) onboard Compton Gamma-ray Observatory (CGRO) in the 20–100 keV band. (Harmon et al. 1995). It is a low-mass X-ray binary (LMXB) having the mass of the compact object $M = 7.02 \pm 0.22 \text{M}_\odot$ (Orosz & Bailyn 1997). It has also shown signatures of ejection of superluminal jets. It showed an increased X-ray activity in the late 2005 February as it entered into a new outburst (Markwardt & Swank 2005). As the outburst evolved the X-ray spectrum passed through various spectral states of low/hard, high/soft and very high states. Fig. 1 shows the 1 d averaged All-Sky Monitor (ASM) daily light curve of this source during the outburst in the 1.5–12 keV energy band.

For the MDP calculation the data were analysed in two stretches MJD 53442–53449 and MJD 53511–53525, when the spectrum was found to be the most blackbody dominated in all the three energy bands of our interest. Fig. 2 shows the best-fitting spectrum of the source on 2 d. The first spectrum is of MJD 53514, when the source was blackbody dominated and was hence included in the analysis of the MDP. The second spectrum is of MJD 53503 which is mostly power-law dominated in the energy bands of our interest and hence has not been added in the analysis. Figs 3 and 4 show the two components (thermal and non-thermal) of the flux during the outburst and also the MDP in the three energy bands for the two stretches analysed during the outburst. Although the MDP calculated on individual days for the source may exceed 100 per cent on some days (which means that polarization in the source...
cannot be detected with a 5σ statistical detection on those days), specially in the 11–15 keV band and in some days in the 9–11 keV band, the net MDP obtained by integrating over all the days can be constrained to a much smaller and reasonable value. However, in the figures showing the MDP calculated, the days exceeding 100 per cent MDP have not been plotted.

4.2 GX 339–4

GX 339–4 is a recurrent dynamically constrained black hole candidate. It was first discovered with OSO 7 in 1972 (Markert et al. 1973a,b). Since then it has undergone several outbursts during which it passed through the various X-ray spectral states. The mass of the compact object is \( \geq 5.8 \, M_\odot \) (Hynes et al. 2003). Radio jets have also been observed in the system. It entered into one of its outbursts which started early in 2002 April (Fender et al. 2002; Belloni et al. 2003, 2005). The X-ray spectrum passed through its various spectral states of low/hard intermediate and then into the high/soft state which it entered beyond MJD 52411. The 1 d averaged daily ASM light curve of this source during the outburst is shown in Fig. 5.

We have analysed the data in the stretch of MJD 52472–52518 to calculate the MDP. The net MDP was found to be the lowest in this case (<1 per cent) since apart from this being a very bright outburst, the source was also integrated for a long stretch \( \approx 47 \) d. The comparison of the thermal and non-thermal flux and the MDP obtained in the three energy bands is shown in Fig. 6.

4.3 CYGNUS X-1

Cygnus X-1 is one of the brightest X-ray sources in the sky and is the most extensively investigated object among all black hole candidates. It was first discovered in a 1964 June rocket flight (Bowyer et al. 1965). The companion mass is in a range between \( \approx 15 \) (Herrero et al. 1995) and \( 30 \, M_\odot \) (Gies & Bolton 1986). This mass together with the mass function gives an estimate of compact object mass between \( \approx 6.5 \) and \( \approx 20 \, M_\odot \). The X-ray spectrum undergoes a transition between the low/hard and the high/soft one. Most of the time the source is in the hard state but it makes occasional transitions to the soft state which is dominated by a soft blackbody-like component. During 1996 it made a complete transition form the low/hard to the high/soft state (Cui 1996; Cui, Focke & Swank 1996; Zhang et al. 1997). However, the blackbody temperature was not very high and the flux increase from its low/hard was only moderate as compared to the high/soft state transitions of the other transient black hole candidates. Fig. 7 shows the 1 d averaged ASM daily light curve of the source during its soft state transition.

The data analysed to calculate the MDP ranged between MJD 50225–50242 and MJD 50250–50252. The MDP\(_{\text{net}}\) integrated over...
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Figure 4. Same as Fig. 3, but for the second stretch of its outburst of GRO J1655−40 in the year 2005.

Figure 5. 1 d averaged long-term ASM light curve of GX 339−4 showing the 2002 outburst of GX 339−4.

all the days is higher than the upper limit on the polarization obtained by OSO 8 (Long, Chanan & Novick 1980) from Cygnus X-1 except in the 6–9 keV with a lithium scatterer. Therefore, polarization of the thermal component of Cygnus X-1 most probably cannot be observed with the Thomson polarimeter. This is because the flux increase in the X-ray spectrum is only moderate and the power-law component of the spectrum is quite comparable to the blackbody component of the spectra on most days. Comparison of the thermal and non-thermal fluxes and the calculated MDP in the two energy bands is shown in Fig. 8.

4.4 H1743−322

H1743−322 is a bright X-ray transient. It was first discovered with Ariel V ASM in 1977 (Kaluzienski et al. 1977) and its precise position was provided by HEAO 1. Despite lack of dynamical confirmation of the mass of the compact object it is believed to be a black hole due to its spectral and temporal characteristics (Corbel, Tomsick & Kaaret 2006; Kalemci, Tomsick & Rothschild 2006). The source also shows relativistic jet emission. The source entered into one of its outbursts in 2003 during which it showed state transitions. The outburst was discovered by Revnivtsev, Chernyakova & Capitanio (2003) on March 21 using INTEGRAL and rediscovered a few days later by Markwardt & Swank (2003), and RXTE observations of the source was carried out during the outburst. Fig. 9 shows the 1 d averaged ASM light curve of this source during its outburst. The data were analysed from MJD 52823 to MJD 52843 to calculate the MDP. Fig. 10 shows the comparison of the two fluxes and the MDP in the three energy ranges.

4.5 XTE J1817−330

XTE J1817−330 was discovered as a new bright X-ray transient with the RXTE ASM on 2006 January 26 (Remillard et al. 2006) with a flux of 0.93(±0.03) Crab (2−12 keV) and a very soft spectrum thus making it a strong black hole candidate (White & Marshall
wavelengths (D’Anavzo, Goldoni & Covino 2006; Torres, Steeghs & Jonker 2006a; Torres, Steeghs & McClintock 2006b). The 2006 outburst lasted for approximately 160 d where the source reached a maximum of \(\sim 1.9\) Crab on 2006 January 28, following an exponential decline of the X-ray flux. Fig. 11 shows the 1 d averaged ASM daily light curve of the source during its outburst.

To calculate the MDP the data were analysed between MJD 53765 and MJD 53780 when \textit{RXTE} pointed observations were available and the source was in blackbody-dominated days. The MDP\textsubscript{net} integrated over all the days was found to be similar to the other sources in 6–9 and 9–11 keV but much worse in the 11–15 keV energy band since the power-law flux was significantly higher and totally dominant over the blackbody flux over this energy band. Fig. 12 shows the comparison of the two fluxes and the MDP in the specified energy ranges on each day during this time.

Calculated values of MDP\textsubscript{net} for all the sources during the respective stretches are given in Table 2.

5 DETERMINATION OF THE ERROR IN THE ANGLE OF POLARIZATION MEASUREMENT

Since polarization from accreting black holes in their thermally dominated state is also expected to have a rotation in the net angle of polarization in the inner parts of the accretion disc as discussed previously, determination of the error or uncertainty in the angle of
Figure 8. Panels (A) and (B) show the blackbody and the power-law fluxes in the two energy bands for Cygnus X-1 during its soft state transition in 6–9 and 9–11 keV, respectively. Star indicates the blackbody flux, and circle indicates the power-law flux. Panel (C) shows the value of the MDP in the two energy bands for this source on each day. Cross indicates MDP in 6–9 keV, and square indicates MDP in 9–11 keV. The solid line indicates calculation done with lithium as a scatterer and dashed line indicates beryllium as a scatterer. The thermal emission from Cygnus X-1 is very weak in the 11–15 keV band and is not shown here.

Figure 9. 1 d averaged long-term ASM light curve of H1743−322 showing the 2003 outburst of H1743−322.

polarization measurement is also necessary to specify how well one would be able to constrain the angle of polarization measurement for a specified $n\sigma$ statistical detection. To determine the error in the angle of polarization measurement we generated a modulated signal riding on a background superimposed with random errors as would be expected to obtain from the actual measurement of a polarized signal with the Thomson polarimeter. Adjusting the amplitude and background to fix the signal at specified $n\sigma$ levels of detection we determined the broadening in the phase (angle of polarization) measurement, i.e. the $1\sigma$ uncertainty in the polarization angle measurement at each $n\sigma$ level. Similar results have been found by Weisskopf et al. (2010). Fig. 13 shows the $1\sigma$ deviation in phase versus the number of sigma ($\sigma$) detection.

6 DISCUSSION AND CONCLUSIONS

We have shown that provided some of the sources go into similar outburst/state transition during the lifetime of the mission, detection of polarization in the disc emission would be possible with the Thomson polarimeter. This can be done by performing spectropolarimetric observations in different energy bands to map the energy-dependent polarization for these sources in their disc emission dominated state.

X-ray emission from the disc in accreting black holes is polarized due to electron scattering from the plane-parallel atmosphere of the disc with the polarization vector lying in the plane of the disc. However, relativistic effects like beaming and gravitational lensing
give a non-trivial rotation to the integrated net polarization vector resulting in energy-dependent rotation in the plane of polarization. Recent Monte Carlo ray tracing simulations (Schnittman & Krolik 2009) predict a decrease in the degree of polarization along with its rotation in the inner parts of the accretion disc for direct radiation, and a net rotation of 90° in the plane of polarization in the same region considering returning radiation. They have also simulated the results that would be expected with the polarization measurement taken by the GEMS mission polarimeter which is a photoelectron polarimeter working in the 2–10 keV range. Here we produce the results that we would expect to get with the Thomson polarimeter. The results could also be complimented with the GEMS enabling extensive wide-band spectropolarimetric studies. The main conclusions of this paper are as follows.

(i) The net MDP obtained for these sources in the three energy bands of 6–9, 9–11 and 11–15 keV is in most cases less than the degree of polarization expected from accreting black holes in their thermal state from the simulations of Schnittman & Krolik (2009), the degree and the net rotation in the integrated polarization vector being a strong function of the black hole spin. A comparison of the net MDP presented in Table 2 for three different energy bands with the predicted degree of polarization (Schnittman & Krolik 2009, figs 7 and 8) shows that for sources with favourable inclination angle (∠ > 75°) spectropolarimetric measurements will be possible with the proposed Thomson X-ray polarimeter and these measurements will also be useful to constrain the spin parameter of the black hole. In some cases, however, where the spectrum is almost entirely power law dominated in the 11–15 keV band, the MDP obtained is above the degree of polarization expected to be detected from such sources in case of a 5σ statistical detection. A lower significance detection, however, may be possible in such cases as a 3σ detection gives a
lower achievable value of MDP. The calculated error in the angle of polarization obtained for a 3σ statistical detection onwards is also within reasonable limits. Hence spectropolarimetric observation of such sources for a few weeks during their thermally dominated spectral state would possibly enable us to map the transition radius from horizontal to vertical polarization. This could provide us with some estimates on the parameters of the black holes, like their spin and/or the emissivity profile.

(ii) Observation of polarization in the 6–9 keV energy range necessitates the use of lithium as the scattering element which would set the dynamic range of the experiment to 5–30 keV. Use of beryllium, however, limits the lower energy threshold to 8 keV thus making observation in the 6–9 keV band having the lowest MDP impossible. This study thus strongly supports the use of lithium as the scattering element for the Thomson polarimeter.

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Figure 13. The 1σ deviation in position angle versus the number of σ statistical detection.

REFERENCES

Bellazzini R. et al., 2006, Nuclear Instrum. Methods Phys. Res. A, 560, 425
Belloni T. et al., 2003, in Durochoux Ph., Fuchs Y., Rodriguez J., eds, Fourth Microquasars Workshop, New Views on Microquasars. Center for Space Physics, Kolkata, India, p. 83
Belloni T., Homan J., Casella P., Van der Klis M., Nespoli E., Lewin W. H. G., Miller J. M., Mendez M., 2005, A&A, 440, 207
Bowyer S., Bryan E. T., Chubb T. A., Friedman H., 1965, Sci, 147, 394
Chandrasekhar S., 1960, Radiative Transfer. Dover Press, New York
Connors P. A., Piran T., Stark R. F., 1980, ApJ, 235, 224
Corbel S., Tomsick J. A., Kaaret P., 2006, ApJ, 636, 971
Cui W., 1996, IAU Circ., 6404, 1
Cui W., Focke W., Swank J., 1996, IAU Circ., 6439, 1
D'avanzo P., Goldoni P., Covino S., 2006, Astron. Tel., 724, 1
Dovciak M., Muleri F., Goodmann R. W., Karas V., Matt G., 2008, MNRAS, 391, 32
Fender R., Corbel S., Tzioumis T., Tingay S., Brocksopp G., Gallo E., 2002, Astron. Tel., 107, 1
Gies D. R., Bolton C. T., 1986, ApJ, 304, 371
Harmon B. A., McCollough M. L., Zhang S. N., Paciesas W. S., Wilson C. A., 1995, IAU Circ., 6196, 1
Herrero A., Kudritzki R. P., Gabler R., Vilchez J. M., Gabler A., 1995, A&A, 297, 556
Hynes R. I., Steeghs D., Casares J., Charles P. A., O'Brian K., 2003, BAAS, 35, 615
Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W. W., Morgan E. H., 1996, in Siegmund O. H. W., Gummin M. A., eds, Proc. SPIE Vol. 2808, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VII. SPIE, Bellingham, p. 59
Kaluzienski L. J., Holt S. S., Swank J. H., Boldt E. A., Serlemitsos P. J., 1977, BAAS, 9, 592
Li L.-X., Narayan R., McClintock J. E., 2008, ApJ, 691, 847
Long K. S., Chanan G. A., Novick R., 1980, ApJ, 238, 710
Makishima K. et al., 1986, ApJ, 308, 635
Markert T. H., Clark G. W., Lewin W. H. G., Schnopper H. W., Sprott G. F., 1973a, IAU Circ., 2483, 1
Markert T. H., Canizares C. R., Clark G. W., Lewin W. H. G., Schnopper H. W., Sprott G. F., 1973b, ApJ, 184, L67
Markwardt C. B., Swank J. H., 2003, Astron. Tel., 179, 1
Markwardt C. B., Swank J. H., 2005, Astron. Tel., 414, 1
Miller J. M., Homan J., Steeghs D., Torres M. A. P., Wijnands R., 2006, Astron. Tel., 743, 1
Mitsuda K. et al., 1984, PASJ, 36, 741
Morrison R., McCammon D., 1983, ApJ, 270, 119
Orosz J. A., Bailyn C. D., 1997, ApJ, 482, 1086
Rees M. J., 1975, MNRAS, 171, 457
Remillard R., Levine A. M., Morgan E. H., Markwardt C. B., Swank J. H., 2006, Astron. Tel., 714, 1
Revnivtsev M., Chernyakova M., Capitano F., 2003, Astron. Tel., 132, 1
Rishin P. V., Paul B., Duraichelvan R., James M., Devasia J., 2009, in Bellazzini R., Costa E., Matt G., Tagliaferri G., eds, X-Ray Polarimetry: A New Window in Astrophysics, Cambridge Univ. Press, Cambridge, p. 83
Rupen M. P., Dhawan V., Mioduszewski A. J., 2006, Astron. Tel., 721, 1
Schnittman J. D., Krolik J. H., 2006, ApJ, 636, 971
Schnittman J. D., Krolik J. H., 2009, ApJ, 701, 1175
Silver E. H., Weisskopf M. C., Kestenbaum H. L., Long K. S., Novick R., Wolff R. S., 1979, ApJ, 232, 248
Sunyaev R. A., Titarchuk L. G., 1985, A&A, 144, 374
Swank J., Kallman T., Jahoda K., 2008, in Proc. 37th COSPAR Scientific Assembly, p. 3102
Torres M. A. P., Steeghs D., Jonker P. G., 2006a, Astron. Tel., 733, 1
Torres M. A. P., Steeghs D., McClintock J., 2006b, Astron. Tel., 749, 1
Weisskopf M. C., Cohen G. G., Kestenbaum H. L., Long K. S., Novick R., Wolff R. S., 1976, ApJ, 208, L125
Weisskopf M. C., Elsner R. F., O'Dell S. L., 2010, in Arnaud M., Murray S. S., Takahashi T., eds, Proc. SPIE. Vol. 7732, Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray. SPIE, Bellingham, p. 77320E
White N. E., Marshall F. E., 1984, ApJ, 281, 354
Zhang W., Giles A. B., Jahoda K., Swank J. H., Morgan E. H., 1993, in Siegmund O. H. W., eds, Proc. SPIE Vol. 2006, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy IV. SPIE, Bellingham, p. 324
Zhang S. N., Cui W., Harmon B. A., Paciesas W. S., 1997, in Dermer C. D., Kalemci E., Tomsick J. A., Rothschild R. E., 2006, ApJ, 639, 340

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