



## Observing galactic black hole sources in hard X-rays

A. R. Rao\*

*Tata Institute of Fundamental Research, Mumbai, India*

**Abstract.** Observations of Galactic black hole sources are traditionally done in the classical X-ray range (2 – 10 keV) due to sensitivity constraints. Most of the accretion power, however, is radiated above 10 keV and the study of these sources in hard X-rays has the potential to unravel the radiation mechanisms operating at the inner region of the accretion disk, which is believed to be the seat of a myriad of fascinating features like jet emission, high frequency QPO emission etc. I will briefly summarise the long term hard X-ray observational features like spectral state identification, state transitions and hints of polarised emission, and describe the new insights that would be provided by the forthcoming Astrosat satellite, particularly emphasising the contributions expected from the CZT-Imager payload.

*Keywords :* black holes: accretion – observations: technique – X-rays: stars

### 1. Introduction

Though Cygnus X-1 was suggested to be a black hole ‘candidate’ source in the early seventies (Webster & Murdin 1972), it carried the suffix ‘candidate’ upto the late nineties. It is only during the past two decades, particularly during the ‘RXTE era’, that we have firm identifications of several black hole sources. The All Sky Monitor (ASM) onboard RXTE (Levine et al. 1996) quickly identified several soft X-ray transients (and made the data publicly available) and the quick manoeuvring capabilities of the pointed instruments PCA and HEXTE (Jahoda et al. 2006; Rothschild et al. 2008) ensured that extensive X-ray spectro-temporal observations are available for a large number of objects. Further, quick optical follow up observations using the ground based optical telescopes provided radial velocity measurements for these transients (Ozel et al 2010 and references therein). The fact that many black hole sources are low mass X-ray binaries with less than 1 solar mass for the optical companion, did not leave much uncertainties in the estimation of the mass function and

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\*email: arrao@tifr.res.in

**Table 1.** Black hole masses

Source name	$P_{orbit}$ (days)	$M_{BH}$ ( $M_{\odot}$ )	D(kpc)	References <sup>a</sup>
A0620-003	0.33	6.6±0.25	1.06±0.12	1
4U 1543-47	1.12	9.4±1.0	7.5±0.5	1
XTE J1550-564	1.54	9.1±0.6	4.4±0.5	1
GRO J1655-40	2.62	6.3±0.27	3.2±0.5	1
V4641 Sgr	2.82	7.1±0.3	9.9±2.4	1
GS 2023+338	6.47	12±2	2.39±0.14	1
M33 X7	3.45	15.65±1.45		1
LMC X-1	3.91	10.91±1.54		1
Cyg X-1	5.60	14.8±1.0		2
GRS 1915+105	33.5	14±4	9±3	3
LMC X-3	1.704	7.6±1.3		3
H1705-250	0.520	6±2	8.6±2.1	3
GS 1124-684	0.433	7.0±0.6	5.89±0.26	3
GS 2000+250	0.345	7.5±0.3	2.7±0.7	3
GRS 1009-45	0.283	5.2±0.6	3.82±0.27	3
GRO J0422+32	0.212	4±1	2±1	3
XTE J1118+480	0.171	6.8±0.4	1.7±0.1	3

Notes: (a) References: 1. Ozel et al. (2010); 2. Orosz et al. (2011) 3. Casares 2006.

the derivation of the masses of the compact objects. Now we have secure measurements of the masses of about 17 black hole candidate sources. A compilation of these sources is given in Table 1.

One of the lasting legacies of RXTE is the wide X-ray coverage for a large number of sources (see Remillard & McClintock 2006 for a comprehensive review). The early observations suggested systematic variations of emission properties enabling a data driven definition of spectral states which took into account the spectral shape as well as the variability characteristics. The mining of the vast RXTE archives is still an ongoing process and what it has firmly established in the X-ray domain is the systematic variations in the spectral states in the X-ray transients. The accompanying multi-wavelength observations also identified the occurrence of jet emission, coupled to the X-ray states. This has led to a comprehensive picture of the black hole accretion in terms of emission from the various putative emission regions.

## 2. The current accretion paradigm

The current observational paradigm for black hole accretion runs as follows (see Zhang 2013 and Fender & Belloni 2012 for comprehensive reviews). At very low accretion rates, the sources are in a hard state with a hard spectrum and high variabil-

ity. Flat spectrum radio emission, coming from a core jet, is seen in this state and the X-ray and radio emissions are strongly correlated (whether the extremely faint quiescent stages have a similar spectral state is probably still an open question - see Plotkin et al. 2013). During the onset of an X-ray transient, presumably due to an increase in the accretion rate due to accretion instability, the source intensity increases with the spectral shape remaining roughly the same. This shows a vertical path in the hardness intensity diagram and a diagonal path in the variability-intensity diagram. The spectral and timing properties drastically change and the source enters into a Hard Intermediate State (HIMS). A myriad of observational episodes occur in this state like transition into different QPOs, superluminal jet emission etc. The source can exhibit multiple crossing and can settle into a soft state and return to quiescence via a Soft Intermediate State (SIMS). One other characteristic is the cessation of jets and the onset of strong winds in the soft state. The transition luminosity and the peak soft X-ray luminosity and the rate of change in luminosity are strongly correlated (Yu et al. 2004; Yu & Zhen 2009). The short lived transitions show different jet emission mechanisms and these can be broadly classified into core jet, episodic jet emission and superluminal jet emission. The variability and QPO characteristics show a definite pattern and by associating the characteristics QPO frequency to some length scale in the accretion disc, it is easy to visualise a specific accretion disc radius. This can be characterised as a truncation radius responsible for various activities like QPO generation, jet launching etc. Such well established patterns in the emission characteristics prompted observers to define a “small number of states and their association with jets providing a good frame work to base theoretical studies” (Belloni et al, 2011).

## 2.1 Theoretical considerations

Most of the observational features can be coupled to the current ideas of accretion physics. The Shakura-Sunyaev (SS) disk (Shakura & Sunyaev 1973) is extensively used to understand the thermal emission. The non-thermal emission is identified with the various forms of inverse Compton scattering (Done et al. 2007). In this sort of theoretical paradigms, each observations is identified with a perceived emission region/ mechanism.

Chakrabarti and his collaborators, on the other hand, assumed that the accretion can have two components, a SS disk coexisting with a sub-Keplerian disk (Chakrabarti & Titarchuk 1995). This formalism enabled them to avoid prescribing viscosity, but the accretion rate, however, was parameterised with two components: a disk accretion rate and a halo accretion rate. By this method, the transition to the inner regions could be connected through a Centrifugal pressure dominated boundary layer (CENBOL) and the flow beyond the CENBOL could be studied through inviscid transonic flow formalism (Chakrabarti 1989). Existence of shocks could be proved for certain flow parameters. Though this model has several attractive features like explaining the spectral states and their association with the QPOs (Chakrabarti et al. 2008; Nandi et al. 2012; Debnath et al. 2013), it is still to be widely accepted in the community.

In the following, I give a personalised observers perspective on the requirements

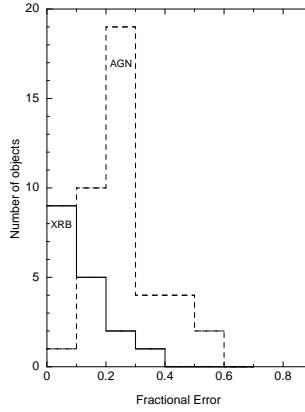
of a good accretion theory. As highlighted by (King 2012), the viscosity in the accretion disk, parametrized in the SS disk, is not understood from basic Physics. Till we have a clear understanding of the viscosity in the accretion disk, accretion theory will not have predictive power like the stellar structure theory and hence "we are still a long way from a theory of accretion discs with real predictive Power" (King 2012). Second, the innermost region of the accretion disk is difficult to understand and new observations seem to challenge the prevailing views: for example the peculiar variability characteristics of GRS 1915+105 is possibly due to the very high accretion rate and this concept is challenged by the discovery of IGR J17091-3624 showing a behaviour similar to that of GRS 1915+105, but with a vastly lower luminosity (Altamirano et al. 2011; Rao & Vadawale 2012; Pahari et al. 2012). The mechanism of superluminal ejection (whether it is a series of events or one large emission) is unknown and the exact energy source is still an ongoing debate (King et al. 2013).

## 2.2 Mass estimates based on scaling laws

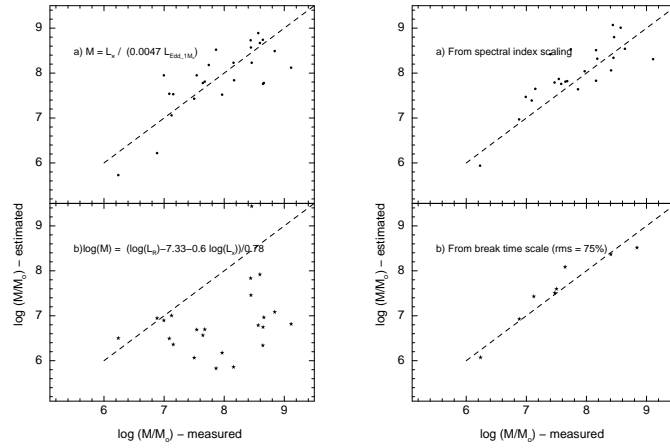
One of the most fundamental parameter of the black hole is its mass and they are measured with a reasonable accuracy. In Figure 1 I have plotted the accuracy in the mass measurements available for 39 AGNs and 17 XRBs. It can be seen that a typical accuracy of  $\sim 30\%$  for AGNs and  $\sim 10\%$  for X-ray binaries are achieved. One of the ways to have a clear paradigm of accretion theory is to predict the mass of the black hole using the observations coming close to the black hole: this will clearly establish the basic boundary conditions. In Figure 2, left panel shows the estimated mass for AGNs simply by assuming that the X-ray luminosity ( $L_X$ ) is proportional to the Eddington luminosity ( $L_{Edd}$ ). The bottom-left panel uses the fundamental plane of black hole activity tying  $L_X$  and radio luminosity to the black hole mass (Merloni et al. 2003). The measured X-ray spectral index is found to be correlated to  $L_X$  and this relation is used as a proxy to measure mass by Gliozzi et al. (2011) and this result is given in the top right panel. McHardy et al. (2006) derived a tight correlation between the variability time scale, bolometric luminosity and the mass of the black hole and this relation is used to predict the mass of black holes in the bottom right panel of Figure 2 (see Gonzalez-Martin & Vaughan 2012). As can be seen from the figure, these scaling laws are unable to predict the mass of the black holes. The best achieved, so far, is the break time scale relation of McHardy et al. (2006) and that too at 75% rms accuracy. Hence, to establish the accretion disk paradigms, it is necessary to evolve a clear theoretical basis which can clearly provide a definite relation between the observables (X-ray luminosity, timing features, spectral features etc.) and the most fundamental feature of the black hole, its mass.

## 3. Hard X-ray observations using Astrosat

Our current understanding of the accretion onto black holes primarily is the result of the vast amount of data available at the low energies. The radiation mechanism, however, could be understood by making a detailed spectral study in the hard X-rays.



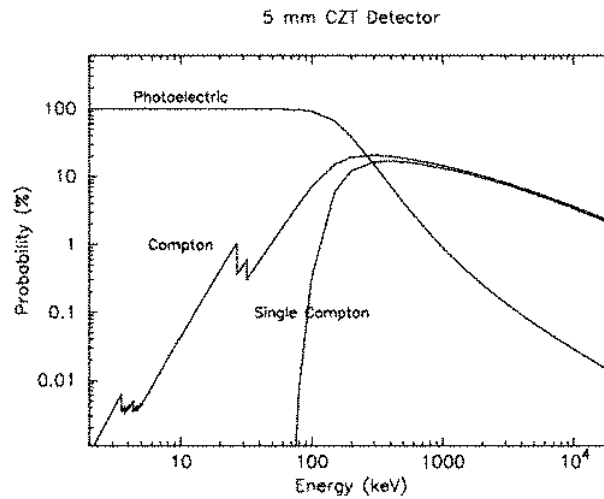
**Figure 1.** A histogram of fractional errors in mass for black hole sources in X-ray binaries and AGNs.



**Figure 2.** The observed and estimated masses for AGNs (see text).

This is inherently a difficult field because of the difficulties of hard X-ray astronomy like lack of source photons, high background etc.

For example, measurement of the polarisation in the hard X-rays can be used to constrain the emission mechanism. In Cygnus X-1, Laurent et al. (2011) detected strong polarisation above 250 keV and weak polarisation below that, thus hinting at different components in the spectrum. This result, however, does not agree with the overall spectral energy distribution of Cygnus X-1 (Zdziarski et al. 2012), thus highlighting the difficulty of measuring hard X-ray polarisation. Nustar uses hard X-ray focusing optics and the Nustar data is used to identify high spin for the supermassive black hole at the centre of NGC 1365 (Risaliti et al., 2013). It probably highlights the difficulties in the hard X-ray spectral measurements that this result is indeed amenable



**Figure 3.** The absorption probability in the 5 mm CZT detector in the CZT-Imager payload of Astrosat. The Compton scattering probability is separately shown.

to an alternate explanation without requiring high spin for the black hole (Miller & Turner 2013). In this context, the forthcoming Astrosat satellite is extremely topical for the study of accretion physics.

Astrosat is an observatory class satellite dedicated for multi-wavelength observations (Agrawal 2006). It contains five dedicated instruments and wide band X-ray spectroscopic observations are done by the co-aligned X-ray instruments: Soft X-ray Telescope (SXT), Large Area Xenon-filled Proportional Counter (LAXPC) and Cadmium Zinc Telluride Imager (CZTI). The Sky Survey Monitor (SSM) provides a continuous record of the X-ray sky (Seetha et al 2006) and the Ultra-violet Imaging Telescope (UVIT) makes simultaneous optical and ultra-violet observations (Kumar et al. 2012). There are a few very important observational features which make Astrosat an unique laboratory to understand accretion onto black holes.

LAXPC has the largest ever area above 10 keV and it will extend the RXTE timing capabilities to higher energies. The SXT can routinely monitor bright sources (Kothare et al. 2009) and hence the crucial high spectral resolution sensitive measurements at low energies are available for bright transients. The LAXPC and CZTI-I have individual photon handling capability which is very essential for the understanding of the systematic in the data (Rao et al. 2010). The very low inclination ( $\sim 8^\circ$ ) orbit ensures very low cosmic ray induced background. The flexibility to change/ adjust observation time of SSM pointing is very crucial to track black hole transients.

The CZT-Imager has large area ( $1000 \text{ cm}^2$ ), good energy resolution ( $\sim 5\%$ ), and individual pixel handling and calibration facility. A coded aperture mask is used for simultaneous background measurement and identifying multiple sources in the field of view ( $\sim 6^\circ$ ). It acts as a pointed collimated detector upto about 80 – 100 keV and an

open all sky monitor above this energy. In conjunction with SSM it will provide crucial spectral state monitoring of bright black hole sources. A continuous simultaneous record in soft and hard X-ray sources for bright ( $>100$  mCrab) sources will prove very useful for a detailed study of state transitions in bright X-ray transients. The CZT-I also has individual photon counting capability and very good relative time-tagging capability ( $20 \mu\text{s}$ ). The Compton scattering probability is shown in Figure 3. It can be seen that there is sufficient probability to detect double events and these can be identified by the precise time-tagging. With a pixel size of 2.5 mm, there is sufficient sensitivity to measure the azimuthal distribution of the Compton scattered photons. This results in polarisation sensitivity above 150 keV and it can measure Crab polarisation in about a day. Observations using Astrosat have the potential to establish the basic paradigms of accretion onto black holes:

**X-raying the birth of jets:** In Astrosat, the SSM has flexible observing capability which will provide, to a reasonable accuracy, the possible time of ejection of a superluminal jet. A coordinated observation, lasting for a few days, with Astrosat and other ground based observatories like GMRT, will provide a very detailed and clear picture of the accretion disk emission properties responsible for the jet emission.

**Disk/ jet symbiosis:** It is still an ongoing debate about the contribution of base of the jet for the X-ray spectrum. The CZTI payload can measure polarisation in bright black hole sources like Cygnus X-1 which will help in a clear segregation of the disk and jet emission in black hole binaries.

**An atlas of spectra of black hole states:** Astrosat has hard X-ray observations simultaneous with SXT along with UV and optical observations. This will provide a vast amount of good quality spectral and timing data for at least a dozen black hole sources in different spectral states.

**Finding new black holes:** In the course of the life time of Astrosat (3 - 5 years), it is expected to discover at least half a dozen new X-ray transients and it will help in increasing the number of known black hole sources.

**Finding faint black hole transients:** Pointing Astrosat near the Galactic centre in a scan mode will give a sensitive search for faint black hole sources. With the wide field of view of CZTI and the superior sensitivity of SXT, the sources discovered by LAXPC can be quickly identified and faint black hole sources like IGR J17091-3624 could be discovered.

In conclusion, black holes in X-ray binaries is a firmly established paradigm. The general concepts of accretion are known reasonably well but establishing a firm paradigm requires predictability and better observations, particularly in the hard X-ray range.

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