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Hard X-ray spectro-polarimetry of Black Hole sources

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Abstract. We emphasise the need of a precise hard X-ray spectroscopy, including polarimetry, to decouple the accretion disk and jet contribution in black hole sources across mass scales: X-ray binaries, Gamma-ray bursts and Active Galactic Nuclei. The expected results from CZT-Imager of Astrosat will be discussed along with the prospect of hard X-ray polarimetry.

Keywords : black hole physics – accretion – techniques: polarimetric – X-rays: binaries

1. Introduction

Matter accreting onto black holes is expected to form disks, due to angular momentum considerations, and traditionally, the theoretical solutions obtained for geometrically thin disks under the assumption of viscosity scaling with pressure, the so called SS disk (Shakura and Sunyaev 1973), were thought to be applicable in black hole sources. General considerations under SS disk were successful in explaining the dwarf nova outbursts and the behaviour of transients in Low Mass X-ray Binaries with black holes. The stability of such disks and the inner boundary conditions at the event horizon were found to be difficult to satisfy under the premises of SS disks and the geometrically thick hot accretion flow solutions (Shapiro et al. 1976) where electrons and protons are existing at their respective virial temperatures are thought to be applicable close to the black holes. Existence of stable spectral states in black hole sources with the soft state dominated by a blackbody with a constant radius and the hard state dominated by a power-law with a cutoff were seen as a vindication of the existence and switching between these two accretion disk solutions. The vast amount of data collected in the past two decades on Galactic black hole binaries were generally understood and examined under these broad premises of the existence of these

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two accretion disk geometries: a geometrically thin disk and a hot corona (Done et al. 2007; Remillard and McClintock 2006).

Theoretically, as yet, *there is no acceptable global model of accretion onto a compact object* (Gilfanov 2010). The major reason for this is the fact that when the inner boundary conditions are used the eigenvalue problem is extremely difficult to solve and generally this has been circumvented in three ways: use self-similar equations for accretion flows and find global solutions for some specific parameter ranges and boundary conditions (Narayan et al. 1997), make detailed magneto-hydrodynamic simulations or, as described in detail by Chakrabarti (2015, this volume), use the clever technique of using different sets of boundary conditions at inner sonic points and the outer boundary, tying them neatly with a disk and halo flow. The self similar solutions are shown to be consistent with the magnetohydrodynamic simulations (Yuan and Narayan 2014), but applicable to some specific accretion rates. The observations do indicate length scales in accretion disks and hence any self similar solutions should be applicable to some specific cases. The complete solutions advocated by Chakrabarti and his collaborators as the Two Component Accretion Flow (TCAF) model is quite successful in explaining the relationship between the X-ray timing (QPO period variations) and spectral properties (Debnath et al. 2015), but it includes the jet emission only partially. The myriad observations of black hole sources, ranging from stellar mass to supermassive and also the nascent black hole jet in Gamma-ray Bursts, do show a close interplay between the disk and the jet emission, that too at a very short time scales. Hence, it is highly important to validate some of the basic premises of black hole accretion and evolve an universally acceptable paradigm to examine and understand the various astrophysical objects and phenomena. It is argued here that a wide-band spectroscopy with polarisation using the Astrosat satellite, will address several of these questions and help refine the models and come up with a accretion paradigm fully acceptable to the community.

2. The Astrosat satellite

Astrosat, the first Indian multi-wavelength satellite, aims to provide wide band X-ray spectroscopic data using multiple instruments (Singh et al. 2014). It contains a Soft X-ray Telescope (SXT) which uses focusing technique and provides good quality spectroscopic data in the 0.3 – 8 keV range (Kothare et al. 2009). The Large Area Xenon-filled Proportional Counters (LAXPC), with deeper detectors filled with Xenon gas at higher pressure (Agrawal 2006), aims to extend the fast X-ray timing observation legacy of RXTE PCA to higher energies and it will help in pinning down the spectral components by examining their variability characteristics. The Sky Survey Monitor, SSM, (Seetha et al. 2006) can identify the spectral states of bright Galactic sources and the Ultra-violet Imaging Telescope, UVIT, (Kumar et al. 2012) will provide simultaneous optical and ultra-violet observations. The role of CZT-Imager, CZTI, (Rao et al. 2010; Vadawale et al. 2015) is to complement these observations with high energy (above 10 keV) measurements so that a good wide band spectroscopy is possible.

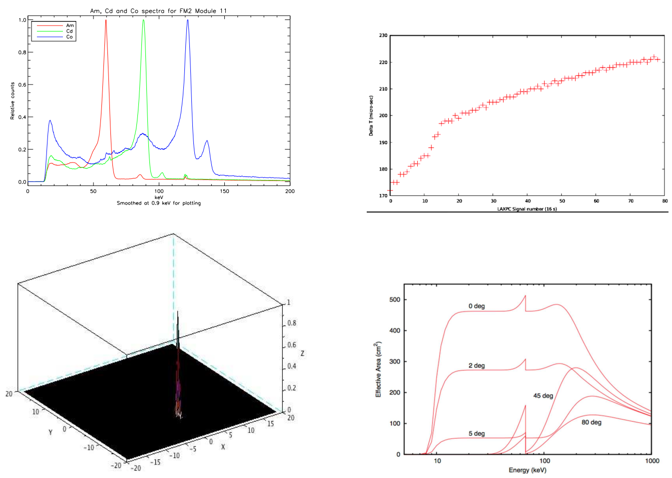

Figure 1. Some of the important characteristics of CZT-Imager. *Top Left:* Spectral response for radioactive sources; *Top Right:* The residual time, in μs, of CZT time compared to GPS time (in units of LAXPC pulses every 16 s), confirming timing calibration correct to μs, *Bottom Left:* Image of a point source at a known distance demonstrating the complete geometric modelling, *Bottom Right:* Geometric area as a function of energy (10 to 1000 keV) and incidence angle (0, 2, 5, 45, and 80 degrees), showing the significant area above 100 keV (~300 cm^2) for large offset angles, making CZTI a good hard X-ray all sky monitor.

Since CZTI has sensitivity for polarimetric measurements in the 100 - 300 keV range, it will add a new dimension to the observations of black hole sources. Cadmium Zinc Telluride Imager (CZTI) is one among the four X-ray instruments on ASTROSAT. It is a hard X-ray imaging instrument covering the energy band from 10 to 100 keV, has a detector area of 976 cm^2 constructed using CZT modules and uses a Coded Aperture Mask (CAM) for imaging. Collimators above each detector module restrict the Field of View to 4.6° × 4.6° at photon energies below 100 keV. At energies above that the collimator slats and the coded mask become progressively transparent. For Gamma Ray Bursts, the instrument behaves like an all-sky open detector. The detectors have multi-pixel detection capability and hence CZTI can be used as Compton scattering detector, thus having modest polarisation (and detection) sensitivity in the 100 - 300 keV region (Vadawale et al. 2015). The instrument characteristics are displayed in Figure 1, demonstrating the good energy response, timing accuracy, imaging characteristics, and effective area for large angles. The good timing accuracy is used to tag individual photons correct to 20 μs accuracy and associate them with scattered photons in the neighbouring pixels. This characteristics has a demonstrated ability for measuring polarisation above 100 keV (Chattopadhyay et al. 2014; Vadawale et al. 2015). The payload is configured such that above 100 keV it acts as a good all sky monitor making it an effective instrument to measure fluxes above 100 keV of bright sources and also as a GRB spectro-polarimeter. In Figure 2, left panel, the effective area for Compton scattering above 100 keV is given.

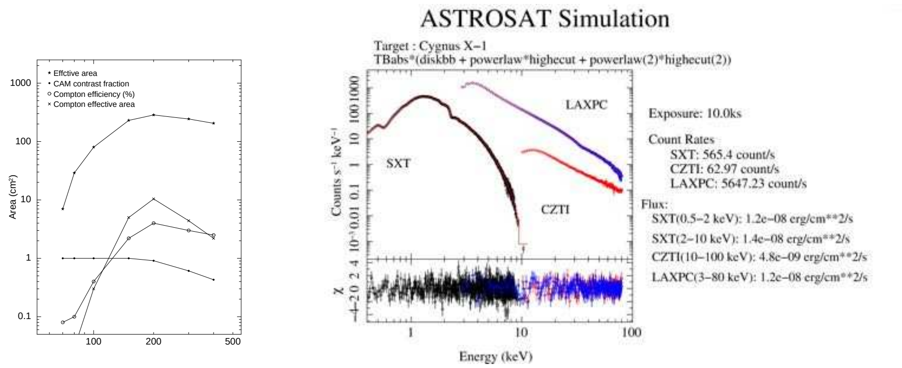

Figure 2. *Left:* The effective area for Compton scattering demonstrating significant polarisation sensitivity, *Right:* Expected spectrum using Astrosat for 10 ks observations of Cygnus X-1.

2.1 Study of black hole sources using Astrosat

Wide band X-ray spectroscopy, along with polarisation measurement for bright sources, is the strength of Astrosat. This is complemented by the simultaneous measurement in optical and UV bands using UVIT and for a few sources observations in a campaign mode can be made using several ground based observatories. Hence, we would have a simultaneous view of accretion disk emission, emission from the base of the jet and the outer accretion disk. This will have far reaching implications for the study of Galactic black hole binaries, nearby AGN and gamma-ray bursts. We first highlight the possible results that could be obtained for Cygnus X-1, the archetypical Galactic black hole source.

2.1.1 *Cygnus X-1: a case study*

Cygnus X-1 is one of the brightest hard X-ray sources in the sky. It is a black hole X-ray binary with an estimated black hole mass of $14.8 \pm 1.0\, M_\odot$ (Orosz et al. 2011). The wide band X-ray spectroscopic characteristics of this source have been studied in detail. The Suzaku observations (Makishima et al. 2008; Yamada et al. 2013) showed that the wide band ($0.7 - 400$ keV) spectra in the hard state consists of a cool disk emission, two Compton continua, along with reflection and Fe-K line emission. There were evidences for the disk to be truncated ($\geq 15\, R_g$). On the other hand, Parker et al. (2015) fit the simultaneous Suzaku and NuSTAR observations of this source in the hard state with a single component for the non-thermal continuum. These authors used a relativistically blurred line profile and absorption from the companion wind, and correspondingly find a high spin and a small inner disk radius. Thus the spectral modelling critically depends on the assumed models.

In the hard state, the source is also found to have a strong high energy tail extending upto the MeV regime. Polarisation of high modulation is also reported in this source in the high energy band $>$ 250 keV (Laurent et al. 2011). Malyshev et al. (2013) used the 4σ detection of Cyg X-1 in the 0.03 – 300 GeV range (Fermi LAT data) along with the non-simultaneous wide band data ranging from radio to gamma-rays. These authors concluded that the jet magnetic field should be much above the equipartition values, if the wide band emission is to be consistent with the high polarisation. This implies a fast cooling for the electrons, requiring a very hard acceleration index, which is not generally seen in usual acceleration processes. Hence, it is very important to understand the various observed features and identify them with the accretion disk geometry in the hard state, in particular by verifying the polarisation detection in hard X-rays and segregating the contribution from disk and jet emission. Note that, while the inner accretion disk is observed in X-rays, the jet is primarily observed in radio wavelengths. Figure 2, right panel, displays the broad-band X-ray spectrum of Cyg X-1 in the hard state, for a possible Astrosat observation of 10 ks. As explained in detail in Vadawale et al. (2015) polarisation above 100 keV can also be determined. This excellent multi-wavelength capability along with several ground based observations like a two-band (610 MHz and 1.4 GHz) observations using GMRT, supplemented with infra-red observations from Mt. Abu and HCT, will help to identify the radiation mechanisms, geometry of the emission and the disk-jet connection. This study has the potential of providing the crucial information like the precise length scale in the accretion disk, spin of the black hole, size of the inner jet emission region, jet acceleration mechanism etc.

2.1.2 *AGN and GRBs*

Astrosat will help sharpen our tools of multi-wavelength time resolved studies of Galactic black hole sources and these tools can be used for nearby AGN. Note that to study a black hole source of mass M at a distance d in its characteristic inner disk time scale (which scales as mass) emitting close to its Eddington luminosity (again scaling with mass), the sensitivity of observation goes as M^2/d^2 (for focusing low background detectors) or $M^{1.5}/d^2$ (for non-focusing detectors). Hence a low mass AGN (mass about $10^6 M_\odot$) residing at, say, 10 Mpc, can be studied with 50 - 1000 times more sensitivity than Galactic black hole sources. Hence, multi-wavelength observations of nearby AGN would be one of the most interesting area of research that will emerge from Astrosat.

Similarly, for Gamma-ray bursts, understanding the emission mechanisms of the prompt emission and relating them to the emitting object (the putative black hole), would be one of the thrust areas of Astrosat The observation strategy would be to select bright Swift/ Fermi GRBs and identifying them with those that are in the wide field of view of CZTI. Detailed position information would be available from Swift or other ground based follow up observations. From the prompt spectral analysis, interesting bursts would be identified and a detailed optical/ radio (GMRT) follow up observations would be made. A detailed comparison of the prompt spectro-polarimetric parameters with multi- wavelength afterglow observations, will help us in making a detailed calorimetry of the object and identify the emission radiation mechanism and the source geometry.

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