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# Searching for black holes in nearby galaxies with Simbol-X

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**Abstract.** The study of black holes links astrophysics to fundamental physics and to especially to general relativity. General relativity constrains the value of the spin of a black hole to be between 0 and 1. Only by finding many examples of black holes and measuring their spin can we verify that they are all within the regime of theoretical predictions. Nearby galaxies are likely to contain many examples of compact binaries containing black holes. By measuring their X-ray spectra and determining their mass from studies of the optical companion with the new generation of large telescopes we will be able to compare their sets of properties to what general relativity allows. By extrapolating spectral band fluxes of the sources in several nearby low inclination galaxies detected by Chandra as reported in the literature, we estimate the strength of a putative hard X-ray component for each source. For a few values of angular resolution we simulate Simbol-X 12 to 60 keV images that would be obtained by pointing at these galaxies. The most luminous objects in the 12 to 60 keV band are more likely to be black hole binaries than neutron star binaries or supernova remnants and therefore are the most promising targets for optical telescopes.

**Key words.** Black Holes – Hard X-rays – Simbol-X

## 1. Introduction

The behavior of matter in very strong gravitational fields is a very important test of general relativity. Very few experiments can be performed under controlled conditions so the only recourse is astronomical observations of environments dominated by very strong gravitational fields that exist near neutron stars and black holes. When the black hole or neutron star is an accreting member of a compact binary system the innermost orbits of the accretion disk where the gravity field is very high is a region of thermal X-ray emission. However, it is more difficult to relate the X-ray emission of neutron stars to the transformation of gravitational energy because neutron stars contain strong magnetic fields that can act along with or even dominate the X-ray emission due to gravitational forces. They also experience occasional episodes of nuclear burning at the surface, which add more complications to the problem of isolating the X-rays resulting from gravitational infall. Also the mass of neutron stars is limited in theory to about 3 solar masses and in fact most that have been found cluster around 1.4 solar masses. Therefore with cleaner environments and no theoretical upper limit on their mass black holes are much superior test objects for studying strong gravity. Black holes are also found as supermassive objects (SMBHs) at the centers of galaxies. However, the scope of this paper is limited to the search for black holes binary systems in nearby galaxies.

## 2. Black Holes in compact binary systems

The relation among three observable parameters can test one of general relativity's predictions. The parameters are the mass of the black hole, the luminosity, and temperature of the black body component of its X-ray spectrum when it is an accreting member of a binary system.. The thermal X-ray emission comes primarily from the innermost stable orbit of the matter falling upon the black hole. The mass of the black hole is determined by studying the optical companion (McClintock & Remillard (1986), Orosz et al. (2002)). The temperature and luminosity of the black body component of the X-ray spectrum is measured directly. (However, Blaes al. (2006) have claimed that analyzing the X-ray spectrum should take into account magneto hydrodynamic heating of the accretion disk.) A value for the spin of the black hole is derived from the measurements of X-ray temperature, X-ray thermal luminosity, and the mass.

According to general relativity the spin of the black hole must be between 0 and 1. This means that there are limits upon the phase space that the three measurable parameters can occupy. If a value of the spin is found outside of this range then either our model for a black hole binary or our understanding of general relativity is incorrect.

Values for all three of the parameters are determined directly or indirectly from X-ray measurements. The luminosity and temperature of the black body component of the object's X-ray spectrum are measured directly after taking the power law component into account. Measuring the precise position of the X-ray source enables identifying the optical companion. The mass of the black hole is estimated from visible light measurements of the binary system period, the spectrum, velocity, and distance of the visible member, whose mass can be estimated from the star's magnitude and distance. Data from many examples of compact binary systems containing black holes are needed to check upon the validity of general relativity's limits upon the spin.

The number of permanently radiating compact binaries in our galaxy that are certified black hole systems is limited to only Cygnus X-1. There are several cases where the nature of the compact member is ambiguous because the optical counterpart is too faint. Transient X-ray black hole binaries have appeared at a rate of nearly one per year during the 30 years or so of scanning the sky. However for only a few were conditions favorable for estimating the mass and spin of the dark member. In some cases the transient X-ray source was very close to the galactic plane. X-rays with energy < 1 keV, were absorbed by the interstellar medium making measurements of the temperature and luminosity of the black body component highly uncertain. In some other cases the optical counterpart was too faint or too reddened by interstellar absorption for measuring velocities and determining masses for the two members of the binary system.

## 3. Black Holes in nearby galaxies

Despite the lower flux observing X-ray binaries in external galaxies has advantages over those in the Milky Way. The most obvious is that many objects are studied simultaneously rather than one at a time.The Sun and almost all compact binaries lie in the galactic plane where soft X-rays, i.e. energy < 1 keV, are absorbed in the interstellar medium. Consequently, it can be difficult to measure the temperature and flux of the black body component of a black hole candidate in our galaxy. In contrast, there are several nearby galaxies of low inclination and well off the galactic plane where soft X-rays are much less absorbed. There is less ambiguity about the thermal component of the spectrum. In addition the distance of the galaxy and therefore of the object, is already known.

The Chandra X-Ray Observatory, XMM-Newton, and ROSAT have observed and detected many point sources in external galaxies with significant X-ray flux. Table 1 lists several galaxies that were observed by Chandra and the number of X-ray sources that were de-

**Table 1.** Four Low Inclination Galaxies Observed by Chandra

| | Distance | Nh/cm$^{-2\dagger}$ | Reference | Exp.(ksec) | Num. Sources |
|---|---|---|---|---|---|
| M83 | 4 | $3.7 \times 10^{20}$ | Soria & Wu (2003) | 51 | 127 |
| M51 | 8.3 | $1.5 \times 10^{20}$ | Terashima & Wilson (2004) | 42 | 113 |
| M104 | 15 | $3.7 \times 10^{20}$ | Di Stefano al. (2003) | 18.5 | 122 |
| M33 | 0.84 | $5.7 \times 10^{20}$ | Grimm et al. (2005) | 180 | 261 |
| | | | Haberl & Pietsch (2001) | 456 | 184$^{\ddagger}$ |

$^{\dagger}$ "Colden" values of the hydrogen column density within the Milky Way. $^{\ddagger}$ ROSAT observation of a larger region of M33. Chandra sources include some but not all of the ROSAT sources.

tected. The upper energy limit of the Chandra measurements is 8 keV and that of the single ROSAT measurement is 2 keV. These objects are of course much fainter optically than objects within our own galaxy but with the future generation of large ground based telescopes such as the 22 m (equivalent) Giant Magellan Telescope, the 30 m Keck, and ultimately ESO's 100 m OWL, it will be possible in many cases to identify the optical companion, measure the orbital dynamics of the system, determine which contain black holes and measure its mass. A point source that is not an AGN and where the mass is estimated to exceed the 3.2 solar mass limit of a neutron star would be a black hole candidate.

The sources whose number is listed in Table 1 include black hole binaries, neutron star binaries, supernova remnants, and background AGNs. Measuring a finite size by Chandra would identify the supernova remnants. However, they are a relatively small fraction of the total. The remaining sources are still quite numerous with the black hole systems being only a minority. The ultra luminous sources, which some theorists claim are systems containing black holes with a mass between stellar type size black holes and SMBH's obviously stand out but are only a small number of each group. With the expected high degree of competition for observing time on the new, large optical telescopes it will not be possible to study all the remaining candidates. Some other indicator is needed for determining which of the remaining objects are more likely to be black holes. That information could come from the X-ray spectrum. According to Barret et al. (1996) black hole binaries tend to have a harder X-ray spectrum than the neutron stars. While the existence of a strong hard component in the spectrum is not an infallible signature it does increase the probability that the object is a black hole binary and should be given priority by optical observers who intend to study black holes. The objectives of the following section are to estimate how many objects in each of four galaxies observed by Chandra have hard spectra and to simulate how a Simbol-X image would appear.

## 4. Simulating Simbol-X observations

### *4.1. Count rates*

The references for each galaxy contains tables that provide the X-ray flux in two or three energy bands below 8 keV for all of the sources. We have used this information to estimate the number of counts that Simbol-X would detect in the 12 to 60 keV band. We also simulated Simbol-X images for several values of angular resolutions ranging from 60 to 10 arcseconds HPW. The functional form of the telescope's point response function was assumed to the same as XMM-Newton's, for both core and the halo. The angular scale was adjusted appropriately for each value of angular resolution assumed. The effective area expected of Simbol-X as a function of energy was obtained from the Simbol-X web site. We assumed that above 12 keV the spectrum of each source was a single component power law. By fitting a

**Table 2.** Number of Simbol-X sources expected with > 50 and > 100 counts in 12 – 60 keV band for 105 second exposure†

| | Number of sources with >50 counts | Number of sources with >100 counts |
|---|---|---|
| M83 | 41 | 28 |
| M51 | 47 | 28 |
| M104 | 57 | 34 |
| M33 | 102 | 47 |

† Presumed time on each source. Several pointings may be required to cover the galaxy

power law spectrum to the observed Chandra flux in two bands and taking interstellar absorption within the Milky Way into account we estimated the spectral index of each object.

This procedure is actually incorrect because the sources' spectra contain both a softer, thermal component and a harder power law component. The soft component contributes to only the softer Chandra band while the power law component contributes to both bands. If the flux in the lower energy band were high due to the existence of a strong soft component our representing the spectrum as a single power law would result in a spectrum that declines with energy too rapidly and estimates too few counts above 12 keV, even if the flux in the harder Chandra band were substantial. The effect is that our simulations are conservative in predicting the number of 12 to 60 keV counts that would be detected by Simbol-X. They are not necessarily correct for any individual source but the simulation of the entire source ensemble should be conservatively representative of the actual 12 to 60 keV counts that would be obtained by Simbol-X. Calculating the number of counts more accurately would requires analyzing the Chandra spectrum of each source individually, which is beyond the scope of this paper. The background at the Sun-Earth L2 region was based upon the model of Armstrong et al. (2000).

Table 2 lists for each of the four galaxies the number of sources expected to contain more than 50 and more than 100 counts in the 12 - 60 keV band with a Simbol-X exposure of 105 seconds. More than one pointing would be needed to cover all of the Chandra sources within a galaxy. Detecting all the sources and matching them with the precise Chandra positions should not be an issue except in a few cases where there may be some source confusion. On the basis of its presumed larger effective area the number of Simbol-X counts below 10 keV should exceed the Chandra rates by a factor of 1.5 to 2.

### 4.2. *Simulated images and comparison to other hard X-ray telescopes*

Using the Chandra positions and the estimated count rates described in the preceding section we simulated 12 - 60 keV images of the four galaxies for various values of the angular resolution ranging from 60 arcsec HPW down to 1 arcsec. With limited space we show only the 60 arcsec and 15 arcsec images of M83 in Fig. 1.

The 15 arcsec image is clearly much superior to the 60 arcsec image with respect to sensitivity and source confusion. Fewer sources are visible by eye in the 60 arcsec image and a significant number of sources that are resolved in the 15 arcsec image are confused at 60 arcsec. Side by side comparison of the 15 arcsec and 60 arcsec images has relevance for our expectations of future missions, at least for searching for black holes in external galaxies. Three missions containing hard X-ray telescopes are being planned that are likely to be launched within a few years of each other during the period 2011-2013. They are a NASA Small Explorer mission known as NuStar, NEXT a program of Japan, and

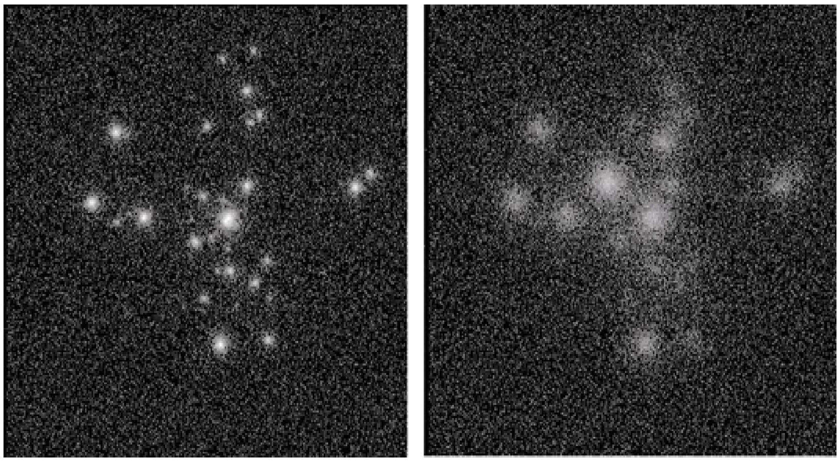

**Fig. 1.** Simulated images of the galaxy M83 for the 12 to 60 keV band as it would be seen by a telescope having the same effective area as Simbol-X. Background according to the model of Armstrong et al. (2000) is included. In the left panel the angular resolution is assumed to 15 arcsec HPW; in the right panel, it is 60 arcsec.

Simbol-X. The descriptions of these missions that appear in the literature and talks at meetings suggest to this author that the angular resolution of NuStar and NEXT will be about 60 arcsec. The angular resolution of Simbol-X is specified at 15 arcsec. Considering that the Simbol-X telescope will be constructed by a method similar to that of XMM-Newton whose angular resolution is 15 arcsec there is reason to expect that the resolution of Simbol-X will be about the same.

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