Subluminous X-ray binaries
Armas Padilla, M.A.P.

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The discovery of the first X-ray binary, Scorpius X-1, by Giacconi et al. 1962, marked the birth of X-ray astronomy. Following that discovery, many additional X-ray sources were found with the first generation of X-ray rockets and observatories (e.g., UHURU and Einstein). The short-timescale variations in their X-ray luminosity and the detection of the optical counterparts, established the binary nature of many of these X-ray sources. In such systems (the so-called X-ray binaries) a regular star is transferring material on to a neutron star (NS) or a black hole (BH) (Shklovskii 1967; Pringle & Rees 1972). Half a century later and after several generations of X-ray instruments, many new phenomena have been discovered and studied. This led to new insights in fundamental fields like the behaviour of ultra-dense matter or in the theory of general relativity in extreme gravitational fields, among others.

In the last decades, a new generation of X-ray telescopes with revolutionary capabilities, such as RXTE, XMM-Newton, Chandra or Swift have opened up previously inaccessible regions of study, improving our understanding of accreting compact objects. Their improvement in spatial resolution and sensitivity have made it possible to obtain high quality data at very low luminosities. This thesis focusses on the study of the family of subluminous of X-ray binaries, shedding new light on the properties at low accretion regimes and challenging current evolution and accretion models.

1.1 X-ray binaries

X-ray binaries are systems in which a normal star transfers matter on to a compact object, a BH or a NS. The accretion of the material takes place via a disc which is formed around the compact object in order to conserve the angular momentum of the in-falling matter. The combination of the viscosity of the material and the extreme
gravitational fields naturally yields temperatures above $10^7$ K in the innermost part of the accretion disc, and therefore a large amount of X-ray emission is produced.

Based on the mass of the donor star, the X-ray binaries are divided into **high mass X-ray binaries** (HMXBs) and **low mass X-ray binaries** (LMXBs). HMXBs are those with a companion star which has a mass of $M_{\text{donor}} \gtrsim 10\ M_\odot$ and spectral type O-B. They are concentrated in the Galactic plane and their lifetime is determined by the quick evolution of the donor ($10^5$-$10^7$ years). The accretion in these systems usually takes place through capture of material from a circumstellar disc around the donor star or from the intense stellar wind produced by the bright companion star, which dominates the luminosity emitted by the system ($L_{\text{opt}}/L_X > 1$). On the other hand, the companion of LMXBs are typically stars with spectral type G-K-M and have a similar mass as the Sun or lower ($M_{\text{donor}} \lesssim 1\ M_\odot$). They are located (on average) at different Galactic latitudes than the HMXBs and their evolution is dictated by the transfer of material through the internal Lagrange point when the donor star overflows its Roche-Lobe ($\gtrsim 10^7$ years; see Fig. 1.1). Given the low luminosity of the companion star, the radiation generated in the accretion disc of LMXBs dominates the energy distribution ($L_{\text{opt}}/L_X < 0.001$). They are systems with a relative short orbital period (with a $P_{\text{orb}}$ of hours to a few days) although there are several systems with $P_{\text{orb}} \lesssim 80$ minutes that form a subclass of LMXBs, the ultra compact X-ray binaries (UCXBs). These are thought to harbour an hydrogen-poor, white dwarf companion.
star (Nelson et al. 1986).

Companion stars with intermediate masses ($M_{\text{donor}} \sim 1 - 10 M_\odot$) are rarely observed, probably as a result of a selection effect. In these intermediate-mass X-ray binaries the efficiency of wind accretion is very low since the companions are not massive enough to have strong stellar winds, resulting in low X-ray luminosities that are difficult to detect. On the other hand, if the accretion occurs through Roche-lobe overflow, the large mass ratio (mass ratio is defined as $q = M_2 / M_1$, where $M_2$ is the mass of the donor star and $M_1$ is the mass of the compact object) between the binary components causes the system to evolve on very short time-scales ($\sim 10^3$yr) making the chance to detect them very low (van den Heuvel 1975).

### 1.1.1 The compact object: Neutron Star or Black Hole

The X-ray binaries studied in this thesis have either a NS or a BH as compact object. The canonical NS has a mass $M \sim 1.4 M_\odot$ and a radius $R \sim 10$ km, while BHs have a mass $M > 3 M_\odot$ that are compressed to a size which is smaller than their Schwarzschild radius\(^1\). Therefore, in contrast to NSs that have a solid surface, a defining feature of a BH is its event horizon, the radius of which depends on both its mass and spin (in case the BH is rotating).

**Compact primary identification**

Determining the nature of the accretor is not trivial. NSs have radii of only a few times their Schwarzschild radius. Therefore the accretion flow in X-ray binaries with a NS or with a BH accretor is very similar, such as their fast X-ray variability, their very soft X-ray spectra and the presence of a high-energy power-law tail. However, there are some observational phenomena that can constrain the nature of the compact object.

The best way to infer the nature of the compact object is measuring its mass, or at least determining its mass function (see e.g., the review by Casares 2006). The latter follows from the combination of the second and third Kepler laws, and it provides a lower limit on the mass of the compact primary. Systems with a $M_1 > 3 M_\odot$, which exceeds the maximum stable mass of a NS in general relativity (Rhoades & Ruffini 1974; Kalogera & Baym 1996), are assumed to have a BH as a compact object.

On the other hand, NSs are revealed by the occurrence of events that need a solid surface or a magnetic field (or both) to be produced. **Thermonuclear X-ray**

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\(^1\) The Schwarzschild radius ($R_s$) is the radius of a not rotating sphere such that, if all the mass of an object is compressed within that sphere, the escape velocity from the surface of the sphere would equal the velocity of light. $R_s$ is expressed as $R_s = \frac{2GM}{c^2}$, where $G$ is the gravitational constant, $M$ the mass of the object and $c$ the velocity of light in vacuum.
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bursts are a distinctive feature of NSs. The material accreted is accumulated on to the surface of the NS and then further compressed when new material falls on to the surface, making the density and temperature high enough to produce thermonuclear burning of hydrogen and/or helium. Under some circumstances this burning process is unstable and causes an entire surface layer to ignite, resulting in a brief and intense flash of X-ray emission that can temporarily outshine the X-ray binary’s accretion luminosity (Fujimoto et al. 1981; Galloway et al. 2008).

Equally, the detection of coherent pulsations with periodicities from a few milliseconds to up to several hours indicates a NS compact primary as well. When the magnetic field of the NS is strong enough, the accreted material follows the magnetic field lines and will impact on the surface at the magnetic poles of the NS. This produces a hot-spot at the magnetic poles with temperatures of \( \sim 10^7 \) K, which produce modulations in the detected X-rays that track the spin frequency of the NS.

The accretor in sources where the radial velocities of the secondary cannot be measured (e.g., because the secondary is too faint or the optical spectrum of the binary is dominated by the disc emission even in quiescence) and have shown neither burst nor pulsations can still be preliminary classified by studying their patterns of the correlated spectral and timing behaviour (see, e.g., Lewin et al. 1995). However this classification is not definitive, as it has been found that systems initially classified as strong BH candidates turned out to be NS systems because they suddenly displayed thermonuclear bursts.

1.2 Persistent versus transient X-ray binaries

According to their long-term behaviour, LMXBs can be divided in two subgroups. The persistent systems are those which always display similar luminosities (their luminosities are roughly constant within a factor of 10 or less). In these systems the disc is hot enough to be fully ionized (i.e. \( T > 6500 \) K assuming an 100% hydrogen disc), and it remains in a stable (hot) equilibrium.

On the other hand, transient X-ray binaries have most of the time cold discs that emit at very low X-ray luminosities. They spend most of their life in a dim, quiescent state. However, sporadically they undergo bright X-ray outbursts as a result of a sudden increase in the accretion rate on to the accretor. The X-ray brightening is triggered by a thermal-viscous instability in the disc thought to occur when, due to the accumulation of matter, the opacity experience an abrupt increase, yielding temperatures high enough for the hydrogen to become (partially) ionized.

Therefore, the temperature of the disc is going to govern the persistent-transient dichotomy, and therefore, the associated \( \dot{M} \) (see Equation 1.4). King et al. (1996) determined an expression for the critical mass-transfer rate that discriminates between
persistent and outbursting systems taking in account both the effective temperature powered by local viscous dissipation and the effective temperature due to irradiation from the central X-ray source.

\[ \dot{M}_{\text{crit}} = \dot{M}_{\text{irr}} M_1^{2/3} P_3^{4/3} \] (1.1)

where \( \dot{M}_{\text{irr}} \sim 5 \times 10^{-11} \text{M}_\odot \text{yr}^{-1} \) and \( P_3 \) is the orbital period in units of 3 hours (King et al. 1996; Coriat et al. 2012). For a typical NS system \( \dot{M}_{\text{crit}} \sim 10^{-10} \text{M}_\odot \text{yr}^{-1} \), which is the reason why many NS sources are persistent, while \( \dot{M}_{\text{crit}} \sim 10^{-9} \text{M}_\odot \text{yr}^{-1} \) for a BH. The latter is in agreement with the fact that most of the BH X-ray binaries are transients. From the same relation, it is expected that systems with short orbital periods are probably persistent, as the \( \dot{M}_{\text{crit}} \) is smaller. Alternatively, the sources with long orbital periods tend to have transient behaviour (van Paradijs 1996; Coriat et al. 2012).

### 1.3 The disc and accretion rate regimes

If all the gravitational energy released is radiated at the moment that the infalling matter hits the surface of the compact object, of mass \( M \) and radius \( R_\star \), then the accretion luminosity is

\[ L_{\text{acc}} = \frac{G M \dot{M}}{R_\star} \] (1.2)

where \( G \) is the gravitational constant and \( \dot{M} \) is the mass-accretion rate (Frank et al. 2002). The rate at which the energy is released by the accretion process depends, for a fixed compactness \( (M/R_\star) \) of the accreting object, on the rate at which the matter is accreted \( (\dot{M}) \). The balance between the force of radiation generated in the accretion acting outward and the gravitational force acting inward marks a limit for the \( L_{\text{acc}} \), which is designated as the Eddington Luminosity or Eddington limit \( (L_{\text{Edd}}) \). For a steady, spherically symmetrical accretion flow, \( L_{\text{Edd}} \) can be expressed as:

\[ L_{\text{Edd}} \approx 2.5 \times 10^{38} \left( \frac{M}{M_\odot} \right) (1 + X)^{-1} \text{erg s}^{-1} \] (1.3)

where \( X \) is the hydrogen fraction. At greater luminosities the radiation pressure acting outward prevails over the inward gravitational attraction and accretion would be interrupted. Therefore, the maximum luminosity for a system which harbors a NS \( (M = 1.4 \text{M}_\odot \text{ and } R=10 \text{ km}) \) would be \( \sim 10^{38} \text{erg s}^{-1} \), whereas for a system with a BH \( (M = 10 \text{M}_\odot \text{ and } R=34 \text{ km}) \) it could exceed \( 10^{39} \text{erg s}^{-1} \).
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Figure 1.2: The three main components of the X-ray emission from an accreting compact object (top) and a plausible geometry of the accretion flow in the hard spectral state (bottom) (from Gilfanov 2010).

1.3.1 X-ray spectra

In the X-ray spectrum of active LMXBs (i.e. persistent / transient in outburst), soft and hard spectral components can be identified (see Fig. 1.2). The soft component is believed to be produced by a geometrically thin, optically thick accretion disc (Shakura & Sunyaev 1973), whose emission can be modelled by a superposition of modified blackbody spectra originated at different annuli of the disc. The disc temperature at a given radius can be expressed as:

$$T_{\text{eff}}^4 = \frac{3GM\dot{M}}{8\pi\sigma R^3} \quad (1.4)$$

therefore, the closer the disc is to the compact object the higher is the disc temperature. The overall, emerging radiation peaks in the soft X-ray band.

The hard spectral component is explained by the inverse Compton scattering pro-
1.3 The disc and accretion rate regimes

Soft photons coming from the disc and/or the NS surface (if the accretor is a NS) are up-scattered by a hot cloud of electrons (hot, optically thin plasma) in the vicinity of the compact object; the density and temperature of this cloud regulate the efficiency of the energy dissipation. There is not a consensus for the geometry and properties of this "corona" of electrons and a wide range of coronal models have been proposed (e.g., Galeev et al. 1979; Poutanen et al. 1997).

One of the difficulties in modelling the corona is its complicated connection with the disc, which in turn has a debated shape as well. Perhaps, the most widely accepted accretion disc model predicts that its inner radius changes with the accretion rate. The disc is believed to reach the innermost stable orbit (ISCO\(^2\)) at high accretion rates, whereas when the accretion rate drops the disc is truncated far from the compact object and its inner region is filled with a hot, advection-dominated accretion flow (ADAF; Narayan & Yi 1994; Narayan et al. 1997). In an ADAF, most of the energy released via viscous dissipation is advected with the flow instead of radiated away (as in the thin disc), resulting in low radiative efficiencies. In BH systems, this 'stored' energy can even be advected beyond the event horizon before it is emitted. In NS systems, this energy will eventually be released when the matter hits the NS surface.

Part of the radiation emitted by the corona illuminates the accretion disc. This X-ray irradiation is reprocessed and reflected by the thin disc producing a reflection spectral component with several spectral features. The most distinctive feature is the excess emission at 6-7 keV, the so-called iron K\(\alpha\) line, which broadness should be affected by relativistic effects (Fabian et al. 1989) and, e.g., can in principle provide insights on the inner boundaries of the accretion flow (e.g., to measure BH spin; Bardeen et al. 1972).

1.3.2 Spectral states and geometry

Different X-ray states can be distinguished depending on the geometry and the properties of the accretion flow at a given moment (see Fig. 1.3).

During the soft state the X-ray spectrum is dominated by a thermal profile below 10 keV, and a weak, steep power-law component that extends to over 100 keV (see Fig. 1.4). The thermal component is produced by the thin accretion disc that extends close to the compact object with a peak of temperature in the range of 0.7-1.5 keV. This component typically contributes \(\sim 75\%\) to the total flux. The steep power-law (with a typical photon index \(\Gamma > 2\)) is attributed to the gain of energy of the soft photons emitted from the disc via inverse Compton scattering by the ultra-relativistic electrons that form the corona. The power density spectra (PDS) show

\(^2\)In a Schwarzschild geometry the ISCO lies at \(R_{ISCO} = 6R_g\) and at \(R_{ISCO} = R_g\) for an extreme Kerr BH. \(R_g\) is defined as \(R_g = \frac{GM}{c^2}\).
very weak variability at this state and generally there is no detection of any type of quasi-periodic oscillations (QPOs).

Spectral and temporal properties are quite different during the **hard state**. The energy spectrum can be modelled by a power-law function with a photon index of 1.4-2.1. The power law origin is also inverse Compton scattering, but with an unsaturated thermal Comptonization (hotter corona), the transfer of energy in each collision being higher, and therefore producing a harder power-law (see Fig. 1.4). In some cases, there is a soft X-ray excess that can be modelled using a thermal component with low temperatures in the range $\sim 0.1 - 0.2$ keV. If this component originates from a truncated disc, its contribution to the total radiation would depend on the disc truncation radius, increasing as the disc moves inwards. However, alternative geometries which include an untruncated disc are also used to explain this soft component (e.g., Miller et al. 2006b). If the compact object is a NS, another possible origin for the soft component is thermal emission produced by low-level accretion onto the NS surface (Zampieri et al. 1995). In the hard state, there is strong variability in the X-ray flux with often strong QPOs as well.

In the **quiescent** state, in which X-ray transients spend most of their lives, the X-ray luminosity is very low ($L_X = 10^{30} - 10^{33} \text{erg s}^{-1}$) and the disc is truncated at very large inner radius and an ADAF is thought to dominate. The existence of a solid surface in the NS systems, which is absent in the BH binaries, would cause differences in the quiescence spectrum. While a single power-law with a photon index of $\Gamma \sim 2$ describes the BH spectra, the NS spectra can be described by a soft thermal component with temperatures 0.1-0.2 keV, a power-law that dominates above 2 keV, or a combination of both. The soft component is interpreted as thermal surface radiation from the cooling NS which has been heated by the accretion of matter during outburst, although it cannot be ruled out that it is due to low-level accretion onto the NS surface (Zampieri et al. 1995). The origin of the hard component still remains
1.4 Very faint X-ray binaries

The improvement both in sensitivity and resolution of the new generations of X-ray instruments have provided new insights in accretion phenomena. In particular, the improved sensitivity at low luminosities unveiled the existence of a subgroup of X-ray binaries that manifest themselves with a few orders of magnitude lower accretion luminosities than the hitherto known systems. Thereby, X-ray binaries can be also classified based on their observed 2-10 keV maximum luminosities (Wijnands et al. 2006). The (very-) bright X-ray binaries reach luminosities of $L_X \sim 10^{37-39}$ erg s$^{-1}$, and those with maximum luminosities of $L_X \sim 10^{36-37}$ erg s$^{-1}$ are the faint systems. Intensive studies of the large amount of available data have along the years yielded a good understanding of their behaviour along the years. The population of very faint X-ray binaries (VFXBs), that up to date is comprised of a few tens of systems, displays maximum luminosities of only $L_X \sim 10^{34-36}$ erg s$^{-1}$ (see Fig. 1.5). The detection of X-ray thermonuclear bursts in several sources, either in transient or persistent configuration, identify the accretor as a NS (Cornelisse et al. 2002; Del Santo

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**Figure 1.4:** Energy spectra of a black hole (Cyg X-1 left) and a neutron star (4U 1705-44 right) in the soft and hard spectral states (Gilfanov et al. 2000; Gilfanov 2010).

elusive.

The above X-ray states are known as the "canonical" states. However, more sophisticated states, including also information at other wavelengths, have been identified (see, e.g., reviews by Nowak 1995; McClintock & Remillard 2006; van der Klis 2006b; Fender 2006; Belloni et al. 2011).

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Figure 1.5: On the top: artist impression of bright (left) and very faint (right) transients LMXB in outburst. On the bottom: superposition of the lightcurve of a bright (black) and very faint (red) X-ray transient.

et al. 2007b; Degenaar et al. 2010). So far, in only one of such systems the BH nature of the accretor has been conclusively been identified (Chapter 5, Corral-Santana et al. 2013).

Their low X-ray luminosities imply that the mass accretion rates of the VFXTs are a factor of 10-100 less than the mean rates of the brighter systems. Hence, these very faint sources are ideal to study the relatively unexplored low-accretion rate regimes and therefore provide valuable inputs in several accretion-related phenomena, such as accretion physics (e.g., Chapter 3 and Chapter 5), binary evolution models (e.g., King & Wijnands 2006; Degenaar & Wijnands 2009; Maccarone & Patruno 2013) and the theory of nuclear burning on the surface of accreting NSs (e.g., Cooper & Narayan 2007; Peng et al. 2007; Degenaar & Wijnands 2010).

The physics behind the existence of these sources and why they exhibit such faint accretion luminosities remain unclear. Their characteristics (e.g., their spectra, their outburst light curves, timing properties; e.g., Sakano et al. 2005; Muno et al. 2005; Degenaar & Wijnands 2009 and Chapter 3) indicate that they are not a homogeneous class of sources but that different types of accreting NSs and BHs show themselves as VFXBs and a variety of models are needed to explain all systems. It has been proposed that persistent VFXBs could be UCXBs (King 2000). However, although a
very short orbital period could explain the low luminosity for some sources, it cannot explain all systems (Degenaar & Wijnands 2010). A short orbital period scenario is also proposed by Maccarone & Patruno (2013) to justify the low luminosity of the transient VFXBs, but the existence of several bright X-ray binaries with similar orbital periods implies that the cause of their sub-luminous nature needs additional arguments (Maeda et al. 1996; Degenaar et al. 2010).

VFXBs challenge in several ways the current theoretical models for binary evolution. Those models have, in particular, difficulties to explain the existence of those VFXBs which have very low mass-transfer rates. Exotic evolutionary scenarios (e.g., NSs or BHs accreting from brown dwarf or planetary companions) might be required to explain them (e.g., King & Wijnands 2006; Degenaar & Wijnands 2009; Maccarone & Patruno 2013). Several of the thermonuclear bursts displayed by several VFXBs have unusual properties, giving new insights in to the theory of nuclear burning on the surface of accreting NSs (e.g., Cornelisse et al. 2002; Peng et al. 2007; Cooper & Narayan 2007; Degenaar et al. 2010).

1.5 X-ray observatories

A number of X-ray observatories have been used in this thesis. Their main characteristics are described below.

1.5.1 Swift

The multi-wavelength observatory on board of the Swift satellite (see Fig. 1.6) was designed to study gamma-ray bursts (GRBs; Gehrels et al. 2004). However, during ~ 9 years of existence since its launch in 2004, the science fields covered by Swift go far beyond its initial mission goals. For example, it has been used to study active galaxies, supernovae, accreting white dwarfs, and even comets. But a special mention is deserved, in particular for this thesis, to its contribution to the study of X-ray binaries. The Burst Alert Telescope (BAT; Barthelmy et al. 2005), designed to cover a large fraction of the sky in the 15-150 keV energy range in order to detect and locate new GRBs events, has detected many X-ray bursts; most originated from known X-ray binaries, but some also from several unknown systems. With these detections, several VFXB systems were discovered (e.g., Palmer et al. 2005; Krimm et al. 2011a).

The X-ray telescope (XRT; Burrows et al. 2005) is a focusing X-ray telescope with a 110 cm² effective area, 23.6 x 23.6 arcmin FOV, 18 arcsec resolution (half-power diameter), and 0.2-10 keV energy range. The XRT has 2 commonly used operating modes, depending on the flux of the astronomical target. As the emission fades or rises, the XRT will automatically change from one mode to the other when a certain threshold count rate is reached. This automatic mode-changing allows the
XRT to observe over a large range of more than 7 orders of magnitude in flux. The photon counting (PC) mode is operated at low fluxes ($<2.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). In this mode a 2 dimensional image is obtained, which provides position with an angular resolution of $\sim$2 arcseconds radius, and spectral information for any source in the field of view with a 2.5 sec timing resolution. At higher fluxes the XRT is operated in windowed timing mode (WT), which is very useful to observe bright sources because it reduces the pile-up problems that those sources have when are observed in PC mode. The one dimensional image using the 200 central column window (which covers the central 8 arcminutes of the field of view), does not provide positional information, but it provides a time resolution of 1.8 msec.

The UltraViolet/Optical telescope (UVOT; Roming et al. 2005) provides simultaneous data in the range of 170-650 nm over a 17 $\times$ 17 arcmin field using a variety of optical and UV filters.

If there is a characteristic that distinguished Swift from the other X-ray missions, is its rapid ToO response and scheduling flexibility, which makes it possible to undertake frequent monitoring observations of our targets (e.g., soon after a new source is discovered).

1.5.2 XMM-Newton

The European X-ray Multi-Mirror Mission telescope (see Fig. 1.6), called XMM-Newton in honour of Sir Isaac Newton, was launched in 1999 for an original lifetime of two years. Today, after more than 13 years of life, XMM-Newton is still providing data from its three on board X-ray telescopes.

**Figure 1.6:** On the left: Swift satellite with its three instruments: BAT, XRT and UVOT. On the right: schematic illustration of the XMM-Newton observatory (relative sizes not to scale).
The European Photon Imaging Camera (EPIC) consists in two MOS CCD camera’s (Metal Oxide Semi-conductor Turner et al. 2001) and one pn CCD camera (Strüder et al. 2001), each one located at the focus of one of the three X-ray telescopes. The three cameras can operate independent from each other in different configurations. They offer the possibility to perform extremely sensitive imaging observations over the telescope’s field of view (FOV) of 30 arcmin, covering the energy range 0.15-15 keV with moderate spectral (E/ΔE~20-50) and angular resolution (6 arcsec FWHM). The PN and MOS type camera can be operated in a variety of modes depending on the brightness of the target and the goals of the observations.

The two Reflections Grating Spectrometers (RGS; den Herder et al. 2001) share the focus with the MOS cameras of two of the three telescopes, and therefore they receive about half of the X-ray light. Each RGS consists of an array of reflection gratings which diffracts the X-rays to an array of dedicated CCD detectors. The RGS instruments allow high spectral resolution (E/ΔE=100 to 500) measurements in the soft X-ray range (6 to 38 Å or 2.1 to 0.3 keV). The energy range covered by the RGS has a particularly high density of X-ray lines, offering a large number of diagnostic tools to investigate the physical conditions and chemical composition of the emitting material.

On board XMM-Newton is also the Optical/UV Monitor Telescope (OM), which allows multiwavelength observations of the targets, simultaneously in the X-ray and ultraviolet/optical bands (between 170 nm and 650 nm) of the central 17 arc minute square region of the X-ray field of view.

1.5.3 Chandra

The Chandra X-ray Observatory (see Fig. 1.7), named in memory of the Nobel-prize winner Subrahmanyan Chandrasekhar, was launched in 1999 and still is operative, despite its planned life was only 5 years. The two main science instruments on board Chandra are the High Resolution Camera (HRC; Kenter et al. 2000) and the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). Both detectors cover a similar energy range (0.1-10 keV). The ACIS, with a energy resolution of 130 eV (at 1.49 keV) and field imaging FOV of 16.9×16.9 arcmin, is used for imaging and to obtain broad-band X-ray spectra of our targets. The HRC provides the largest field of view (30 x 30 arcmin) with the highest spatial resolution, ideal for imaging observations when the highest possible spatial resolution is needed. Chandra is currently the only X-ray telescope that can provide sub-arcsecond resolution.
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Figure 1.7: Artistic impression of Chandra and RXTE observatories (relative sizes not to scale).

1.5.4 RXTE

The Rossi X-ray Timing Explorer (RXTE; Bradt et al. 1993, see Fig. 1.7), named in honour of Bruno Rossi, was launched in 1995 and it was active during 16 years, significantly longer than the 2-5 years planned lifetime. On board RXTE there were three scientific instruments. The proportional counter array (PCA; Jahoda et al. 1993, 2006), the high energy X-ray timing experiment (HEXTE; Rothschild et al. 1998) and the all-sky monitor (ASM; Levine et al. 1996). Between the three detectors, X-ray variability of X-ray sources could be studied on timescales ranging from microseconds to years.