CHAPTER 3

X-RAY BINARY SYSTEMS AND SOFT X-RAY TRANSIENTS

Black Hole Sun, won't you come
To wash away the rain?
(Soundgarden 1994)

3.1. NEUTRON STARS

The observations made with artificial satellites carying instruments sensitive to X-ray emission have revealed the presence, in our galaxy as well as in other nearby ones, of a considerable quantity of objects that are intense sources of this type of radiation; in addition, most of them are binary systems in which it is assumed that mass transfer occurs onto a collapsed star, and it is through the gravitational energy released during accretion that one can account for the existence of such an energetic emission.

But before we enter into this topic, it is however useful to rapidly review which objects can convert into high-frequency radiation the energy extracted from accretion.

In the previous chapter we saw what WDs are and what is their genesis. In the cases in which the mass of the stellar core is instead sufficient to trigger carbon burning and, after this, the burning of heavy elements also, the star will not have a WD as its final stage of evolution, but rather a far more compact object: a **neutron star** (**NS**).

Depending on the mass of the star core, an object of this type can be formed with three different processes (van den Heuvel 1983): all of them, however, will produce a NS through the explosion of the star as a supernova.

Supernova events able to create NSs may also occur in WDs within close systems when, through accretion processes, they exceed the Chandrasekhar mass limit: only under particular conditions, however, the WD implodes creating a NS (Canal et al. 1980; Sugimoto & Nomoto 1980; Iben et al. 1987); in the majority of cases, it explodes without leaving any residual object since thermonuclear burning takes place in a highly degenerate environment.

NSs are therefore objects in which the electron degeneration pressure is not sufficient to halt the collapse, because the energy balance has forced the atomic nuclei to capture these particles, making the stellar core composed almost entirely of neutrons. These, becoming degenerate as well, eventually produce a stronger and alternative degeneration pressure able to sustain the collapse of the internal parts of the star and to ensure that the external ones are expelled by the shock wave that forms during this phenomenon.

These objects have a star-like mass contained in a radius of about ten kms, and therefore a compactness factor of $\sim 10^{27}$ g cm^{-1} and a density of the order of 10^{14} g cm^{-3}, comparable to that of atomic nuclei: this indicates that the neutrons in these stars are **nearly in physical contact**; the structure of the NS is therefore supported by baryonic interactions that, at this scale, become predominant over any other kind of force.

NSs may carry an extremely intense magnetic field ($\approx 10^{12}$ gauss at the star surface), which is formed, as in WDs, due to the fact that it remains "frozen" in stellar matter during the collapse, and precisely with the **oblique magnetic rotator** model one can explain their emission: the field, coupled to the surface, rotates around the spin axis of the star and behaves like an oscillating magnetic dipole able to accelerate along the magnetic axis charged plasma particles distributed around the star by extracting kinetic rotational energy from the star itself. If the observer is located along the magnetic axis s/he receives, because of the spin, the typical pulsed emission which is often associated with these objects; because of this, whn this effect is apparent, these sources are also called **pulsars**.

If such an object is part of a binary system and accretes matter, in analogy with the previous chapter, we obtain an accretion energy per mass unit of the order of

$$\frac{\Delta E_{\rm acc}}{m} = G\frac{M_{\rm NS}}{R_{\rm NS}} \sim 10^{20}\,{\rm erg\,g^{-1}}, \tag{3.1}$$

that is, two orders of magnitude larger than that obtainable from hydrogen nuclear fusion. This shows that, in these systems it is not difficult to obtain high luminosities associated also with a large X-ray emission, even if the accretion is not extreme: indeed, with reference to Eq. (1.23) also in this case, the characteristic temperature T_* will be of the order of 10^7 K and the average emission will fall in the medium-energy X-ray spectral range ($kT_* \approx 5$ keV).

Even around these stars accretion via gravitational instability may produce a disk; it, however, is often not present in the inner parts since, because of the strong $\vec{B}$ field, the Alfvèn radius remains outside the stellar surface and also in a position which is generally closer to the star with respect to $R_{\rm circ}$; in this way the aqccreted matter, after having formed a disk and having reached the radius $R_{\rm A}$, is channeled towards the magnetic poles, thereby creating a 'hybrid' between an accretion disk and accretion columns. From these, similarly to the case of polars, most of the radiation will be emitted: this will allow an observer who lies along the line of sight of one of the columns to receive pulsed X-ray emission (**X-ray pulsar**; see e.g. Frank et al. 1992) because of the geometric reason explained above concerning the emission from an isolated NS.

When an NS accreting from inner Lagrangian point has instead a relatively weak $\vec{B}$ field unable to modify the disk shape, a contact zone of contact, called **boundary layer**, will form between the disk and the neutron star surface. In it, He and H thermonuclear reactions can take place, which may give rise to periodic instabilities in the burning material: this produces an **X-ray burst**, that is, a sudden increase by a factor of up to 10 of the X-ray emission from the system, followed by a slower decay. The duration of these phenomena is of the order of minutes, and they occur with intervals from hours up to days. For a complete treatment of these events we refer the reader to Lewin et al. (1995).

Thus, in summary, **the pulsed X-ray emission or the presence of X-bursts in a binary system definitely indicate the presence of an accreting NS**, in which the accreted matter is originated by gravitational instability of the secondary.

It is remarked that ccretion from stellar is also very important for systems hosting a NS given that, to obtain luminosities of 10^{37} erg s^{-1}, it is sufficient a mass accretion rate of 10^{-9} - 10^{-10} $M_{\odot}$ yr^{-1} (thus comparable with the mass loss via stellar wind of an early-type Main Sequence star); moreover, as we will see, with this mechanism it is possible to interpret the X-ray emission of several high-mass X-ray binaries, in which a NS captures the wind emitted by an OB-type Main Sequence star. In this case however, as mentioned at the end of Chap. 1, a disk will hardly be formed: most likely one will have spherical accretion, eventually channeled towards the NS magnetic poles. Of course, this is possible if the binary system remains bound after the supernova explosion that generates the collapsed object: indeed, according to Verbunt & van den Heuvel (1995), the system survives the supernova phase only if the amount of matter ejected in the explosion is less than half of the initial mass of the system.

3.2. BLACK HOLES

We have seen that WDs have a mass limit above which the electron degeneration pressure within the stellar core is no longer able to halt the collapse and to maintain the object in a condition of stable equilibrium. A similar limitation also exists for NSs, although the value of this mass is not known precisely due to the fact that the shape of the potential of the strong nuclear force is known but with a rather large error margin. One can however give estimates for it: because of evolutionary reasons (Joss & Rappaport 1984), it is considered unlikely that a NS exceeds 1.4 - 1.6 $M_{\odot}$, and that it cannot have a mass larger than the so-called **Ruffini limit** (Rhodes & Ruffini 1974), which is equal to 3.2 $M_{\odot}$; if however particularly “soft” potentials are considered, such a value can shift up to ~5 $M_{\odot}$ (Shapiro & Teukolsky 1983). Nevertheless, according to Kalogera & Baym (1996), it seems that a resonable mass upper limit for the NS structure stability is 2.9 $M_{\odot}$.

Therefore, if the mass of the stellar core exceeds this value, its collapse cannot be stopped by the degeneration pressure of neutrons; rather, it continues indefinitely until reducing what remains of the star to the limit of a geometric point of null radius and infinite density.

However, an external observer will never be able to see this peculiar state of matter, because eventually a situation will be reached in which the gravitational energy of the object will be so strong that it will prevent the light (and therefore any type of electromagnetic wave) to escape from it: a **black hole** (**BH**) is thus formed. The only way for this object to communicate its existence to the rest of the universe is, as a matter of fact, its powerful gravitational field.

Let us now ask what is the radius which marks the boundary between the BH and the outer space: it can roughly be defined as the radius at which the kinetic energy of matter with speed equal to that of light equals its own gravitational energy; one then obtains

$$R_{\mathrm{S}} = \frac{2GM_{\mathrm{BH}}}{c^2} \cong 3\left(\frac{M_{\mathrm{BH}}}{M_{\odot}}\right) \text{ km}, \tag{3.2}$$

Which is called **Schwarzschild radius** (actually, this radius corresponds to a singular solution to the Einstein's General Relativity equations). This radius is a property of all bodies of nonzero mass and, as it has been said above, identifies a sphere having the BH as its center and which acts in practice as a separator with the outside Universe and through which the material can only enter: this sphere is called **event horizon**.

The energy obtained through accretion onto BH is comparable, assuming a same quantity of captured matter, to that generated by NSn, since the masses of these two types of objects are of the same order of magnitude and the average radius of a NS is comparable to R_S; a similar point can be made concerning the average spectral emission (see the previous Section) and for the compactness factor.

Rather, what makes the accretion onto a BH remarkably different with respect to other compact objects is the fact that there is no visible impact on a solid surface: indeed matter, once has reached and entered the event horizon, is no longer able to send radiation to the outside, and thus its possible impact on the central object will not be observable. This implies that the X-ray emission in these systems is mostly produced in the accretion disk; also, when the accreted gas reaches a distance around $3R_S$ from the BH, gravitational perturbations produced by the compact object do not allow stable orbit within the above distance and matter collapses almost in free fall towards the event horizon, reaching it in $\sim 10^{-4}$ s. Within this time lapse the matter cannot produce substantial hard X-ray emission, which thus is normally emitted by the inner part of the disk and in the impact with the central accreting object in case it has a solid surface (Frank et al. 1992).

Instead, in the case of spherical accretion, intense energy production is not expected since in this occurrence the falling time is shorter than gas radiative cooling time; thus matter cannot efficiently emit its energy content before reaching the Schwarzschild radius (Tananbaum & Tucker 1974). Therefore, for the calculation of the accretion luminosity in BHs it is preferably used, instead of Eq. (1.13), the following modification:

$$L_{\rm acc}^{\rm BH} = \eta \frac{GM_{\rm BH}}{R_{\rm S}} \dot{M} = 2\eta \frac{GM_{\rm BH}}{\frac{2GM_{\rm BH}}{c^2}} \dot{M} = \eta \dot{M} c^2, \tag{3.3}$$

In which η is the accretion efficiency parameter which takes into account of the problems outlined above and which indicates the efficiency with which the energy is extracted from the accreted matter; generally $\eta \sim 0.1$. Moreover, equating Eq. (3.3) with Eq. (1.13) one obtains that

$$\eta = \frac{GM_*}{R_* c^2}: \tag{3.4}$$

for NSs, the value of this coefficient may reach 0.15, indicating that not necessarily BHs are the most efficient "gravitational machines" of the Universe; for WDs, in general we have $\eta \sim 10^{-4}$.

The presence of magnetic fields in the disk can also produce strongly emitting zones due to the encounter between the magnetic field lines of force which in this way, by orbiting around the BH, produce variable emission; alternatively, they can create Alfvèn waves capable of generating quasiperiodic pulsation with timescales of the order of 0.1, or of accelerating electrons which eventually produce synchrotron emission (Tananbaum & Tucker 1974).

Observationally, one defines **BH candidate** (**BHC**) an object for which the **mass function**, that is the quantity

$$f(M_X) = \frac{M_X^3 sen^3 i}{(M_c + M_X)^2} = \frac{P_{orb} K_c^3}{2\pi G} \tag{3.5}$$

(in which i is the inclination of the orbital plane with respect to the plane normal to the line of sight, K_c is the orbital velocity of the secondary star with respect to the system centre of mass, and M_X and M_c are the masses of the compact object and of the secondary, respectively), is larger than 3 $M_\odot$. Eq. (3.5) indeed gives a firm lower limit to the mass of the collapsed star: therefore, if the mass function exceeds the Ruffini limit, we have a good probability to be dealing with an object which is far more compact and massive than a NS. In a less restrictive sense, we call BHC all objects for which, if M_c and i are independently known, the use of the mass function formula allows establishing that M_X is larger than the Ruffini limit.

Actually, it seems quite unlikely for a star (being it single or in a binary system) to evolve up to the BH stage (van den Heuvel 1983); on the other hand, the Galaxy contain about one thousand BHs, and up to now about a dozen of *bona fide* BHC were identified (Tanaka & Lewin 1995).

3.3. X-RAY BINARIES

It is therefore clear, from the considerations made up to now, that in order to have strong X-ray emission from star-like objects is necessary to rely on the accretion phenomenon onto an extremely compact object.

Furthermore, this object must necessarily accrete at the expense of another star because, to produce X-ray emission, accretion from the interstellar medium is definitely negligible due to the low density of the latter (10^2 atoms of H per cm^3 in the best hypothesis, against 10^9-10^{11} atoms of H per cm^3 ttypical of the envelope of a blue supergiant): it has indeed been evaluated (Frank et al. 1992) that the luminosity produced by a NS accreting from the interstellar medium is about 10^{31} erg s^{-1}.

Tananbaum & Tucker (1974) pointed out that X-ray binary systems have some fundamental common features:

1) 2÷10 keV band X-ray luminosity between 10^{35} and 10^{38} erg s^{-1};
2) evidence of accretion from the other star of the system;
3) X-ray spectrum indicating the presence of hot gas with temperature of several hundred thousands of degrees K;
4) rapid variations in the X-ray emission, sometimes of periodic type.

If the last three points in the above list may be justified with what illustrated up to now, the first one can be explained by the fact that the rate of accreted mass has a very precise upper limit because, if the luminosity produced by accretion exceeds a certain value, the radiation pressure acting on the falling matter will slow it down and eventually will push it away, until L returns below a limiting value, due to the reduction of $\dot{M}$ (see e.g. Frank et al. 1992). This value, called **Eddington luminosity limit**, in the case of continuous spherical accretion of matter composed of pure hydrogen is

$$L_{\rm Edd} = 1.25 \cdot 10^{38} \left(\frac{M_{\rm X}}{M_\odot} \right) \text{erg s}^{-1}; \tag{3.6}$$

in actual cases (non-spherical accretion, gas with chemical composition typical of stars), the critical value does not deviate much from the above one, which can therefore be considered an acceptable first approximation. Equating Eqs. (3.6) and (1.13), we can give an estimate of the maximum quantity that each of the three types of compact objects can accrete for unit of time: we obtain $\dot{M}_{\rm Edd}^{\rm WD} \sim 10^{-5}\ M_\odot$ yr^{-1} for WDs, and $\dot{M}_{\rm Edd}^{\rm NS} \sim 10^{-8}$ $M_\odot$ yr^{-1} for NSs and BHs.

We thus have a self-adjusting process, with which we can explain the typical luminosity values for these objects. Let us however now continue the review about X-ray binary systems, starting with their classification.

X-ray binary systems are divided into two main groups, depending on the mass of the secondary star: **massive X-ray binaries** (**MXRBs**) and **low-mass X-ray binaries** (**LMXBs**).

Systems composed of a massive star (with mass larger than 10 $M_\odot$) of early spectral type which loses mass to a NS by Roche lobe overflow or via stellar wind belong to the first group. These binaries are mainly found on the Galactic plane (Fig. 3.1a), and this strengthens the fact that the secondary stars hosted in them belong to Population I, that is, are relatively young (~ 10^8 years).

It is then possible to make a further division within MXRBs: one subclass is made of **standard** MXRBs, in which the massive star (~20 $M_\odot$) is out of (or is about to exit) the Main Sequence and loses mass via wind or Roche lobe overflow to a NS which circularly orbits the secondary with a period between 2 and 10 days and which persistently emits X-rays (in several cases eclipses of this emission are seen due to the orbital motion). With this form of accretion, often pulsed X-ray emission from the magnetic poles of the NS arises, while the main optical contribution comes from the mass-losing star, because in general there is no formation of a disk, given the kind of accretion and the strong $\vec{B}$ field of the NS. The optical light curve may thus show small double-humped periodic oscillations of about 0.1 magnitudes due to the ellipsoidal deformation of the secondary and tied to its orbital motion.

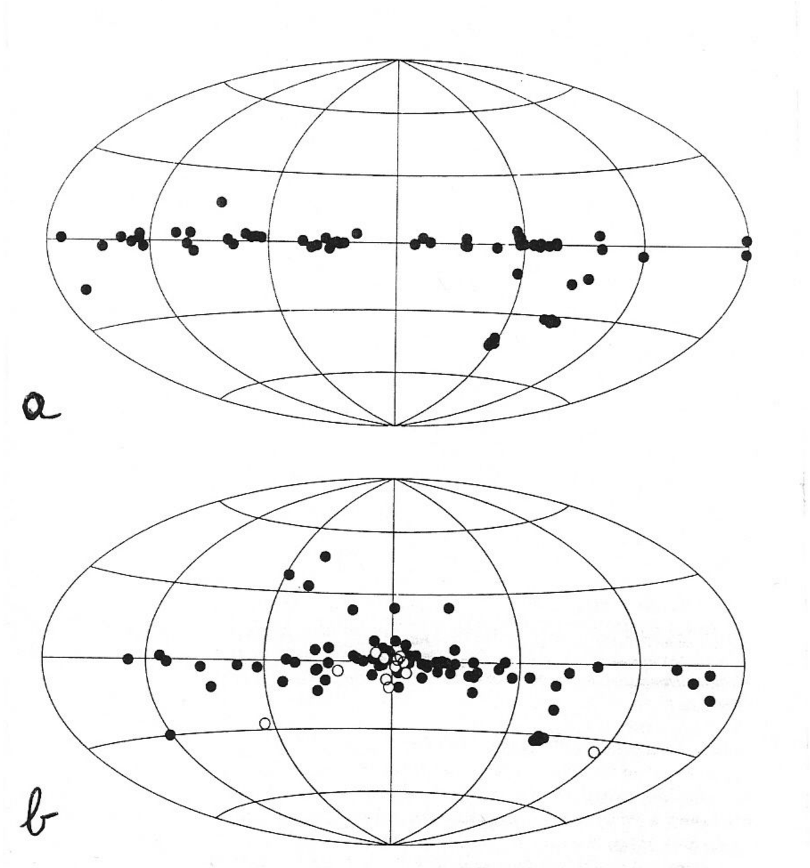

Fig. 3.1. Galactic distribution of **a** MXRBs and **b** LMXBs. The clusterings below the Galactic equator on the right of top panel correspond to MXRBs belonging to the Magellanic Clouds (from: van Paradijs 1995).

Besides standard MXRB, there exist **Be-X systems**, with mass-losing star of 10 - 20 $M_{\odot}$ which is still in the Main Sequence. This star loses matter via wind or expulsion along the equatorial plane (because of centrifugal effect due to the rapid rotation of the star) to a NS which, generally revolving along a substantially elliptical orbit in 20 days or more, accretes and emits X-rays not persistently but rather in a transient form, and which hardly undergoes eclipses. This is due to the fact that the neutron star accretes more matter when it is close to the periastron, thus producing transient hard X-ray emission.

It seems (Rappaport & van den Heuvel 1982) that this division between the two subclasses is due to the evolutionary path of the systems and that it depends on the mass of the NS progenitor.

A complete review on the optical properties of MXRBs can be found, for example, in van Paradijs & McClintock (1995).

The other main class, that of LMXBs, is composed of low-mass stars (less than 2 $M_{\odot}$) still on the Main Sequence or slightly evolved, which lose mass onto a compact object through gravitational instability; therefore, these systems host an accretion disk, which dominates their optical emission, while the X-ray emission from the accreting compact object is mostly "soft", i.e. mainly emitted at energies below 10 keV. These binaries (Fig. 3.1b) are mostly found towards the Galactic Center or in the halo, which indicates that they belong to Population II (old stars in the halo or the bulge) or to late Population I in the disk.

Again in this case we can identify two subgroups, which are based on the age and the position of the system in the galaxy: in the first one there are LMXBs **of young population** (below some billions of years of age and placed along the galactic disk), in which the compact object accretes from a star with similar or slightly larger mass, which gives a substantial contribution to the total optical emission of the system; the orbital period of these systems varies from several tenths of a day up to about 10 days. In them, eclipses are easily observed, both in X-rays and in the optical. The second subgroup contains instead **old population** LMXBs (that is, bulge-halo objects more than 5 billion years old), having an orbital period of a few hours and in which the mass of the companion star (of K or M spectral type) is much lower than that of the compact object: this makes its optical emission intrinsically very weak and negligible when compared to that of the accretion disk; eclipses are seldom observed because of selection effects related to the rather large physical thickness of the disk, and pulsed X-ray radiation is observable if the line of sight does not pass through the orbital plane of the system, since dissipative phenomena make the magnetic axis to almost coincide with the rotation axis as the system grows older.

A quite frequent and evident phenomenon, especially in systems of the first subgroup, is that of X-ray of the side of the secondary star facing the collapsed object: this modifies spectral type and brightness of that side, and causes a periodic sinusoidal modulation, connected with the orbital motion, of the optical light curve and color indices of the system; in the other subgroup, one can instead observe a modulation in the *R*, *I* and infrared bands similar to that observed in the optical light curves of MXRB and due to ellipsoidal deformation of the mass donor star.

A thorough review on the classification of MXRBs and LMXBs can be found in van den Heuvel (1983).

The average optical properties of LMXBs (in particular those belonging to the second sugroup), corrected for the interstellar absorption, are the following (van Paradijs 1983; van Paradijs & McClintock 1995): U-B = -0.93 ± 0.20, B-V = 0.01 ± 0.29, M_V = 1.2 ± 1.0, B-X = 21.5 ± 1.1 (where M_V is the absolute magnitude in the V band, whereas X indicates the "X-ray magnitude", that is, $X = -2.5 \cdot \mathrm{Log} F_\mathrm{X}$, in which F_X is the average X-ray flux in the 2÷11 keV band in terms of μJy[(1)]); this latter difference corresponds to a ratio $L_\mathrm{X}/L_\mathrm{opt} \sim 350$.

Moreover, according to van Paradijs & McClintock (1994), in the case of LMXBs the following relation holds:

$$\mathrm{M}_V = 1.57 - 2.27 \mathrm{Log}\Sigma, \tag{3.7}$$

in which

$$\Sigma = \left(\frac{P_\mathrm{orb}}{1\,\mathrm{hr}} \right)^{\frac{2}{3}} \cdot \left(\frac{L_\mathrm{X}}{L_\mathrm{Edd}} \right)^{\frac{1}{2}}. \tag{3.8}$$

(1) One Jansky (Jy) corresponds to 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}.

The presence of BHCs seems to be higher in LMXBs rather than in MXRBs (vd. Tanaka & Lewin 1995).

Even in LMXBs, similarly to what occurs in DNe, there may be cases of disk instability, although less frequently: this causes a sudden increase of the emission, which decays once the collapse of unstable matter ends and when the disk returns to the equilibrium state; when this happens, the system is called **X-ray nova** or **X-ray transient**. A very interesting group of transient LMXBs is that of soft X-ray transients. In the next Section we will review what they and their main features are.

3.4. SOFT X-RAY TRANSIENTS

Soft X-ray Transients (**SXTs**) are LMXBs (optical spectroscopic observations during quiescence indeed indicate the presence of features typical of a star of intermediate or late spectral type, usually still on the Main Sequence or slightly evolved; also see in Fig. 3.2 their Galactic distribution, typical of this class of X-ray binaries) belonging to a population of old stars, in which the X-ray emission is not persistent, but stays at the limit of detectability for up to tens of years; then it suddenly rises and gets very intense, as already anticipated. One can also note that the radiated energy is mostly emitted in the soft X-ray band (hence the name of these objects); this indicates that some phenomenon is keeping the hard X-ray emission to be released or produced in large quantities: it may be due to degradation that this radiation may encounter by interacting with the disk during outburst or, more probably, as mentioned above in Sect. 3.2, the lack of a solid surface in the collapsed object onto which an impact can be produced, or the absence of substantial hard emission from the internal parts of the disk (due to the impossibility of their formation or to the rapidity with which they fall onto the central object).

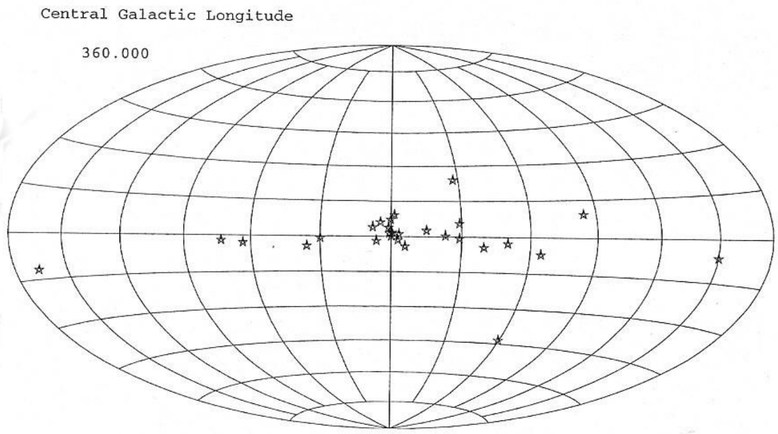

Fig. 3.2. Galactic distribution of SXTs. The SXT in the lower right corner of the figure belongs to the Small Magellanic Cloud.

One thus may think that SXTs are **systems hosting a BH**: actually, this is a bit jumping to conclusions; we should rather say that they *may* be, and that research on BHs hosted in LMXBs should be oriented toward this subclass, for reasons that will be described below. However, accurate spectrophotometric observations are needed to get precise estimates of the mass function of the collapsed star. But what are the characteristics of these objects? We now analyze their behavior during outburst and in quiescence, trying to grasp clues to understand the very nature of the accreting object.

3.4.1. The outburst phase

Going into further details in the SXT phenomenology, we can say that they have very interesting behaviors and characteristics that they on one hand share with Classical Novae, while on the other they greatly differ from that type of systems. For instance, during the outburst, their X-ray brightness hugely rises and, within a few days, these stars may get to be among the strongest X-ray sources in the sky (thay may indeed reach X-ray luminosities of 10^{38} - 10^{40} erg s^{-1}), having fluxes up to some tens of Crab[(2)]; they may reach or even overcome the Eddington limit for objects of 1 $M_{\odot}$ and may get to

(2) One Crab, in the 2÷11 keV band, corresponds to $2.25 \cdot 10^{-8}$ erg s^{-1} cm^{-2}.

have a L_X/L_{opt} ratio between 10^3 and 10^4 (that is, of the order of that of persistent LMXBs). In this they are very different from Classical Novae, which have substantially lower X-ray emission because of the different nature of the accreting object.

These transients are defined as "soft" because, as already mentioned, most of the produced X-rays is emitted as a black-body or thermal bremsstrahlung radiation from the inner parts of the disk, at relatively low energies (a few keV); in any case, a "tail" of hard X-rays, i.e. at higher energies, is nearly always present in the form of a power-law spectrum which extends up to the γ-ray band (Fig. 3.3a). This emission is produced by **Comptonization** (that is, a mixture of synchrotron and Inverse Compton) of relativistic particles in a corona around the disk which is formed during the outburst. In addition to emission from a spectral X-ray continuum, emission lines of highly ionized elements such as Fe, or the line of the e^--e^+ pair annihilation can be observed (Fig. 3.3b; vd. Tanaka & Lewin 1995). For further details on the various types of X-ray emission mechanisms of importance for X-ray binaries, the reader can review Appendix B of this thesis and references therein.

Besides the strong increase of X-ray luminosity, there is also a large increase in the optical one: this phenomenon is due to the heating produced by the X-rays themselves on the outer parts of the accretion disk. This optical jump (usually of the order of 7 - 8 magnitudes in the *V* band), along with other features of the outburst, led these binary systems to be also labeled as **X-ray Novae**. Moreover, the optical light curve closely follows the X-ray one, but with a "delay" of a few days: this is because, since the optical radiation is produced via the degradation of X-rays into less energetic photons by the outer layers the disk or by the side of the companion facing the compact object, and as the reaction of such bodies to the X-ray heating is not instantaneous, these regions need time to produce optical emission proportional to a given X-ray irradiation. This in summary explains the "mismatch" described above between the optical and the X-ray light curves.

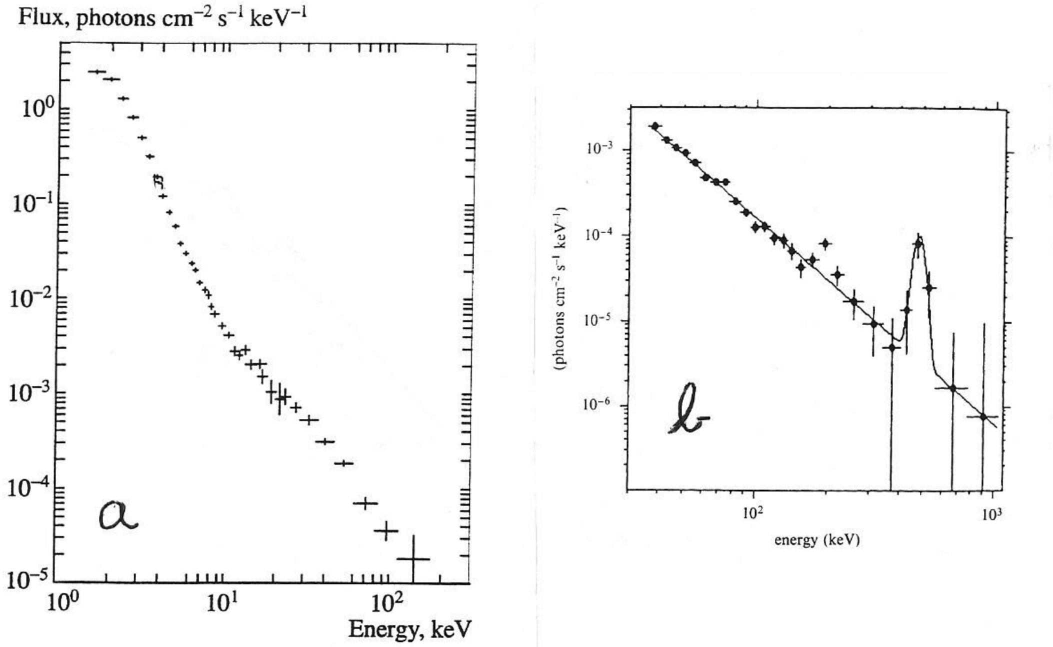

Fig. 3.3. a X-ray spectrum of a SXT during outburst (from: Sunyaev et al. 1994) and **b** e^--e^+ annihilation line in emission (from: Tanaka & Lewin 1995).

Concerning the optical spectra of these sources during maximum (Fig. 3.4a), one should notice that they are very similar to those of erupting CVs, and therefore they show the presence of strong emission lines of the Balmer series, He I, He II, N II as well as N III, often slpit into two components due to the kelperian motion of the disk, which in this phase dominates the system luminosity (at least 95% of the optical light is emitted from the disk during maximum). Thus, the only absorption lines detectable during this phase are those produced by the interstellar matter lying between the Earth and these objects: from the depth of these lines, and in particular from the equivalent width (EW) of the Na I doublet at 5890 Å, it is possible to estimate the amount of matter between us and the outbursting system and, from this, to determine the color excess of the object through the empirical relation (Barbon et al. 1990)

$$E(B-V) = 0.25 \cdot \mathrm{EW}_{\mathrm{NaD}} \; . \qquad (3.9)$$

Consequently, one can give an estimate of the distance to the transient.

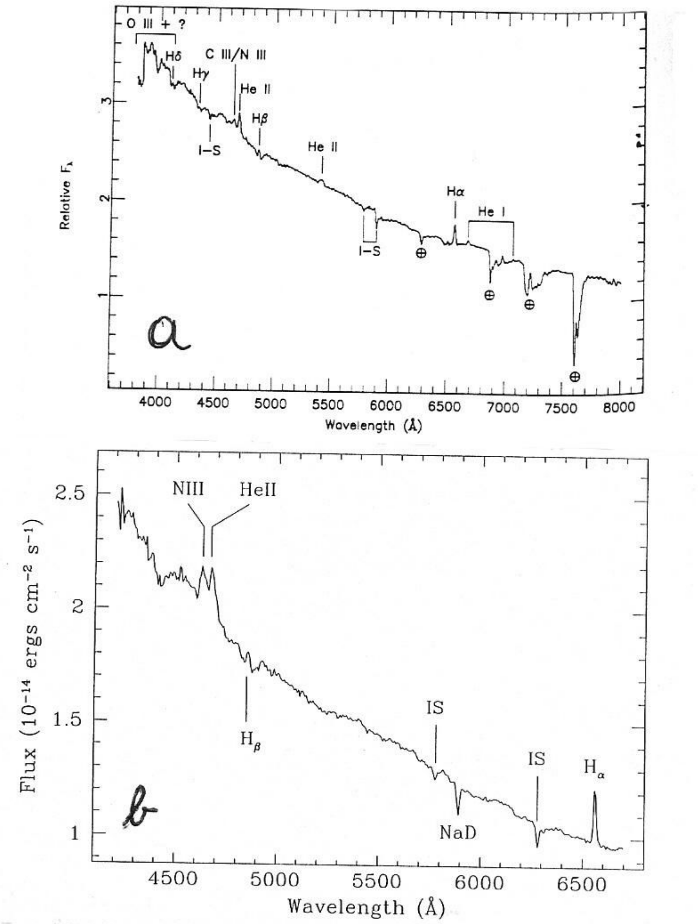

Fig. 3.4. a Optical spectrum of a SXT during outburst (from: Shrader et al. 1994) and **b** average of the decline phase optical spectra shown in Chaps. 5, 6 and 7 of this Thesis.

Several SXT, during maximum or in the first phases of the decay, also show strong transient radio emission lasting a few days and due to the interaction between electrons of the expanding coronal plasma (produced by the outburst and surrounding the collapsed object) and the magnetic field of the corona itself or of the disk (see Hjellming & Han 1995). In one case, that of GRO J1655-40 (see Chap. 6 of this thesis and references therein), radio jets similar to those of active galactic nuclei were observed, although on a much smaller scale, and associated with the X-ray activity of the object.

In the optical band, during maximum or at the beginning of the decay, the superhump phenomenon can develop (Fig. 3.5). It, as already explained in Chap. 2, consists of a sawtooth periodic modulation of the light curve, that is, with rapid rise and slower decay, and has a period that is slightly longer than the orbital one. At least 5 black-hole X-ray Novae (**BHXNe**) showed this behavior during the light maximum or in the early decline (O'Donoghue & Charles 1996, Masetti & Regös 1997; see also Chaps. 4 and 5); it however seems to have slightly different characteristics with respect to those of superhumps in 'classic' SU UMa-type DN (see Chap. 8 for further discussion).

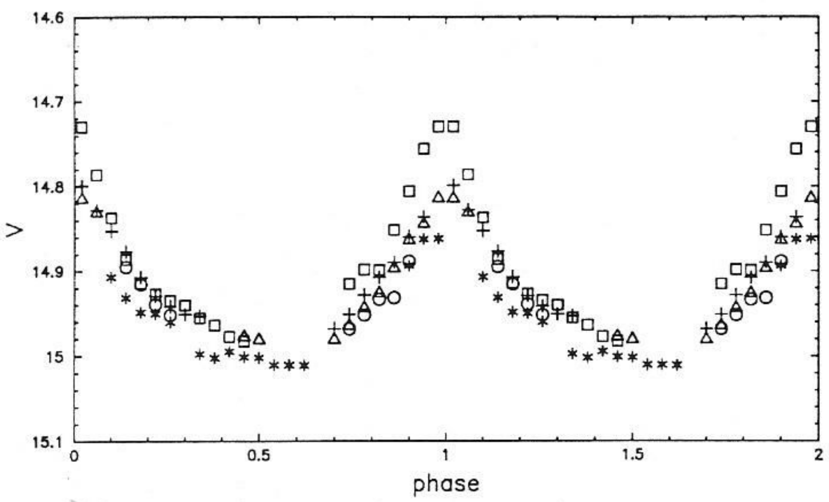

Fig. 3.5. Light curve of a superhump in a SXT (from: Bailyn 1992).

Then, after the maximum, the X-ray light curve (Fig. 3.6) decays very quickly, although often it can show a secondary maximum some tens of days after the main one, and sometimes also a tertiary one, which is visible just before the end of the X-ray activity (Tanaka & Lewin 1995).

This behavior appears to be due to a momentary increase in the mass transfer rate from the secondary in response to cotinuous X-ray irradiation (Augusteijn et al. 1993, Chen et al. 1993) or to the motion of the cooling front of the disk towards the inner part of the disk itself (Chen & Taam 1996). However, neither model is currently able to satisfactorily interpret the observations, and the observational data themselves are too fragmentary to allow one to choose between the two theories above.

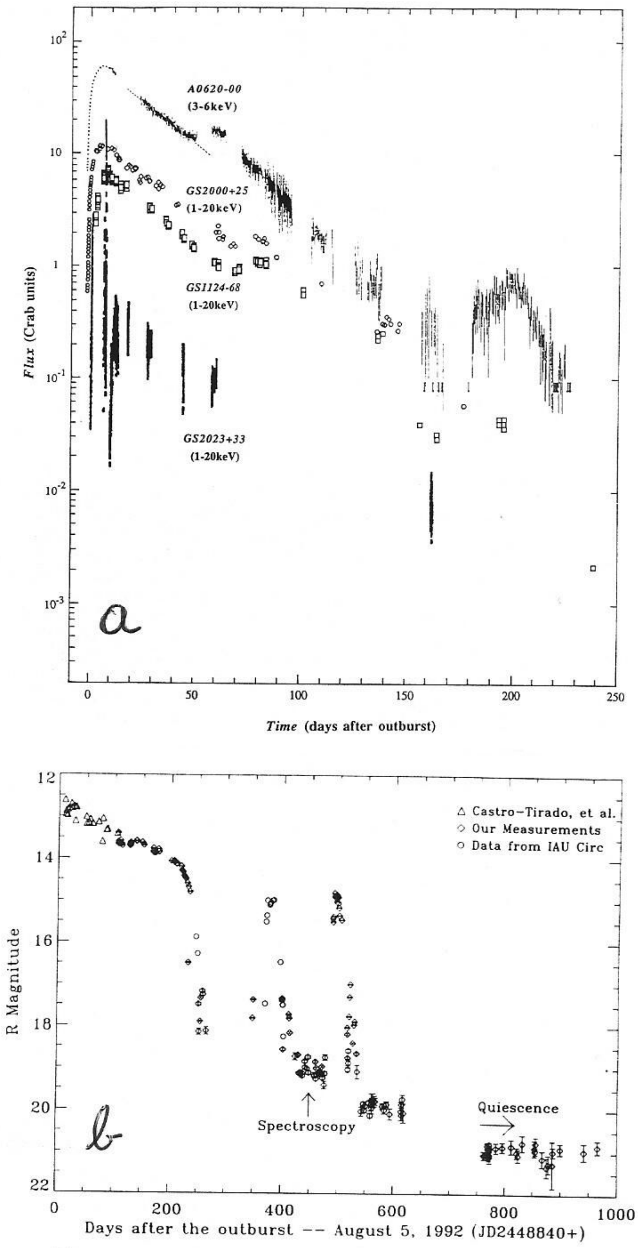

Fig. 3.6. a X-ray light curves of some SXTs (from: Tanaka & Lewin 1995). **b** Optical light curve of SXT V518 Per. One can note two minioutbursts in the late decline phase (from: Garcia et al. 1996).

As the decay progresses, the X-ray spectrum gets harder, that is, the soft component decreases its strength (which indicates that the erupting disk is cooling), while the hard emission does not undergo significant changes. In the optical, instead, the emission lines lose intensity and often one observes that the Balmer emissions are embedded in a corresponding wide absorption, produced by the cooler external parts of the disc itself (Fig. 3.4b).

After that, within a few months, the object returns to have an X-ray luminosity at the border of detectability (10^{31} - 10^{33} erg s^{-1}; see e.g. Verbunt et al. 1994 and also Chap. 8 of this Thesis).

On the other hand, the optical emission takes a much longer time lapse to reach the values which it had before the event, and this is reasonably due to the progressive but slower cooling of the X-ray heated parts of the binary system. In some cases (see Chaps. 5 and 8), sudden brightness increases (labeled as "minioutbursts") lasting about twenty days and of still unknown origin (Fig. 3.6b) were observed during the late decline, but only in the optical band.

Several X-ray novae (and possibly all of them, actually) are recurrent on timescales ranging from a few years to several decades, and have optical properties very similar to those of RNe, which leads again to invoke an accretion-induced instability model in order to understand how these eruptions occur in the X-ray band.

The phenomenon that triggers the instability in these objects is not yet clear, however: according to Hameury et al. (1986, 1988, 1990), in fact, it is due to MTI of the outer layers of the secondary produced by X-ray irradiation from the compact object during quiescence. This scenario is however difficult to reconcile with the very low quiescent X-ray luminosity observed in SXTs. Other authors (e.g. Cannizzo et al. 1995 and referenced therein) believe that the instability is due to ADI occurring in the dick once it reaches a critical mass, similarly to what happens in CVs. They however do not take into account in their discussion the strong X-ray irradiation of the disk which instead, according to van Paradijs (1996), should be considered as fundamental part of this theoretical model. The pure ADI model also produces a decay of the X-ray light curve which is faster than the observed one (Mineshige 1994). Actually (Mineshige 1994), it is likely that both instabilities contribute to the genesis of the outburst, in the sense that a collapse of the disk occurs first, and then, because of strong X-ray emission produced by this collapse, a heavy increase of $\dot{M}$ from the secondary star is triggered, which makes the outburst longer-lasting. This debate is still however far from being settled.

Summarizing, already during the outburst phase is thus possible to obtain a series of indications on the nature and structure of these systems. One should however wait until the objects get back to quiescence in order to continue the analysis on them.

3.4.2. The quiescence phase

Only once the outburst has ended (and in the optical this takes several months, or sometimes even more than a year), and thus the brightness contribution of the disk is significantly reduced, one can directly see the secondary and can study its spectrum to obtain information about its nature and distance, as well as on value of various orbital parameters of the system in order to be able to understand what kind of collapsed object is hosted in it. Observations show that the secondary is usually a dwarf, or in some cases subgiant, star of intermediate or late spectral type; this, as mentioned at the beginning of this paragraph, further supports the fact that SXTs are LMXBs of quite old population. If, therefore, it is possible to obtain spectra from the secondary one can try to derive the mass function for the collapsed object through the classic method of the Doppler shift measurement of the spectral lines.

The optical spectrum of SXTs to at light minimum (Fig. 3.7a) is composed of a continuum typical of a late spectral type star, therefore with molecular and metallic absorption lines and bands; a significant contribution to its blueward emission, along with a strong and visible H_{α} emission, is however produced by the accretion disk even if it is in a quiescent state.

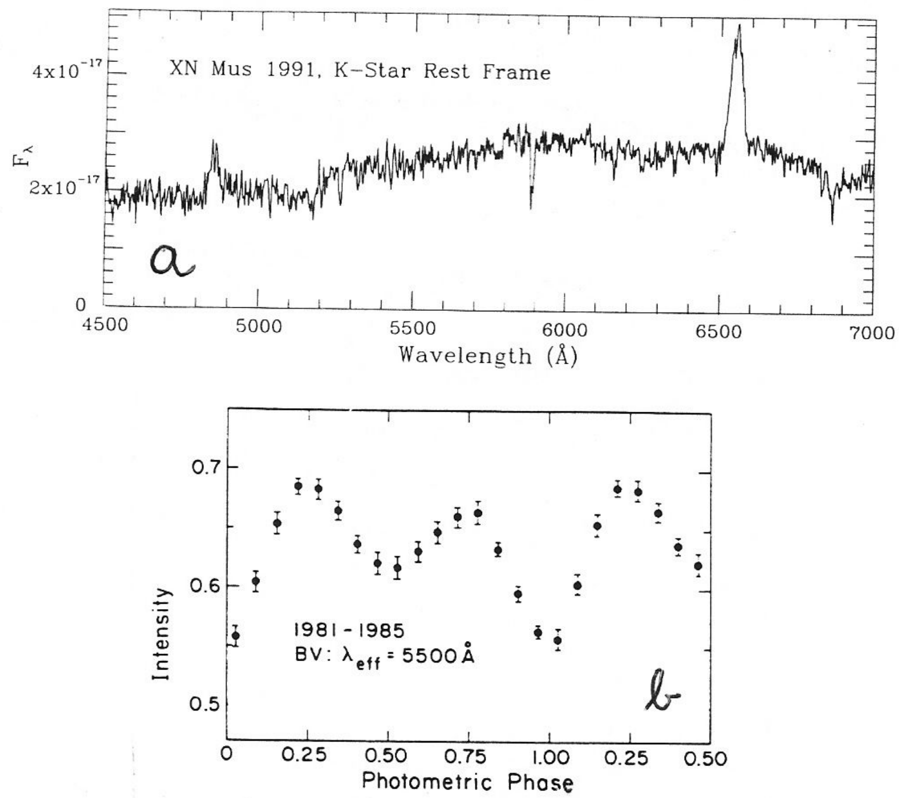

Fig. 3.7. a Optical spectrum (from: Remillard et al. 1992) and **b** ellipsoidal light curve (from: van Paradijs & McClintock 1995) of a SXT during quiescence.

Often, however, it is extremely difficult to construct radial velocity curves for these objects, given the intrinsic faintness of the secondary star (the value of *V*-band magnitudes of SXTs at minimum is around 21, or even fainter) and, therefore, the first approach to the study of the system is the photometric analysis of the quiescent light curve. Indeed, since the secondary reasonably fills its Roche lobe, one expects a periodic modulation due to the ellipsoidal deformation of the star (Fig. 3.7b). Of course, as mentioned in the previous Chapter, one should double the periodicity found with this method to determine the actual orbital period of the SXT. Once this period is known, it will become clearer how to conduct quiescent spectroscopic observations to a minimum and, if the superhump period is known as well, it will be possible to give an estimate of the mass of the compact object through the use of Eq. (2.8).

Even in quiescent SXTs, of course, this modulation becomes more evident as the system is observed at longer optical wavelengths, that is, moving towards the infrared band: this is because in this part of the spectrum the secondary dominates over the accretion disk the quiescent emission of the system. The comparative analysis of the amplitude of this modulation in the various optical and infrared bands has revealed that, in quiescence, the disk contributes to the brightness in the V band by not more than 50% (see e.g. McClintock & Remillard 1986), and with increasingly smaller percentage when the system is observed at longer wavelengths, eventually becoming almost negligible in the J (12500÷15500 Å), H (16500÷20500 Å) and K (22000÷28000 Å) infrared photometric bands.

In addition, by studying the shape of the light curve folded according to the orbital period, it is possible to determine important orbital parameters (such as q and the inclination i of the system) from the depth and the breadth of the light curve minima (Bochkarev et al. 1979).

A further measurement of inclination and the size of the system is possible if eclipses are observed. This can already be done during the outburst (in cases in which the inclination of the system is high, the secondary can produce deep optical and X-ray eclipses when it transits in front of the disk) and can give additional information about the size of the disk and of the secondary once that the brightness is back to quiescence.

An interesting feature, observed in the spectrum of the secondaries of some SXTs, is the presence of lithium lines in absorption (see Martin et al. 1996 and references thesein; see also Chap. 8). According to the evolutionary theory of low-mass stars (e.g., Michaud & Charbonneau 1991), this element should not be present anymore in the atmospheres of stars which are some billions of years old. This means that it has been created again, and most likely through spallation (that is, breakup) of C, N and O nuclei in the atmosphere of the secondary due to strong irradiation of γ-ray photons or relativistic particles produced during the outburst (Martin et al. 1994); this is supported by the fact that the presence of lithium is not detected in the secondaries of Novae and DNe, which are very similar to the SXT systems except for the lack of production of high-energy radiation (Martin et al. 1995).

These measurements obtainable during the quiescent phase, in any case, are made possible thanks to the transient nature of these objects: indeed, only when the accretion disk ceases to be active one can detect the emission from the secondary, carrying on radial velocity measurements from its absorption lines and studying its light curve. All this, on the contrary, it is extremely difficult or even impossible in the case of persistent LMXBs in which, as already said in the previous Section, the disk dominates the optical emission at any time.

3.4.3. The compact object: BH or NS?

The awareness of the fact that SXTs are a substantially homogeneous subclass is relatively recent, and only nowadays the scientific community is shedding a clearer light on the phenomenology of these systems. So far, 28 SXTs have been studied thoroughly; to them, a dozen of objects must be added which are however not unanimously considered to belong to this subgroup because of their characteristics or because of the scarcity of observations during their X-ray outburst (see more details about this issue in Chap. 8).

The broad scientific interest focused on these systems in recent years lies exactly in the study of the nature of the compact object that they host; in other words, it seems that **SXTs are the best candidates to host a BH**. Indeed, at least 20 systems of this class seem to show in the X-ray band during the outburst at least one of the characteristics of accretion onto a BH, that is:

- mostly “soft” X-ray spectrum;

- power-law shaped hard X-ray spectral tail;
- flickering or quasi-periodic oscillations (QPO) in the X-ray light curve;
- e^--e^+ annihilation line in the γ-ray band;
- lack of X-ray bursts or regular X-ray pulsations.

For 6 of them there is moreover a spectroscopic confirmation to this hypothesis, in the sense that their mass estimate exceeds the mass stability upper limit for a NS. To them one should add a seventh candidate (V518 Per; Filippenko et al. 1995) which, although having a mass function of only 1.21 $M_\odot$, very likely hosts an optical object of about 3.6 $M_\odot$, therefore with a mass substantially larger than the NS mass stability upper limit.

Not all SXTs, however, contain a BH candidate: 5 of them definitely host a NS, despite some peculiarities during the outburst which make them similar to the fellow systems with BH candidates of this subclass of binaries; it has been possible to determine the NS nature of the accretor because X-ray bursts during the outburst were observed in these systems, that is, when their behavior is similar to that of persistent LMXBs (including the presence of X-ray bursts). The following classification was thus introduced for SXTs: **Type I transients** if they definitely contain a NS and **Type II transients** or **BHXNe** if they host a BH.

Thus, to date, the only parameter that allows us to safely discriminate between a NS and a BH, in SXTs as well as in any other type of X-ray binary, is the mass function, that is the spectroscopic estimate of the lower limit for the mass of the compact object.

It seems that for SXTs there are still other auxiliary parameters which, although less firm than the mass function, already allow a preliminary estimate (or at least a first suggestion) of the compact object mass. They are derived mostly from observations of X these objects. Among these, the first possible in chronological order from the beginning of the X-ray outburst is the X-ray spectral classification. White & Marshall (1984) classified the X-ray sources according to the ratio between their “hard” and “soft” X-ray emissions; in this subdivision one finds that the “hard” sources do not correspond to accretion onto a BH, but rather onto a NS with strong field magnetic. Paradoxically, then, BHs are "soft" sources because, although much more compact than NSs, do not possess a solid surface: this causes the matter to be engulfed by the BH without substantial release of the associated energy. Thus, a "hard" X-ray transient most likely contains a NS. Indeed, as has already been said, Be-X systems produce transient X-ray phenomena related to the orbital motion of the NS and with particularly intense spectral emission above 20 keV (Rappaport & van den Heuvel 1982).

Also, the presence of X-ray bursts, that is, intense and isolated X-ray flashes lasting a few seconds, unequivocally indicate the presence of a NS in the system, as remarked in Sect. 3.1.

Similarly, the presence of a NS is confirmed if one detects periodic X-ray and/or optical pulses from the system: this implies that it contains a pulsar. If instead the X-ray emission shows random variations (the so-called X-ray flickering) or QPOs, or gamma-ray emission indicating the presence of the phenomenon of e^{-}-e^{+} annihilation, one is prone to believe that the collapsed star is a BH, as these are common features of BH in systems of both small and large mass during periods of enhanced X-ray activity.

There are further diagnostics, such as the outburst recurrence time, the quiescent X-ray luminosity and the abundance of lithium on the secondary, but they will be more thoroughly discussed in Chap. 8 as an integral part of the analysis of the general properties of the SXT subclass. They, however, as the evidence or absence of X-ray bursts or the X-ray spectral classification, do not give estimates for the mass of the compact object but rather they can simply allow us to say whether the accreting source is a NS or possibly a BH.

The parameters that may instead provide us with even rough estimates for the mass of the collapsed object can be determined from X-ray observations as well as from optical ones.

In X-rays, a first study of the nature of the collapsed object can be performed once the **decay time $\tau_{1/e}$ of the X-ray light curve** is measured. Mineshige et al. (1993) indeed found that that this decay time, that is the time SXTs take to decay by a factor *e* their X-ray luminosity, is directly proportional to the ratio between the mass M_1 of the central object and the adimensional parameter α characterizing the viscous friction within the accretion disk; one therefore obtains

$$\tau_{1/e} \propto \frac{M_1}{\alpha}: \tag{3.10}$$

this means that the longer it takes to the transient to decay in the X-ray band, the larger the mass of the compact object harbored in the system is. Unfortunately, however, this quantity is not very reliable to estimate M_1 because only rough values can be given to α, although in these systems it should not vary much in the various cases: accroding to King (1995), α should be about 0.1 during outburst.

In the optical band, instead, a preliminary estimate of the mass of the compact object is in principle already possible during the eruption if in these systems the so-called superhump phenomenon occurs. Since all BHXNe and almost all Type I SXTs have a mass ratio *q* (see Chap. 8) such as to allow the formation of an elliptical accretion disk (Whitehurst & King 1991) we can expect that, when an asymmetric modulation of the optical light curve during the eruption is observed, it may indeed be a superhump (O'Donoghue & Charles 1996): this is because during light maximum the emission is dominated by the disk, the outer edge of which is now unanimously consitered as the place in which superhumps originate (O'Donoghue 1990). Thus, according Mineshige et al. (1992), assuming that the modulation that is observed in the light of these objects during the outburst is due to superhumps (see Sect. 2.4), in these cases also it would be possible to estimate a lower limit for the mass of the degenerate star through Eq. (2.7) when the frequency of this phenomenon is known; a further, refined value is then obtainable with the use of Eq. (2.8) in the case in which the orbital period is known as well.

The use of the above approach proposed by Mineshige et al. (1992), however, may be inappropriate as it is based on the assumptions that both SXTs and DNe have low-mass, Main Sequence secondary stars which fill their Roche lobe and that the dynamic structure of the disk is not severely altered by strong X-ray irradiation. Therefore, the analogy with DNe could not be fully justified, given that not all SXT have a secondary star on the Main Sequence (see Chap. 8) and that strong X-ray illumination makes the disk structure more stable (King et al. 1996; van Paradijs 1996).

However, it is a fact that **the absolute majority (7 out of 8) of galactic BHCs is found among SXTs**. It was therefore deemed interesting to focus the scope of the research performed during the three years of this PhD course on the study of some of these objects, also because of the possibility of analyzing new observational data on the outbursts of 4 SXTs, two of which are spectroscopically confirmed BHXNe, while the other two, thanks to the work presented below, were classified as possible BHCs.

An entire chapter of this Thesis was dedicated to the study of each one of those systems, that is, V2293 Oph, MM Vel, GRO J1655-40 and GU Mus, respectively; each chapter contains a brief description on the up-to-date information on each system, as well as the original work performed during the PhD course and described in detail.

REFERENCES OF CHAPTER 3

- Augusteijn T., Kuulkers E., Shaham J., 1993, A&A, 279, L13
- Bailyn C.D., 1992, ApJ, 391, 298
- Barbon R., Benetti S., Cappellaro E., Rosino L., Turatto M., 1990, A&A, 237, 79
- Bochkarev N.G., Karitskaya E.A., Shakura N.I., 1979, SvA, 23, 8
- Canal R., Isern J., Labay J., 1980, ApJ, 241, L33
- Cannizzo J.K., Chen W., Livio M., 1995, ApJ, 454, 880
- Chen W., Livio M., Gehrels N., 1993, ApJ, 408, L5
- Chen X., Taam R.E., 1996, ApJ, 466, 404
- Frank J., King A.R., Raine D.J., 1992, Accretion power in astrophysics. Cambridge Univ. Press, Cambridge

- Filippenko A.V., Matheson T., Ho L.C., 1995, ApJ, 455, 614
- Garcia M.R., Callanan P.J., McClintock J.E., Zhao P., 1996, ApJ, 460, 932
- Hameury J.-M., King A.R., Lasota J.-P., 1986, A&A, 162, 71
- Hameury J.-M., King A.R., Lasota J.-P., 1988, A&A, 192, 187
- Hameury J.-M., King A.R., Lasota J.-P., 1990, ApJ, 353, 585
- Hjellming R.M., Han X., 1995, Radio properties of X-ray binaries. In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 308
- Iben I., Nomoto K., Tornambè A., Tutukov A.V., 1987, ApJ, 317, 717
- Joss P.C., Rappaport S.A., 1984, ARAA, 22, 537
- Kalogera V., Baym G., 1996, ApJ, 470, L61
- King A.R., 1995, Accretion in close binaries. In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 419
- King A.R., Kolb U., Burderi L., 1996, ApJ, 464, L127
- McClintock J.E., Remillard R.A., 1986, ApJ, 308, 110
- Michaud G., Charbonneau P., 1991, Space Sci. Rev., 57, 1
- Mineshige S., Hirose M., Osaki Y., 1992, PASJ, 44, L15
- Mineshige S., Yamasaki T., Ishizaka C., 1993, PASJ, 45, 707
- Martín E.L., Spruit H.C., van Paradijs J., 1994, 291, L43
- Martín E.L., Casares J., Charles P.A., Rebolo R., 1995, A&A, 303, 785
- Martín E.L., Casares J., Molaro P., Rebolo R., Charles P.A., 1996, New Ast, 1(3), 197
- Masetti N., Regös, 1997, MNRAS, submitted
- O'Donoghue D., 1990, MNRAS, 246, 29
- O'Donoghue D., Charles P.A., 1996, MNRAS, 282, 191
- Rappaport S., van den Heuvel E.P.J., 1982, X-ray observations of Be stars. In: Jaschek M., Groth H.-G. (eds.) Be-stars, IAU Symp. n° 98. Reidel Pub. Co., Dordrecht, p. 327
- Remillard R.A., McClintock J.E., Bailyn C.D., 1992, ApJ, 399, L145
- Rhodes C.E., Ruffini R., 1974, Phys. Rev. Lett., 32, 324
- Shapiro S.L., Teukolsky S.A., 1983, Black holes, white dwarfs and neutron stars - The physics of compact objects. John Wiley & Sons, New York
- Shrader C.R., Wagner R.M., Hjellming R.M., Han X.H., Starrfield S.G., 1994, ApJ, 434, 698
- Sugimoto D., Nomoto K., 1980, Space Sci. Rev., 25, 155
- Sunyaev R.A., Borozdin K.N., Alexandrovich N.L. et al., 1994, Astron. Lett., 20, 777
- Tanaka Y., Lewin W.H.G., 1995, Black-hole binaries. In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 126
- Tananbaum H., Tucker W.H., 1974, Compact -ray sources. In: Giacconi R., Gursky H. (eds.) X-ray astronomy. Reidel Pub. Co., Dordrecht, p. 207
- van den Heuvel E.P.J., 1983, Formation and evolution of X-ray binaries. In: Lewin W.H.G., van den Heuvel E.P.J. (eds.) Accretion-driven stellar X-ray sources. Cambridge Univ. Press, Cambridge, p. 303
- van Paradijs J., 1983, Optical observations of compact galactic X-ray sources. In: Lewin W.H.G., van den Heuvel E.P.J. (eds.) Accretion-driven stellar X-ray sources. Cambridge Univ. Press, Cambridge, p. 189
- van Paradijs J., 1995, X-ray Binaries. In: Alpar M.A., Kizioglu Ü., van Paradijs J. (eds.) The Lives of the Neutron Stars. Kluwer Acad. Publ., Dordrecht, p. 281
- van Paradijs J., 1996, ApJ, 464, L139
- van Paradijs J., McClintock J.E., 1994, A&A, 290, 133
- van Paradijs J., McClintock J.E., 1995, Optical and ultraviolet observations of X-ray binaries. In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 58
- Verbunt F., van den Heuvel E.P.J., 1995, Formation and evolution of neutron stars and black holes in binaries. In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 457
- Verbunt F., Belloni T., Johnston H.M., van der Klis M., Lewin W.H.G., 1994, A&A, 285, 903
- White N.E., Marshall F.E., 1984, ApJ, 281, 354
- Whitehurst R., King A.R., 1991, MNRAS, 249, 25