Recent Trends in the Study of Compact Objects (RETCO-II): Theory and Observation
ASI Conference Series, 2015, Vol. 12, pp 159-165
Edited by Indranil Chattopadhyay, Anuj Nandi, Santabrata Das and Samir Mandal

Understanding galactic black hole binary systems in the era of Astrosat and beyond

S. V. Vadawale*
Physical Research Laboratory, Ahmedabad - 380 009, INDIA

Abstract. Galactic black hole binaries (GBHB) are among the most extreme astrophysical systems in the universe. Detailed studies of GBHBs promises insights into some of the most intriguing questions of modern era such as how far the general theory of relativity is valid in strong gravity regime and how does a black hole influence the evolution of its surrounding. Vast amount of observational data from various international observatories have provided wealth of information on black hole binaries. However, there are still many uncertainties regarding the radiation processes and the exact accretion geometry in the region close to the black hole during various spectral states. With many new observatories being launched in next couple of years, this is likely to be a new golden era for X-ray astronomy. Particularly, Astrosat, the upcoming Indian multi-wavelength astronomy mission, is likely to significantly enhance the understanding of black hole binaries. However, I will try to argue here that the additional data will qualitatively be the same as existing data; and that the measurement of X-ray polarization properties is one avenue which can provide completely new observational inputs necessary to get fundamentally new insights into the physics of black hole binaries.

Keywords : Black hole – Astrosat – X-ray spectroscopy – X-ray polarimetry

1. Motivation

The existence of black holes is one of the most dramatic prediction of the General Theory of Relativity, considered to be one of the greatest intellectual achievements of 20th century. There has been a reasonable observational evidence of exotic astrophysical objects having very large mass confined in a very small volume and peculiar radiative properties which are interpreted as astrophysical black holes. However, it is not obvious that these objects are the black holes predicted by General Relativity i.e. physical singularity where density becomes infinite. This is an important issue because existence of such singularities is incompatible with another great achievement

---

*email: `santoshv@prl.res.in`

of 20th century, namely quantum mechanics. It is expected that such singularities will, somehow, be removed in a ‘true’ quantum theory of Gravity. In this context, it is believed that the General Relativistic predictions may become imprecise as the physical conditions approach such singularities. It is well known that the General Theory of Relativity has been extensively tested in the weak field limit and all of its predictions are found to be accurate (see Will 2014). This raises a very important question - at what level the predictions of General Relativity starts deviating from the reality under the strong field regime, if at all? Natural sites to expect such deviations, if any, are in the close vicinity of extreme astrophysical objects such as neutron stars or black holes and among these, typically black holes are preferred choice for such investigation. Astrophysical black holes are found in two broad classes - supermassive black holes at the center of galaxies and stellar mass black holes in the X-ray binaries. Since the curvature of the space-time close to the event horizon, which determines the strength of gravitational field, is more in case of stellar mass black holes (Psaltis 2008), galactic black hole binaries offer best opportunity to probe General Relativity in strong field limit. The fact that galactic black hole binaries are among the brightest X-ray sources in the sky is also greatly helpful in utilizing them as probe of general relativity in strong field limit. Therefore it is very important to understand various radiation processes and the geometry of the inner accretion region so as to accurately decipher the general relativistic signatures impinged on it.

2. Probing General Relativity using black hole spin

The astrophysical black holes are characterized by two parameters; mass, M, and angular momentum, J. The angular momentum of a black hole is typically described by a dimension less spin parameter, $a = J/M$. The effect of black hole spin on surrounding space time is a unique feature of general relativity. Thus the black hole spin is very important tool for probing general relativity in a strong field limit. However, it is very difficult to measure spin of a black hole because it does not have any Newtonian analogue and has effect only in the close vicinity. Thus the spin has to be inferred from its effect on the X-ray emission itself, unlike mass of the black hole which can be determined by observations of distant objects such as companion star in case of a binary system or close by orbiting stars in case of galactic center. The spinning black holes are described by the Kerr metric, which predicts that the space-time immediately outside the event horizon also dragged along with the black hole rotation, an effect known as *frame dragging*. While the frame dragging effect has been experimentally verified by very precise measurements from the earth orbiting satellites, it is difficult to observe in the context of black holes. More important observational manifestation of black hole spin is in the form of variation of *Innermost Stable Circular Orbit (ISCO)*, which ranges from, ranges from 1 R_g, for maximally co-rotating black hole to 9 R_g for maximally counter rotating black hole. Since the ISCO corresponds to the smallest possible inner edge of the accretion disk and the accretion efficiency depends on how close the matter can reach to the black hole before being plunged into it, the dependence of ISCO on black hole spin provides a good handle to measure spin by appropriately modeling the X-ray spectra from the disk. This technique of measuring black hole spin is known as *continuum fitting* method

(McClintock et al. 2011), and has been successfully employed to determine spin of many black holes (McClintock et al. 2014). Most of the astrophysical black holes are found to have positive spin i.e. co-rotating accretion disk, however, recently there have been suggestions of some black holes having negative spin i.e. counter rotating accretion disks (Rao and Vadawale 2012; Morningstar et al. 2014).

Another important observational manifestation of the ISCO dependence on black hole spin is in the form of the effect of enhanced gravitational redshift of photons originating from the innermost regions of the accretion disk. This effect can be best observed as the skewed profiles of the fluorescent $Fe\ K\alpha$ lines, which acquire long low energy tail as originally suggested by (Fabian et al. 1989). Accurate measurement of the $Fe\ K\alpha$ line profiles can provide measurements of the inner radius of the accretion disk and thus the spin of the black hole (Miller 2007). More general effect of this can be observed as relativistic blurring of the sharp absorption features in the reflection component, which has been recently used to constrain spin of many black holes using sensitive measurements of high energy X-ray spectra (Reynolds 2014). Both the techniques employed at present to determine the black hole spin, require accurate modeling of X-ray spectra in the energy range of ~1 to ~50 keV. It is well known that such a wide band X-ray spectra of black hole binary systems consists of many spectral components such as accretion disk, Comptonized component, reflection component, high energy power law tail etc. and relative contribution of these components varies with spectral state of the system. Thus in order to determine spin of the black hole, it is essential to understand the black hole binary system as a whole, including the accretion geometry, ejection of matter as either jet or winds as well as various radiative processes occurring in the inner regions.

3. Present observational scenario - Advantage of Astrosat

As noted in the previous section, the essential requirement to understand properties of black hole binaries is to accurately measure wide band X-ray spectra from ~1 keV to ~50 keV with energy resolution better then 5%. No current mission or instrument provide such measurements. RXTE was the main workhorse for black hole binary (or in general X-ray binaries) observations during last decade and has provided astonishing amount of data covering all most all aspects of the black hole binaries. However, because of its lower energy range is limited to ~3 keV, the best wide band (e.g. see Remillard and McClintock 2006; Done et al. 2007, and reference therein). spectral modeling was almost always arrived at by using simultaneous RXTE and other X-ray observatories such as ASCA, Chandra, XMM-Newton or Suzaku The same was true for independent observations with these telescopes as well. The ASCA and Suzaku observatories did have instrument covering higher energy range, their sensitivity was significantly low compared the primary X-ray telescopes. Thus simultaneous observations with RXTE-PCA which had very high sensitivity above 10 keV always yielded best results for wide band X-ray spectroscopy. Another issue with these highly sensitive X-ray telescopes is that the the Galactic X-ray binaries are too bright for them and hence such observations require some special instrument modes which are not always the best understood or calibrated. In the recent years, NuSTAR is providing wealth of data on black hole binaries and is likely to become next work horse. Being a focusing hard x-ray telescope, it provides the most sensitive hard X-ray (10 – 80 keV) spectral measurements to date. However, its lower energy limit is 3 keV and hence it still requires simultaneous observations with other soft X-ray telescopes to properly constrain the wide band X-ray spectrum.

In this scenario, Astrosat, the Indian multi-wavelength astronomy satellite planned to be launched during September 2015, provides an ideal combination, of instruments to study the black hole binary spectra. It consists of four different instruments - 1. SXT, a soft X-ray telescope; 2. LAXPC, a large area Xenon filled proportional counter; 3. CZTI, a hard X-ray imaging spectrometer based on pixelated CZT detectors and 4. UVIT, an ultra-violet telescope (see Singh et al. (2014) for detailed specifications of these instruments). The suit of three X-ray instruments will provide accurate measurement of the X-ray spectra in energy range of 0.5 to 100 keV. This coupled with an added advantage of having simultaneous measurements in UV and visible bands, makes Astrosat really a unique observatory. However, the best advantage of Astrosat lies in the well matched sensitivities of SXT and LAXPC. The SXT is a moderate size X-ray telescope and hence can easily observe the bright galactic X-ray sources and provide typical CCD resolution X-ray spectra in 0.5 to 8 keV energy range. The LAXPC is a similar instrument to the RXTE-PCA but much better sensitivity at higher energies (>30 keV) due to high pressure Xenon gas. This makes every observation by Astrosat to be equivalent to a coordinated multi-mission simultaneous observation involving RXTE. Further with slightly larger active area then PCA, LAXPC will also better capabilities for timing studies. Particularly with the event mode data for even the bright X-ray binaries sources, LAXPC will allow new analysis techniques such as phase resolved spectroscopy, frequency resolved spectroscopy, joint temporal and spectral fitting etc. which are difficult with existing RXTE-PCA data because of its constraints on availability of full resolution spectral data on time intervals less then 16 s. It should be noted that the same fact makes Astrosat better suitable for observing the bright X-ray binaries than its contemporary missions planned to be launched in next couple of years such as Astro-H and Spectrum Roentgen-Gamma (SRG) because their primary thirst is towards observations in the soft X-ray band. Thus Astrosat is certainly going to provide wealth of data on X-ray binaries and is likely to make a long lasting impact on the field.

4. Beyond Astrosat - X-ray polarimetry

As discussed in the second section, accurate measurement of black hole spin is very important for probing the general relativity in strong field regime. While Astrosat will provide large amount of data to estimate black hole spin, qualitatively it is going to be the same as the data that is already available with multi-mission simultaneous observations, and hence will still be subject to the uncertainty in our knowledge of inner accretion region, most importantly inclination of the inner accretion disk. Both the methods used to determine black hole spin in recent days, assumes knowledge of the inclination angle to be available from independent measurements. The independent measurements of the inclination angle are typically based on radio observations of jets or radial velocity observations of the secondary star. However, these observations measure the inclination angle of the orbital plane of the binary system, which is not necessarily the plane the inner accretion disk. It is generally believed that black hole spins are natal and do not change significantly due to the accreted matter (King and Kolb 1999; Miller and Miller 2015). Hence it is quite likely that the spin axis remains misaligned with the orbital axis for long duration (McKinney et al. 2013). In this situation, the plane of the inner accretion disk would be the plane perpendicular to the spin axis creating warped in the outer regions disk (King et at. 2005, 2013). In such cases, the inclination applicable to determine the black hole spin from the spectral fitting would be that of the inner accretion disk, but there is no independent way to determine this angle. Thus any spin estimates derived using the inclination of the orbital plane could possibly be incorrect. It should be noted that this limitation would apply to the other upcoming observatories such as Astro-H, NICER, SRG or even the future very large observatories such as LOFT and Athena. Thus it is necessary to have independent method to measure inclination angle of the inner accretion disk from the X-ray data itself, which originates from the inner accretion region. One way to do so is by measuring polarization of X-rays. There are many studies on the polarization properties of X-rays from black hole binaries where it has been shown that accurate measurements of energy dependent X-ray polarization in the energy range of 1 to 100 keV can not only provide estimation of the inclination angle but also provide independent measurement of the black hole spin (Dovciak et al. 2008; Schnittman and Krolik 2010). The spin dependence of X-ray polarization properties arises from its effect on the space-time in close vicinity of the black hole, which is an independent physical effect predicted by the general relativity. Thus, along with providing an estimation of a critical parameter to determine black hole spin from X-ray spectroscopy, X-ray polarimetry also provides an independent measurement of spin which can substantiate the overall predictions of the general relativity.

Scientific importance of X-ray polarimetry has been realized from very days of X-ray astronomy and there has been extensive literature on this topic (Krawczynski et al. 2011, and references therein). However, the actual progress in observational X-ray polarimetry is rather feeble due to variety of technical and non-technical reasons (e.g. see Weisskopf 2010). Recent technological advances, particularly the development of photo-electron tracking based detectors, have made it possible to realize sensitive X-ray polarimeters (Costa et al. 2001, 2010). One limitation of the X-ray polarimeters based on photo- electron tracking is that, their energy range is limited to $\sim$20 keV. A complimentary technique of measuring polarization of X-rays is by measuring the azimuthal distribution of the scattered X-rays, which can be used at higher energies (Vadawale et al. 2010). Particularly, by using an active scatterer and selecting only the Compton scattered X-rays by demanding coincidence between the scatterer and the absorber, very sensitive X-ray polarimeter can be designed. Such polarimeter as a focal plane detector for a hard X-ray optics can provide meaningful sensitivity in the energy range of 20 to 80 keV, with the higher energy range limited only by the hard X-ray optics (Chattopadhyay et al. 2013). In this context, our group at Physical

Research Laboratory, have been developing a Compton X-ray polarimeter as a focal plane detector (Chattopadhyay et al. 2014). Recently we have completed fabrication of a proto-type and successfully tested it with partially polarized as well as unpolarized X-rays and demonstrated its readiness (Chattopadhyay et al. 2015). Though, this configuration is optimized for polarimetric sensitivity, a slight modification and inclusion of appropriate semi-conductor detector can make it as multi-purpose X-ray polarimeter (Vadawale et al. 2012); simultaneously providing spectroscopic, timing and polarimetric measurements. Such an instrument can not only provide much needed fresh observational insights on black hole binaries, but also cater to a much wider range of interest of Indian X-ray astronomy community. It should be noted that the CZTI instrument onboard Astrosat will have polarimetric capability at energies >100 keV, however, its sensitivity will be limited to few brightest sources (Chattopadhyay et al. 2014; Vadawale et al. 2015). Thus it would be an ideal choice if the follow-up mission to Astrosat is conceived with hard X-ray focusing optics and a focal plane instrument providing multi-purpose measurements including polarimetry.

5. Summary

The astrophysical black hole binaries provide the best opportunity to probe general relativity in the strong field limit. Accurate measurement of the black hole spin holds the key to utilize these systems as probe general relativity. However, in order to determine the black hole spin from X-ray observations, it is essential to understand these binary systems as a whole including the radiative processes and the accretion / ejection geometries in the inner accretion region. Wide band X-ray spectroscopy along with the high throughput timing observations are essential to understand the black hole binaries. Hence, Astrosat is likely to play a key role in near future to significantly enhance our knowledge on these systems. However, for making fundamentally new insights into them, it is essential to adopt new measurement techniques such as X-ray polarimetry. Energy dependent measurement of the degree and angle of polarization of X-rays from black hole binaries can provide independent constraints on the black hole spin as well as on the geometry of the inner accretion region. Thus wide band spectro-polarimetry of X-rays from the black hole binaries, provide an excellent opportunity of unraveling the mysteries of these systems and using them to probe general relativity in the strong field limit.

Acknowledgements

I would like to thank A. R. Rao and Mithun Neelakandan for useful discussions and careful reading of the manuscript. I would also like to acknowledge entire Astrosat team at ISRO as well as various institutions involved in developing the instruments, whose hard work of many years have brought Astrosat on the verge of launch.

References

Chattopadhyay T., et al., 2013, *Exp. Astr.*, 35, 391
Chattopadhyay T., et al., 2014, *ApJS*, 212, 12

Chattopadhyay T., et al., 2015, *Exp. Astr.*, accepted

Chattopadhyay T., et al., 2014, *Exp. Astr.*, 37, 555

Costa E., et al., 2001, *Nature*, 411, 662

Costa E., et al., 2010, *Exp. Astr.*, 28, 137

Done C., Gierliński M., Kubota A., 2007, *AARv*, 15, 1

DovÄŊiak M., et al., 2008, *MNRAS*, 391, 32

Fabian A. C., et al., 1989, *MNRAS*, 238, 729

King A. R., Kolb U., 1999, *MNRAS*, 305, 654

King A. R., et al., 2005, *MNRAS*, 363, 49

King A. R., et al., 2013, *MNRAS*, 431, 2655

Krawczynski H., et al., 2011, *Astropart. Phys.*, 34, 550

McClintock J. E., et al., 2011, *Class. Quant. Grav.*, 28, 114009

McClintock J. E., 2014, *Space Science Rev.*, 183, 295

McKinney J. C., et al., 2013, *Science*, 339, 49

Miller J. M., 2007, *ARAA*, 45, 441

Miller C. M., Miller J. M., 2015, *Phy. Rep.*, 548, 1

Morningstar W. R., et al., 2014, *ApJL*, V. 784, L18

Psaltis D., 2008, *Living Rev. Relativity*, 11, 9

Rao A., Vadawale S. V., 2012, *ApJL*, 757, L12

Remillard R. A., McClintock J. E., 2006, *ARAA*, 44, 49

Reynolds C. S., 2014, *Space Science Rev.*, 183, 277

Schnittman J. D., Krolik J. H., 2010, *ApJ*, 701, 1175

Singh K. P., et al., 2014, *Proc. SPIE*, 9144, 91441S

Vadawale S. V., et al., 2012, *Proc. SPIE*, 8443, 84434P

Vadawale S. V., et al., 2010, *Nucl. Inst. & Meth.*, 618, 182

Vadawale S. V., et al., 2015, *A&A*, 578, 73

Weisskopf M. C., 2010, in *X-ray Polarimetry: A New Window in Astrophysics*, Cambridge University Press, Cambridge, ISBN: 9780521191845, p. 1

Will C. M., 2014, *Living Rev. Relativity*, 17, 4