X-ray and optical studies of black-hole X-ray transients

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X-ray and Optical Studies of Black-Hole X-ray Transients

Frank van der Hooft
X-ray and Optical Studies of Black-Hole X-ray Transients

Röntgen en Optische studies van Zwarte Gaten
(met een samenvatting in het Nederlands)

Academisch Proefschrift

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Introduction

This thesis investigates black holes, or to be more precise, stellar-mass black holes. One can study such sources in several ways, both from a theoretical and an observational point of view. It is clear that black holes, like many stars, are very intriguing objects to study, but have properties that are absolutely fantastic. This has led Kip Thorne to the following characterization of black holes:

*Of all the conceptions of the human mind, from unicorns to gargoyles, to the hydrogen bomb, perhaps the most fantastic is the black hole: a hole in space with a definite edge over which anything can fall and nothing can escape; a hole with a gravitational field so strong that even light is caught and held in its grip; a hole that curves space and warps time. Like the unicorn and the gargoyle, the black hole seems much more at home in science fiction or in ancient myth, than in real universe. Nevertheless, the laws of modern physics virtually demand that black holes exist. In our Galaxy alone there may be millions of them* (taken from Novikov 1995).

Although mind boggling, phenomena like curvature of space and time in the immediate vicinity of black holes, traveling inside the event horizon of a black hole, or the information paradox in which a black hole slowly evaporates by emission of thermal radiation, will not be addressed in this thesis. Instead, we report on optical and X-ray observations of binary star systems for which we have good reasons to believe that they contain a black-hole primary. The analyses discussed in this thesis are based on observations made at both optical and hard X-ray wavelengths and are presented in six chapters; three on X-ray and optical data each. For one source, GRO J1655−40, we make an accurate measurement of the mass of the primary, and thereby show its firm black-hole candidacy. Here, in this introductory chapter, the concept of a black hole as it occurs in observational astrophysics, is outlined and our current understanding of black holes is briefly reviewed, in order to provide the necessary background information to the work presented here.

1.1 History

Black holes, a prediction of theoretical physics, constitute a physical singularity in space-time. The firsts who actually considered the possibility of what we would nowadays call ‘black stars’, were Michell (1783) and Laplace (1795) by the end of the 18th century. After Newton, who had already hypothesized that light might be subject to gravitation, they independently argued that the most massive stars in the universe would be invisible, i.e., would be black. They reasoned
that for a sufficiently massive (and compact) star, the escape velocity at its surface would exceed the speed of light, and therefore, light cannot escape from it.

However, this was not truly a prediction of the existence of black holes, as their reasoning was entirely based on classical mechanics. Einstein showed early this century that for very strong gravitational fields Newtonian mechanics no longer holds, and the theory of general relativity has to be applied instead. Also, Michell and Laplace could not be aware of the fact that, according to the theory of special relativity (also postulated by Einstein in the early 1900s), nothing in nature can exceed the speed of light. Therefore, if light cannot escape from a region in space, nothing is able to emerge from it, and no communication with its outside world is possible. Such a star is therefore not only black, but also a true hole in space, from which nothing can escape.

The (classical) escape velocity from the surface of a star of mass $M$ and radius $r$ is given by $v = (2GM/r)^{1/2}$. By setting $v$ to the speed of light $c$, the radius of the star would be

$$R_s = \frac{2GM}{c^2}$$

It turns out that this expression coincides with the radial distance parameter which occurs in the spherically symmetric Schwarzschild metric, describing the metric of a non-rotating object of mass $M$. The surface which corresponds to this radius is the event horizon; no information from inside this horizon can be communicated outward. Matter flowing to a black hole, cannot stop at or inside this event horizon. Once the horizon is reached, matter has to fall inevitably to the center of the black hole at which it collapses to a point, and where all of the mass is concentrated at essentially infinite density. Note that the center of the black hole is a singularity where our current physical understanding breaks down, while the event horizon itself is not particularly special from a physical point of view. Although it is generally regarded as the 'point of no return', passage of an object or observer through the event horizon of a black hole is a 'non-event'. When the black hole is sufficiently large (or massive), the observer will not yet experience severe gravitational tidal forces upon passage of the event horizon.

The process of the relativistic gravitational collapse of a star was first calculated by Oppenheimer & Snyder (1939). They studied the collapse of a homogeneous sphere of pressure-free fluid, applying the theory of general relativity, and found that if all thermonuclear sources of energy of a sufficiently heavy star are exhausted, the star will collapse. This contraction will continue indefinitely and the sphere will close itself from communication with a distant observer. For a black hole of one solar mass, the event horizon will be three kilometers from the center, however, for a black hole with the mass of the Galaxy, the horizon is $\sim 10^{12}$ km from its center.

### 1.2 Formation of black holes in binaries

During the stellar evolution, the nuclear fuel content of a star becomes depleted. Loss of energy due to radiation leaving the stellar surface causes its core to contract, thereby enabling the conditions under which a next stage of nuclear burning can start. When, after successive cycles of core contraction and subsequent nuclear burning the nuclear fuel is finally exhausted, the core of a sufficiently massive star implodes and its outer layers are expelled. Sufficiently massive stars may leave a neutron star or black-hole remnant at the supernova (SN) explosion,
depending on their initial mass. The lower limits to the initial mass of such progenitor stars for the formation of (binary member) neutron stars or black holes are about 10 and 40–60 $M_\odot$, respectively. However, the latter limit is rather uncertain as massive stars suffer heavy mass loss during their evolution, which is still poorly understood.

Based on extensive observational work in the 1970s, it has become clear that there are two types of X-ray binaries. They are distinguished by the mass of the mass donor, which is either $\gtrsim 10$ $M_\odot$ (high-mass X-ray binaries [HMXBs]), or $\lesssim 1$ $M_\odot$ (low-mass X-ray binaries [LMXBs]). Black-hole candidates have been found among both groups. In contrast to the production of a HMXB, the formation of LMXBs is an exceedingly rare event (van den Heuvel 1983), which implies that the progenitor binary system should fulfill a set of restrictive conditions in order to successfully produce a LMXB (see, e.g., Kalogera & Webbink 1998). Such a progenitor binary most probably has an extreme mass ratio, as the black hole must have formed from a very massive star, while its low-mass companion started out with approximately its currently observed mass of $\lesssim 1$ $M_\odot$. However, when the binary member which explodes as a SN is the most massive one, the system can easily be dissolved. Disruption will occur if more than half of the binary mass is lost in the SN explosion. If the exploding star still has its initial mass at the moment of the SN explosion, the mass lost in the SN event exceeds half of the binary mass, unless the initial mass ratio is close to unity (Verbunt & van den Heuvel 1995).

However, if the SN progenitor reduces its mass by transferring its envelope to the companion star (conservative mass loss), it becomes relatively easy to keep the system bound after the SN explosion (Blaauw 1961; Boersma 1961). This must happen in the case of HMXB formation, where large amounts of mass are transferred to the companion star, or are lost from the system, before the SN explosion occurs. A massive secondary orbiting a neutron star or black hole is left.

Conservative mass transfer cannot take place for binary stars with an extreme mass ratio, for which reason LMXBs need to be formed through different channels (see, e.g., van den Heuvel 1992; Webbink 1992). For such systems a phase of common-envelope evolution is required. When the more massive star evolves and becomes a giant, its envelope engulfs the light companion which will spiral inwards due to frictional drag. Only when the initial binary separation, mass ratio and fractional drag fulfill certain conditions, the binary system will survive this so-called common-envelope phase, and merging of the secondary star with the core of the primary is prevented. During this phase, most of the mass is lost as the envelope is stripped from the system. The remaining core (a helium star) continues its evolution and explodes as a SN. The mass loss during the collapse of the primary is so severe that the system would be disrupted if the explosion were symmetric. However, if the compact star receives at birth a kick velocity, the apparent result of asymmetric core collapse, there is a small probability that the binary remains bound. A kick velocity of the appropriate magnitude and direction can keep the binary system from becoming unbound even in the case of severe mass loss. Also other, more exotic LMXB formation scenarios have been proposed, including, e.g., triple-star progenitors (Eggleton & Verbunt 1986), and direct SN explosion without a preceding phase of mass transfer (Kalogera 1998). Therefore, although tightly constrained by the restrictive conditions a possible progenitor system has to fulfill, formation of a binary consisting of a black hole and a low-mass secondary star appears to be possible.

The binary system only becomes visible as a luminous source of X-rays at the moment mass is transferred to the black-hole primary. This will happen after the low-mass companion expands as it ages, or the binary system has shrunk significantly by emission of gravitational radiation.
and/or magnetic braking. The low-mass star will then start overflowing its critical Roche lobe. Matter is transferred towards the black hole, forming an accretion disk around it, in which matter gradually spirals inwards, and finally accretes onto the black hole. The luminosity arising from the accretion of matter onto a compact object of mass $M$ and radius $R$ is given by

$$L = \frac{GM\dot{M}}{R}$$

Here $\dot{M}$ is the rate at which mass flows to the compact star; most of this energy is liberated near the surface of the object at radius $R$. For a one solar mass primary the accretion rate needs to be $10^{-8} M_\odot$ per year to release a luminosity of $10^{38}$ erg s$^{-1}$, close to the maximum observed from galactic X-ray sources. However, we cannot apply this approach to the case of black holes, as such stars lack a hard surface. The maximum energy per unit mass which can be extracted by way of accretion to a black hole, is the specific binding energy of the innermost stable circular orbit, i.e., the orbit at three Schwarzschild radii. The efficiency at which the matter is converted into energy, depends on the angular momentum of the black hole.

It is interesting to compare the efficiency, $\eta$, at which matter is converted into energy in the accretion process onto compact stars, with that of the efficiency of nuclear reactions. For a white dwarf, $\eta$ is of order $\sim 0.001$, which is comparable to the efficiency of nuclear reactions: $0.001-0.007$. For accretion onto a neutron star or black hole, however, the efficiency of converting matter into energy can become very large in comparison to the efficiency of nuclear reactions.

For a neutron star, $\eta$ is of order $\sim 0.1$; the maximum efficiency of extracting energy from matter accreting onto a black hole depends on its angular momentum: $\eta = 0.06$ (non-rotating black hole), $\eta = 0.42$ (maximal rotating black hole, Kerr solution). Therefore, release of gravitational energy by way of accretion onto a black hole can be highly efficient. The release of such large amounts of gravitational energy in a small volume leads to high temperatures ($\gtrsim 10^7$ K), at which the bulk of the energy is emitted as X-ray photons.

### 1.3 Signatures of black holes

It is likely that most phenomena related to accretion flows around a compact object are influenced by basic intrinsic properties of the compact object itself, such as its mass $M$, its magnetic moment $\mu$, and its spin rate $\omega$. By studying the accretion flow phenomena in detail, one might hope to deduce information on the intrinsic properties of neutron stars and black holes. However, it has turned out to be difficult to distinguish binary systems containing a low-magnetic field neutron star from those with a black hole, based on X-ray spectral characteristics or rapid X-ray variability alone. A neutron star of nominal mass ($M = 1.4 M_\odot$) and radius ($R = 10$ km), is only about three times as large as its Schwarzschild radius, for which reason the accretion flow around a weakly magnetized neutron star and a black hole of comparable mass will bear many similarities, including similar characteristic time scales. For instance, the dynamical time scale $\tau_d \equiv (r^3/GM)^{1/2}$ at the surface of a $1.4 M_\odot$ neutron star is $\sim 0.1$ ms, while at the innermost stable orbit (i.e., at three Schwarzschild radii) of a $3 M_\odot$ black hole, $\tau_d \sim 0.2$ ms.

As is mentioned in Section 1.1, black holes are singular points in space and do not have a hard surface; therefore, matter is indifferent to flowing through the black hole event horizon. In contrast to black holes, neutron stars do possess a solid surface on which matter can accrete. The presence or absence of a solid surface on which matter can accrete, might give rise to
observable differences between the energy spectra and rapid X-ray variability of neutron star and black-hole systems. A direct positive identification of a neutron star primary arises from the observation of type I X-ray bursts, and of regular X-ray pulsations, which require a solid surface on the compact object, and therefore rule out the presence of a black hole in the binary system. In the absence of X-ray bursts or X-ray pulsations, one might attempt to distinguish between a neutron star or black-hole primary on the basis of their spectral and X-ray variability characteristics. However, some of these characteristics are found among both black-hole and neutron star systems. For instance, the X-ray variability characteristics of atoll sources, which harbor a neutron star primary, are very similar to those of black-hole candidates in the low state (see, e.g., Section 1.3.4). Also, their 1–20 keV X-ray spectra can become quite hard, like is the case in black-hole candidates in the low state. The ultra-soft spectral component in the X-ray spectra of black-hole candidates in the high state, is also not a characteristic unique of black-hole systems, as ultra-soft spectra have been detected from ‘anomalous’ X-ray pulsars too (Stella et al. 1998). Therefore, the observation of an ultra-soft spectrum and/or a high-energy power-law tail above 20 keV, together with the existence of different spectral states (high-soft, and low-hard) and millisecond variability, is used to infer the presence of a black hole in an X-ray binary based on X-ray diagnostics. These criteria have proven to be quite successful, as demonstrated by subsequent dynamical studies of such binary systems. A more detailed discussion of black-hole candidate characteristics (rapid X-ray variability, X-ray spectra, source states, mass function) is given in Sections 1.3.2 to 1.3.5.

Based on general physical considerations, e.g., the sound speed should not exceed the speed of light (Hartle 1978), one can derive that the mass of a neutron star cannot exceed a certain maximum value. Nauenberg & Chapline (1973) and Rhoades & Ruffini (1974) have shown on the basis of these considerations that the maximum gravitational mass of a slowly rotating neutron star, independent of the equation of state (EOS) of high-density matter, is ~ 3 M\(_\odot\). Detailed modeling of neutron stars, yield masses mainly between 1.3 and 1.9 M\(_\odot\) for different EOS, although Arnett & Bowers (1977) and Prakash, Ainsworth & Lattimer (1988) have shown that the neutron star mass may reach 2.7 M\(_\odot\) for extreme cases with very stiff EOS. Rapid uniform rotation (for extreme EOS) further increases the maximum neutron star mass up to ~ 3.2 M\(_\odot\) (Friedman, Ipser & Parker 1986). The measured masses of neutron stars in binary systems lie in the range 1.0–1.8 M\(_\odot\) (Thorsett et al. 1993; Finn 1994; van Kerkwijk, van Paradijs & Zuiderwijk 1995; van Paradijs 1998). Although a dynamical mass estimate of a compact object exceeding ~ 3 M\(_\odot\) is rather compelling, it is still no conclusive evidence of their being a black hole. As argued above, black holes are characterized in particular by the absence of a solid surface, but such evidence is hard to provide. Therefore, since systems with dynamical mass estimates exceeding ~ 3 M\(_\odot\) cannot be neutron stars, these are commonly denoted by the term black-hole candidate (BHC).

### 1.3.1 The first BHC: Cyg X-1

The first X-ray source of which the binary nature was established, also provided the first observational evidence for the existence of black holes: the X-ray source X-1 in the constellation Cygnus. The X-ray source was discovered during a rocket flight in 1965 by Bowyer et al. (1965) and is the brightest persistent X-ray source in the sky at energies > 20 keV. Subsequent X-ray observations narrowed down its X-ray error box (Rappaport, Zamen & Doxsey 1971), which led to the detection of a likely radio counterpart (Braes & Miley 1971; Hjellming & Wade
1 22  1: Introduction

**Figure 1.1**: Typical power density spectra of black-hole candidates in the low state (Cyg X-1) and in the high state and very high state (GS 1124–68) observed with GINGA. The high state power spectrum was shifted down by one decade for clarity (from van der Klis 1995b).

1971). Confirmation that the radio source is associated with Cyg X-1 was established when its radio brightness showed a large increase correlated with a major hardening of the 2–10 keV X-ray spectrum (Tananbaum et al. 1972). Based on the accurate radio position, Cyg X-1 was optically identified by Webster & Murdin (1972) and Bolton (1972) with HD 226868 (V1357 Cyg), an O9.7 supergiant with an orbital period of 5.6 days. The mass function of Cyg X-1 is only 0.24 $M_\odot$, but since the mass of the secondary likely exceeds $\sim 15 M_\odot$, the mass of the compact object in Cyg X-1 is higher than 4 $M_\odot$, which exceeds the maximum possible mass of a neutron star. Therefore, the HMXB Cyg X-1 was from the beginning considered a strong black-hole candidate.

Spectral transitions of BHCs were first noticed in the X-ray spectra of Cyg X-1 (Tananbaum et al. 1972). The source exhibits two spectral states; the common low (or hard) state, characterized by a hard X-ray spectrum, and the relatively rare high state, when the spectrum consists of an ultra-soft component and a high-energy tail (see, e.g., Sect. 1.3.4). Cyg X-1 is a bright radio source when it is in the low state, whereas it is radio weak in the high state. Rapid variability of the X-ray flux was detected first in Cyg X-1, its flux varies on all time scales down to a few milliseconds. This variability is strongly correlated with the spectral hardness of Cyg X-1 (Tanaka & Lewin 1995; Crary et al. 1996a).
1.3.2 Rapid X-ray variability

Matter accreting onto a compact object moves across small distances under the influence of a strong gravitational force, due to which large accelerations are produced. The resulting short characteristic time scales are in the order of milliseconds for both neutron stars and black holes. Therefore, rapid X-ray variability may occur in binaries containing a compact object. Such fast, aperiodic X-ray variability on a time scale less than 0.1 sec was observed first in Cyg X-1 in 1971 (Oda et al. 1971), shortly before it was proposed that Cyg X-1 contained a black-hole primary. This observation led to the idea that strong, rapid X-ray variability might be a signature of an accreting black hole. However, similar fast-variability characteristics were detected from V0332+52, a Be/X-ray transient containing a pulsar with a period of 4.4 sec (Stella et al. 1985). Since X-ray pulsars are neutron stars, this observation disqualified rapid X-ray variability as a unique black-hole signature.

Much later it was found that several BHCs show low-frequency (0.04–0.8 Hz) quasi-periodic oscillations (QPOs) (van der Klis 1995b; van der Hooft et al. 1996). However, QPOs of comparable frequency have also been observed from the Rapid Burster (Lubin et al. 1992; Lubin et al. 1993), which harbors a neutron star (Lewin, van Paradijs & Taam 1995). Therefore, low-frequency QPOs are not a conclusive diagnostic of the presence of a black hole either. Typical black-hole candidate power spectra are displayed in Figure 1.1.

1.3.3 X-ray spectra

The X-ray spectra of BHCs generally consist of two components, whose relative strengths can vary by a large factor. The high-energy part of the spectrum (>20 keV) is dominated by a power law, sometimes detected up to several hundred keV, with a typical photon index ~1.5 to ~2.5. This component is interpreted as the result of Compton up-scattering of low-energy photons in a very hot medium, generally associated with a disk corona, or a geometrically thick disk (Sunyaev & Titarchuk 1980). The second component in the energy spectra is ultra-soft. This component is limited to energies below 10 keV and can roughly be described by a Planck function with a blackbody temperature of ~1 keV. It is interpreted as emission arising from an optically thick, geometrically thin accretion disk around the compact object. X-ray spectra of four BHCs, showing both the hard power-law tail and the ultra-soft component, are shown in Figure 1.2. It has been suggested that the presence of the hard power-law tail in the X-ray spectrum (>20 keV) may be the signature of a black hole (see, e.g., Sunyaev et al. 1991b). This conjecture was put forward based on both theoretical considerations (Sunyaev & Titarchuk 1989), as well as observational data. All dynamically proven black-hole binaries exhibit, at least sometimes, the hard spectral component (Gilfanov et al. 1995). However, low-luminosity neutron star LMXBs, often exhibit a single power-law type spectrum which can extend up to 100 keV and beyond (Barret et al. 1991). Therefore, the hard power-law spectrum alone is not a feature unique in BHCs. Van Paradijs & van der Klis (1994) have shown that there exists a general anticorrelation between the hardness of the 20–100 keV spectra and the luminosity of non-pulsating LMXBs. However, BHCs may be the only type of systems which exhibit a hard X-ray spectrum at high luminosities.
Figure 1.2: The X-ray spectra of the black-hole candidates GS 1124–68, GS 2023+338, Cyg X-1, and GS 2000+25 (shifted down by one decade for clarity), observed with Mir-Kvant and GRANAT. All sources show a hard power-law tail up to several hundred keV. The energy spectra of GS 1124–68 and GS 2023+338 show in addition a significant ultra-soft component (from Gilfanov et al. 1995).

1.3.4 Source states

The simultaneous analysis of spectral and rapid temporal variability of BHCs has led to the distinction of different source states (see, e.g., van der Klis 1995b). In the low (or hard) state (LS) the energy spectra are dominated by a hard power-law component with photon spectral index of $\sim 1.5–2$, while the ultra-soft spectral component is weak or absent. The power density spectra (PDSs) show a strong broad-band noise component with a flat top below $0.03–0.3$ Hz, and fractional rms amplitudes up to 50% which is not strongly dependent on photon energy. At higher frequencies the PDS can be described by a power law of slope 2 and a variable low-frequency cut-off. Belloni & Hasinger (1990a) found that as this break frequency changes, the high-frequency part of the PDSs remained approximately constant. As a result, the power integrated over a frequency range below the break frequency is strongly anticorrelated with the break frequency. In several sources, low-frequency QPOs were observed in hard X-rays at frequencies similar to the cut-off frequency (van der Klis 1995b; van der Hooft et al. 1996). In the high (or soft) state (HS) the 1–10 keV flux is an order of magnitude higher than in the LS due to the ultra-soft spectral component. The LS power-law spectral component is sometimes still visible at higher energies, with usually a somewhat steeper slope ($\sim 2–3$). The amplitude
of the X-ray variation is small (fractional rms amplitude less than \( \sim 10\% \)); the PDSs can be represented by a power law with index \( \sim 1-1.5 \). The very-high state (VHS) has similar spectral characteristics as the HS (at a higher 1–10 keV luminosity), but can be distinguished from the HS by its broad-band noise properties and the 3–10 Hz QPOs, with (sub)harmonics (see Fig. 1.1).

'Low', 'high' and 'very high' refer to the source flux in the classical 1–10 keV energy band, and it has been suggested based on the ordering of these states during the X-ray outburst of a BHC, that the sequence LS \( \rightarrow \) HS \( \rightarrow \) VHS is one of increasing mass accretion rate (van der Klis 1994b). Indeed, during its 1991 outburst, GS 1124–68 sequentially went through the very high, high and low state while its count rates decreased. In addition, the PDS showed characteristics of the VHS when the source moved from the HS to the LS, indicative of a possible intermediate state. Such an intermediate state has also been observed in Cyg X-1 (Belloni et al. 1996) and GX 339–4 (Méndez & van der Klis 1997). Also, rapid variability similar to that seen in the LS, is sometimes observed in the HS and VHS. LS temporal characteristics were observed in GS 2023+338 and GRO J0422+32 while these sources were very bright. Note that as the soft spectral component is virtually constrained to the \( \lesssim 10 \) energy band, the high energy (\( \sim 100 \) keV) X-ray flux in the low state may become larger than in the high state (see Fig. 1.2).

### 1.3.5 Mass function

The most reliable method to distinguish a black hole from a neutron star is determining its mass. As the conventional mass limit of a neutron star is believed to be 3–3.2 \( M_\odot \), a compact object with a mass exceeding this value is generally viewed as a strong black-hole candidate. The mass of the compact object can be determined by studying the absorption line spectrum of the companion star, i.e., solving the mass function, \( f_{\text{opt}}(M) \). The mass function can be derived from the orbital period, \( P_{\text{orb}} \), and the observed semi-amplitude, \( K_{\text{opt}} = v_{\text{opt}} \sin i \), of the radial-velocity variations of the secondary star, and is defined by

\[
f_{\text{opt}}(M) = \frac{M_X^3 \sin^3 i}{(M_X + M_{\text{opt}})^2} = \frac{K_{\text{opt}}^3 P_{\text{orb}}}{2 \pi G}
\]

in which \( i \) is the binary inclination of the orbit to the line of sight, and \( M_X \) and \( M_{\text{opt}} \) denote the mass of the compact object, and secondary star, respectively. From this expression it follows that the mass function itself represents a firm lower limit to the mass of the compact object; \( M_X \) cannot be less than \( f_{\text{opt}}(M) \). Therefore, a mass function in excess of 3 \( M_\odot \) directly provides dynamical evidence that the compact object in the binary system is a black hole. During the past decade, this method has proven to be quite successful in classifying several LMXBs as BHCs; in almost all cases \( f_{\text{opt}}(M) > 3 M_\odot \) (see Table 1.1). In the case the secondary star is massive (i.e., for a HMXB), the mass function reduces to a small number as the mass of the compact object is comparable to (or smaller than) the mass of the secondary star. Therefore, in order to derive a reliable value of \( M_X \), both \( M_{\text{opt}} \) and \( i \) (or, equivalently, \( q \) and \( i \)) must be accurately known, which introduces the potential of systematic uncertainties in the mass estimation of the compact object.

Several systematic effects may modify the amplitude of the radial-velocity variations of the secondary star, and therefore, determination of the mass of the compact object (van Paradijs & McClintock 1995). The observed radial-velocity variations of the secondary star are averaged
Figure 1.3: Theoretical radial velocity (top) and optical light curve (bottom) of Nova Sc 1994, together with a model picture of the binary system at four different orbital phases. The light curve and model pictures were computed with the theoretical model described in Chapter 7, and the following parameters: mass of the compact star $M_X = 7.0 \, M_\odot$, mass of the secondary star $M_{\text{opt}} = 2.3 \, M_\odot$, binary inclination $i = 67^\circ 50$, orbital period $P = 2.62$ days, optical luminosity $L_{\text{opt}} = 41 \, L_\odot$, fractional radius of the accretion disk (in terms of the effective Roche lobe) $\alpha = 0.8$, flaring angle of the disk $\gamma = 2^\circ$, a temperature at the outer edge of the disk $T_{\text{edge}} = 100 \, K$, and a gravity darkening coefficient $\beta = 0.25$. The radial-velocity curve is a sinusoid with radial-velocity semi-amplitude $K = 228 \, \text{km s}^{-1}$, and a space velocity of $-142 \, \text{km s}^{-1}$.

over its surface. Therefore, temperature variations across the stellar surface due to tidal distortion, and/or X-ray heating by the compact object, may cause the observed radial velocities to deviate significantly from the center-of-mass velocity. Also, possible contamination of the stellar absorption lines by emission lines arising in the accretion disk, an accretion stream towards the disk, or circumstellar material, can make determination of accurate radial velocities hazardous.

As the secondary fills its Roche lobe, and under the assumption of co-rotation, the ratio of its effective radius and the orbital semi-major axis is determined by the mass ratio $q = M_{\text{opt}}/M_X$. By using Paczyński’s (1971) expression for the radius of the Roche lobe of the secondary, the radial-velocity semi-amplitude $K_{\text{opt}}$ and rotational broadening $v_{\text{rot}} \sin i$ are related to the mass ratio via

$$\frac{v_{\text{rot}} \sin i}{K_{\text{opt}}} = 0.46[(1 + q)^2 q]^{1/3}$$
Therefore, by comparing the radial-velocity amplitude of the secondary star and its projected rotational velocity as observed from the broadened spectral lines, the mass ratio of the binary system can be measured. This procedure is thought to be reliable, but technically challenging as typical values of the rotational broadening are $30-80 \text{ km s}^{-1}$. High-dispersion, high signal-to-noise observations are required, making this method applicable to the brightest systems only. Further constraints on the mass of the compact object and secondary star require knowledge of the orbital inclination, which can be obtained by studying the ellipsoidal variations of the secondary by way of optical photometry.

Ellipsoidal light curves are caused by the tidal and rotational distortion of the secondary star, and a non-uniform surface brightness distribution (gravity darkening). The double-waved shape of the ellipsoidal light curve reflects the observed projected surface area of the non-spherical secondary star: equal maxima occur near quadratures, minima near conjunctions. The deepest minimum in the ellipsoidal light curve occurs at superior conjunction of the secondary with respect to the compact star. At this orientation, the observer views a region of the star at which the surface gravity, and therefore the surface brightness, is minimal. A theoretical ellipsoidal light curve, together with model pictures of the binary system and a theoretical radial-velocity curve, are shown in Figure 1.3. If the secondary star fills its Roche lobe, the shape of the ellipsoidal light curve is completely determined by the mass ratio and binary inclination only. However, X-ray heating by the compact star, the presence of a (bright) accretion disk, and intrinsic variability of the secondary may alter the shape of the ellipsoidal light curve significantly. Nevertheless, by taking such disturbing effects into account when necessary, one can derive constraints to $q$ and $i$ by studying the ellipsoidal light curves in detail (van der Hooft et al. 1997, 1998a).

1.4 Black-hole X-ray transients

Soft X-ray transients (SXTs) are among the best studied examples of accreting stellar mass black holes (van Paradijs & McClintock 1995; Tanaka & Lewin 1995; Tanaka & Shibazaki 1996). In the 1970s, these transients were studied in the $2-10 \text{ keV}$ energy band first, which resulted in the detection of an ultra-soft component in the energy spectra. The classification ‘soft’ distinguishes this subclass of LMXBs from the hard X-ray transients which are associated with massive Be star systems. However, later spacecraft often observed an additional very hard power-law component in the X-ray spectra of SXTs at higher energies, which is detectable up to several hundreds of keV. Four SXTs have shown type I X-ray bursts (Cen X-4, Aql X-1, 1608$-$522, and 1658$-$298), which establishes that the compact object in these systems is a neutron star. Radial-velocity studies of Cen X-4 (McClintock & Remillard 1990; Shahbaz, Naylor & Charles 1993) show that the mass of its primary is consistent with $1.4 \, M_\odot$, i.e., the canonical mass for a neutron star. Remarkably, dynamical studies indicate that at least eight, and possibly all of the remaining SXTs which do not show X-ray bursts, appear to contain a black-hole primary. Therefore, these systems are often referred to as black-hole X-ray transients (BHXTs).

BHXTs are characterized by outbursts (typical duration weeks to months) driven by accretion instabilities, during which their X-ray luminosity suddenly increases, separated by long periods of quiescence with very low emission of X-rays. The outbursts are recurrent on a time scale of typically years to decades; therefore, these sources spend most of their life in the quiescent
1: Introduction

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$^a$ Mean brightness varies between 16.7–17.5

$^b$ Beekman et al. (1997) report 10$^\circ$–31$^\circ$, and $M_X$ ≥ 9 $M_\odot$

$^c$ Shahbaz, Naylor & Charles (1994a) report 31$^\circ$–54$^\circ$, and $M_X$ = 10 $M_\odot$

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**Table 1.1:** Properties of HMXB and LMXB black-hole candidates. Both the system name, as well as the name commonly used to denote the optical counterpart (if known), are listed. The third column gives the orbital period in hours derived from photometry and/or spectroscopy, except for 4U 1755–33, for which the period was derived using X-ray dips. The next three columns list the quiescent V-band magnitude, mass function, and binary inclination. The final two columns give the limits to the mass of the compact object and secondary star, respectively. Data have been taken from Tanaka & Lewin (1995), van Paradijs (1995), Chen, Shrader & Livio (1997) and references therein, Orosz et al. (1998), and van Paradijs (1998).
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\(^a\) Also optical outburst in 1917
\(^b\) Also 1967, and possibly 1971
\(^c\) Outbursts are recurrent at a period of \(~ 600\) days
\(^d\) 1–20 keV energy band
\(^e\) 2–200 keV energy band
\(^f\) 4–300 keV energy band
\(^g\) 2–11 keV energy band
\(^h\) Also optical outburst in 1938, 1956, and possibly 1979

**Table 1.1: (continued)** The second column lists the year of first X-ray detection, note however that several sources have shown recurrent outbursts. The third column contains the calibrated peak flux in the 0.4–10 keV energy band, unless indicated otherwise. The next two columns give the properties of the X-ray spectra; ultra-soft (US), or soft (S) component, and index of high energy power-law tail (PL). For some sources the entries are distinguished between the off state (OS), low state (LS), high state (HS) and the very high state (VHS). The final column lists the (range of) QPO frequencies observed in X-rays. Data for GRO J0422+32 were adapted from Pietsch et al. (1993) and Denis et al. (1994); GRS 1009-45 from Shahbaz et al. (1996); GRO J1655-40 from Greiner, Predehl & Pohl (1995); GRO J1719-24 from van der Hooft et al. (1996); GRS 1737-31 from Cui et al. (1997b); remaining data were taken from Tanaka & Lewin (1995), van Paradijs (1995), Chen et al. (1997) and references therein.
state. During outburst, the X-ray luminosity of BHXTs can increase by factors up to $\sim 10^6$, while the optical luminosity increases by factors of a few hundred. The optical light of the system becomes dominated by the contribution of the bright accretion disk, and any variation in the brightness of the disk related to a hot spot, or to gas flows to the disk, dominate the ellipsoidal variations of the main-sequence secondary star. However, during quiescence most of the optical light comes from the faint secondary star.

The importance of SXTs relative to the class of LMXBs as a whole, is that as luminous X-ray sources they signify the presence of a neutron star or black hole in the system, while as transients they hold out the rare prospect of observing the secondary star directly, when the dominant light from the accretion disk has faded. Observations of BHXTs have so far been mainly concentrated on X-ray and optical/near-IR wavelengths, while more recently the importance of quick radio follow-up observations have become clear. Detection of the X-ray outburst of a previously unknown BHXT requires the presence of instruments capable of monitoring the whole sky (so-called all sky monitors [ASMs]) at X-ray wavelengths. In the past decade the ASMs on the GINGA and GRANAT satellites and on the Mir-Kvant space station, and the Burst And Transient Source Experiment on board of the Compton Gamma Ray Observatory have detected bright transient X-ray sources at a rate of 1–2 per year. Optical follow-up observations performed shortly after the initial X-ray detection led to the identification of these sources with faint stars, which brightened by several magnitudes together with the increase in X-ray flux. Subsequent dynamical studies during the quiescent state have led to the conclusion that a significant fraction of these sources are BHXTs.

Properties of individual HMXB and LMXB BHCs are listed in Tab. 1.1.

### 1.4.1 A 0620–00 (V616 Monocerotis)

A 0620–00 (V616 Monocerotis, Nova Mon 1917/1975) is a recurrent transient which exhibited outbursts in 1917 (Eachus, Wright & Liller 1976) and 1975, when it was discovered with Ariel 5 (Elvis et al. 1975). Within a few days the X-ray flux rose to $\sim 50$ Crab ($\sim 1.3–6$ keV). At first the X-ray flux decreased exponentially with a decay time of $\sim 24$ days (Matilsky et al. 1976), and then showed a distinct second, and a broad third maximum, about 55 and 200 days, respectively, after the primary maximum. The energy spectrum of A 0620–00 was ultra-soft (Ricketts et al. 1975; White & Marshall 1984), and softened during the decay. The spectrum contained a hard tail above 10 keV (White, Kaluzienski & Swank 1984).

During its X-ray maximum the source was identified with a blue star of $V \sim 12$ (Boley et al. 1976) which decayed in 15 months to its quiescent brightness of $V \sim 18.3$ (Murdin et al. 1980). The decay in the optical was $\sim 0.015$ mag per day during the first $\sim 125$ days, then a flattening occurred during the next $\sim 70$ days, followed by a fast decline of $\sim 3$ mag in $\sim 3$ weeks (Whelan et al. 1977, and references therein; Lloyd, Noble & Penston 1979). Optical spectroscopy during quiescence showed the characteristic absorption lines of a K5 V dwarf, superimposed on a blue continuum with double-peaked Balmer emission lines characteristic of an accretion disk (Oke 1977; Whelan et al. 1977; Murdin et al. 1980). The quiescent optical emission is modulated with the orbital period of 7.75 hr (McCintock et al. 1983).

In quiescence, A 0620–00 is a relatively bright object and McClintock & Remillard (1986) were able in 1985 January to measure the radial-velocity curve of the K5 dwarf. The $K$-velocity amplitude of $457 \pm 8$ km s$^{-1}$ led to a mass function of $3.18 \pm 0.16$ M$_\odot$, based on which they
concluded that the compact object in A 0620–00 is probably a black hole. With this observation, A 0620–00 became the third stellar mass BHC based on dynamical arguments (the other two candidates being the HMXBs Cyg X-1 and LMC X-3), and the first member of the class of BHXTs.

1.5 Recent results

1.5.1 Accretion instability

It is generally accepted that dwarf nova outbursts are caused by a thermal-viscous instability in the accretion disk around the white dwarf, and can occur if the mass accretion rate is sufficiently low. In this model, the entire accretion flow (both in quiescence and during outburst) is assumed to be in the form of a thin disk which extends to the innermost stable orbit (Mineshige & Wheeler 1989). The mass accretion rate $M$ critical for occurrence of the instability depends on the orbital period. Van Paradijs (1996) and King, Kolb & Burderi (1996) have shown that the distribution of SXTs and persistent LMXBs in a ($P_{\text{orb}}, M$) diagram may be understood within the concept of the dwarf nova instability if X-ray heating of the accretion disk is taken into account. Crucial in the argument is that the temperature of the accretion disk is determined by X-ray heating. The relation dividing the transient from the persistent sources, agrees well with the observed separation of persistent LMXBs and SXTs. These results show the importance of X-ray heating: stability of the mass accretion flow onto the compact star is not determined by the rate of the mass transfer itself, but by the X-ray luminosity. Therefore, X-ray heating of the accretion disk by the central source should be included when modeling the outbursts of SXTs.

1.5.2 Transient nature of SXTs

The fraction of BHCs among SXTs is significantly larger than that among persistent LMXBs. It has been suggested that this reflects the lower mass-transfer rates in the black-hole systems (White, Kaluzienski & Swank 1984), which results in unstable accretion disks and subsequent X-ray outbursts. The mass transfer rate one expects for a main-sequence secondary star may cause the accretion disk in such BHXTs to become unstable, however, the same scenario would apply to neutron star LMXBs, while the majority of these are observed to be persistent. Recently, it was shown that X-ray irradiation of the accretion disk by the central source is important in determining the stability of the disk (van Paradijs 1996, see also Section 1.5.1), decreasing the upper limit on the critical mass transfer rate for systems to become transient.

Irradiation of the accretion disk by the central source suppresses the transient behavior of short-period neutron star LMXBs (orbital period $\lesssim 1$ day), except at extremely low mass transfer rates, making them persistent X-ray sources. Despite the effects of X-ray irradiation, most long-period neutron star LMXBs with a low-mass giant donor ($\gtrsim 1$ day) will be transient (King, Kolb & Burderi 1996; King et al. 1997). Therefore, a significant fraction of the neutron star LMXBs have mass transfer rates low enough to be transient. Most short-period black-hole systems will form with unevolved main sequence secondaries and generally have much higher mass transfer rates. The fact that the majority of such black-hole systems are nevertheless transient, led King, Kolb & Szuszkiewicz (1997) to argue that X-ray irradiation differs sharply for a neutron
star and a black-hole X-ray binary. Irradiation of the accretion disk is much weaker if the accreting object is a black hole rather than a neutron star. As a black hole does not have a solid surface, it cannot act as a point source for irradiation. Instead, the X-ray luminosity of a black hole is released in the inner region of the accretion disk, i.e., a flat surface nearly parallel to the outer layers of the disk. In such a configuration, the accretion disk is likely to be irradiated less effectively, and most black-hole binary appear transient, even at mass transfer rates larger than those of neutron star binary. Moreover, if the accretion flow onto a black hole is dominated by advection, its X-ray luminosity will be decreased significantly (see, e.g., Section 1.5.3). The observation that the majority of the black-hole binary are transient, may therefore be related directly to the fundamental property of black holes: the absence of a solid surface.

1.5.3 Advection-dominated accretion

Although SXT outbursts are in some respects similar to those observed in dwarf novae, and basic features of the light curves of BHXTs can be well described by the disk instability model, the estimated recurrence time between successive outbursts disagrees significantly with the observed constraints (Lasota, Narayan & Yi 1996). Furthermore, McClintock, Horne & Remillard (1995) showed for A 0620–00 that its optical and X-ray data are inconsistent with any accretion model purely based on a thin accretion disk. Narayan, McClintock & Yi (1996) recently proposed that this can be solved with a model in which the accretion flow occurs as a thin disk outside a transition radius $r_t$, only, while the accretion inside this radius occurs via an advection-dominated accretion flow (ADAF). The transition to such ADAF occurs at low mass accretion rates $\dot{M}$, at which the time scale for radiative cooling of the inner disk becomes longer than the radial-flow time scale. Therefore, the liberated gravitational potential energy is stored in the accreting gas, rather than being radiated locally. In the case of a black hole as central accretor,
most of these internal energy will then flow through its event horizon. Therefore, in contrast to thin accretion disks, most of the energy is advected with the gas flow into the black hole.

Apart from this ADAF at low values of \( M \), there is another solution to the accretion disk flow problem, which is associated with very high \( M \). The flow is then optically thick, and most of the generated photons will be dragged into the black hole by the accreting gas (Katz 1977; Begelman 1978). The high \( M \) ADAF has not yet found application to real sources. It has been shown that the low \( M \) ADAF is both thermally and viscously fully stable (Abramowicz et al. 1995; Narayan & Yi 1995), and the low \( M \) ADAF has been applied to explain the quiescent state of SXTs. The quiescent optical and X-ray spectra of GS 2023+338 and A 0620–00 (Narayan, McClintock & Yi 1996), and GRO J1655–40 (Hameury et al. 1997) can be explained by an inner optically thin ADAF extending from the black-hole radius to \( \sim 10^4 \) Schwarzschild radii, and an outer geometrically thin disk beyond this radius. Also, the observed delay of the X-ray to the optical flux during the 1996 April outburst of GRO J1655–40 provides support to the ADAF model (Orosz et al. 1997).

The five distinct spectral states observed in BHXTs, can be ordered in a sequence of increasing luminosity: quiescent state, low state, intermediate state, high state, and very high state (see, e.g., Sect. 1.3.4). All of these states, except for the very high state, can be unified by a model in which the accretion flow consists of two zones, an inner ADAF and an outer thin disk (Esin, McClintock & Narayan 1997). The ADAF radiates inefficiently at low luminosity (quiescent state), but starts to radiate more and more efficiently when the mass accretion rate increases (low state). At higher accretion rates the ADAF shrinks and the spectrum changes from hard to soft (intermediate state). When the accretion rate increases even more, the ADAF disappears and the thin disk extends down to the marginally stable orbit (high state). Most sources are observed in a single state, excursions to other states being rare. However, in its 1991 outburst, GS 1124–68 went rapidly from quiescence to the very high state, and subsequently decayed via the high, intermediate and low state to the quiescent state. The above model naturally describes these state transitions, although the very high state still remains to be explained.

### 1.5.4 Lithium in SXTs

Significant \( \text{Li} \) \( \lambda 6708 \) Å absorption was first discovered by Martín et al. (1992) in optical spectra of the BHXT GS 2023+338. Since then, high lithium abundances have been observed in the spectra of the secondaries of four other SXTs (Martín et al. 1996), one of them having a neutron star primary (Cen X-4), the others being (firm) BHXTs (A 0620–00, GS 2000+25, and GS 1124–68). Detection of lithium in these systems at an abundance of 20–200 times solar, is surprising as comparable lithium abundances are observed only in relatively young stars; as a low-mass star gets older its initial lithium content is reduced due to convective mixing to hot inner regions of the star, where it is destroyed by nuclear burning. In ordinary late-type stars, the Li \( \lambda \) \( 6708 \) Å absorption line is usually absent or at most very weak. The secondaries of the SXTs in which lithium is observed, are all evolved, and are not expected to be very young.

Two mechanisms have been proposed for the production of lithium in these stars. Podsiadlowski et al. (1995) proposed that SXTs are the descendants of massive Thorne-Zytkov objects, i.e., red supergiants with a neutron star core which formed as a result of common-envelope evolution. Lithium may be produced around the neutron star core, and distributed outwards to cooler regions in the envelope where it cannot be destroyed anymore. Mass accretion to the neutron star core is supposed to lead to the formation of a black hole, while the secondary is formed from
the collapsing envelope of the Thorne-Żytkov object. Martín, Spruit & van Paradijs (1994) proposed that lithium is produced by spallation, i.e., by the breakdown of heavier elements due to bombardment with high-energy particles, during an outburst of a SXT. The observation of a 476 keV γ-ray line from GS 1124−68 by GRANAT (Sunyaev et al. 1992) gives some support for the production of lithium by spallation. Although this line was originally interpreted as a gravitational redshifted \( e^+ - e^- \) annihilation line, it was suggested later to be associated with the 478 keV line of \(^7\)Li, which also provides a more natural explanation for the width of the line (Charles 1994). If lithium is produced by spallation, it is likely formed in an excited state, and will produce the 478 keV lithium line upon decay to the ground state.

1.5.5 Kerr black holes

The ultra-soft spectral component observed in many BHCs is thought to arise from the inner region of the accretion disk, i.e., close to the horizon of the black hole. However, the ultra-soft component was absent in the energy spectra of several BHCs observed during their X-ray bright state (see Tab. 1.1). Zhang, Cui & Chen (1997) have recently suggested that the strength of the ultra-soft spectral component is directly related to the spin of the black hole, and proposed a classification scheme based upon this.

They assumed a standard geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973) around a Kerr black hole. The spin of the black hole affects both the radius of its horizon, and the radius of the innermost stable orbit around the black hole (Bardeen, Press & Teukolsky 1972). The radius \( R_K \) of the Kerr horizon is smaller than that of a non-spinning black hole and depends on the dimensionless specific angular momentum \( a_s = a/R_g \). It can be expressed in terms of the gravitational radius \( R_g = G M/c^2 \) as \( R_K = R_g [1 + (1 - a_s^2)^{1/2}] \). For a non-spinning black hole (\( a_s = 0 \)) the black-hole radius becomes equal to the Schwarzschild radius \( R_K = 2 R_g \) (see, e.g., Sect. 1.1); for a maximally spinning black hole (\( a_s = \pm 1 \)) the Kerr radius becomes equal to the gravitational radius \( R_K = R_g \). In all other cases \( R_K > R_g \).

The radius of the last stable orbit of the accretion disk around a rotating black hole depends on its mass and spin:

\[
R_{\text{last}} = R_g \left\{ 3 + A_2 \pm \left[(3 - A_1) (3 + A_1 + 2A_2)\right]^{1/2} \right\}
\]

where \( A_1 = 1 + (1 - a_s^2)^{1/3} [(1 + a_s)^{1/3} + (1 - a_s)^{1/3}] \), \( A_2 = (3a_s^2 + A_1^2)^{1/2} \) (Bardeen et al. 1972). The plus and minus signs are for a prograde (i.e., rotating in the same direction as the black hole) and a retrograde disk, respectively. For a non-spinning black hole the innermost stable orbit occurs at \( R_{\text{last}} = 6 R_g \) (\( a_s = 0 \)), while in the case of a Kerr black hole it occurs at \( R_{\text{last}} = 9 R_g \) (prograde disk, \( a_s = +1 \)), or \( R_{\text{last}} = 9 R_g \) (retrograde disk, \( a_s = -1 \)). Therefore, a prograde disk may fully extend to the horizon of the Kerr black hole, i.e., the radius of its inner region becoming much smaller than that of a retrograde disk. Zhang et al. (1997) show that as a result the disk color temperature and disk luminosity are influenced by the spin of the Kerr black hole; prograde disks systems will, at the same \( \dot{M} \), have a higher color temperature, while systems containing a retrograde disk show a softer component in their spectra.

Based on the spin of the black hole, Zhang et al. (1997) proposed a classification into extreme retrograde, non- or slowly-spinning, and extreme prograde BHCs. GRO J1655−40 is proposed to be a member of the last group since its inner disk radius is well within the innermost stable orbit of a non-spinning black hole at the known mass of the black hole in the system. If one
assumes the black hole in GRO J1655−40 to spin, the angular momentum of the black hole is found to be at 70–100% of the maximum possible value (Zhang et al. 1997). The case of GRS 1915+105 is less clear, although the observations seem to suggest its Kerr black hole is progradely spinning extremely fast as well. Three BHCs (GS 1124−68, GS 2000+25, and LMC X-3) appear to be spinning slowly, and would therefore be in the second group. As yet, no BHCs have been detected which qualify as (extreme) retrograde systems. Such systems would have a (very) soft component in their energy spectra, possible not efficiently detectable with current instruments. Therefore, Zhang et al. (1997) postulate that BHCs for which no ultra-soft spectral component is observed during their X-ray bright state, may very well be extreme retrograde systems.

Zhang et al. (1997) also proposed that the spectral changes (hard-low, versus soft-high state) of Cyg X-1, may be explained in terms of temporary reversal of the rotation of the accretion disk from a retrograde to a prograde system. Cyg X-1 is a wind fed system, and theoretical simulations have shown that reversal of the direction of the accretion disk rotation can actually occur in such systems (Matsuda, Inoue & Sawada 1987; Benensohn, Lamb & Taam 1997).

1.5.6 Superluminal jet sources

Episodic ejection of relativistic jets have been observed in two BHXTs so far; these systems are often called superluminal jet sources or micro-quasars. GRS 1915+105 was the first BHXT to show bipolar, jet-like outflow in radio observations (Mirabel & Rodríguez 1994). These jets show apparent superluminal motion, which can be explained as a relativistic effect with the radio-emitting plasma moving at speeds close to that of light (0.92c). Radio observations of GRO J1655−40 also revealed two highly collimated jets, opposite directed and moving at 92% of the speed of light (Hjellming & Rupen 1995). Both jets expand and decay over a time scale of days. GRO J1655−40 is a dynamically proven BHC containing a black hole of about 7 M⊙ (Orosz & Bailyn 1997; Chapter 7). Due to severe extinction in the direction of GRS 1915+105, its optical counterpart is undetectable, however, the source is suspected to be a black hole binary because of its similarities to GRO J1655−40.

The superluminal radio jets observed in these sources provide a link between BHXTs and active galactic nuclei (AGN), a subset of which also eject superluminal radio jets. AGN and BHXTs appear to follow one and the same relation between the surface brightness and size of the jets, and the accretion rate onto the central source (Sams et al. 1997). Therefore, the presence of jets in both AGN and galactic stellar mass black holes, appears to be independent of the central accretors total mass.

X-ray observations obtained with the Rossi X-ray Timing Explorer (RXTE) have shown a remarkable richness in the X-ray variability behavior of GRS 1915+105. It showed QPOs with frequencies ranging from 10⁻³ to 67 Hz (Morgan, Remillard & Greiner 1997), and on several occasions its X-ray light curve showed a complicated pattern of dips and rapid transitions between high and low intensity, which repeated on time scales of 30 to 400 minutes (Greiner, Morgan & Remillard 1996). Fractions of the X-ray light curve of GRS 1915+105, showing its typical complicated behavior on a broad range of time scales, are displayed in Figure 1.5. Belloni et al. (1997a) found that the complicated X-ray intensity curve can be described in terms of rapid removal and replenishment of matter forming the inner part of an optically thick accretion disk, probably caused by a thermal-viscous instability like the one active in dwarf novae.
Figure 1.5: X-ray light curves of GRS 1915+105 obtained with RXTE (2–60 keV) at four different epochs during 1996 and 1997, showing its very complex behavior on a broad range of time scales (courtesy T. Belloni).
GRO J1655–40 is a remarkable SXT due to the fast recurrence of its successive X-ray outbursts since the first X-ray detection of the source in 1994. The X-ray outbursts were initially separated by intervals of about 120 days (Zhang et al. 1995) and lasted many weeks, followed by a relatively long X-ray quiescent period (1995 August to 1996 April). Also, GRO J1655–40 became again X-ray detectable in 1996 April; this X-ray outburst was covered by RXTE through 1997. Using RXTE, Remillard (1998) observed a ~300 Hz QPO in GRO J1655–40. The first evidence for orbital variations in the X-rays of GRO J1655–40 were reported by Kuulkers et al. (1998), who discovered X-ray dips in the X-ray light curve of GRO J1655–40 with a duration on the order of minutes. The occurrences of these dips are consistent with the optically determined orbital period, and were found between photometric phases 0.72 and 0.86. Méndez, Belloni & van der Klis (1998) showed that during the 1997 X-ray outburst of GRO J1655–40, the source went through the high, intermediate, and low state (and probable was in the very high state at the start of the outburst), just like other black-hole candidates.
Time scale invariance of rapid X-ray variability of the black-hole candidate GRO J1719–24


Abstract
We present the results of an analysis of the time variability of the soft X-ray transient GRO J1719–24 (Nova Oph 1993) as observed with BATSE. Our analysis covers the entire ∼ 80 day outburst, beginning with the first detection of this black-hole candidate on 1993 September 25. We obtained power density spectra (PDSs) of the data in the 20–100 keV energy band covering the frequency interval 0.002–0.488 Hz. The PDSs show a significant QPO peak, the centroid frequency increased from ∼ 0.04 Hz at the onset of the outburst, to ∼ 0.3 Hz at the end. Additional noise is present in the PDSs, which we describe in terms of two components. We find that the evolution of the PDSs can be described as a gradual stretching by a factor ∼ 7.5 in frequency of the power spectrum, accompanied by a decrease of the power level by the same factor, such that the integrated power in a scaled frequency interval remains constant.

2.1 Observations
GRO J1719–24 (= GRS 1716–249, Nova Oph 1993) was detected independently with BATSE, on board of the Compton Gamma Ray Observatory and the SIGMA telescope on Granat on 1993 September 25 (Ballet et al. 1993; Harmon et al. 1993b). The source reached a maximum flux of ∼ 1.4 Crab (20–100 keV) on September 30 and was remarkable for the stability of its emission on a time scale of days. A linear fit to the X-ray light curve between October 1 and November 22 showed that the flux decreased by only ∼ 0.3 ± 0.05%
Figure 2.1: Flux history of GRO J1719–24 in the 20–100 keV energy band. The first detection of the source was made on 1993 September 25, and it reached a maximum flux of ~1.4 Crab in six days. After 70 days at a slowly decreasing, high flux level, the source exhibited a rapid decrease of the flux and became undetectable by BATSE after 83 days.

per day (Harmon et al. 1993c). From December 9 (day 75 of the outburst), the 20–100 keV flux of GRO J1719–24 suddenly decreased within six days from $1.1 \pm 0.1$ to $0.4 \pm 0.08$ Crab, and on December 16–18 it dropped below the BATSE $3\sigma$ one-day detection limit of 0.1 Crab (Harmon & Paciesas 1993). A daily average flux history in the 20–100 keV energy band, as determined using the Earth occultation technique (Harmon et al. 1993d), is displayed in Figure 2.1.

The 20–100 keV energy spectrum softened steadily during the entire outburst; the photon index increased from 2.0 to 2.3 ± 0.05 during the rise to peak intensity, and from there on the spectrum softened more gradually. No marked changes in the spectral shape were observed during the sudden decrease in X-ray flux in 1993 December. After this outburst, GRO J1719–24 remained undetectable for BATSE until 1994 September, when it was detected with both SIGMA (Churazov et al. 1994) and BATSE (Harmon et al. 1994). This later period of activity is not discussed here.

### 2.2 Time-series analysis

We have used 1.024 sec time resolution count-rate data from the large-area detectors (four broad energy channels) and applied an empirical model (Rubin et al. 1996) to subtract the signal due to the X-ray/gamma-ray background. This model describes the background by a harmonic expansion in orbital phase (with parameters determined from the observed background variations), and includes the risings and settings of the brightest X-ray sources in the sky. It uses eight orbital harmonic terms, and its parameters were updated every three hours.
For our analysis, we considered uninterrupted data segments of 512 successive time bins (of 1.024 sec each) on which we performed fast Fourier transforms (FFTs) covering the frequency interval 0.002–0.488 Hz. Per day, we typically obtained 35 of such segments while the source was above the Earth horizon. For each data segment and for each of the eight detectors separately, we calculated and coherently summed the FFTs of the lowest two energy channels (20–50, 50–100 keV). For those detectors which had the source within 60° of the normal, these FFTs were again coherently summed (weighted by the ratio of the source to the total count rates) and converted to Power Density Spectra (PDSs). The PDSs were normalized such that the power density is given in units of rms/mean² Hz⁻¹ (see, e.g., van der Klis 1995a) and finally averaged over an entire day.

The PDSs show a significant peak, indicative of quasi-periodic oscillations (QPOs) in the time series. The centroid frequency of this peak slowly shifts towards higher frequencies. This remarkable evolution is illustrated in the dynamical spectrum shown in Figure 2.2. From this figure can be seen that the centroid frequency of the QPOs doubled from ~0.04 to ~0.08 Hz during the rise to maximum flux, and then gradually increased to ~0.3 Hz. During this period, significant deviations from the general, approximately linear trend of increasing centroid frequency occur, with a particularly large positive excursion near day 60 of the outburst. The QPOs are absent when the flux starts rapidly decaying at day 75. The observed rise of the PDSs below ~0.01 Hz (see also Figure 2.3) is probably not caused by the source, since it also appears in the PDSs obtained while GRO J1719–24 was occulted by the Earth. Therefore, we excluded the frequency range below 0.01 Hz from the analysis.

A careful examination of the dynamical spectrum revealed the presence of structure in the PDS which we described in terms of two Lorentzians, one on each side of the QPO peak. The position of these additional structures seemed to scale with the frequency of the QPO. To further investigate this, we made fits to the PDSs using a combination of a power law and three Lorentzian profiles. To improve statistics, we made fits to the average PDSs of 3 consecutive days, obtaining 23 three-day averaged PDSs. The model required 11 parameters (3 for each Lorentzian, 2 for the power law) to be determined, which left 23 degrees of freedom (the PDSs were logarithmically rebinned to 34 frequency bins). Reduced χ² values of the fits were between 0.6 and 2.2. For the fit to the three-day averaged PDS starting at days 61 and 70 we used a combination of a power law and two Lorentzian profiles only, since the noise component at the highest frequency is no longer well defined as it reaches the Nyquist frequency. A typical three-day averaged power spectrum (days 13–15) and the model is shown in the top panel of Fig. 2.3; the bottom panel displays the residuals. The centroid frequencies of the three Lorentzian profiles (ν₁, ν₂ and ν₃, in order of increasing frequency), are strongly correlated (see Figure 2.4).

Over a wide frequency interval, the centroid frequencies of the QPOs and the two noise components are consistent with being linearly related. We applied fits of the form νᵢ = A + B νⱼ (taking the errors in both νᵢ and νⱼ into account, see, e.g., Press et al. 1992) to the data points, also shown in Fig. 2.4. The parameters of these fits are tabulated in Table 2.1. A linear fit offers a good description of the data, resulting in a reduced χ² of 2.5 and 0.68 for the fits to (ν₁, ν₂) and (ν₂, ν₃), respectively. When extrapolated, both fits pass through the origin, which indicates that the frequencies scale with a single factor. Therefore, we attempted a second series of fits, this time forced to pass the origin by setting A = 0. This also resulted in acceptable fits, shown as dashed lines in Fig. 2.4, and a more precise determination of the slope. Based on this last series of fits, we find that there is no significant difference between the frequency ratios (ν₁/ν₂) and (ν₂/ν₃); we can exclude that these ratios have integer values.
Figure 2.2: Dynamical spectrum of the set of daily averaged, $(\text{rms/mean})^2$ Hz$^{-1}$ normalized PDSs (20–100 keV) covering the outburst of GRO J1719–24. The frequency scale has been logarithmically rebinned; dark colors indicate a high power level. A dark band, the centroid frequency of which gradually shifts to higher frequencies, is clearly visible.
Figure 2.3: The three-day averaged power spectrum for days 13–15 and the best-fit model (power law and three Lorentzian profiles) (top), and the residuals (bottom).

This result led to the hypothesis that the PDSs may be described with a single characteristic profile, the frequency scale of which stretched proportionally during the outburst of GRO J1719–24. To test this hypothesis, we scaled each power spectrum in frequency by a factor such that the centroid frequency \( \nu_2 \) of the QPO peak became equal to 0.1 Hz. Two such frequency-scaled PDS are shown in Figure 2.5. It is evident that their shapes are very similar. The relative stretch factors of these two spectra is as large as 3.2.

As can be seen in Fig. 2.5, the power spectrum obtained during the later stage of the outburst of GRO J1719–24 (when the QPO was at the highest frequencies) has the lowest power densities. This led to the idea that the total power [and therefore, in our chosen \((\text{rms/mean})^2 \text{ Hz}^{-1}\) normalization, the fractional rms amplitude] integrated over corresponding (but relatively scaled) frequency intervals, was constant throughout the outburst. Therefore, we determined the fractional rms amplitude from each three-day averaged power spectrum, in a frequency range corresponding to 0.01–0.15 Hz in the frequency scaled domain. These fractional rms amplitudes are shown in Figure 2.6. Indeed, these values are approximately constant throughout the
Figure 2.4: Values of the centroid frequencies of the three Lorentzian profiles, plotted versus each other. The left panel contains \((\nu_1, \nu_2)\) and covers day 4–72, the right panel contains \((\nu_2, \nu_3)\) and covers day 4–60. Fits of the form \(\nu_i = A + B \nu_j\) are also shown; parameters are listed in Tab. 2.1. The dashed line represents the fit which is forced to pass through the origin.

Figure 2.5: The nine-day averaged PDSs (starting at days 4 and 52, respectively) rescaled in frequency by such factors that the centroid frequency of the QPOs became equal to 0.1 Hz. The relative stretch factor of these two spectra is 3.2.
Table 2.1: Parameters of fits shown in Figure 2.4. Quoted errors are 1σ single parameter errors.

<table>
<thead>
<tr>
<th>Centroid Frequencies</th>
<th>A</th>
<th>B</th>
<th>N°</th>
<th>$\chi^2_{\text{red}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\nu_1, \nu_2$)</td>
<td>-0.017 ± 0.008</td>
<td>2.70 ± 0.16</td>
<td>23</td>
<td>2.5</td>
</tr>
<tr>
<td>($\nu_1, \nu_3$)</td>
<td>-0.036 ± 0.042</td>
<td>6.13 ± 0.91</td>
<td>19</td>
<td>1.2</td>
</tr>
<tr>
<td>($\nu_2, \nu_3$)</td>
<td>0.008 ± 0.022</td>
<td>2.19 ± 0.18</td>
<td>19</td>
<td>0.68</td>
</tr>
<tr>
<td>($\nu_1, \nu_2$)</td>
<td>0.0</td>
<td>2.363 ± 0.041</td>
<td>23</td>
<td>2.6</td>
</tr>
<tr>
<td>($\nu_1, \nu_3$)</td>
<td>0.0</td>
<td>5.40 ± 0.19</td>
<td>19</td>
<td>1.2</td>
</tr>
<tr>
<td>($\nu_2, \nu_3$)</td>
<td>0.0</td>
<td>2.257 ± 0.048</td>
<td>19</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*Indicates the number of data points.

outburst. This makes it likely that the X-ray variability of GRO J1719–24 can be described by a single process, the characteristic time scale of which becomes shorter, but the fractional amplitude of which is invariant, during the entire outburst.

2.3 Discussion

Soon after the X-ray detection of GRO J1719–24, a possible optical counterpart was discovered (Della Valle, Mirabel & Rodriguez 1994), the photometric and spectroscopic properties of which suggest that GRO J1719–24 is a low-mass X-ray binary. Since the orbital period and mass function of the system are not determined yet, GRO J1719–24 is regarded a black-hole candidate (BHC) based on its hard energy spectrum only.

In Z sources, which form a subclass of the accreting neutron stars with low magnetic-fields, two types of QPOs have been observed that have properties thought to be related to the accretion rate $\dot{M}$ (see van der Klis 1995b and references therein). In horizontal-branch oscillations (HBO) the frequency (13–55 Hz) of the QPOs increases with source intensity. Such observations led to the introduction of the beat-frequency model. The flaring- and normal-branch oscillations (F/NBO) have an approximately constant frequency between 5 and 7 Hz, and have been modeled in terms of near-Eddington accretion. On phenomenological grounds, it does not seem likely that these mechanisms can explain the observed QPOs in GRO J1719–24; the time scale of the variations in GRO J1719–24 is much longer than those associated with Z sources, the dynamic range in frequency (0.04–0.3 Hz) is considerably larger than in the Z sources, and the source intensity decreases by 20% when the QPO frequency increases by a factor 7.5.

Low-frequency (0.04–0.8 Hz) QPO have been observed in the BHCs Cyg X-1, LMC X-1, GX 339–4 and GRO J0422+32 (van der Klis 1995b). These QPOs were observed while the sources were in their so-called low state, with the exception of LMC X-1 where a 0.08 Hz QPO was found while an ultrasoft component dominated the energy spectrum, showing that the source was in the high state. The large variation in QPO frequency seen in this source gives support to the idea that all low-frequency (≤ 1 Hz) QPOs in BHCs have the same origin. It is important to mention that the intermediate frequency QPOs in GX 339–4 (6 Hz, Miyamoto et al. 1991) and GS 1124–68 (3–10 Hz, Miyamoto et al. 1993) occurred while these sources were in the very high state.
In spite of the large range in frequency of the QPOs, the PDSs of GRO J1719–24 obey a remarkable regularity; their shape, after introducing a frequency scaling factor, does not appear to change much, and the power, integrated over a frequency range scaled by the appropriate frequency scaling factor, remains invariant. In the power density versus frequency plane, each point in the PDSs follows a $\nu^{-1}$ track towards higher frequencies and lower power densities during the outburst. This PDS behavior is consistent with a signal in the time domain whose time scale is stretched, but whose amplitude remains the same, like an accordion. This is reminiscent of the time scale invariance of the type II burst profiles of the Rapid Burster (Lewin, van Paradijs & Taam 1995), which harbors a neutron star (Hoffman, Marshall & Lewin 1978). If these phenomena are related, this would imply that the mechanism responsible for the $\approx 1$ Hz QPOs is not unique to BHCs.

Since the dynamical time scale in the inner region of a disk surrounding a stellar-mass black hole is in the millisecond range, the QPOs in GRO J1719–24 may have an origin farther out in the disk. The inner regions of viscous accretion disks surrounding black holes may suffer thermal-viscous instabilities when radiation pressure is important (Piran 1978). Chen & Taam (1994) have recently suggested that low-frequency QPOs ($\sim 0.04$ Hz) in BHCs may be explicable by such thermal-viscous instabilities. A general property of this disk instability is that the frequency of the oscillation is a function of $M$. Assuming a direct relation between source intensity and $\dot{M}$, one would expect that the frequency increases when the intensity decreases (Chen & Taam 1994). In GRO J1719–24 the QPO frequency increased by a factor 7.5 while the 20–100 keV flux decreased by only 20%; it is not clear whether such a large change in QPO frequency for such a small change in $\dot{M}$ can be explained by this thermal-viscous model. More recently, Abramowicz, Chen & Taam (1995) proposed a model in which the mass accretion and angular

**Figure 2.6:** Fractional rms amplitudes, determined from the three-day averaged PDSs, integrated over frequency ranges scaled by the appropriate frequency scaling factors. The fractional rms amplitude remains approximately constant at an average of $11.35 \pm 0.60\%$. 
momentum transport take place in an optically thick disk, but a fraction of the gravitational energy is dissipated in a corona. Stabilization of the disk depends not only on the rate of coronal energy dissipation but also on the location of the inner radius of the optically thick disk. Their results suggest that the QPO frequency can change, even if the mass accretion rate remains constant.

Acknowledgments

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Hard X-ray lags in GRO J1719–24


Submitted to The Astrophysical Journal

Abstract

We have used the Fourier cross spectra of GRO J1719–24, as obtained with BATSE, to estimate the phase lags between the X-ray flux variations in the 20–50 and 50–100 keV energy bands as a function of Fourier frequency in the interval 0.002–0.488 Hz. Our analysis covers the entire ~80 day X-ray outburst of this black-hole candidate, following the first X-ray detection on 1993 September 25. The X-ray variations in the 50–100 keV band, lag those in the 20–50 keV energy band by an approximately constant phase difference of $0.072 \pm 0.010$ rad in the frequency interval 0.02–0.20 Hz. The peak phase lags in the interval 0.02–0.20 Hz are about twice those of Cyg X-1 and GRO J0422+32. These results are consistent with models for Comptonization regions composed of extended non-uniform clouds around the central source.

3.1 Introduction

THE SOFT X-RAY transient GRO J1719–24 (= GRS 1716–249, Nova Oph 1993) was detected simultaneously with BATSE on board the Compton Gamma Ray Observatory, and the SIGMA telescope on GRANAT, on 1993 September 25 (Harmon et al. 1993b; Ballet et al. 1993). The source reached a maximum X-ray flux of $\sim 1.4$ Crab (20–100 keV) within five days after first detection, and was remarkable for the stability of its hard X-ray emission on a time scale of days; its hard X-ray flux declined at a rate of $\sim 0.3 \pm 0.05\%$ per day (Harmon et al. 1993c). GRO J1719–24 was detected above the BATSE $3\sigma$ one-day detection threshold of 0.1 Crab (20–100 keV) for $\sim 80$ days following the start of the X-ray outburst (Harmon & Paciesas 1993). A time-series analysis of the hard X-ray variability of GRO J1719–24, observed with BATSE in the 20–100 keV energy band, was presented by van der Hooft et al. (1996).
They analyzed the entire 80 day X-ray outburst of GRO J1719–24 in the frequency interval 0.002–0.488 Hz. The power density spectra (PDSs) of GRO J1719–24 show a significant peak, indicative of quasi-periodic oscillations (QPOs) in the time series, whose centroid frequency increases from \( \sim 0.04 \text{ Hz} \) at the start of the outburst, to \( \sim 0.3 \text{ Hz} \) at the end. Van der Hooft et al. (1996) discovered that the evolution in time of the PDSs of GRO J1719–24 can be described by a single characteristic profile, the frequency scale of which is being stretched during the outburst. The total power in each PDS, integrated over corresponding (but relatively scaled) frequency intervals, remained constant throughout the outburst. Therefore, it is likely that the X-ray variability during the entire outburst of GRO J1719–24 can be described by a single process, the characteristic time scale of which becomes shorter, but the fractional amplitude of which is invariant. This may be related to the strong anticorrelation of the break frequency and power density at the break observed in the PDSs of several black-hole candidates (Belloni & Hasinger 1990a). Méndez & van der Klis (1997) suggest a correlation with mass accretion rate may exist, i.e., the break frequency increases (and the power density decreases) with increasing mass accretion rate.

GRO J1719–24 remained undetectable until 1994 September, when several X-ray flares were detected with both SIGMA and BATSE (Churazov et al. 1994; Harmon et al. 1994). Subsequent to strong X-ray flares in 1995 February (Borozdin, Alexandrovich & Sunyaev 1995), a rapidly decaying radio flare was detected, followed by recurrent radio flaring activity (Hjellming et al. 1996). The relation between X-ray and radio events is similar to that observed in the superluminal radio-jet sources GRO J1655–40 and GRS 1915+105 (Hjellming et al. 1996; Foster et al. 1996): radio emission follows the peak, or onset to decay of X-ray flares observed with BATSE in the 20–100 keV energy band, by intervals ranging from a few to 20 days (Hjellming et al. 1996). GRO J1655–40 is a galactic black-hole candidate (BHC) with a dynamically determined mass of \( 7.0 \pm 0.7 \text{ M}_\odot \) (Orosz & Bailyn 1997; van der Hooft et al. 1998a).

A possible optical counterpart to the X-ray source was discovered by Della Valle, Mirabel & Rodriguez (1994), the photometric and spectroscopic properties of which suggest that GRO J1719–24 is a low-mass X-ray binary. The optical brightness of GRO J1719–24, measured during three weeks after first X-ray detection, is modulated at a period of 0.6127 days, thought to be the superhump period (Masetti et al. 1996). Quiescent optical photometry and/or spectroscopy of GRO J1719–24 has not been reported. The source is considered a black-hole candidate on the basis of its X-ray and radio analogies to dynamically proven BHCs.

We have investigated the phase (or, equivalently, time) lags in the hard X-ray variability of GRO J1719–24 during its 1993 X-ray outburst. We calculated lags between the 20–50 and 50–100 keV energy bands of the 1.024 sec time resolution BATSE data and compare our results with those obtained in recent similar studies of the black-hole candidates Cyg X-1 (Cui et al. 1997a; Crary et al. 1998) and GRO J0422+32 (Grove et al. 1997; van der Hooft et al. 1998b).

### 3.2 Analysis

A time-series analysis of the hard X-ray (20–100 keV) data of the entire 1993 outburst of GRO J1719–24 was presented by van der Hooft et al. (1996). These data were obtained in two broad energy channels (20–50 and 50–100 keV) with the large-area detectors of BATSE, collected during 80 days following first X-ray detection on 1993 September 25. Fast Fourier Transforms were created for 524.288 sec long time intervals (512 time bins of 1.024 sec each);
Figure 3.1: Average phase (left panel) and time (right panel) lags of GRO J1719-24 between the 20–50 and 50–100 keV energy bands (hard lags appear as positive angles). These averages cover the full 80 day outburst of the source. The frequency scale has been logarithmically rebinned into 34 bins. Triangles indicate data points or error bars which are outside the scale of the figure.

The corresponding frequency interval covered 0.002–0.488 Hz. The average number of uninterrupted 512 bin segments available with the source unocculted by the Earth was approximately 35 per day. See van der Hooft et al. (1996) for a detailed description of the reduction and analysis of these data.

The complex Fourier cross spectra were created from the Fourier amplitudes in a way identical to that described by van der Hooft et al. (1998b). These cross spectra were averaged daily. Errors on the real and imaginary parts of the daily averaged cross spectra were calculated from the respective sample variances, and formally propagated when computing the phase and time lags. The phase lags, $\phi_j$, as a function of frequency were obtained from the cross spectra via $\phi_j = \arctan(\text{Im}(C_j^{12})/\text{Re}(C_j^{12}))$, and the corresponding time lag $\tau_j = \phi_j/2\pi\nu_j$, with $\nu_j$ the frequency in Hz of the $j$-th frequency bin. With these definitions, lags in the hard X-ray variations (50–100 keV) with respect to the soft X-ray variations (20–50 keV) appear as positive angles.

Cross spectra for a large number of days must be averaged and converted to lag values in order to obtain sufficiently small errors (see, e.g., Crary et al. 1998; van der Hooft et al. 1998b). Therefore, we averaged the phase and time lags between the 20–50 and 50–100 keV energy bands of the entire 80 day X-ray outburst of GRO J1719–24. These are presented in Figure 3.1. The time lags are displayed on a logarithmic scale. Time lags at frequencies above $0.5\nu_{Nyq}$ are displayed but not not taken into account to our analysis, as Crary et al. (1998) have shown that data binning effects distort the shape of the cross spectra at these frequencies. These data show that at the lowest frequencies the phase lags are consistent with zero (0.021 ± 0.028 rad, average of 0.001–0.02 Hz; 9 bins). At frequencies above 0.02 Hz, the hard X-rays lag the soft by 0.072 ± 0.010 rad (average of 0.02–0.20 Hz; 94 bins). The phase lags averaged over two 40 days intervals are similar to those averaged over the entire 80 day outburst. The time lags of GRO J1719–24 decrease with frequency as a power law, with index 1.04 ± 0.13 for frequencies $\geq 0.01$ Hz. The extrapolation of this power law for frequencies smaller than 0.01 Hz is well above the measured time lags.
3.3 Discussion

The 20–100 keV energy spectrum steadily softened during the entire X-ray outburst of GRO J1719–24 in 1993; the photon index increased from 2.0 to 2.3 ± 0.05 during the rise to peak intensity, beyond which the spectrum softened more gradually. No marked changes in the spectral shape were observed during the sudden decrease in X-ray flux in 1993 December (van der Hooft et al. 1996). It is not possible, on the basis of 20–100 keV BATSE observations alone, to distinguish between black hole source states. However, observations at low X-ray energies during the decay of the X-ray light curve of GRO J1719–24, suggest that the source was most likely in the low (or hard) state. The 2–300 keV X-ray spectrum, obtained about 30 days after first detection of GRO J1719–24 by combining SIGMA data with quasi-contemporaneous data taken by TTM on board Mir-Kvant, was quite similar to the low state spectrum of Cyg X-1. The 2–300 keV spectrum of GRO J1719–24 then had a power-law shape without a soft component, and a cut off at energies above 100 keV (Revnivtsev et al. 1998). Therefore, these observations indicate that 30 days after the X-ray outburst had started, GRO J1719–24 was in the low state. The lack of significant changes in the hard X-ray properties (van der Hooft et al. 1996) of GRO J1719–24, suggest that this conclusion applies to the entire 1993 outburst.

Recently, Crary et al. (1998) and van der Hooft et al. (1998b) have studied lags between the X-ray flux variations in 20–50 and 50–100 keV BATSE data of the black-hole candidates Cyg X-1 and GRO J0422+32. Cui et al. (1997a) measured hard X-ray time lags in 2–60 keV RXTE data of Cyg X-1, obtained during 1996. Crary et al. (1998) studied Cyg X-1 for a period of almost 2000 days, during which the source was likely in both the low, and high or intermediate state. They found that the lag spectra between the X-ray variations in the 20–50 and 50–100 keV energy bands of Cyg X-1 do not show an obvious trend with source state. They grouped the phase lag data according to the squared fractional rms amplitude of the noise, integrated in the frequency interval 0.03–0.488 Hz. The average phase lags of Cyg X-1 are reproduced in Figure 3.2. They find that at the lowest frequencies the phase lag is consistent with zero. For higher frequencies the phase lag increases to a maximum of 0.04 rad near 0.20 Hz, and decreases again to near zero at the Nyquist frequency.

Crary et al. (1998) showed that binning effects decrease the observed hard X-ray time lags to zero at the Nyquist frequency. Therefore, time lags obtained for frequencies between 0.5 ν$_{Nyq}$ and ν$_{Nyq}$ may be affected by data binning. The Cyg X-1 X-ray variations in the 50–100 keV band lag those in the 20–50 keV band over the 0.01–0.20 Hz frequency interval by a time interval proportional to $\nu^{-0.8}$. The time lags in the Cyg X-1 hard X-ray data are reproduced as a function of frequency in Figure 3.3.

Cui et al. (1997a) studied Cyg X-1 during its 1996 spectral transitions. The observed period can be divided into a transition from the hard state to the soft state, a soft state, and a transition from the soft state back to the hard state. The lag spectra obtained by Cui et al. (1997a) cover the frequency range 0.01–100 Hz. They find that during the state transitions the time lags between energy bands with average energy $E_0$ and $E_1$, scale with photon energy roughly as log($E_1/E_0$). Such a scaling is consistent with the predictions of thermal Comptonization in the corona (see, e.g., Payne 1980; Hua & Titarchuk 1996; Kazanas, Hua & Titarchuk 1997). In the soft state, the time lags become much smaller. This implies that in the soft state the size of the corona becomes much smaller.

Van der Hooft et al. (1998b) determined lags in the hard X-ray variability of GRO J0422+32 during its 1992 outburst. Their time-series analysis covered the entire 180 day X-ray outburst. GRO J0422+32 is a dynamically proven black-hole candidate; during its 1992 outburst it was...
most likely in the low state (van der Hooft et al. 1998b). They averaged the phase lags of GRO J0422+32 over a 30 day interval following first X-ray detection of the source, and over a flux-limited sample of the remaining data (95 days). Statistically significant lags were derived for the shorter interval only. The 30 day averaged phase lags of GRO J0422+32 are shown in Figure 3.4. They find that at the lowest frequencies the phase lag of GRO J0422+32 is consistent with zero (0.014±0.006 rad, 0.001–0.02 Hz). At frequencies ≥0.02 Hz, the variations in the 50–100 keV band lag those in the 20–50 keV band by 0.039±0.003 rad (average of 0.02–0.20 Hz).

The time lags of GRO J0422+32, during the first 30 days of its outburst, decrease with frequency as a power law, with index ~0.9 for ν > 0.01 Hz (van der Hooft et al. 1998b). The 30 day averaged time lags of GRO J0422+32 are shown in Fig. 3.4. Grove et al. (1997) studied the time lags of GRO J0422+32 between the X-ray variations in the 35–60 keV band and 75–175 keV band with OSSE. They find that the hard X-ray emission lags the soft emission at all Fourier frequencies, decreasing roughly as ν⁻¹ up to about 10 Hz. At frequencies of ~0.01 Hz, hard time lags as large as 0.3 sec are observed. The hard time lags of GRO J0422+32 obtained by Grove et al. (1997), are consistent with those obtained by van der Hooft et al. (1998b).

The phase lags of GRO J1719–24 are very similar to those of GRO J0422+32 and Cyg X-1. At the lowest frequencies the phase lags are consistent with zero, at frequencies of ~0.10 Hz the variations in the 50–100 keV band lag those in the 20–50 keV band. The phase lags of GRO J1719–24, averaged in the interval 0.02–0.20 Hz, are about twice as large as those detected in GRO J0422+32 and Cyg X-1.

Figure 3.2: Phase lags between 20–50 and 50–100 keV data for various daily averaged squared rms levels, s, of Cyg X-1. All data with s > 0.03 (a), 0.03 < s < 0.05 (b), 0.05 < s < 0.07 (c), and s > 0.07 (d). Figure taken from Crary et al. (1998).
These results show that the hard time lags observed in GRO J1719−24, GRO J0422+32 and Cyg X-1 are all very similar. The hard X-ray radiation lags the soft X-ray radiation by as much as $\sim 0.1$−1 sec at low frequencies. The time lags are strongly dependent on the Fourier frequency, and decrease roughly as $\nu^{-1}$. The $\nu^{-1}$ dependence of the hard time lags is very different from the lags expected from simple models of Compton upscattering of soft X-rays by a cloud of hot electrons near the black hole. In such a case, the energy of the escaping photons increases with the time they reside in the cloud. Therefore, higher energy photons, lag the photons with lower energies by an amount proportional to the photon scattering time. If the hard X-rays are emitted from a compact region near the black hole, the resulting time lags should be independent of Fourier frequency and of the order of milliseconds.

However, analysis of the hard time lags in the X-ray variability of black-hole candidates can provide information on the density structure of the accretion gas (Hua, Kazanas & Titarchuk 1997). Kazanas et al. (1997) argued that the Comptonization process takes place in an extended non-uniform cloud around the central source. They showed that such a model can account for the form of the observed PDS and energy spectra of compact sources. Hua et al. (1997) showed that the phase and time lags of the X-ray variability depend on the density profile of such an extended scattering atmosphere. Their Monte Carlo simulations of scattering in a cloud with a density profile proportional to $r^{-1}$ agree with our time lag data both in magnitude ($\sim 0.1$ sec at 0.10 Hz) and frequency dependence ($\nu^{-1}$). The results presented here support the idea that the Comptonizing regions around the black holes in Cyg X-1, GRO J0422+32 and GRO J1719−24 are quite similar in density distribution and size.
Figure 3.4: Average phase (left) and time (right) lags of GRO J0422+32 between the 20–50 and 50–100 keV energy bands (hard lags appear as positive angles). These averages cover 30 days following first X-ray detection of the source. The frequency scale has been logarithmically rebinned into 34 bins. Upper (lower) limits are indicated by triangles. Figure taken from van der Hooft et al. (1998b).

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Hard X-ray variability of the black-hole candidate GRO J0422+32 during its 1992 outburst


Abstract

We have studied the X-ray variability of the soft X-ray transient GRO J0422+32 with BATSE in the 20–100 keV energy band. Our analysis covers 180 days following the first X-ray detection of the source on 1992 August 5, fully covering its primary and secondary X-ray outburst. We computed power density spectra (PDSs) in the 20–50, 50–100, and 20–100 keV energy bands, in the frequency interval 0.002–0.488 Hz. The PDSs of GRO J0422+32 are approximately flat up to a break frequency, and decay as a power law above, with index ~ 1. During the first 70 days of the X-ray outburst, the PDSs of GRO J0422+32 show a significant QPO peak near ~ 0.2 Hz, superposed on the power-law tail. The break frequency of the PDSs obtained during the primary X-ray outburst of GRO J0422+32 occurs at 0.041 ± 0.006 Hz; during the secondary outburst the break is at 0.081 ± 0.015 Hz. The power density at the break ranged between 44 and 89% Hz$^{-1/2}$(20–100 keV). The canonical anticorrelation between the break frequency and the power density at the break, observed in Cyg X-1 and other BHCs in the low state, is not observed in the PDSs of GRO J0422+32.

We compare our results with those of similar variability studies of Cyg X-1. The relation between the spectral slope and the amplitude of the X-ray variations of GRO J0422+32 is similar to that of Cyg X-1; however, the relation between the hard X-ray flux and the amplitude of its variation is opposite to what has been found in Cyg X-1. Phase lags between the X-ray flux variations of GRO J0422+32 at high and low photon energies, could only be derived during the first 30 days of its outburst. During this period, the variations in the 50–100 keV, lag those in the
4.1 Introduction

Soft X-ray transients (SXTs) are low-mass X-ray binaries consisting of a neutron star or black-hole primary that undergoes unstable accretion from a late-type companion. Disk instabilities (van Paradijs 1996; King, Kolb & Burderi 1996) cause brief but violent outbursts, typically lasting weeks to months, during which the X-ray luminosity abruptly increases by several orders of magnitude, to \( \sim 10^{37} - 5 \times 10^{38} \text{ erg sec}^{-1} \), separated by quiescent intervals lasting from years to many decades.

The SXT GRO J0422+32 (Nova Persei 1992) was detected with the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory on 1992 August 5 (Paciesas et al. 1992). Initially, the hard X-ray flux of the source increased rapidly, reaching a maximum of \( \sim 3 \text{ Crab} \) (20–300 keV) within three days after first detection (Paciesas et al. 1992), at which level it remained for the following three days (Harmon et al. 1992). Subsequently, the hard X-ray intensity (40–150 keV) of GRO J0422+32 decreased exponentially with a decay time of 43.6 days (Vikhlinin et al. 1995). About 135 days after the primary X-ray maximum, the X-ray flux of GRO J0422+32 reached a secondary maximum, after which the flux continued to decrease with approximately the same decay time as before. The source was detected above the BATSE 3\( \sigma \) one-day detection threshold of 0.1 Crab (20–300 keV) for \( \sim 200 \) days following the start of the X-ray outburst. The daily averaged 40–150 keV flux history of GRO J0422+32 during this period is displayed in Figure 4.1.

The X-ray spectrum of GRO J0422+32 was hard and could be well described by a cut-off power law with photon index \( \sim 1.5 \) and break energy \( \sim 60 \text{ keV} \), detected up to 600 keV with OSSE (Grove, Kroeger & Strickman 1997). In observations of GRO J0422+32 during X-ray maximum with COMPTEL, the source was detected up to \( \sim 1-2 \text{ MeV} \) (van Dijk et al. 1995). Timing analysis of the hard X-ray data revealed quasi-periodic oscillations (QPOs) centered at 0.03 and 0.2 Hz (20–300 keV BATSE data, Kouveliotou et al. 1992, 1993) and 0.3 Hz (40–150 keV SIGMA data, Vikhlinin et al. 1995). These QPOs detected in hard X-rays were confirmed by ROSAT observations in the 0.1–2.4 keV energy band (Pietsch et al. 1993). The power density spectra (PDSs) of GRO J0422+32 were flat for frequencies, \( \nu \), below the first QPO peak at 0.03 Hz, and fall as \( \nu^{-1} \) between both QPOs (Kouveliotou et al. 1992). The total fractional rms variations of the 40–150 keV flux in the \( 10^{-3} - 10^{-1} \) Hz frequency interval, ranged between \( \sim 15\% \) and \( \sim 25\% \) (Vikhlinin et al. 1995). The observed hard X-ray spectrum and rapid X-ray variability resemble the properties of dynamically proven black-hole candidates (BHCs) (Sunyaev et al. 1991a; Tanaka & Lewin 1995; see however, van Paradijs & van der Klis 1994), which led to the suggestion that GRO J0422+32 is also a BHC (Roques et al. 1994).

Soon after its first X-ray detection, the optical counterpart of GRO J0422+32 was independently identified by Castro-Tirado et al. (1992, 1993) and Wagner et al. (1992) at a peak magnitude of \( V = 13.2 \). This object was absent on the POSS down to a limiting magnitude of \( R \approx 20 \) (Castro-Tirado et al. 1993). During the first 210 days of the X-ray outburst the optical light curve declined exponentially with an e–folding time of 170 days (Shrader et al. 1994). Then the
Figure 4.1: Flux history of GRO J0422+32 measured by BATSE in the 40–150 keV energy band. The source was detected first on 1992 August 5 and reached a maximum flux of ~3 Crab within 3 days. Hereafter the X-ray intensity decreased exponentially, and reached a secondary (local) maximum in X-ray intensity at 139 days after its initial detection. The source became undetectable by BATSE after ~200 days. Dashed lines indicate the levels 0.00 and 0.04 photons/cm² sec⁻¹.

Optical brightness dropped quickly, followed by two mini-outbursts (with an amplitude of ~4 mag each) before it finally reached quiescence at V = 22.35, ~800 days after first detection of the X-ray source (Garcia et al. 1996). Therefore, the outburst amplitude of GRO J0422+32 was about 9 mag in V, the largest observed in any SXT to date (van Paradijs & McClintock 1995). The optical light curve of GRO J0422+32, during and after the X-ray outburst, bears many characteristics similar to those of the so-called 'tremendous outburst amplitude dwarf novae' (TOADs). Kuulkers, Howell & van Paradijs (1996) proposed that these similarities reflect the small mass ratios and very low mass transfer rates in SXTs and TOADs.

During the decay to quiescence, optical brightness modulations were reported at periods of ~2.1, 5.1, 10.2, and 16.2 hr, respectively (Harlaftis et al. 1994; Callanan et al. 1995; Kato, Mineshige & Hirata 1995; Chevalier & Ilovaisky 1995; Martin et al. 1995b). Spectroscopic observations by Filippenko, Matheson & Ho (1995) showed that the orbital period is $5.08 \pm 0.01$ hr, and determined the mass function at $f(M) = 1.21 \pm 0.06 M_{\odot}$. This value of the mass function is confirmed by observations performed by Orosz & Bailyn (1995), $f(M) = 0.40–1.40 M_{\odot}$, and Casares et al. (1995), $f(M) = 0.85 \pm 0.30 M_{\odot}$. The orbital inclination, $i$, of GRO J0422+32 was estimated from an interpretation of the double waved light curve as an ellipsoidal variation. From the $\Delta I \sim 0.03$ mag semi-amplitude modulation Callanan et al. (1996) derived $i \leq 45^\circ$. This implies a mass of $\geq 3.4 M_{\odot}$ for the compact star, i.e., slightly above the (theoretical) maximum mass of a neutron star. Independently, Beekman et al. (1997) constrain the inclination of GRO J0422+32 from infrared and optical photometry to be between $10^\circ$ and $31^\circ$. Consequently, their lower limit to the mass of the compact star becomes $\geq 9 M_{\odot}$. Therefore, the compact star in GRO J0422+32 is most probably a black hole.
Here we report on a temporal analysis of 20–100 keV BATSE data of GRO J0422+32 collected during 180 days following its first detection. We derive the X-ray light curve of the source and discuss its hard X-ray spectrum. We compute daily averaged power density spectra in the frequency interval 0.002–0.488 Hz and show their evolution in time. From the Fourier amplitudes we compute cross spectra and derive the phase and time lags between the hard and soft X-ray variations of GRO J0422+32. We compare our results with those of similar analyses of Cyg X-1.

4.2 X-ray light curve and X-ray spectrum

We have determined the flux of GRO J0422+32 by applying the Earth occultation technique (Harmon et al. 1993d) to data obtained with the BATSE large-area detectors (count rates with a 2.048 sec time resolution in 16 spectral channels). The average number of occultation steps of GRO J0422+32 was 13 per day, ranging from 2 to 24. The systematic error due to the variable orientation of CGRO, is typically ~ 5–10%. The daily averaged flux history of GRO J0422+32 in the 40–150 keV energy band is displayed in Fig. 4.1. The X-ray light curve rises from first detection to a maximum of ~ 3 Crab (20–300 keV) in three days, followed by an exponential decrease with a decay time of 43.6 days (Vikhlinin et al. 1995). During the decay of the X-ray light curve, a secondary maximum is observed at about 135 days after the main X-ray maximum. After the secondary maximum the light curve decays at approximately the same rate as before. The whole 1992 X-ray outburst of GRO J0422+32 lasted for ~ 200 days.

The 40–150 keV X-ray spectrum of GRO J0422+32 measured by BATSE was approximated by a single power law. A single power law does not provide a good fit to the X-ray spectrum, but is useful as a coarse indicator of the spectral hardness. The power-law index of the spectrum was ~ 2.1 at the peak of the primary outburst; the spectrum became harder during its decay.

Figure 4.2: Distribution of the daily averaged flux measurements versus photon power-law index of GRO J0422+32 in the 40–150 keV energy band. The sample consists of daily averaged data and is flux-limited ($F \geq 0.04$ photons/cm$^2$ sec$^{-1}$). The distribution consists of 103 data points taken during the primary outburst, and 23 days of the secondary outburst.
The distribution of one-day averaged flux measurements versus the photon power-law indices of GRO J0422+32 in the 40–150 keV energy band is shown in Figure 4.2. The distribution is flux-limited ($F \geq 0.04$ photons/cm$^2$ sec$^{-1}$) and contains a total of 126 data points, 23 of which corresponding to the secondary outburst. For flux values above 0.20 photons/cm$^2$ sec$^{-1}$, flux and power-law index appear to be correlated positively. For $F \leq 0.20$ photons/cm$^2$ sec$^{-1}$, the photon power-law index is determined less accurately, and remains constant at $1.89 \pm 0.02$ (average of 84 data points, weighted by the individual errors). The weighted average of the photon power-law index obtained during the primary outburst only ($1.89 \pm 0.02$, 61 data points), is consistent with that of the secondary outburst ($1.92 \pm 0.04$, 23 data points).

4.3 Time series analysis

We have used count-rate data from the large-area detectors (four broad energy channels) with a time resolution of $\Delta T = 1.024$ sec and applied an empirical model (Rubin et al. 1996) to subtract the signal due to the X-ray/gamma-ray background. This model describes the background by a harmonic expansion in orbital phase (with parameters determined from the observed background variations), and includes the risings and settings of the brightest X-ray sources in the sky. It uses eight orbital harmonic terms, and its parameters were updated every three hours.

For our analysis we considered data segments of 524.288 sec (512 time bins of 1.024 sec each) on which we performed Fast Fourier Transforms (FFTs) covering the frequency interval 0.002–0.488 Hz. The average number of uninterrupted 512 bin segments available while the source was not occulted by the Earth was 32 per day. For each of the detectors which had the source within 60° of the normal, we calculated the FFTs of the lowest two energy channels (20–50, 50–100 keV) of each data segment separately. These FFTs were coherently summed (weighted by the ratio of the source to the total count rates) and converted to PDSs. The source count rates were obtained from the occultation analysis. The PDSs were normalized such that the power density is given in units of $(\text{rms/mean})^2$ Hz$^{-1}$ (see, e.g., van der Klis 1995a) and finally averaged over an entire day.

4.3.1 Power density spectra (PDSs)

The power spectra of GRO J0422+32 are approximately flat up to a break frequency, and decay as a power law above (see Figure 4.4). During the first ~70 days of the outburst, the PDSs show a significant peak, indicative of QPOs in the time series, superposed on the power-law tail. For all PDSs obtained during this stage of the X-ray outburst, the centroid frequency of the QPO peak is above the break frequency. Beyond day ~70, the QPOs are no longer detected significantly in the PDSs; the power spectra obtained during the remaining part of the outburst are well described by a broken power law only.

The evolution of the daily averaged PDSs (20–100 keV) of GRO J0422+32 during the first 80 days of the outburst is illustrated in a dynamical spectrum (Figure 4.3). In this representation the frequency scale is logarithmically rebinned to 61 bins; the darker the color, the higher is the power level. In Fig. 4.3, a dark shaded band, indicative of QPOs in the time series, is seen at centroid frequencies between 0.13 and 0.26 Hz until approximately day 70 of the outburst. The centroid frequency of the QPO increases slowly until day 20, and gradually decreases
Figure 4.3: Dynamical spectrum of the set of daily averaged, $(\text{rms}/\text{mean})^2$ Hz$^{-1}$ normalized PDSs (20–100 keV) covering the first 80 days of the outburst of GRO J0422+32. The frequency scale has been logarithmically rebinned; dark colors indicate a high power level.
Figure 4.4: The five-day averaged power spectrum (20–100 keV) of GRO J0422+32 for days 33–37 and the best-fit model (broken power law plus Lorentzian profile) (top panel), and the residuals (bottom panel). The frequency scale has been logarithmically rebinned into 34 bins.

... afterwards (see also Figure 4.6). During days 50–70 of the outburst, there is some evidence for the presence of a second, very weak peak in the power spectra. This second feature is much weaker than the main QPO peak, and is found at frequencies between the break of the power law and the centroid frequency of the main QPO. From about 70 days after the start of the outburst onward, neither the main QPO peak nor the second feature are present significantly in the PDSs of GRO J0422+32.

The break in the power spectra of GRO J0422+32 is clearly visible at low frequencies in the dynamical spectrum of Fig. 4.3. During the period displayed in this dynamical spectrum, the break frequency remains constant, and occurs at 0.037 ± 0.004 Hz. As the outburst of GRO J0422+32 proceeds, the power density increases over the total frequency interval of the PDSs. This effect is most prominently seen at low frequencies in the dynamical spectrum, indicated by the darker shaded area starting at day ~ 30, but is present in the total frequency interval of the power spectra. From Fig. 4.3 it also follows that the power density of the PDSs obtained during the first three days of the X-ray outburst of GRO J0422+32 is enhanced with respect to the remaining data, indicating increased rapid variability at the very start of the outburst compared to later stages of the outburst.
4.3.2 Fits to the PDSs

We made fits to the PDSs in the 20–50, 50–100 and 20–100 keV energy bands, using a combination of a Lorentzian profile and a broken power law. To improve statistics, we made fits to the average PDSs of five consecutive days during the first 110 days of the outburst (obtaining 22 five-day averaged PDSs), and averages of ten consecutive days afterward (obtaining 7 ten-day averaged PDSs). A typical five-day averaged power spectrum in the 20–100 keV energy band, together with the model fit, is shown in the top panel of Fig. 4.4. The model requires seven parameters (three for the Lorentzian, four for the broken power law), which left 27 degrees of freedom as the PDSs were logarithmically rebinned into 34 frequency bins. The Lorentzian profile was included during the first 70 days of the outburst only (i.e., 14 five-day averaged PDSs). Inclusion of a Lorentzian profile during later stages of the outburst did not significantly improve the quality of the fit. We routinely obtained reduced $\chi^2$ values between 0.6 and 2.9 for
Figure 4.6: Parameters of Lorentzian profile of the model fit to the five-day averaged PDSs of GRO J0422+32 in the 20–50 (top row), 50–100 (middle row), and 20–100 keV (bottom row) energy bands. The history of the centroid frequency (left column), and full width at half maximum (right column) of the Lorentzian are displayed logarithmically. The Lorentzian component of the fit was included during the first 70 days of the outburst of GRO J0422+32 only.

The fits to the PDSs. As the outburst of GRO J0422+32 continued, the received flux decreased (see Fig. 4.1) for which reason the power spectra became ill-constrained at the local flux minimum near day ~ 120 of the outburst. During the secondary maximum the quality of the PDSs improved slightly.

The histories of the break frequency $\nu_{\text{break}}$, and indices of the broken power-law component for $\nu < \nu_{\text{break}}$, and $\nu > \nu_{\text{break}}$ (29 data points in each energy band), are presented in Figure 4.5. The evolution of the centroid frequency and full width at half maximum (FWHM) of the Lorentzian profile (14 data points per energy band only, as the Lorentzian profile was included only during the first 70 days of the X-ray outburst) are shown in Fig. 4.6. From these figures it can be seen that the centroid frequency of the Lorentzian profile increased during the first 3 weeks of the outburst of GRO J0422+32 from an initial value of ~ 0.15 Hz to a maximum of ~ 0.26 Hz, but from that moment on monotonically decreased to ~ 0.1 Hz 70 days after the onset of the outburst. The FWHM of the Lorentzian is determined best in the PDSs in the 20–100 keV energy bands.
4.3.3 Break frequency

The relation between the break frequency and the power density at the break in the PDSs of GRO J0422+32, is displayed in Figure 4.7 for the 20–50, 50–100, and 20–100 keV energy bands. From the 20–100 keV data it follows that the power density at the break covers a broad range of values (44–89% Hz$^{-1/2}$), while the break frequency appears to cluster at 0.041 ± 0.006 and 0.081 ± 0.015 Hz. Data obtained from the secondary outburst of GRO J0422+32 (7 ten-day averaged PDSs) are indicated in Fig. 4.7 by triangles, while those of the primary outburst (22 five-day averaged PDSs) are denoted by dots. The 20–100 keV data in this figure (right panel), clearly show that the break frequencies near ~0.08 Hz all correspond to PDSs obtained during the secondary outburst of GRO J0422+32. Those of the primary outburst, all cluster at a frequency near ~0.04 Hz. The distribution of the break frequency and the power density at the break determined in the 20–50 keV and the 50–100 keV data shows more scatter, but follows the same trend: the low break frequency corresponds to the primary outburst of GRO J0422+32, while the high break frequency occurs during the secondary outburst.

This effect is illustrated again in Figure 4.8, in which we show two averaged power spectra of GRO J0422+32 in the 20–100 keV energy band, obtained during different stages of its outburst, as well as their respective model fits. The left panel contains two PDSs with equal break
frequency, but different power density at the break, i.e., both PDSs were obtained during the primary outburst of GRO J0422+32. The PDS of day 3–7 (indicated by dots) has a break frequency and power density at the break of \((\nu_{\text{break}}, \text{rms}) = (0.038 \pm 0.004 \text{ Hz}, 55 \pm 2\% \text{ Hz}^{-1/2})\); triangles indicate the PDS corresponding to day 68–72 with \((0.037 \pm 0.002 \text{ Hz}, 76 \pm 2\% \text{ Hz}^{-1/2})\). The right panel displays two PDSs with equal power density at the break, but different break frequency, selected from both the primary and secondary outburst. Dots indicate the PDS obtained during day 3–7 as in the left panel, while the triangles correspond to the PDS obtained during day 153–162. The break frequency and power density at the break in this power spectrum were \((0.073 \pm 0.008 \text{ Hz}, 57 \pm 1\% \text{ Hz}^{-1/2})\).

### 4.3.4 Fractional rms amplitudes

We determined fractional rms amplitudes by integrating the single-day averaged PDSs of GRO J0422+32 in the 20–50, 50–100, and 20–100 keV energy bands over three different frequency intervals. One interval covered the flat part of the power spectrum below the break frequency \((0.005–0.03 \text{ Hz}; 12 \text{ bins})\). A second interval was selected in the power-law tail of the PDSs \((0.10–0.48 \text{ Hz}; 199 \text{ bins})\), and the last frequency interval was chosen across the break frequency \((0.01–0.10 \text{ Hz}; 46 \text{ bins})\), including both the flat part and the power-law tail of the PDSs. The history of the integrated fractional rms amplitudes of GRO J0422+32 in time are given in Figure 4.9. For each frequency interval over which the PDSs were integrated, the general shape of these curves in the three different energy bands are very similar. The largest rapid X-ray variability occurs in the lowest energy band.

During the onset of the primary X-ray outburst of GRO J0422+32, the fractional rms amplitudes decrease rapidly over the total frequency interval in each of the three energy bands of the daily
average PDSs. The fractional rms amplitudes are especially large during the first two days of the outburst in the low frequency intervals, which can also be seen in the dynamical power spectrum of Fig. 4.3. At the X-ray maximum of GRO J0422+32 and shortly thereafter, the rms amplitudes continue to decrease, but at a slower pace. About two weeks after X-ray maximum, the rms amplitudes reach an absolute minimum in each of the three energy bands and in each frequency interval. From that moment on, the fractional rms amplitudes gradually increase until day ~65 of the outburst, after which they suddenly decrease to a local minimum at day ~73. Such variations in the fractional rms amplitude, are present in each of the histories displayed in Fig. 4.9. The flux history of GRO J0422+32 does not show any features during this phase of the outburst, but proceeds its smooth exponential decay (see Fig. 4.1).

After the local minimum in fractional rms amplitude at day ~73 of the outburst, the amplitudes increase again, but become uncertain and are dominated by detector noise at low flux levels of GRO J0422+32 due to unresolved sources in the uncollimated field of view of BATSE. The
Figure 4.10: Fractional rms amplitudes of GRO J0422+32 in the 20–100 keV energy band integrated in the 0.005–0.03 (left column), 0.01–0.10 (middle column), and 0.10–0.48 Hz (right column) frequency intervals, versus the flux (top row) and photon power-law index (bottom row) in the 40–150 keV energy band. The sample is flux-limited ($F \geq 0.04$ photons/cm$^2$ sec$^{-1}$) and consists of 103 data points of the primary, and 23 data points of the secondary outburst.

Largest fractional rms amplitudes are obtained shortly before the onset of the secondary maximum in the light curve. At this secondary maximum, the fractional rms amplitudes obtained in the 0.01–0.10 and 0.10–0.48 Hz frequency intervals again reach a local minimum. The fractional rms amplitudes obtained in the 0.001–0.03 Hz interval do not exhibit such a minimum, but appear to be flat during the remainder of our analysis.

We have plotted the 20–100 keV fractional rms amplitudes obtained in the 0.005–0.03, 0.01–0.10 and 0.10–0.48 Hz frequency intervals, versus the 40–150 keV flux and photon power-law index of GRO J0422+32 in Figure 4.10. The distribution is flux-limited, similar to Fig. 4.2 ($F \geq 0.04$ photons/cm$^2$ sec$^{-1}$), and consists of 103 data points of the primary, and 23 data points of the secondary outburst. The fractional rms amplitudes appear to be anticorrelated with the flux of GRO J0422+32; the smallest rms amplitudes were obtained at the highest flux values. The single point deviating from the general trend in the fractional rms amplitude versus flux distribution in the 0.005–0.03 and 0.01–0.10 Hz frequency intervals corresponds to day 2 of the outburst. Again, this suggests that the low frequency X-ray variability of GRO J0422+32 was exceptionally high during the start of its outburst. The photon power-law indices and fractional rms amplitudes also appear to be anticorrelated: the trend in Fig. 4.10 is one of larger fractional rms amplitudes as the X-ray spectrum of GRO J0422+32 hardens.
4.4 Lag spectra

We have calculated lags between the X-ray variations in the 20–50 and 50–100 keV energy bands of the 1.024 sec time resolution data of GRO J0422+32. The cross amplitudes were created from the Fourier amplitudes \( a_j = \sum_k c_k \exp(i2\pi kj/n) \), where \( n \) is the number of time bins (512), \( c_k \) denotes the count rate in bin \( k = 0, \ldots, n-1 \) and channel number \( l = 0, 1 \) and \( j = -n/2, \ldots, n/2 \) corresponds to Fourier frequencies \( 2\pi j/n\Delta T \). The complex cross spectra of channel 0 and 1 are given by \( C_{01}^{01} = a_j^* a_j^0 \) and were averaged daily. Errors on the real and imaginary parts of these daily averaged cross spectra were calculated from the respective sample variances, and formally propagated when computing the phase and time lags. The phase lags as a function of frequency are obtained from the cross spectra via \( \phi_j = \arctan[\text{Im}(C_{01}^{01})/\text{Re}(C_{01}^{01})] \), and the time lag \( \tau_j = \phi_j/2\pi\nu_j \), with \( \nu_j \) the frequency in Hz of the \( j \)-th frequency bin. With these definitions, lags in the hard (50–100 keV) with respect to the soft (20–50 keV) X-ray variations, appear as positive angles.

The phase lags of GRO J0422+32 between the X-ray variations in the 20–50 and 50–100 keV energy bands, averaged over a 30 day interval at the start of the outburst, and averaged over an interval covering the following 95 days, are presented in Figure 4.11. Cross spectra for a large number of days must be averaged and converted to lag values to obtain sufficiently small errors. Cross spectra of the final 55 days of our analysis were not taken into account in the second average, as inclusion of these data did not significantly improve the quality of the average cross spectrum. Figure 4.12 shows the corresponding time lags on a logarithmic scale. Lags at frequencies above \( 0.5\nu_{Nyq} \) are displayed but not taken into account in our analysis, as Crary et al. (1998) have shown that lags between \( 0.5\nu_{Nyq} \) and \( \nu_{Nyq} \) can be affected by data binning, and therefore, decrease artificially to zero. Our results show that at the lowest frequencies the phase lags are consistent with zero (0.014 ± 0.006 rad, 0.001–0.02 Hz; 9 bins). At frequencies
Figure 4.12: Average time lags of GRO J0422+32 between the 20–50 and 50–100 keV energy bands (hard lags appear as positive delays). The left panel consists of a 30 day average at the start of the outburst, while the right panel displays a 95 day average of a flux-limited sample ($F \geq 0.04 \text{ photons/cm}^2 \text{ sec}^{-1}$) of the remaining data. The frequency scale has been logarithmically rebinned into 34 bins. Upper (lower) limits are indicated by triangles.

$\geq 0.02 \text{ Hz}$, the hard X-rays lag the soft by 0.039 ± 0.003 rad (average of 0.02–0.20 Hz; 94 bins) during the 30 days following start of the outburst of GRO J0422+32. The phase lag derived for the following 95 days (0.017 ± 0.007 rad, 0.02–0.20 Hz) is not statistical significant. During the first 30 days of the outburst of GRO J0422+32, the hard X-rays lag the soft by an amount of 0.02–0.2 sec in the frequency interval 0.02–0.20 Hz. The time lags decrease in this period with frequency as a power law, with index 0.88 ± 0.04 for frequencies $\geq 0.01 \text{ Hz}$. Although primarily consisting of upper limits, the lags in the 95 day average are consistent with those obtained at the beginning of the outburst (power-law index of 1.04 ± 0.32 for $\nu \geq 0.01 \text{ Hz}$).

4.5 Discussion

Soon after the X-ray detection of GRO J0422+32, a possible optical counterpart was identified by Wagner et al. (1992) and Castro-Tirado et al. (1992, 1993). During the decay to quiescence, its optical brightness was reported to be modulated at several periods ranging between 2.1 and 16.2 hr. Filippenko et al. (1995) determined the mass function and orbital period to be $1.21 \pm 0.06 \, M_\odot$, and $5.08 \pm 0.01 \, \text{hr}$, respectively. This relatively low value for the mass function was confirmed by Orosz & Bailyn (1995) and Casares et al. (1995). The mass function of GRO J0422+32 is one of the lowest measured values for the SXTs analyzed to date, and provides by itself no dynamical evidence that the compact star in GRO J0422+32 is a black hole. Callanan et al. (1996) derived an upper limit to the orbital inclination of $45^\circ$ from the ellipsoidal variations. Combined with the spectroscopic measurements, this limiting inclination implies a mass of the compact star in GRO J0422+32 in excess of $3.4 \, M_\odot$. The limits put to the inclination of GRO J0422+32 by Beekman et al. (1997) from infrared and optical photometry ($10^\circ$–$31^\circ$) imply an even higher mass limit of the compact star: $\gtrsim 9 \, M_\odot$. Therefore, based on
Figure 4.13: Cyg X-1 flux (cm$^{-2}$ sec$^{-1}$) versus photon power-law index from a fit in the 45–140 keV band (top-left), and GRO J0422+32 in the 40–150 keV regime (top-right). Fractional rms amplitude (0.03–0.488 Hz) in the 20–100 keV band versus photon power-law index of Cyg X-1 (middle-left), and GRO J0422+32 (middle-right). Fractional rms amplitude (0.03–0.488 Hz) in the 20–100 keV band versus flux of Cyg X-1 (bottom-left) and GRO J0422+32 (bottom-right). Figures of Cyg X-1 are taken from Crary et al. 1996a.
dynamical arguments, it can be concluded that GRO J0422+32 most probably contains a black hole. Thus, the dynamical evidence on GRO J0422+32 supports the early suggestion (Roques et al. 1994), made on the basis of the X-ray properties, that this system contains a black hole.  

It is not possible on the basis of BATSE observations alone, to distinguish between black hole source states. However, two independent observations at low X-ray energies during the decay of the X-ray light curve of GRO J0422+32, suggest that it was in the low (or hard) state. The X-ray spectrum of GRO J0422+32, obtained about 24 days after the start of the outburst by TTM (2–30 keV) and HEXE (20–200 keV) on board Mir-Kvant, had a power-law shape (photons index 1.5), with no strong soft component and an exponential cutoff at energies above 100 keV (Sunyaev et al. 1993). ROSAT HRI (0.1–2.4 keV) observations ~ 42 days after the start of the outburst, also show no indication for an ultra-soft excess in the X-ray spectrum (Pietsch et al. 1993). Therefore, these observations show that 24–42 days after the X-ray outburst had started, GRO J0422+32 was in the low state. The lack of significant changes in the hard X-ray properties (see Section 4.2), indicate that this conclusion applies to the whole outburst.

4.5.1 Comparison to Cyg X-1

From an analysis of approximately 1100 days of BATSE data (20–100 keV) of the BHC Cyg X-1, covering the period 1991–1995, Crary et al. (1996a) found a strong correlation between the spectral slope and both the high-energy X-ray flux and the variability thereof. Although low-energy coverage was lacking, it is likely that Cyg X-1 was in the low state during almost the entire period based on its strong rapid X-ray variability and the presence of a hard spectral component (Crary et al. 1996c). A possible transition to the high state may have lasted for ~ 180 days, starting 1993 September, as the source flux gradually declined over a period of 150 days to a very low level. After that, the flux rose within 30 days, back to the level it approximately had before the low flux episode occurred (Crary et al. 1996c).

The strong correlation of the flux and power-law index of GRO J0422+32 in the 40–150 keV energy band, shown in Fig. 4.2, is different from the correlation between the same quantities in Cyg X-1 as observed by Crary et al. (1996a). For flux values above 0.20 photons/cm² sec⁻¹, the flux and photon power-law index of GRO J0422+32 are related linearly; the larger the high-energy X-ray flux, the softer the X-ray spectrum. The power-law index is constant at 1.89 ± 0.02 for $F<0.20$ photons/cm² sec⁻¹. The correlation between the flux and power-law index of Cyg X-1 in the 45–140 kev energy band, however, is in the opposite direction; the larger the 45–140 keV flux of Cyg X-1, the harder its X-ray spectrum (Crary et al. 1996a). For comparison, the figures of Crary et al. (1996a) are reproduced in Figure 4.13. These show the correlations between the fractional rms amplitude (0.03–0.488 Hz) in the 20–100 keV energy band, and the photon power-law index and flux, for both GRO J0422+32 and Cyg X-1.

The correlations between the photon power-law index and fractional rms variability in Cyg X-1 and GRO J0422+32 are very similar; for both sources, the lower the photon power-law index, the larger the fractional rms amplitude.

As a result, the correlation between the flux and the fractional rms amplitude in the 20–100 keV energy band are entirely different for Cyg X-1 and GRO J0422+32. In the Cyg X-1 data, the distribution of flux and fractional rms amplitude measurements (frequency interval 0.03–0.488 Hz) follows a broad, upturning band, i.e., larger fractional amplitudes at higher flux values (Crary et al. 1996a). However, a strong anticorrelation is found between the 20–100
Figure 4.14: Relation between break frequency and power density at the break, taken from Méndez & van der Klis (1997), with the addition of the GRO J0422+32 data. Filled circles: Cyg X-1 in the LS (Belloni & Hasinger (1990a); filled stars: GRO J1719−24 in the LS (van der Hooft et al. 1996); open circles: GS 2023+338 in the LS (Oosterbroek et al. 1997); asterisk: GRO J0422+32 in the LS (Grove et al. 1994); filled squares: GRO J0422+32 in the LS (this paper); open squares: GX 339−4 in the VHS (Miyamoto et al. 1991, 1993); open diamond: GS 1124−68 in the VHS (Miyamoto et al. 1993); filled triangle: GX 339−4 (Belloni & Hasinger 1990b); open star: GS 1124−68 in the IS (Belloni et al. 1997b); open triangles: GX 339−4 in the IS (Méndez & van der Klis 1997). The marked region corresponds to Cyg X-1 LS data from Crary et al. (1996a).

keV fractional rms amplitude (both 0.01−0.10 and 0.10−0.48 Hz) of GRO J0422+32, and its 40−150 keV flux (see Fig.4.10). This distribution traces a narrow path in the diagram, with the smallest fractional amplitudes occurring at the largest flux values, or equivalently, at the start of the outburst of GRO J0422+32.

Crary et al. (1998) studied the Fourier cross spectra of Cyg X-1 with BATSE during a period of almost 2000 days. During this period, Cyg X-1 was likely in both the low, and high or intermediate state. Crary et al. (1998) found that the lag spectra between the X-ray variations in the 20−50 and 50−100 keV energy bands of Cyg X-1 do not show an obvious trend with source state. The X-ray variations of Cyg X-1 in the 50−100 keV energy band lag those in the 20−50 keV energy band over the 0.01−0.20 Hz frequency interval by a time interval proportional to $\nu^{-0.8}$ (Crary et al. 1998). The general shape and sign of the phase and time lag spectra of GRO J0422+32 are very similar to those of Cyg X-1. Significant phase (or equivalently, time)
lags in the GRO J0422+32 data could only be derived during the early stage of its outburst. During this period, the variations in the 50–100 keV energy band lag those in the 20–50 keV energy band by 0.039(3) rad in the frequency interval 0.02–0.20 Hz. The time lags of GRO J0422+32 during the first 30 days of its outburst, decrease with frequency as a power law, with index $\sim 0.9$ for $\nu > 0.01$ Hz.

4.5.2 Break frequency

In several BHCs the break frequency of the PDSs has been observed to vary by up to an order of magnitude while the high-frequency part remained approximately constant (Belloni & Hasinger 1990a; Miyamoto et al. 1992). As a result, the break frequency and power density at the break are strongly anticorrelated. Méndez & van der Klis (1997) have collected the relevant data on all BHC power spectra in the low, intermediate and very high state for six BHCs, and show that among these sources the break frequency is anticorrelated to the power density at the break. As this correlation appears to hold across different source states, Méndez & van der Klis (1997) suggest a correlation with mass accretion rate may exist, i.e., the break frequency increases (and the power density decreases) with increasing mass accretion rate (see also van der Klis 1994a).

The break frequency and power density at the break in the PDSs of GRO J0422+32 are clearly not anticorrelated (see Fig. 4.7). The power density at the break in the 20–100 keV energy band ranged between 44 and 89% Hz$^{-1/2}$, while the break frequency was rather constant, at either 0.041 ± 0.006 or 0.081 ± 0.015 Hz. All PDSs in which the break of the power spectrum was detected near ~0.04 Hz were obtained during the primary X-ray outburst of GRO J0422+32; all PDSs obtained during the secondary outburst have a break frequency near ~0.08 Hz. Therefore, the relation between the break frequency and power density at the break is different from the one observed in Cyg X-1 (Belloni & Hasinger 1990a; Miyamoto et al. 1992). This contrast between the PDSs of GRO J0422+32 and Cyg X-1 was also reported by Grove et al. (1994) based on OSSE data of the first stage of the X-ray outburst of GRO J0422+32.

The break frequency and power density at the break of BHC power spectra in the low, intermediate and very high state (LS, IS, VHS) collected by Méndez & van der Klis (1997) are reproduced in Figure 4.14, together with the 20–100 keV data of GRO J0422+32. However, this representation should be taken with caution, as it combines data obtained in different energy bands, and data of different source states. Fig. 4.14 shows a clear anticorrelation of the break frequency and power density at the break over two orders of magnitude in both frequency and power density. The low state BATSE data (20–100 keV) of GRO J1719–24 (van der Hooft et al. 1996) and Cyg X-1 (Crary et al. 1996a), and low state EXOSAT data of Cyg X-1 (Belloni & Hasinger 1990a), clearly follows this anticorrelation. However, the power density at the break detected in the PDSs of GS 2023+338 is approximately constant for break frequencies in the 0.03–0.08 Hz interval, but shows a sudden turnover at frequencies <0.03 Hz to large power densities. The absence of the anticorrelation of the break frequency and the power density at the break detected in the power spectra of GS 2023+338 was first reported by Oosterbroek et al. (1997). Although these studies of GRO J0422+32 and GS 2023+338 show that the relation between the break frequency and power density at the break differs in detail from other BHCs in the LS, the data of GRO J0422+32 and GS 2023+338 displayed in Fig. 4.14 does fit the general anticorrelation, observed in several sources over two decades of frequency and power density, within a factor of ~2. It is interesting to note that the absence of an anticorrelation of the break frequency and power density at the break, is found in the PDSs of the two sources which show the lowest break frequencies of all BHCs: GRO J0422+32 and GS 2023+338.
4.5.3 Earlier temporal analyses of GRO J0422+32

The hard X-ray variability of GRO J0422+32 has been studied by Grove et al. (1994) with OSSE (35–600 keV), and by Denis et al. (1994) and Vikhlinin et al. (1995) with SIGMA in the 40–300 and 40–150 keV energy band. The OSSE observations were obtained from 1992 August 11 until September 17, i.e., days 7–44 of the X-ray outburst. Grove et al. (1994) computed PDSs in the 35–60 and 75–175 keV energy band. The power spectra show breaks at frequencies of \( \sim 10^{-2} \) Hz and a few Hz, and a strong peaked noise component at 0.23 Hz. Statistically significant noise is detected at frequencies above 20 Hz. The total fractional rms in the 0.01–60 Hz frequency interval for the entire OSSE pointing is \( \sim 40\% \) (35–60 keV) and \( \sim 30\% \) (75–175 keV), respectively.

SIGMA observed GRO J0422+32 from 1992 August 15 until September 25 (days 11–52). Vikhlinin et al. (1995) computed power spectra in the frequency interval \( 10^{-4} – 10 \) Hz. The power density is nearly constant below a break frequency at 0.03 Hz, and decreases as a power law above, with index \( \sim 0.9 \). A strong QPO peak is detected at a frequency of 0.3 Hz. At the start of the SIGMA observation of GRO J0422+32 (August 15–27), the PDSs show a significant decrease of the power densities for frequencies lower than \( 3.5 \times 10^{-3} \) Hz. Such turnover of the PDSs at low frequencies is unusual; PDSs typically exhibit strong very-low frequency noise, or are constant for such low frequencies. The total fractional rms variations (40–150 keV) of GRO J0422+32 in the frequency interval \( 10^{-3} – 10^{-1} \) Hz increased from \( \sim 15\% \) at the start of the SIGMA observations to \( \sim 25\% \) at the end. Denis et al. (1994) reported an increase of the fractional rms variation over the same period from \( \leq 25\% \) (2\( \sigma \) upper limit) to \( \sim 50\% \) (150–300 keV) in the \( 2 \times 10^{-4} – 1.25 \times 10^{-1} \) Hz frequency interval.

These results of Vikhlinin et al. (1995) and Grove et al. (1994) are consistent with the results presented here. The shape of the power spectrum of GRO J0422+32 in the 0.01–0.5 Hz interval is essentially identical in the three studies, although different, but partly overlapping, energy bands have been used. The values of the break frequency and power-law index (both, below and above the break frequency) determined in the OSSE and SIGMA data, are consistent with those presented here. However, OSSE and SIGMA only covered the early phases of the X-ray outburst of GRO J0422+32, with the exception of its very start. Therefore, the significant change of the break frequency during later stages of the X-ray outburst was missed. Fractional rms amplitudes were determined on a daily basis in the OSSE data (0.01–60 Hz) and SIGMA data (3.6 \( \times 10^{-1} – 8 \times 10^{-2} \) Hz). At the beginning of the OSSE and SIGMA observations, the fractional rms amplitudes remained constant, or perhaps slightly decreasing, followed by a turnover and gradual increase, similar to the fractional rms amplitude histories displayed in Fig. 4.9. However, due to data gaps, the moment of turnover is difficult to determine in the OSSE and SIGMA data.

Low-frequency QPOs (0.04–0.8 Hz) have been observed in the PDSs of several BHCs: Cyg X-1, LMC X-1, GX 339–4 and GRO J1719–24 (van der Klis 1995b; van der Hooft et al. 1996). These QPOs were observed while the sources were likely in the low state, with the exception of LMC X-1 where a 0.08 Hz QPO was found while an ultra-soft component dominated the energy spectrum, showing that the source was in the high state. During our observations GRO J0422+32 was probably in the low state and its PDSs showed a strong QPO peak with a centroid frequency between 0.13 and 0.26 Hz (20–100 keV). Therefore, GRO J0422+32 is the fourth BHC which shows low-frequency QPOs in its PDSs while in the low state.
Peaked noise components and QPO peaks in the power spectra of GRO J0422+32 have been reported by various groups. Kouveliotou et al. (1992, 1993) reported QPO peaks centered at ~0.03 and 0.2 Hz in different BATSE energy bands covering 20–300 keV. Grove et al. (1994) detected a strong peaked noise component in the OSSE data (35–60, 75–175 keV) at a centroid frequency of 0.23 Hz (FWHM ~0.2 Hz), and evidence for additional peaked components near 0.04 and 0.1 Hz with a day to day variable intensity. Vikhlinin et al. (1995) report a strong QPO peak in the SIGMA data (40–150 keV) at 0.31 Hz (FWHM 0.16 Hz), with a fractional rms variability of ~12%. Likely, the reports of strong noise components at a few 10⁻² Hz all refer to the same feature in the PDSs of GRO J0422+32; the strong QPO peak with a centroid frequency ranging between 0.13 and 0.26 Hz (20–100 keV), present in the power spectra of GRO J0422+32 during the first ~70 days of its outburst. The peaked noise at a few 10⁻² Hz reported by Kouveliotou et al. (1992, 1993) and Grove et al. (1994), is detected near the break frequency of the power spectra. These detections may be supported by Vikhlinin et al. (1992), who reported peaked noise at 0.035 Hz (FWHM 0.02 Hz) in 40–70 keV SIGMA data, obtained early in the SIGMA pointing. However, Kouveliotou et al. (1993) report that this peaked noise structure is only detected occasionally in the PDSs of GRO J0422+32. In the analysis presented here, we do not find significant evidence for such peaked noise structures at a few 10⁻² Hz, possibly due to our daily averaging routine, or the fact that these noise components occur close to the break frequency.

4.5.4 Comptonization models

The power law hard X-ray spectral component of accreting BHCs, which dominate the X-ray emission in the low state, can be described well by Compton upscattering of low-energy photons by a hot electron gas (Sunyaev & Trümper 1979). In such a case, the energy of the escaping photons on average increases with the number of scatterings, and therefore, with the time they reside in the cloud. Therefore, high-energy photons lag those with lower energies by an amount proportional to the photon travel time. If the hard X-rays are emitted from a compact region in the immediate vicinity of the black hole, the resulting time lags should be independent of Fourier frequency and of the order of milliseconds.

The hard X-ray photons (50–100 keV) of GRO J0422+32 lag the low-energy photons (20–50 keV) by as much as ~0.1–1 sec at low frequencies. The time lags are strongly dependent on the Fourier frequency, and decrease roughly as ν⁻¹. Similar lag behaviour have been observed in Cyg X-1 (Cui et al. 1997a; Crary et al. 1998) and GRO J1719–24 (van der Hooft et al. 1998b) while in the low state. Recently, Kazanas, Hua & Titarchuk (1997) argued that the Comptonization process takes place in an extended non-uniform cloud around the central source. Such a model can account for the form of the observed PDS and energy spectra of compact sources. Hua, Kazanas & Titarchuk (1997) showed that the time lags of the X-ray variability depend on the density profile of such an extended but non-uniform scattering atmosphere. Their model produces time lags between the hard and soft bands of the X-ray spectrum that increase with Fourier period, in agreement with the observations. Therefore, analysis of the hard time lags in the X-ray variability of black-hole candidates could provide information on the density structure of the accretion gas (Hua et al. 1997). The time lags observed in GRO J0422+32, Cyg X-1 and GRO J1719–24 are quite similar and support the idea that the Comptonizing regions around these black holes are similar in density distribution and size.
However, the observed lags require that the scattering medium has a size of order $10^3$ to $10^4$ Schwarzschild radii. It is unclear how a substantial fraction of the X-ray luminosity, which must originate from the conversion of gravitational potential energy into heat close to the black hole, can reside in a hot electron gas at such large distances. This is a generic problem for Comptonization models of the hard X-ray time lags. Perhaps very detailed high signal-to-noise cross-spectral studies of the rapid X-ray variability of accreting BHCs, and combined spectro-temporal modeling can solve this problem.

### 4.6 Conclusions

We have analyzed the hard X-ray variability of GRO J0422+32. The canonical anticorrelation between the break frequency and the power at the break observed in Cyg X-1 and other BHCs in the low state, is not present in the PDSs of GRO J0422+32. The relation between the photon power-law index of the X-ray spectrum and the amplitude of the X-ray variations of GRO J0422+32 has similarities to that of Cyg X-1; however, the relation between the hard X-ray flux and the amplitude of its variation is opposite to what has been found in Cyg X-1.

**Acknowledgments**

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An ellipsoidal modulation in X-ray Nova Velorum 1993 (= GRS 1009–45)

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Abstract

We present the first optical observations of the soft X-ray transient Nova Velorum 1993, taken during quiescence in 1995 and 1996. From the R-band photometry with a magnitude of 20.6, we find an orbital, ellipsoidal modulation with an amplitude of 0.23 mag at a period of 6.86 ± 0.12 hr. The optical spectra show only broad double-peaked Hα emission presumably arising from the accretion disk. We estimate the spectral type for the secondary to be late-G/early-K, which is consistent with the value for the mean density of the Roche lobe filling secondary star, obtained using the orbital period. By modeling the optical ellipsoidal modulations of the secondary star we determine a firm 95 per cent lower limit to the binary inclination of 37°.

5.1 Introduction

The X-ray transient Nova Velorum 1993 (GRS 1009–45) was discovered by the WATCH instrument on board GRANAT (Lapshov, Sazonov & Sunyaev 1993; Lapshov et al. 1994) and confirmed by the BATSE instrument on board of the Compton Gamma Ray Observatory (Harmon et al. 1993a) on 1993 September 12. The 2–200 keV X-ray spectrum of GRS 1009–45 was similar to the X-ray spectra of the soft X-ray transient (SXT) sources GS 2000+25 and GS 1124–68 (Kaniovsky, Borozdin & Sunyaev 1993), which are both dynamically proven black-hole candidates (Casares, Charles & Marsh 1995; Remillard, McClintock & Bailyn 1992). The X-ray spectrum of GRS 1009–45 consisted of a soft component which could be approximated by a blackbody temperature of 0.5 keV, and a power law with spectral index −2.5 at 10–100 keV (Kaniovsky et al. 1993). The primary X-ray outburst of GRS 1009–45 was similar
to GS 1124–68; however, two later maxima in the hard X-ray flux of GRS 1009–45 occurred at ~30 and ~85 days after the primary maximum, both of them occurring sooner than the secondary maximum observed in GS 1124–68 (Paciesas et al. 1995).

The optical counterpart of GRS 1009–45 was discovered in 1993 November as a blue object with $V = 14.6$ and broad Hα emission (FWHM ~ 30 Å) (Della Valle & Benetti 1993). Bailyn & Orosz (1995) observed the source between 150 and 200 days after the primary outburst in the V-band and found evidence for a secondary optical outburst and repeated mini-outbursts similar to those observed from the SXT Nova Persei 1992 (GRO J0422+32). The brightness of Nova Vel 1993 during these observations varied between $V \sim 16$ and $V \sim 20$. We report here on optical observations of Nova Vel 1993 during quiescence, from which we present a finding chart showing the source to be well resolved from its close neighbor star and also a medium-resolution red spectrum.

### 5.2 Spectroscopy

#### 5.2.1 Observations and data reduction

Optical spectra of Nova Vel 1993 were obtained in 1995 June 3 and 1996 March 25–26 with the 3.5m New Technology Telescope at the European Southern Observatory (ESO) in Chile using the ESO Multi Mode Instrument (EMMI). We used the red arm in medium dispersion mode, order-separating filter OG 530 and grating #8 with a dispersion of ~1.3 Å pixel$^{-1}$ covering 6010–8575 and 6150–8720 Å for the 1995 and 1996 runs. The TEK 2048 × 2048 pixel CCD was used, binned with a factor of two in the spatial direction in order to reduce the readout noise. The dispersion direction was not binned. A slit width of 0′′8 was used which resulted in a resolution of 3.5 Å.

The seeing stayed below 1″ most of the time and conditions were photometric in both runs. The integration time of the spectra was 1800 sec in all cases. The CCD frames were corrected for the bias and flat-fielded in the standard way. For the data of each night an average bias frame (obtained using more than 10 bias frames) was subtracted from all data. The data were then flat-fielded using an average flat field. The stellar spectra were extracted from the CCD frames using an optimal extraction algorithm similar to that of Horne (1986) and wavelength-calibrated using Ar–Ne exposures taken at the same telescope position close in time to the object exposures. Spectra of the flux standards Feige 56 and HD 60778 were taken during the 1995 and 1996 observations, respectively, to obtain the relative flux calibration. Also, spectra of several bright F, G, K and M stars were taken as spectral type standards.

### 5.3 Photometry

#### 5.3.1 Observations

We obtained optical CCD photometry of Nova Vel 1993 on the Danish 1.54m telescope at ESO during two observation runs on 1995 May 8–10 and 1996 February 17–21. For the 1995 run the Tektronix TK1024M CCD was used giving a $6′′7 \times 6′′7$ field of view whereas for the 1996 run the Ford-Loral 2052 CCD was used giving a $13′′3 \times 13′′3$ field of view. The platescale for
Table 5.1: Magnitude of local field stars. The mean magnitude and scatter is quoted for Nova Vel 1993.

<table>
<thead>
<tr>
<th>Star number</th>
<th>R (mag)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 001</td>
<td>20.600 ± 0.100</td>
<td>Nova Vel 1993</td>
</tr>
<tr>
<td>Star 002</td>
<td>17.431 ± 0.002</td>
<td>Bright companion</td>
</tr>
<tr>
<td>Star 003</td>
<td>20.566 ± 0.005</td>
<td>Comparison star</td>
</tr>
<tr>
<td>Star 004</td>
<td>20.895 ± 0.008</td>
<td>Comparison star</td>
</tr>
<tr>
<td>Star 005</td>
<td>20.723 ± 0.007</td>
<td></td>
</tr>
<tr>
<td>Star 006</td>
<td>16.904 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>Star 007</td>
<td>18.357 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>Star 008</td>
<td>18.225 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>Star 009</td>
<td>17.332 ± 0.002</td>
<td>Local Standard</td>
</tr>
<tr>
<td>Star 010</td>
<td>18.030 ± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: Finding chart for Nova Vel 1993 (GRS 1009–45) taken on 1995 May 9 at the Danish 1.54m telescope at ESO. An exposure time of 600 sec was used with a R-band filter. Nova Vel 1993 is marked as star 1 and has a mean magnitude of \( R = 20.6 \). Other field stars are also labeled (see Table 5.1). North is at the top and east is to the left. The field of view is \( 30'' \times 30'' \).
both runs was 0″39 pixel⁻¹. All the observations were taken with the Gunn R-band filter. The median seeing for the 1995 and 1996 runs was 1″1 and 1″2, respectively. We obtained a total of 246 images of Nova Vel 1993, of which 73 were from the 1995 run and 173 from 1996. The median exposure time used for both runs was 600 sec. Photometric standards were also observed during the 1995 observing run which we used to calibrate the data.

5.3.2 Data reduction

First, both sets were debiased and flat-fielded in the standard way. The bias level, obtained from the overscan region of the CCD, was subtracted from all data and the data were then flat-fielded using images of flat fields taken during each observing run. The crowded nature of the field and the faintness of Nova Vel 1993 implied that simple aperture photometry could not be used to separate the target from its bright companion 1″4 South-East. Instead we used the point spread function fitting algorithm DAOPHOT (Stetson 1987) in an ARK-compatible version.

We performed relative photometry on Nova Vel 1993 and stars 3 and 4 (which are of similar brightness to the target) using star 9 as a local standard. Figure 5.1 shows a finding chart in which Nova Vel 1993 is labeled as star 1 along with other stars in the field which we used as comparison stars and local standards. The data were calibrated using four Landolt standard fields (Landolt 1992): PG 0918 (five stars), PG 1323 (three stars), Mark A (four stars) and SA 110 (four stars), observed during photometric conditions in the 1995 observing run. The local standard was then calibrated, yielding a mean magnitude of $R = 17.332$. Observations of local field stars within one night showed that the photometric calibration was stable to within 0.06 mag. Table 5.1 lists the $R$ magnitudes of the comparison stars used as well as various field stars.

5.4 The optical spectrum

For the spectrum of Nova Vel 1993 obtained on 1995 June 3 we rotated the slit such that the close neighbor star with $R = 17.4$ (star 2; see Fig. 5.1, located 1″3 South and 0″6 East of the source) was also in the slit. Although the observing conditions were excellent during this night, extraction of the spectrum of Nova Vel 1993 from the CCD frame was difficult since it was partly blended with the spectrum of this bright neighboring star. The spectrum of this star is blue and shows Hα in absorption. The partly extracted spectrum of Nova Vel 1993, i.e., the part of the spectrum farthest from the contaminating star, is red and featureless, apart from a broad, double-peaked Hα emission line. However, we were not certain of the level of contamination by the neighboring star and decided to obtain more spectra of Nova Vel 1993 during the 1996 March observations.

This time we applied a rotation to the slit such that is was placed across Nova Vel 1993 and the star located 2″1 North and 3″1 East of the source (star 7; see Fig. 5.1). One spectrum of Nova Vel 1993 was obtained at 1996 March 25, and two additional spectra were taken during the next night. These last two spectra are of poorer quality owing to poorer seeing conditions and are possible contaminated by the bright neighbor star; the spectra show a blue excess, the Hα emission is weaker and the overall flux level is increased by a factor ~ 3 with respect to the spectrum taken one night before. Therefore, we excluded these last two spectra of Nova Vel 1993 from our analysis.
The 1995 and 1996 spectra of Nova Vel 1993 are displayed in Figure 5.2. The flux level of the 1995 spectrum is reduced by a factor $\sim 2$ with respect to the 1996 spectrum since it could only be extracted partly due to the blending with the spectrum of the neighboring star. Nevertheless, both spectra are very similar, showing a broad H$\alpha$ emission line superimposed on a red featureless continuum. In the 1995 spectrum the H$\alpha$ emission is clearly double-peaked with a separation between both components of $1020 \pm 51$ km s$^{-1}$ (as derived from fitting Gaussian profiles). The evidence for the presence of a double-peaked structure in the spectrum taken in 1996 is less compelling. The zero-intensity full width at the base of the H$\alpha$ emission line is $2850 \pm 600$ and $2700 \pm 320$ km s$^{-1}$ for the 1995 and 1996 data, respectively.

Fig. 5.2 shows the 1995 and 1996 spectra of Nova Vel 1993 along with a G6, K0 and M2 star. No obvious molecular features are present in the Nova Vel 1993 spectra, thus making it difficult to determine the spectral type of the secondary star. Also, the continuum slope could be misleading because of reddening and disk contamination. However, if the disk contamination is similar to that in the other SXTs, then one would still expect to see some molecular features in the Nova Vel 1993 spectra, if the secondary star were a late-K/M star. Since we do not see any molecular features, the secondary star most probably has a spectral type of an early-K star or even earlier. High-quality spectra are clearly needed in order to determine the spectral type of the secondary accurately.
5.5 The orbital period

In order to find any periodicities present in the data, we first removed data points where the seeing was such that the target and star 2 were blended into one, i.e., when the seeing was greater than about 1″4. In these images the profile-fitting algorithm could not find the target. A total of 20 images were removed by this procedure. Figure 5.3 shows the data for Nova Vel 1993 and two comparison stars of similar brightness to Nova Vel 1993.

Like the other SXTs, we expect the quiescent optical modulation of Nova Vel 1993 to be primarily caused by the ellipsoidal variations of the secondary star. These variations arise since the observer views differing aspects of the gravitationally distorted star as it orbits the compact object (van Paradijs & McClintock 1995). In theory, the modulations should have two maxima and two minima. The two minima may be unequal depending on the binary inclination, but the maxima should be equal. In practice, however, the light from the accretion disk contaminates the ellipsoidal variations of the secondary star, making detailed interpretations of the optical light curves difficult (see Shahbaz, Naylor & Charles 1993).
**Figure 5.4:** Results of the period search using the combined 1995 and 1996 data of Nova Vel 1993 during quiescence. **Top:** phase dispersion minimization (PDM) spectrum. The deepest minimum is found at 3.5 cycle day$^{-1}$ (indicated by the star). All the other minima correspond to twice this frequency or a simple fraction ($2/3, 1/3$) of it (shown by white circles and their sidelobes. **Middle:** Lomb-Scargle power spectrum. The strongest peak is found at a period of 7.0 cycle day$^{-1}$. Similarly to the PDM spectrum, all other peaks correspond to a multiple of this frequency. The orbital period is half the strongest peak, and is indicated by the star. **Bottom:** a Bayesian probability spectrum obtained using a priori knowledge of the expected double-humped modulation. The strongest peak is found at 3.5 cycle day$^{-1}$, and represents the orbital period.
Therefore, we first analyzed the optical light curve of Nova Vel 1993 using the phase dispersion minimization (PDM) algorithm (Stellingwerf 1978). This technique is insensitive to the shape of the modulation, but does not remove the effects of the window function. The method groups the data in phase bins and seeks to minimize the dispersion within the bins. The true period corresponds to the deepest minimum of the statistic. The PDM spectrum was computed in the frequency range 2 to 10 cycle day$^{-1}$ at a resolution of $8.6 \times 10^{-4}$ cycle day$^{-1}$ with 25 phase bins. The deepest minimum is found at 3.50 cycle day$^{-1}$ or 6.86 hr (indicated by the star). All the other minima present in this spectrum are either a multiple (2\(f\)) or submultiple (2\(f/3, f/2\)) of this frequency. All main minima are accompanied by the corresponding sidelobes, which are separated by intervals of 1, 1/2, 1/3 and 1/4 cycle day$^{-1}$ (see Figure 5.4, top panel).

The common method of computing a discrete Fourier transform (DFT) and halving the estimate of the period is equivalent to assuming that the minima are of equal depths. This may not be the case, as other observed ellipsoidal modulation may contain unequal minima depending on the binary inclination and the contamination by the accretion disk. A Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) of the combined 1995 and 1996 data sets was then computed with the same resolution and frequency range as was used for the PDM technique. The strongest peak was found at a period of 3.41 hr (see Fig. 5.4, middle panel), i.e., about half the period obtained using the PDM method.

Using Bayesian methods (Bretthorst 1988) to analyze the data it is possible to include any a priori knowledge about the expected modulation. The results can then be analyzed using probability analysis. The Bayesian periodogram can, in principle, give an accuracy which is an order of magnitude better than the DFT methods (Martin 1995). The ellipsoidal modulation is equivalent to a sinusoid of frequency 2\(f\) which lags by 90° in phase relative to a sinusoid at a frequency \(f\). The difference between the minima is usually small, which means that the amplitude of the sinusoid at a frequency \(f\) will be smaller than that at 2\(f\). This information can be used in a Bayesian two-frequency model to constrain the frequency and phase of the two sinusoids relative to one another.

We performed such a two-frequency Bayesian analysis on the combined 1995 and 1996 data. Fig. 5.4 (bottom panel) shows the Bayesian spectrum computed in the frequency range 2 to 10 cycle day$^{-1}$ at a resolution of 0.001 cycle day$^{-1}$, along with the periodograms obtained using the PDM and Lomb-Scargle methods. The strongest peak in the Bayesian analysis is at 3.505 cycle day$^{-1}$, with a probability of 10$^{37}$. The next strongest peak is at 7.010 cycle day$^{-1}$ with a probability 10$^{11}$ smaller than the 3.505 cycle day$^{-1}$ peak. Thus we conclude that the data can be described best by a modulation at a frequency of 3.505 cycle day$^{-1}$.

The alias pattern from the two data sets can be clearly seen in Fig. 5.5. Rather than being a single line, the plot in the PDM spectrum shows an envelope of power, which is filled in with fine structure. This fine structure is the alias pattern from the two data sets due to their 10 months' separation. Also shown in Fig. 5.5 as a solid line is the PDM spectrum for the 1996 February data alone, where, as expected this alias pattern is not present. However, the line is still broad because of the quality and short baseline of the 1996 February data set being used alone. We thus take the orbital period to be 3.50 ± 0.06 cycle day$^{-1}$ or 6.86 ± 0.12 hr, where the uncertainty quoted is the 1σ width of the line obtained by fitting the line with a Gaussian function.
Figure 5.5: This figure shows part of the PDM spectrum around the orbital period at high resolution. The thin weighted line is the combined 1995 and 1996 data of Nova Vel 1993, and the heavy weighted line is the 1996 data set alone. One can clearly see the 0.0035 cycle day\(^{-1}\) alias pattern between the 1995 and 1996 data sets taken about 10 months apart.

5.6 The ellipsoidal light curve

From the orbital period of 6.86 hr we can calculate the mean density of the secondary star, assuming that it fills it Roche Lobe (Frank, King & Raine 1992). This gives \( \rho = 2.4 \text{ g cm}^{-3} \), which is similar to the value of the mean density of a K5 V star. By comparison with the other SXTs, however, the secondary star could be undermassive for its spectra type (Chevalier et al. 1989; McClintock & Remillard 1990; Shahbaz, Naylor & Charles 1994a), and so this estimate for the spectral type should be used with caution. It should be noted that all the SXTs with a similar orbital period to Nova Vel 1993 have secondary stars with early-K spectral types. The optical spectra presented in Section 2.2 also suggests that the spectrum of the secondary star is an early-type K star.

We can describe the observed 0.23 mag R-band modulation as being due to the ellipsoidal variations of the secondary star. The expected modulation is a double-humped modulation with two maxima and two minima per cycle, the minima being centered on phases 0.0 and 0.5, where phase 0.0 is defined as the superior conjunction of the secondary star. By comparing the amplitude of the optical modulation (\(~0.25\) mag) with other SXTs in quiescence, e.g., A0620−00 (McClintock & Remillard 1986), Cen X-4 (McClintock & Remillard 1990) and GS 2000+25 (Chevalier & Ilovaisky 1993) one can conclude that the binary inclination must be relatively high. For this to be true the deepest minimum must correspond to phase 0.5, since the difference between the minima is only evident when the system is at high inclinations, and is a result of the larger gravity darkening at the inner Lagrangian point. It should be noted
that the observed optical modulation is most probably contaminated by flux arising from the accretion disk, similar to other SXTs. The effect this would have on the optical light is that the true ellipsoidal modulation would be underestimated, implying that the value obtained for the binary inclination will also be underestimated.

Using the data obtained on the night of 1996 February 18, where we observed Nova Vel 1993 for the longest period of time, we can estimate the time of phase 0.0. This estimate was found by fitting the brightest minimum with a Gaussian function in order to determine the epoch of minimum light. We thus obtain the orbital ephemeris to be HJD 245 0132.7973(32) + 0.286(5) × N, where 1σ errors are quoted.

The data were then folded on this ephemeris and binned into 20 phase bins. Ellipsoidal model fits were performed using $T_{\text{eff}} = 4500$ K: the appropriate limb-darkening coefficient was taken from Al-Naimy (1978) and a gravity-darkening exponent of 0.08 was used, appropriate for a convective star. Since the compact object in Nova Vel 1993 is likely to be a black hole, and for a given inclination the ellipsoidal amplitude changes little for $q > 5$ (Shahbaz et al. 1993, 1994a, 1994b) and therefore depends almost entirely on inclination alone, we have assumed $q = 15$, typical of the black-hole SXTs. Folding the data on the orbital ephemeris and fitting it with the ellipsoidal model, we find the binary inclination to be $44° \pm 6°$ (90 per cent confidence). The uncertainty quoted here was calculated according to Lampton, Margon & Bowyer (1976) after the error bars had been rescaled to give a minimum $\chi^2$ of 1.
Figure 5.6 shows the best ellipsoidal fit to the Nova Vel 1993 data. The fit yielded a minimum $\chi^2_\nu$ of 3.2. Also shown are linear fits to the comparison stars. The $\chi^2_\nu$ for these fits were 0.7 and 2.3 for stars 3 and 4, respectively. Changing $T_{\text{eff}}$ by 500 K and using $q = 5$ introduces an extra uncertainty in the inclination of 3°. Therefore, we estimate the total uncertainty in the binary inclination to be 7°, implying $i = 44° \pm 7°$.

In light of the effects the accretion disk will have on the amplitude of the light curve, the value we obtain for the binary inclination should be used as a lower limit. Thus we find the 95 per cent lower limit to the binary inclination to be 37°. A firm upper limit to the binary inclination arises from the absence of X-ray eclipses. This implies $i < 80°$. We thus constrain the binary inclination to lie in the range $37° - 80°$.

## 5.7 Conclusion

The similarity of the X-ray behavior of Nova Vel 1993 during outburst to that of other SXT black-hole candidates, and the absence of any type-I X-ray bursts, suggests that Nova Vel 1993 is a promising black-hole candidate. We have obtained quiescent optical light curves, which show the ellipsoidal variations of the secondary star. We have determined the orbital period to be 6.86 ± 0.12 hr, implying that Nova Vel 1993 is one of the shortest period black-hole candidates. By modeling the ellipsoidal variations we place a firm 95 per cent lower limit to the binary inclination of 37°. From optical spectroscopy we estimate the secondary to be an early-type K star. Unfortunately, it is not possible to derive a mass function for the system as yet, as there is no currently available radial velocity curve for the secondary star. This will be the subject of future studies.

Acknowledgments

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The black-hole transient Nova Scorpii 1994 (= GRO J1655–40): Orbital ephemeris and optical light curve


Abstract

We have measured the brightness of the optical counterpart of the black-hole X-ray binary Nova Sco 1994 (GRO J1655–40) during 40 nights between 1995 May 3 and July 27. From our observations and data from the literature we refine the orbital period to be 2.62040 ± 0.00098 days. We model the R-band light curve as primarily being due to an X-ray heated secondary, using a model that includes a Roche lobe filling secondary star, the effects of X-ray heating on both the concave accretion disk and the X-ray illuminated surface of the secondary, shadowing of the secondary and disk, and mutual eclipses of the disk and the secondary star. From the shape of the light curve we constrain the inclination of the system to lie in the range 65°–76° and constrain the mass ratio $q = M_1/M_2$ to lie in the range 3.8–5.5. This implies a mass range for the secondary star and compact object of 0.95–1.8 $M_\odot$ and 4.9–6.8 $M_\odot$, respectively. The $(V-R)$ and $(R-i)$ color curves do not show evidence of significant variability with orbital phase during 1995 June–July, their average values being 1.06(3) and 0.86(2) mag, respectively.

6.1 Introduction

The SOFT X-RAY transient (SXT) Nova Sco 1994 (GRO J1655–40) was discovered with the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory on 1994 July 27 (Zhang et al. 1994). After its initial three week long outburst, in which a peak intensity of 0.7 Crab (20–100 keV) was reached (Crary et al. 1996b), it remained
active, showing repeated outbursts separated by about 120 days (Zhang et al. 1995) each typically lasting many weeks (Harmon et al. 1995a; Harmon et al. 1995b; Wilson et al. 1995). Radio observations have shown that Nova Sco 1994 exhibits radio outbursts which generally lag the X-ray outbursts by an interval of several days to two weeks (Harmon et al. 1995b; see also Paciesas et al. 1996). During radio outbursts material is ejected from the central source in opposite directions at superluminal speeds (Tingay et al. 1995; Hjellming & Rupen 1995). Models for the radio jets (Hjellming & Rupen 1995) suggest an orbital inclination of $\sim 85^\circ$, indicating that Nova Sco 1994 may be an eclipsing binary.

Bailyn et al. (1995a) identified the optical counterpart of Nova Sco 1994, its visual brightness having increased by about 3 mag to $V = 14.4$ during the initial X-ray outburst. The optical light curve of Nova Sco 1994 shows a primary and secondary minimum, possibly caused by mutual eclipses of the accretion disk and the F3-F6 type secondary star (Bailyn et al. 1995b). This is the earliest spectral type of any of the SXTs known (van Paradijs & McClintock 1995). The optical brightness of Nova Sco 1994 showed a sharp reduction in its optical brightness on 1994 August 17, interpreted by Bailyn et al. (1995a) as a possible eclipse. From radial-velocity variations Bailyn et al. (1995b) established a spectroscopic period of $2.601 \pm 0.027$ days and a mass function $f(M) = 3.16 \pm 0.15 \ M_\odot$. The observed mass function and the possible high orbital inclination leads to the conclusion that the compact object in Nova Sco 1994 is a black hole with a maximum mass of $5.4 \pm 0.2 \ M_\odot$ for secondary masses less than $1.5 \ M_\odot$ and inclination $\geq 80^\circ$ (Bailyn et al. 1995b). It is thus of particular interest as a low-mass black hole (compared to, e.g., V404 Cyg, Casares & Charles 1994) which might have been produced by the accretion-induced collapse of a neutron star (Brandt, Podsiadlowski & Sigurdsson 1995).

We have conducted an extensive optical photometry campaign to study the light curve of Nova Sco 1994 using telescopes in Tasmania and Chile. In Section 2 we describe the observations and the photometric analysis. Average orbital light and color curves, an improved orbital ephemeris and model fitting are presented in Section 3 and our results are discussed in Section 4.

### Table 6.1: Log of observations of Nova Sco 1994 during 1995 May–July.

<table>
<thead>
<tr>
<th>Calendar Date</th>
<th>HJD (−2440000)</th>
<th>Exposures</th>
<th>Telescope</th>
</tr>
</thead>
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<tr>
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<td>9842–9843</td>
<td>38 x B</td>
<td>Danish 1.54m</td>
</tr>
<tr>
<td>May 5–May 6</td>
<td>9842–9843</td>
<td>37 x V</td>
<td>Danish 1.54m</td>
</tr>
<tr>
<td>May 4–May 6</td>
<td>9841–9844</td>
<td>184 x R</td>
<td>Danish 1.54m</td>
</tr>
<tr>
<td>Jun 17–Jul 11</td>
<td>9885–9909</td>
<td>18 x V</td>
<td>Dutch 0.91m</td>
</tr>
<tr>
<td>Jun 16–Jul 12</td>
<td>9884–9910</td>
<td>141 x R</td>
<td>Dutch 0.91m</td>
</tr>
<tr>
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<td>9886–9910</td>
<td>17 x i</td>
<td>Dutch 0.91m</td>
</tr>
<tr>
<td>Jun 21–Jul 12</td>
<td>9889–9911</td>
<td>125 x V</td>
<td>Tasmania 1.0m</td>
</tr>
<tr>
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<td>9889–9911</td>
<td>68 x R</td>
<td>Tasmania 1.0m</td>
</tr>
<tr>
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<td>Tasmania 1.0m</td>
</tr>
<tr>
<td>Jun 27–Jun 30</td>
<td>9895–9898</td>
<td>8 x V</td>
<td>Danish 1.54m</td>
</tr>
<tr>
<td>Jun 27–Jul 1</td>
<td>9895–9899</td>
<td>35 x R</td>
<td>Danish 1.54m</td>
</tr>
<tr>
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<td>8 x i</td>
<td>Danish 1.54m</td>
</tr>
<tr>
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<td>Dutch 0.91m</td>
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<td>Jul 20–Jul 27</td>
<td>9918–9925</td>
<td>8 x i</td>
<td>Dutch 0.91m</td>
</tr>
</tbody>
</table>
6.2 Observations and data analysis

We observed Nova Sco 1994 during the period 1995 May–July with the 1.0m telescope of the University of Tasmania near Hobart, and the Dutch 0.91m and Danish 1.54m telescopes at the European Southern Observatory (ESO) in Chile. All telescopes were equipped with CCD cameras and standard B, V and R filters, and a Gunn i filter. Integration times ranged from 1 to 10 min, depending on the filter, telescope and atmospheric conditions. A log of the observations is given in Table 6.1. All images were corrected for the bias and flat-fielded in the standard way.

We applied aperture photometry to Nova Sco 1994 and several nearby comparison stars within the field of view, using MIDAS and additionally written software operating in the MIDAS environment. We selected 3 comparison stars which were checked for variability during each night separately, and over the entire data set. From the distribution of the relative magnitudes between the comparison stars over the entire data set we conclude that they are stable within 0.02 mag. We estimate the accuracy of a single measurement of the differential magnitude of Nova Sco 1994 (relative to the average of the 3 comparison stars) to be 0.002 mag in the different bands. The differential magnitudes obtained in Tasmania have a small offset (< 0.03 mag) with respect to the data obtained at ESO. Also, the accuracy of these data is less (0.015 mag in R and i, 0.03 mag in V) due to poorer observing conditions and a lower signal-to-noise ratio.

Calibration of data obtained with the Danish and Dutch telescopes was performed using four different Landolt standard fields (Landolt 1992), PG 0918 (five stars), PG 1323 (three stars), Mark A (four stars), and SA 110 (four stars), during photometric nights that had 1" seeing or better. Observations of different standard fields within one night showed that the accuracy of the photometric calibration was better than 0.05 mag. The differential magnitudes of Nova Sco 1994 measured with the Tasmanian telescope were given an offset such that they overlapped the data obtained contemporaneously at the Danish and Dutch telescopes.

6.3 Results

A history of the brightness variations of Nova Sco 1994 is given in Figure 6.1. During the period 1995 May–July the optical brightness increased (apparently steadily) by about 0.9 mag in V and R to 15.7 and 14.7, respectively; in the same period the i magnitude increased to 13.8. We removed this long-term trend from the differential magnitudes by applying linear fits to the two extended data sets (June–July Dutch data, Tasmanian data, respectively) independently, and subtracting the mean from each of the remaining smaller data sets. Due to the uniform (orbital phase) sampling of the data, the detrend could be applied satisfactorily to each data set.

6.3.1 Orbital ephemeris

A Lomb-Scargle periodogram (Press & Rybicki 1989) of the detrended R-band data (483 data points) is shown in Figure 6.2. The periodogram has a distinct maximum corresponding to 1.3106 days; the second maximum occurs at 2.6246 days, very close to twice this period. When a temporally contiguous subset of the R-band data (i.e., excluding the data taken during the start of 1995 May and the end of 1995 July; 244 remaining data points) is subjected to a periodicity analysis we find a maximum corresponding to a period of 1.3123 days, close to the period found in the analysis of all available R-band data.
Figure 6.1: $R$-band magnitudes of Nova Sco 1994 (bottom) and one of the comparison stars (top) during the period 1995 May–July. Apart from a long-term trend, Nova Sco 1994 is clearly variable on a time scale of hours. The differential magnitude of one of the three reference stars (relative to the remaining two) shown in the top panel is stable within 0.01 mag. The start of the hard X-ray outburst on 1995 July 22 detected by BATSE is indicated by an arrow.

The periodogram of the $V$-band data (158 data points, excluding the 1995 May $V$-band data since they were taken in a single night during which Nova Sco 1994 was constant within 0.01 mag) shows a maximum at a period of 1.3038 days. The period search in the $i$-band data (99 data points during 1995 June–July) results in a period of 1.3039 days. Given the long baseline (85 days), and the largest number of data points (483) we consider the period of 1.3106 days derived from the $R$-band data as the most reliable.
Figure 6.2: Lomb-Scargle periodogram of the complete set of detrended (see text) R-band data. The distinct maximum corresponds to a period of 1.3106 days. The inset shows an enlargement of the same periodogram for periods longer than one day.

We calculated sinusoidal fits with a fixed period of 1.3106 days to the R-band data of each set of observations separately, having the extensive data set obtained at the Dutch telescope split further into two subsets. The accuracy of the arrival times of minimum light was estimated to be 0.05 days. From a least-squares fit to these arrival times and the respective cycle numbers we derive a photometric ephemeris for Nova Sco 1994 with $\chi^2 = 4.20$ for 4 degrees of freedom. Following the results obtained by Bailyn et al. (1995b) and further supported by the difference in the two minima of the light curve, we assume that the light curve has 2 minima per orbital cycle. Hence, the implied orbital period of Nova Sco 1994 is twice the value obtained from the least-squares fit, i.e., 2.6212 days. The times of the primary (deeper) minima are described by the following photometric ephemeris:

$$T_{\text{min}}(\text{HJD}) = 2449885.592(21) + 2.6212(16) \times N$$

where N denotes the number of cycles. The detrended R-band light curve, folded at this photometric ephemeris, is shown in Figure 6.3. The light curve shows two clear minima, differing by about 0.1 mag in depth, and two maxima of equal brightness. The peak-to-peak modulation of the light curve is $\sim 0.35$ mag. We have determined the relative phasing of the four extremes by fitting parabolae. The maxima occur at phase 0.30(1) and 0.69(1), the minima occur at 0.0 (by definition) and 0.51(1), with the first value corresponding to the deepest minimum. The detrended R-band light curve, folded at the photometric ephemeris and binned into 20 phase bins, is shown in the bottom panel of Figure 6.4. To prevent possible distortion of the binned light curve due to the detrending, we excluded in this figure the data taken during 1995 May which covered less than one orbital cycle.
Figure 6.3: Detrended R-band light curve of Nova Sco 1994, folded at the photometric ephemeris $T_{\text{min}} \ (\text{HJD}) = 2449885.592(21) + 2.6212(16) \times N$. The light curve is shown twice for clarity.

We calculated the $(V-R)$ and $(R-i)$ color curves of Nova Sco 1994 from the 1995 June–July observations using consecutive $V$, $R$ and $i$ measurements taken close in time. The $(V-R)$ and $(R-i)$ color curves folded at the photometric ephemeris and binned into 20 phase bins, are displayed in the top panels of Fig. 6.4. These color curves do not show evidence of significant variability with orbital phase. The average values for the $(V-R)$ and $(R-i)$ colors during this period were 1.06(3) and 0.86(2) mag, respectively. The average $(B-V)$ and $(V-R)$ colors derived during the night of 1995 May 4 were 1.480(8) and 1.026(5) mag.

6.3.2 Orbital inclination

We observed Nova Sco 1994 while it was $\sim$1 mag brighter in the $R$-band than its quiescent brightness, the extra light probably arising from the accretion disk. Although the optical light curves of Nova Sco 1994 are reminiscent of the ellipsoidal variations of the secondary star (Shahbaz, Naylor & Charles 1993), one must take into account the effects of X-ray heating of the secondary star and accretion disk, which will alter the shape of the light curve (van Paradijs & McClintock 1995).

In order to interpret the optical light curves, we used a model that includes a Roche lobe filling secondary star, the effects of X-ray heating on the secondary and a concave accretion disk, shadowing of the secondary star and the disk, and mutual eclipses of the disk and the secondary star. The intensity distribution on the secondary star is calculated using Kurucz model atmospheres and the concave accretion disk is assumed to radiate as a blackbody. The temperature distribution of the accretion disk is calculated according to Vrtilek et al. (1990). This model is similar to the models described by Tjemkes, Zuiderwijk & van Paradijs (1986) and de Jong, van Paradijs & Augusteijn (1996), which have been applied to 1254–690 and 1755–338 (de Jong et al. 1996).
Figure 6.4: Detrended R-band light curve of Nova Sco 1994 (bottom) and (V−R) and (R−i) color curves (top), folded at the photometric ephemeris $T_{\text{min}}(\text{HJD}) = 2449885.592(21) + 2.6212(16) \times N$ and binned into 20 phase bins. Each bin of the binned R-band light curve and the binned (V−R) and (R−i) color curves contain on average 15, 10 and 7 data points, respectively. The error bars show the rms fluctuations about the mean. All curves are shown twice for clarity.
We performed least-squares fits to the R-band light curve using the model described above. The model parameters are the binary mass ratio, $q=M_1/M_2$, inclination, $i$, the mass of the secondary star, $M_2$, the X-ray luminosity, $L_X$, the size of the accretion disk, $R_{\text{disk}}$ (as a fraction of the distance to the inner Lagrangian point $R_{L1}$) and the flaring angle of the accretion disk, $\alpha$. The albedo of the accretion disk and secondary star were taken to be 0.95 and 0.40 respectively (see results obtained by de Jong et al. 1996).

We used two values for $L_X$, $1 \times 10^{36} \text{ erg s}^{-1}$ and $3 \times 10^{36} \text{ erg s}^{-1}$ (the $3\sigma$ BATSE upper limit during the period of our observations, Harmon, private communication), and searched for solutions in the $(i, q, R_{\text{disk}})$ plane, using only parameter combinations that satisfied the mass function, i.e., given each set of $(i, q)$ values we determined $M_2$, which was subsequently used in the model fit. We searched $i$ in the range $40^\circ$–$90^\circ$, $q$ in the range 3–10, and $R_{\text{disk}}$ in the range 0.4–0.7 $R_{L1}$.

Figure 6.5 shows the solutions in the $(i, q)$ plane, obtained by collapsing the solutions along the $R_{\text{disk}}$ axis onto the $(i, q)$ plane. The 90 percent confidence regions are shown, calculated according to Lampton, Margon & Bowyer (1976) with 5 interesting parameters $(i, q, R_{\text{disk}}, \alpha$, and the normalization), after the error bars had been scaled to give a minimum $\chi^2$ of 1. We
find that the best fits are those with a small accretion disk, \( R_{\text{disk}} = 0.42 \ R_{L1} \). The solid and dotted lines in Fig. 6.5 mark the contours for fits using \( L_x = 1 \times 10^{36} \) erg s\(^{-1}\) and \( 3 \times 10^{36} \) erg s\(^{-1}\), respectively. We also show the physical bounds placed on the geometry of the system: the absence of X-ray eclipses implies \( i < 76^\circ \) and the maximum size allowed for the accretion disk (i.e., the tidal radius \( 0.75 \ R_{L1} \)) implies \( i > 65^\circ \). Therefore, we constrain the system to lie at an inclination between 65°–76°. From Fig. 6.5 it follows that we can constrain the mass ratio \( q \) to lie in the range 3.8–5.5 at the 90 percent confidence level. Figure 6.6 shows the \( R \)-band light curve with model fits for \( i = 68^\circ \), \( R_{\text{disk}} = 0.4 \) and 0.7 \( R_{L1} \) and \( L_x = 1 \) and 3 \( \times 10^{36} \) erg s\(^{-1}\), respectively.

### 6.4 Discussion

During the period of our observations the optical brightness of Nova Sco 1994 increased (apparently steadily) by 0.9 mag to \( V = 15.7 \). Bailyn et al. (1995b) found the average brightness of Nova Sco 1994 to be \( V = 16.5 \) (1995 March 18–25) and \( V = 16.7 \) (1995 April 5–24), close to the quiescent brightness of \( V = 17.3 \) (Bailyn et al. 1995a). Between 1995 June 26 and July 3, and during 1995 August 4–7, Orosz, Schaefer & Barnes (1995) measured \( V = 15.9 \) consistent with the observations discussed here.

On 1995 July 22 the onset of an outburst of hard X-rays (> 20 keV) from Nova Sco 1994 was detected with BATSE which reached a maximum intensity of 650 ± 30 mCrab (20–100
keV) on August 1 (Harmon et al. 1995c; Harmon, Paciesas & Fishman 1995). Our measurements show that the optical brightness of Nova Sco 1994 increased long before and during the onset of this X-ray outburst. The maximum of the X-ray outburst was not covered by our observations, but those performed by Orosz et al. (1995) during the decay of the X-ray outburst in early August, showed that the optical brightness of Nova Sco 1994 decreased as well. The \((V-R)\) and \((R-i)\) color curves of Nova Sco 1994 did not show variability with the orbital period and had average values of 1.06(3) and 0.86(2) mag, respectively. However, Bailyn et al. (1995b) detected a color variation in the light curves of Nova Sco 1994 through orbital phase during their observations in 1995 March and April, with the source being redder during inferior conjunction of the secondary and bluer at the other conjunction.

The analysis of our photometric observations leads to an orbital period of 2.6212(16) days. The accuracy of this measurement can be improved by combining our results with those published in other investigations. Bailyn et al. (1995b) determined the moment of maximum redshift of the velocities for the secondary star in Nova Sco 1994 to occur at Heliocentric Julian Day (HJD) 2449839.083(3). This epoch corresponds to photometric phase 0.257(13) (calculated with respect to the ephemeris given above), indicating that the photometric minimum at phase 0.0 corresponds to inferior conjunction of the secondary star. The change of blue-to-redshift of the velocities for the secondary star, as determined by Casares (private communication) occurred at HJD 2449885.589(19). This corresponds to photometric phase 0.001(11). Adding the corresponding two spectroscopic epochs of minimum light to our photometric epochs leads to the following ephemeris:

\[
T_{\text{min}}(\text{HJD}) = 2449838.4277(89) + 2.62040(98) \times N
\]

where the errors in the zeropoint and period were calculated by requiring \(\chi^2_\nu = 1.0\) for 6 degrees of freedom.

Bailyn et al. (1995b) observed a fiducial minimum in the V-band light curve of Nova Sco 1994 on 1995 April 2 (HJD 2449809.70) which they used to improve their spectroscopic ephemeris. However, they could not phase all photometric and spectroscopic data with this ephemeris and suggest that activity in the disk may be responsible for the apparent phase offset. The April 2 minimum occurs at phase 0.04 (calculated with respect to the refined ephemeris given above), close to the expected photometric minimum at phase 0.0. In view of the different shape of this narrow minimum compared to the light curve observed on all other occasions, we choose not to use this epoch in our effort to improve the orbital period of Nova Sco 1994. The possible eclipse event on 1994 August 17 reported by Bailyn et al. (1995a) occurred at HJD 2449581.62(5) (according to their Fig. 4) and corresponds to photometric phase 0.997(27) when using the refined ephemeris given above. However, since this possible eclipse event did not recur and given the lack of data during this particular minimum and the strong photometric variability of Nova Sco 1994 at that time, we choose not to include this epoch either.

The folded light curve of Nova Sco 1994 (after removal of the long-term trend) shows two equally bright maxima, occurring at phases 0.302 and 0.691, and two unequal minima at phases 0.0 (by definition) and 0.505, when fitted by parabolae. Within one orbital cycle the light curve is smooth. Cycle-to-cycle variations in the shape of the light curve of \(\pm 0.1\) mag occur as well. During our observations the average V-band brightness of Nova Sco 1994 was about \(\sim 1\) mag brighter than in quiescence. As a result, ellipsoidal variations contribute at most a minor part of the observed brightness modulations. The light curve of Nova Sco 1994 is fairly similar to those of high inclination systems such as CAL 87, 2A 1822–371 and Her X-1.
Figure 6.7: The \((M_2, M_1)\) plane together with the limits placed on the mass of the secondary from evolutionary arguments \((0.23 \leq M_2 \leq 2.3 \, M_\odot)\) and the limits obtained from calculating model fits to the \(R\)-band data. The mass of the compact object is restricted to lie in the range \(4.94 - 6.79 \, M_\odot\) and the mass of the secondary star in the range \(0.95 - 1.78 \, M_\odot\).

(van Paradijs & McClintock 1995). The light curves of these systems are dominated by X-ray heating of the secondary star, and by mutual eclipses of the secondary star and the accretion disk. The luminous accretion disk provides an independent source of light, which, in the absence of mutual eclipses, will decrease the amplitude of the light curve, and may cast an X-ray shadow on the secondary, decreasing the effect of X-ray heating substantially. Haswell (1996) has shown recently that small brightness variations of an accretion disk can affect the detailed shape of the double-waved optical light curves of quiescent SXTs. The optical contribution of a bright accretion disk will change in the different pass bands and is expected to be least in the red. Superhump variations may affect the detailed shape of the light curve as well (King 1995; O’Donoghue & Charles 1996).

From a special-relativistic kinematic model of the superluminal radio source in Nova Sco 1994, Hjellming & Rupen (1995) have derived an inclination angle of \(85^\circ\). At this inclination regular eclipses of the compact X-ray source by the secondary should occur. These are not observed (Harmon et al. 1995b) and our modeling of the \(R\)-band light curve constrains the inclination of Nova Sco 1994 to lie between \(65^\circ - 76^\circ\). The absence of X-ray eclipses while viewing the binary system at a high orbital inclination can possibly be explained by a model in which the X-rays are generated in a region much larger than the secondary; for \(R_2 \sim R_\odot\) this would imply that the size
of the X-ray source may be as large as $\sim 10^{12}$ cm. This is much larger than the size of accretion disk coronae (ADC) seen in some high inclination low-mass X-ray binaries which scatter a few percent of the primary X-rays generated near the compact star (White, Nagase & Parmar 1995). In the case that the observed X-rays all originate from an ADC with no direct view of the compact star, then the real X-ray luminosity of Nova Sco 1994 is likely to be one or two orders of magnitude higher than the observed value of $\sim 10^{36}$ erg s$^{-1}$, i.e., close to the Eddington luminosity for a black-hole mass of $\sim 5$ M$_{\odot}$. We therefore conclude that our results are inconsistent with an inclination angle of $i = 85^\circ$.

### 6.5 Conclusion

Since Nova Sco 1994 was clearly not in quiescence during the period of our observations, we included the effects of X-ray heating on the secondary star and the concave accretion disk in calculating model fits to the R-band data, using values for the X-ray luminosity consistent with the BATSE upper limit. For these model fits we constrain the inclination and the mass ratio of Nova Sco 1994 to lie in the range 65°–76° and 3.8–5.5, respectively. From evolutionary arguments, Brandt et al. (1995) restrict the mass of the secondary star to lie in the range 0.23–2.3 M$_{\odot}$. These limits are shown in the ($M_2$, $M_1$) plane (Figure 6.7) along with the limits placed on the mass of each of the binary components obtained from the fitting procedure. We thus limit the mass of the compact object in Nova Sco 1994 to lie in the range 4.94–6.79 M$_{\odot}$ and the mass of the secondary star in the range 0.95–1.78 M$_{\odot}$.

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The quiescence optical light curve of Nova Scorpii 1994 (= GRO J1655–40)

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Abstract

We report on extensive V, R, and i band photometry of the black-hole candidate Nova Sco 1994 (GRO J1655–40) obtained during 1996 March, when the source was close to its quiescent pre-outburst optical brightness (V = 17.3). From our observations and data taken from the literature we derive a refined ephemeris for inferior conjunction of the secondary star: HJD 244 9838.4198(52) + 2.62168(14) × N. We have modeled the V, R, and i band light curves in terms of a Roche lobe filling secondary and an accretion disk around the compact star, the latter described as a flat cylinder with a radial temperature distribution. From the shape of the light curve we constrain the binary inclination and mass of the secondary star to lie in the ranges 63°7–70°7 and 1.60–3.10 M\(_{\odot}\), respectively. This limits the mass of the black hole to the range 6.29–7.60 M\(_{\odot}\). The mass range we obtained for the secondary star is supported by the results of stellar evolution calculations.

7.1 Introduction

Soft X-ray transients (SXTs) are low-mass X-ray binaries consisting of a neutron star or black-hole primary, which undergo unstable accretion from a late-type companion. Disk instabilities (van Paradijs 1996) cause brief but violent outbursts, typically lasting weeks to months, during which their X-ray luminosity abruptly increases by several orders of magnitude, to \(~10^{37}–5 \times 10^{38}\) erg s\(^{-1}\). During such an outburst, the optical flux becomes dominated by the contribution of the accretion disk and is enhanced by several magnitudes. In the intervals between outbursts, which typically last years to decades, the X-ray luminosity is extremely low, and the optical flux is dominated by the luminosity of the secondary star (see Verbunt et al.
1994; van Paradijs & McClintock 1995; Narayan, McClintock & Yi 1996 for reviews of the quiescence X-ray and optical properties of SXTs). Therefore, the properties of the secondary star can be studied during the quiescent episode.

The SXT Nova Sco 1994 (GRO J1655−40), discovered on 1994 July 27 with BATSE (20–100 keV) on board the Compton Gamma Ray Observatory (Zhang et al. 1994), has been studied extensively during the past two years in X-rays and at optical and radio wavelengths (Tingay et al. 1995; Bailyn et al. 1995a; Harmon et al. 1995b; Hjellming & Rupen 1995; Zhang et al. 1995; Bailyn et al. 1995b; Paciesas et al. 1996; van der Hooft et al. 1997). CCD photometry of Nova Sco 1994 revealed a double-waved modulation of the optical light at a period of 2.6 days (Bailyn et al. 1995b; van der Hooft et al. 1997). Strong evidence that the compact object in Nova Sco 1994 is a black hole was presented by Bailyn et al. (1995b) who established a spectroscopic period of 2.60 ± 0.02 days and a mass function \( f(M) = 3.16 ± 0.15 M_\odot \). The secondary was classified as an F3–F6 IV type star (Orosz & Bailyn 1997).

As an SXT, Nova Sco 1994 is remarkable, due to the fast recurrence of its successive X-ray outbursts since the first X-ray detection of the source in 1994. The X-ray outbursts of Nova Sco 1994 were initially separated by intervals of about 120 days (Zhang et al. 1995) and lasted many weeks (Harmon et al. 1995a, b; Wilson et al. 1995). During these periods the optical brightness of Nova Sco 1994 was between 1 and 2 mag above its quiescent \( V = 17.3 \) pre-outburst level (Bailyn et al. 1995a), which likely reflects the contribution of the accretion disk and X-ray heating of the secondary star. Most photometric observations of Nova Sco 1994 were made during this period.

However, in the interval 1995 September to 1996 April, no significant X-ray flux was detected from Nova Sco 1994 indicating a (temporary) longer period of quiescence. We present in this paper the results of extensive \( V \), \( R \), and \( i \)-band photometry of Nova Sco 1994 obtained during 1996 March, and derive its quiescence light and color curves. We derive limits on the system parameters based on \( \sim 30000 \) theoretical light and color curves in the three photometric bands, calculated for a wide range of parameters of a model describing a Roche lobe filling secondary star supplemented with a model of an accretion disk around the compact star. The limits on the mass of the secondary star are compared with theoretical evolutionary tracks which we computed for both single and binary star evolution.

### 7.2 Observations and data reduction

We observed Nova Sco 1994 (GRO J1655−40) during 28 consecutive nights starting 1996 March 5 with the Dutch 0.91m telescope at the European Southern Observatory (ESO) in Chile. The telescope was equipped with a CCD camera and the observations were made using standard \( V \) and \( R \) filters and a Gunn \( i \) filter. Integration times were 10 min for the \( V \) filter and 5 min for the \( R \) and \( i \) filters. We obtained 67 images of Nova Sco 1994 in the \( V \)-band, and 69 in the \( R \) and \( i \)-bands each. All images were corrected for the bias, and flat-fielded in the standard way. A \( 3' \times 3' \) \( R \)-band find chart of the field of Nova Sco 1994 (taken on 1996 March 5), in which Nova Sco 1994 and five nearby comparison stars are indicated, is shown in Figure 7.1.

We applied aperture photometry to Nova Sco 1994 and five nearby comparison stars using MIDAS and additionally written software operating in the MIDAS environment. The five comparison stars were checked for variability over the entire data set. From the dispersion of the relative magnitudes of each comparison star over the entire observing period (\( \leq 0.008 \) mag) we
Figure 7.1: $3' \times 3'$ $R$-band find chart of the field of Nova Sco 1994, taken on 1996 March 5. The exposure time was 300 sec; North is at the top, East to the right. Nova Sco 1994 is indicated by a circle and is numbered 1, the five comparison stars are numbered 2-6.

conclude that the brightness of these stars is constant. The accuracy of a single measurement of the differential magnitude of Nova Sco 1994 (relative to the average of the five comparison stars), taking into account Poisson noise only, is typically 0.006 mag in each of the three bands.

Photometric calibration of the data was performed using images of two Landolt standard fields (Landolt 1992), Rubin 149 (8 stars) and PG 1323 (4 stars), during nights of good photometric quality. Observations of different standard fields within one night showed that the accuracy of the photometric calibration was better than 0.05 mag.
7.3 Results

7.3.1 Quiescence light and color curves of Nova Sco 1994

During the period of our observations the average $V$ magnitude of Nova Sco 1994 was 17.25 and the light curve showed a modulation with two equal maxima and unequal minima, whose depths are 0.31 and 0.48 mag. The average $V$ magnitude of Nova Sco 1994 is consistent with the pre-outburst brightness of $V = 17.3$ (Bailyn et al. 1995b), which indicates that the source was in quiescence during the period of our observations. During two successive pointings on March 8, separated by $\sim 5$ hr, we detected a very low optical brightness of Nova Sco 1994 in each of the three filters (for the $V$-band we then found $V = 17.48$ and $V = 17.53$ mag, respectively).

There is remarkably little variability superposed on the quiescence light curve of Nova Sco 1994 in comparison to several other quiescent SXTs, which show cycle-to-cycle variations of the order of a few percent (McClintock & Remillard 1986; Remillard et al. 1992; Martin et al. 1995a; Chevalier & Ilovaisky 1996; Shahbaz et al. 1996). Haswell (1996) has recently suggested that such brightness variations may be similar to those seen in superhumps during superoutbursts of SU UMa type cataclysmic variables.

The data in the three bands were independently searched for periodicities using a Lomb-Scargle periodogram (Press & Rybicki 1989). The periodograms show five strong peaks, corresponding to half the orbital period and its one-day aliases, and associated with each peak the characteristic pattern resulting from the data sampling. In each band we found a distinct maximum at a fundamental period of 1.312 days. Since the light curve of Nova Sco 1994 features two minima with unequal depth, we folded the data on twice this period, using a trial zero point (chosen in the center of the data set). The time of inferior conjunction of the secondary, $T_{\text{inf}}$, was derived from the folded light curve, by fitting a parabola to the shallow minimum, which yielded a phase offset to be applied to the trial zero point. The shallow minimum occurs close to the epoch of inferior conjunction of the secondary star as predicted by the ephemeris of Nova Sco 1994 reported in previous investigations (see, e.g., Bailyn et al. 1995b; van der Hooft et al. 1997).

The photometric period of 2.6246 days of Nova Sco 1994 is slightly longer than previous measurements of the period based on both photometric and spectroscopic observations (see, e.g., Bailyn et al. 1995b; van der Hooft et al. 1997). In order to improve the accuracy of the orbital period we combined 9 photometric measurements of $T_{\text{inf}}$ from our 1995 and 1996 data with photometric measurements by Bailyn et al. (1995b) and Orosz & Bailyn (1997), and two spectroscopic measurements by Casares (private communication) and Orosz & Bailyn (1997). From a least-squares fit of this set of 13 arrival times to their respective cycle numbers (spanning 140 cycles) we derived the following refined ephemeris for the times of inferior conjunction of the secondary star: HJD 2449838.4198(52) + 2.62168(14) × N, with $\chi^2_d = 2.3$ for 11 degrees of freedom. In Figure 7.2 we present the $V$, $R$ and $i$ light curves of Nova Sco 1994 folded at this ephemeris. The drawn lines represent light curves which were computed using a theoretical model of the secondary star which will be described in detail in Section 7.3.2.

We calculated the $(V-R)$, $(R-i)$, and $(V-i)$ color curves using consecutive $V$, $R$ and $i$ measurements taken close in time ($\lesssim 20$ min). These color indices, folded at the above ephemeris, are displayed in Figure 7.3, together with theoretical color curves (see Sect. 7.3.2). They show a clear modulation with the photometric period. The peak-to-peak amplitudes in the $(V-R)$ and $(R-i)$ color curves are $\sim 0.06$ and $\sim 0.05$ mag, respectively. The color curves have two unequal
maxima and two equal minima. The maxima of the color curves occur near phase 0.0 and 0.5 (the largest occurs near phase 0.5), indicating that Nova Sco 1994 is reddest near conjunctions; the system is bluest near quadratures (phases 0.25 and 0.75).

7.3.2 Modeling the light curves: ellipsoidal model

To construct theoretical light curves we calculated the flux of the secondary emitted into the direction of the observer as a function of orbital phase, by numerical integration of the contributions from a large number of small elements on the secondary's surface. We used a numerical model, discussed in detail by Tjemkes, Zuiderwijk & van Paradijs (1986), based on a description of the tidal and rotational distortion of the secondary in terms of an equipotential surface. The non-uniform surface brightness distribution across the secondary is described according to von Zeipel's theorem. We adopted 0.25 as the value of the gravity darkening coefficient \( \beta \), valid for stars with a radiative envelope (von Zeipel 1924). For each surface element we used a blackbody approximation (at the local effective temperature) for the perpendicularly emerging specific intensity. We applied a standard linear limb darkening law, with limb darkening coefficients as a function of temperature taken from Al-Naimy (1978). For the theoretical spectra calculated by Kurucz (1979) one finds that over the effective temperature interval 5500 to 8000 K (covering virtually all surface elements on the secondary) the average deviation of the gradient \( \partial \log F_{\nu} / \partial T \) with respect to the blackbody approximation is \( \sim 6\% \) (similar results were obtained for the dependence of \( F_R \) and \( F_i \) on \( T \) [\( \sim 3-4\% \)]). To estimate the effect of our blackbody approximation on our results we have made trial calculations in which the Planck functions were multiplied by an arbitrary function of \( T \) which accounts for the difference with the Kurucz spectra. We find that the depth of the deepest minimum changes by \( \lesssim 2\% \) (V-band) and \( \lesssim 1\% \) (R and \( i \)-band) with respect to the blackbody approximation, while the depth of the shallow minimum changes by \( \lesssim 4\% \) (V-band) and \( \lesssim 2\% \) (R and \( i \)-band). These differences are small enough that their effect on the solutions in the \((i,M_2)\) plane (see below) can be ignored compared to the effects of uncertainty in the system parameters.

Initially, the possible contribution of an accretion disk to the emergent flux was not included in our modeling, nor were mutual eclipses and the effect of X-ray heating on the secondary. In our calculations we used the secondary mass, \( M_2 \), and the orbital inclination, \( i \), as free parameters. The observed mass function \( f(M) = 3.16 \pm 0.15 \, M_\odot \) (Bailyn et al. 1995b) then fixes the primary mass, \( M_1 \), and the mass ratio, \( q = M_1/M_2 \). Together with the bolometric luminosity, \( L_{\text{opt}} \), of the secondary, the temperature distribution across the latter's surface, and the light curve, are determined.

We calculated a first set of 81 light curves (and their corresponding color curves) for \( i \) between 50°–90° (steps of 5°), and secondary masses in the range 0.5 \( \leq M_2 \leq 4.5 \, M_\odot \) (steps of 0.5 \( M_\odot \)). We adopted a bolometric luminosity for Nova Sco 1994 of \( L_{\text{opt}} = 41 \, L_\odot \), as determined from the mean V brightness (\( V = 17.25 \), see Fig. 7.2), a distance to the system of 3.2 kpc (Hjellming & Rupen 1995), a bolometric correction \( B.C. = -0.03 \) mag (F5 V type star; Popper 1980) and a color excess \( E(B-V) = 1.3 \) mag (Horne et al. 1996). Each of the theoretical light curves were given an offset such that the data observed at the shallow minimum (phase 0.0) was matched. We found that none of these light curves could reproduce the sharp and deep minimum at phase 0.5, indicating that our model requires additional structure. Near this phase the compact object is in front of the secondary star, and the light curve shows significant scatter whereas it is smooth during the remaining part of the orbital cycle. Both the sharpness of the minimum and
Figure 7.2: V, R and i light curves of Nova Sco 1994 folded at the photometric ephemeris $T_{\text{inf}} \text{(HJD)} = 2449838.4198(52) + 2.62168(14) \times N$. The curves are repeated over 1.5 cycles for clarity. Phase 0.0 corresponds to inferior conjunction of the secondary with respect to the compact star. The drawn lines represent a theoretical light curve computed for a binary inclination and secondary mass of (67:25, 1.60 $M_\odot$).
Figure 7.3: \((V-R), (R-i)\) and \((V-i)\) color curves folded at the photometric ephemeris \(T_{\text{inf}}(\text{HJD}) = 244\,9838.4198(52) + 2.62168(14) \times N\). The curves are repeated over 1.5 cycles for clarity. Phase 0.0 corresponds to inferior conjunction of the secondary with respect to the compact star. The drawn lines represent a theoretical color curve computed for a binary inclination and secondary mass of \((67.25, 1.60\, M_\odot)\).
Figure 7.4: 1, 2, 3σ confidence contours in the $i$ versus $M_2$ plane for intrinsic luminosities of 31 (dashed), 41 (solid), and 54 $L_\odot$ (dashed-dotted). The average effective temperatures from the secondary, calculated from the intrinsic luminosity and the effective radius of the secondary, are indicated for 6300 and 6600 K.

The increased scatter near phase 0.5 likely result from the presence of an accretion disk around the compact star, which is obscuring (part of) the light of the secondary at this phase. There is no evidence for a disturbance of the light curve near phase 0.0; we therefore, in this first phase of our analysis, computed a $\chi^2$ for each set of parameters, using the light curves in the three photometric bands simultaneously from which the data obtained between photometric phase 0.35 and 0.65 were excluded.

We found that the only acceptable solutions are for $i$ in the range 60°–75°, for any of the secondary masses between 0.5–4.5 $M_\odot$. We made a new set of theoretical light (and color) curves, using a denser grid of $i$ and $M_2$ values: $61^\circ \leq i \leq 74^\circ$ (0.25 step size) and $0.2 \leq M_2 \leq 5.0$ $M_\odot$ (0.1 $M_\odot$ step size), respectively.

From the fits of the theoretical to the observed light curves we find that the binary inclination and mass of the secondary star can be well constrained. The $\chi^2$ contours in the $i$ versus $M_2$ plane trace a narrow, ellipse-shaped region. Such a correlation between $i$ and $M_2$ is expected as the amplitude of the brightness modulation will decrease with both smaller inclination angles and larger mass of the secondary star (the distortion of the secondary, and therefore the temperature contrast across the stellar surface decreases as $M_2$ increases). A minimal $\chi^2$ of 2.54 (130 d.o.f.) was found at (67.25, 1.60 $M_\odot$), which indicates that minor variations are present in the light...
curve in the phase interval 0.65–1.35. The 1, 2 and 3σ confidence contours in the $(i, M_2)$ plane are shown in Figure 7.4, which were computed by scaling the required $\Delta \chi^2$ by the minimum value of $\chi^2_{\nu}$.

The assumed value of the bolometric luminosity of the secondary star of Nova Sco 1994 (41 L_☉) is sensitive to errors in both the distance to the source and its color excess. The latter is probably the most important source of uncertainty as the distance is well determined at $3.2 \pm 0.2$ kpc (Hjellming & Rupen 1995) based on a kinematic model of the radio jets; other distance estimates are consistent with this value [3.5 kpc (McKay & Kesteven 1994); 3–5 kpc (Tingay et al. 1995) both based on H I absorption; $\sim 3$ kpc (Bailyn et al. 1995a) based on interstellar absorption; $\sim 3$ kpc (Greiner, Predehl & Pohl 1995) based on a dust scattering halo]. A minimal value of the color excess was reported by Bailyn et al. (1995a) $[E(B - V) = 1.15$ mag based on the equivalent width of the Na D-lines in optical spectra taken in 1994 August], while a largest $E(B - V)$ of 1.5 mag was reported by Horne et al. (1996) [based on a power-law spectral fit to UBVRI photometry taken during 1996 May]; deep 220-nm absorption in a HST spectrum of Nova Sco 1994 taken in 1996 May suggested $E(B - V)$ of 1.3 mag (Horne et al. 1996). Therefore, we assumed $E(B - V)$ to lie in the range 1.2–1.4 mag, with the corresponding value of $L_{\text{opt}}$ in the range 31–54 L_☉. We therefore also calculated theoretical light and color curves for secondary luminosities of 31 (for which we took $50^\circ \leq i \leq 74^\circ$), and 54 L_☉ (with $62^\circ \leq i \leq 78^\circ$); the steps in $i$ were 0:25. In all calculations we covered the range $0.2 \leq M_2 \leq 5.0$ M_☉, respectively, with steps of 0.10 M_☉.

From these theoretical light curves we derived ellipse-shaped $\chi^2_{\nu}$ contours in the $i$ versus $M_2$ plane similar to those derived for the curves calculated for $L_{\text{opt}} = 41$ L_☉. However, the location of the contours in the $(i, M_2)$ plane depends on $L_{\text{opt}}$. For 31 L_☉ the $\chi^2_{\nu}$ contours shift towards lower binary inclinations, whereas they shift to larger inclination for 54 L_☉. Minimal $\chi^2_{\nu}$ values (for 130 d.o.f.) were found at $(63^\circ:75, 1.30$ M_☉) [$\chi^2_{\nu} = 2.60; 31$ L_☉], and $(71^\circ:25, 1.90$ M_☉) [$\chi^2_{\nu} = 2.52; 54$ L_☉]. The 1, 2 and 3σ confidence contours were computed similar as in the case of 41 L_☉, and are displayed in Fig. 7.4.

### 7.3.3 Inclusion of an accretion disk to the model

The model described in Sect. 7.3.2 quite well describes the data obtained at inferior conjunction of the secondary star, but not those obtained near superior conjunction, when we observe less light than the model predicts. A natural explanation for the flux deficit near phase 0.5 is that an accretion disk around the compact star obscures part of the secondary at certain viewing angles. In the second stage of our modeling efforts we included an accretion disk in the model, described as a flat cylinder with a radial temperature distribution. The vertical outer edge of the disk is assumed not to emit radiation. By including such an accretion disk the number of parameters in the model is increased by three: the radius of the disk as a fraction of the effective Roche lobe, $\alpha$, the flaring angle of the disk, $\gamma$, and the temperature at the outer edge of the disk, $T_{\text{edge}}$. In view of the very low X-ray luminosity of Nova Sco 1994 during the period of our observations, we assumed that the radial temperature distribution in the disk follows an $r^{-3/4}$ dependence (Pringle 1981).

We computed $\sim 25,000$ theoretical light and color curves for intrinsic luminosities of 31, 41 and 54 L_☉, a fractional disk radius between 0.6 and 1.0 (step size of 0.1), outer disk temperatures of 100 or 1000 K, and a flaring angle of the disk of either 2° or 10°. We used step sizes of 0:25 and 0.1 M_☉ for $i$ and $M_2$, respectively. We performed several tests (using a less dense grid for
Figure 7.5: 1, 2, 3σ confidence contours in the $i$ versus $M_2$ plane for intrinsic luminosities of 41 [top-left panel], and 31 (dashed), 41 (solid), and 54 L⊙ (dashed-dotted) [other panels], for accretion disk models with outer edge temperature $T_{\text{edge}} = 100$ K, flaring angle $\gamma = 2^\circ$, and fractional disk radii between 0.6 and 1.0. Average effective temperatures of the secondary star are indicated in the top-right panel. In the bottom-left panel, the solutions are constrained by the
Figure 7.5: (continued)
smooth curves tangent to the $\alpha = 0.7, 0.9$, and $31, 41$ and $54 \, L_\odot$ confidence contours. The solutions in the $i$ versus $M_2$ plane which are constrained by these limits are indicated by the hatched area in the bottom-left panel. Finally, the total collection of solutions for this ($T_{\text{edge}}, \gamma$) is given in the bottom-right panel.
Figure 7.6: Total collection of solutions in the $i$ versus $M_2$ plane for $(T_{\text{edge}}, \gamma) = (100 \, \text{K}, 2^\circ)$ [top-left], (1000 K, $2^\circ$) [top-right], (100 K, $10^\circ$) [bottom-left], and (1000 K, $10^\circ$) [bottom-right].
Figure 7.6: (continued)
The hatched area’s are constructed similar as in Fig. 7.5.
i, and $M_2$) in which temperatures at the outer edge of the disk were selected between 100 and 6000 K. Light curves computed with $T_{\text{edge}} > 1000$ K do not resemble the data well: for such outer edge temperatures the accretion disk contributes too much to the total flux of the system, which decreases the amplitude of the ellipsoidal modulation and changes the relative depth of the minima in the light curve. At superior conjunction of the secondary star, the contribution of the disk to the total flux is $\leq 4\%$ for $T_{\text{edge}} = 1000$ K, and is entirely negligible for lower values of $T_{\text{edge}}$. Thus, the main effect of the disk is to occult a fraction of the secondary star near phase 0.5.

In calculating $\chi^2$, we did not include the six deviating points (two in each of the three passbands) obtained during subsequent pointings on March 8; they must be caused by variations in the disk structure, which cannot be incorporated into our model.

For each set of parameters, the 1, 2 and 3σ confidence contours in the $(i, M_2)$ plane were computed as before. The confidence contours corresponding to models having an accretion disk with a flaring angle $\gamma = 2^{\circ}$, and an outer-edge temperature $T_{\text{edge}} = 100$ K, are shown in Figure 7.5. The top-left panel of this figure displays the confidence contours for $L_{\text{opt}} = 41$ L$_\odot$ and fractional disk radii between 0.6 and 1.0. These contours trace narrow ($\sim 1.5$ wide) ellipses in the $(i, M_2)$ plane. Since the light curve of Nova Sco 1994 is dominated by ellipsoidal variations (see Sect. 7.3.2), the ‘islands’ derived for the different fractional disk radii are located in the same general area of the $(i, M_2)$ plane as the contours which were derived from the pure ellipsoidal model (see Fig. 7.4). As expected, for increasing values of $\alpha$ the confidence contours move toward smaller values of $i$.

In the top-right panel of Fig. 7.5, the confidence contours for intrinsic luminosities of 31 (dashed), 41 (solid) and 54 L$_\odot$ (dashed-dotted) are displayed, with the other parameters unchanged. From this panel it follows that for a given fractional disk size, and intrinsic luminosities between 31 and 54 L$_\odot$, the solutions move along a rather narrow track in the $(i, M_2)$ plane. Solutions for larger secondary masses are found at smaller inclination angles, since an accretion disk of a given relative size can obscure the light of the secondary star at smaller values of $i$ as $M_2$, and therefore, the size of the secondary, increases. In the remainder of our analysis we have assumed that the fractional disk radius is in the range 0.7 to 0.9 (see, e.g., Paczyński 1977; Frank, King & Raine 1992).

We can further constrain the system parameters by noting that the spectral type of the secondary limits the range of its effective temperature (averaged over the secondary surface), and therefore of the secondary radius. Since the secondary is assumed to fill its Roche lobe (this fixes its average density), for a given value of $L_{\text{opt}}$ this requirement limits the position of the system in the $(i, M_2)$ plane. The effective temperature decreases with both smaller intrinsic luminosity and larger mass of the secondary star (for a Roche lobe filling secondary the average density depends only on orbital period). The secondary of Nova Sco 1994 has been classified as an F3–F6 type star (Orosz & Baily 1997). According to Popper (1980), effective temperatures of such stars are in the range 6330–6620 K. The $M_2$ ranges corresponding to this range in average effective temperatures have been indicated for each intrinsic luminosity individually in the top-right panel of Fig. 7.5. In the bottom-left panel of Fig. 7.5 this constraint is combined with those obtained from the fitting of the light curves.

For $L_{\text{opt}} = 54$ L$_\odot$, average effective temperatures of $\leq 6600$ K are obtained for secondary masses of 3.6 M$_\odot$ and higher. This limiting mass is much larger than the maximum mass of the secondary allowed by the disk models for this luminosity. Therefore, taking the mass limit imposed
by the average effective temperature of the secondary star into account, we can exclude an intrinsic luminosity of 54 $L_\odot$ for Nova Sco 1994 (see top-right panel of Fig. 7.5). For the other two intrinsic luminosities, the average effective temperature limits the secondary mass to the range $1.6-2.1 M_\odot$ ($31 L_\odot$) and $2.4-3.1 M_\odot$ ($41 L_\odot$), well inside the collection of solutions for these disk models. The combined constraints for these two values of $L_{\text{opt}}$ have been indicated by hatched polygons in the lower-left panel of Fig. 7.5.

Given the smooth variation of the location of the confidence contours in the $(i, M_2)$ plane in response to changes in the fractional disk radius or bolometric luminosity, we connected both hatched areas by smooth curves, thereby producing a final constraint on the system in the $(i, M_2)$ plane, which is shown in the lower-right panel of Fig. 7.5. Note that the final constraint shown in Fig. 7.5 is derived for the case $T_{\text{edge}} = 100$ K and $\gamma = 2^\circ$ only.

In Figure 7.6 we have collected the results of similar analyses for four combinations of outer-edge temperature and flaring angle of the disk: (100 K; $2^\circ$) [top-left panel], (1000 K; $2^\circ$) [top-right panel], (100 K; $10^\circ$) [bottom-left panel], and (1000 K; $10^\circ$) [bottom-right panel]. This figure shows that the solutions corresponding to models for $T_{\text{edge}} = 1000$ K (right panels) are not shifted much with respect to those for 100 K (left panels). The models with a flaring angle of $\gamma = 10^\circ$ (bottom panels) are slightly shifted toward lower binary inclination with respect to the models for $(\gamma = 2^\circ$, top panels).

In Figures 7.7 and 7.8 theoretical light and color curves are shown, computed for the parameters $i = 68.75^\circ$, $M_2 = 2.10 M_\odot$, $L_{\text{opt}} = 41 L_\odot$, $\alpha = 0.8$, $T_{\text{edge}} = 100$ K, $\gamma = 2^\circ$, typical for the collection of solutions we obtained.

### 7.4 Discussion

#### 7.4.1 Quiescence light curves

The average $V$ magnitude of Nova Sco 1994 during our 1996 March observations was 17.25, consistent with the pre-outburst brightness of $V = 17.3$ (Bailyn et al. 1995a), which indicates that the source was then in quiescence. This is confirmed by X-ray observations of Nova Sco 1994 made with ASCA and ROSAT during 1996 March, which showed that its X-ray luminosity then was $2 \times 10^{32}$ erg/s (Robinson et al. 1998). No significant X-ray flux of Nova Sco 1994 was detected with RXTE during the period of our observations ($3\sigma$ upper limit of 12 mCrab in the 2–12 keV band); X-rays were first detected from Nova Sco 1994 with RXTE on 1996 April 23 (Remillard et al. 1996).

Also, the smoothness of the $V$, $R$ and $i$ light curves (spanning 11 consecutive cycles of Nova Sco 1994) is in contrast to earlier reports of significant cycle-to-cycle variations in the Nova Sco 1994 light curve during periods of known X-ray activity (Bailyn et al. 1995b; van der Hooft et al. 1997). The relative depth of the two minima in the light curves of Nova Sco 1994 is consistent with a quiescence optical light curve caused by ellipsoidal variations, the deepest minimum occurring at superior conjunction of the secondary star as expected. The brightening in X-rays in late 1996 April was followed by increased activity at optical, and radio wavelengths (Horne et al. 1996; Hunstead & Campbell-Wilson 1996; Hjellming & Rupen 1996).

We determined a revised ephemeres for inferior conjunction of the secondary star with respect to the black hole by combining our measurements of $T_{\text{inf}}$ with those published in other investigations, spanning a total of 140 orbits of Nova Sco 1994. This period differs by $2.7\sigma$ from
Figure 7.7: Photometric data as presented in Fig. 7.2, from which six data points have been removed (see text). The drawn lines represent a theoretical light curve computed for a binary inclination and secondary mass of (68°75, 2.10 M☉), an intrinsic luminosity of 41 L☉ and a disk ($T_{\text{edge}} = 100$ K, $\xi = 0.75$) with a fractional size of 0.80 and a flaring angle of 2°.
Figure 7.8: Photometric data as presented in Fig. 7.3, from which six data points have been removed (see text). The drawn lines represent a theoretical color curve computed for a binary inclination and secondary mass of \(68.75, 2.10 \, M_\odot\), an intrinsic luminosity of \(41 \, L_\odot\) and a disk \((T_{\text{edge}} = 100 \, K, \xi = 0.75)\) with a fractional size of 0.80 and a flaring angle of 2°.
the period we derived previously (van der Hooft et al. 1997), and 0.8σ from the spectroscopic period derived by Orosz & Bailyn (1997).

The colors of Nova Sco 1994 show a double-waved orbital modulation, with amplitudes of ~0.06 mag in (V−R), ~0.05 mag in (R−i) and ~0.11 mag in (V−i). The system is reddest near the conjunctions, bluest at the quadratures. This color variation reflects the varying temperature across the surface of the secondary; its pronounced appearance is the result of the wavelength and temperature dependence of the limb darkening, which gives relatively low weight to emission from near the apparent horizon of the secondary.

The light curve of Nova Sco 1994 can be understood in terms of a model of a distorted secondary star in combination with an accretion disk. The disk eclipses part of the secondary near phase 0.5, but does not give a significant contribution to the total luminosity of the system. The largest variability in the light curve of Nova Sco 1994 occurs close to phase 0.5, and is most likely caused by variability in the structure of the outer disk, causing variability in the fraction of the secondary that is being eclipsed.

### 7.4.2 Mass determination

Our modeling of the light curves has led to constraints on the system parameters, which have been summarized in Fig. 7.6, in the form of allowed regions in the (i, M₂) plane. These regions incorporate solutions over the full range in bolometric luminosity of the secondary. From Fig. 7.6 it appears that there is some dependence of the solutions on the assumed value of the flaring angle γ of the disk, but that it is virtually independent of its temperature structure. The reason is that the light curve away from phase 0.5 does not allow the disk to contribute substantially to the optical emission of the system, which sets an upper limit to its outer temperature of ~1000 K; for these temperatures the main effect of the disk is to eclipse the secondary. Since for a given value of i the fraction of the secondary that is eclipsed increases with γ, we find an anticorrelation between γ and i for the allowed solutions (compare the top and bottom panels in Fig. 7.6).

Since the mass function of the system is relatively well determined, a region in the (i, M₂) plane allowed by the light curves corresponds to a range of allowed values of the mass ratio and the mass of the compact object in Nova Sco 1994. For γ = 2° we find inclination angles in the range 66°2−70°7 and secondary masses between 1.6 and 3.1 M⊙. This then implies a mass ratio, q, and mass of the compact object, M₁, in the ranges 2.43−3.99 and 6.29−7.60 M⊙, respectively. For γ = 10° the allowed ranges of i and M₂ are 63°7−68°1, and 1.6–2.45 M⊙, respectively. The corresponding allowed ranges of q and M₁ are 2.93–4.20 and 6.35–7.18 M⊙, respectively. In Figure 7.9 we present the region in the M₂ versus M₁ plane occupied by the collection of allowed solutions, for a flaring angle of the accretion disk of 2° (solid lines) and 10° (dashed lines).

### 7.4.3 Theoretical evolutionary tracks

Since the bolometric luminosity and effective temperature of the secondary are well constrained, it is possible to compare the position of the secondary star of Nova Sco 1994 in the Hertzsprung-Russell diagram (HRD) with theoretical evolutionary tracks. We have calculated tracks for both single stars and stars in a binary system with a recent version of the evolution code developed by Eggleton (1971). The equation of state and the opacity tables have recently been discussed
Figure 7.9: Collection of solutions in the $M_2$ versus $M_1$ plane for a flaring angle of the accretion disk of 2° (solid lines) and 10° (dashed lines). The mass of the secondary star is restricted to 1.6–3.1 $M_\odot$, while the mass of the compact object lies in the range 6.29–7.60 $M_\odot$.

by Pols et al. (1995). The mass-loss in the binary calculations was assumed to be conservative and in all calculations we used a metallicity of $Z = 0.02$.

In Figure 7.10 we present a HRD with theoretical evolutionary tracks of single stars with masses 2.0, 2.25, 2.5, 3.0, and 4.0 $M_\odot$ (solid lines). Based on this figure, we position the secondary of Nova Sco 1994 on the track of a star with a mass of $\sim 2.2 M_\odot$. Assuming a mass of 7 $M_\odot$ for the black-hole primary, we obtain an orbital period of about 2.6 days (by adopting a radius for the Roche lobe filling secondary from the evolution track at the center of the error box [see Fig. 7.10], applying Kepler's third law and the relation between orbital separation and effective Roche radius of a star). This value is in good agreement with the observed period of 2.62 days. However, this is not the only evolutionary track that fits the observations.

Since the secondary is losing mass, it must have been evolved from an initially more massive star. Therefore, we computed several evolution tracks of the secondary star in a black-hole binary system, for which we adopted in all cases a total system mass of 9.2 $M_\odot$. The effect of a different value for the total system mass (8–11 $M_\odot$) does not change the outcome of our results significantly. It follows from Fig. 7.10 that a secondary with an initial mass as large as 4.0 $M_\odot$ can also evolve to the current HRD position of the secondary of Nova Sco 1994. When the tracks of such stars, which lose mass on a thermal time scale, intersect the error box bounded by $1.49 \leq \log L_{\text{opt}}/L_\odot \leq 1.73$ and $3.80 \leq \log T_{\text{eff}} \leq 3.82$, the orbital period and mass are about equal to the case of an evolved single star. This is not surprising as the secondary is less massive
than the accreting star, fills its Roche lobe and starts losing mass on the main-sequence. The mass loss then occurs on a nuclear time scale, as is the case for a secondary with an initial mass of 4 $M_\odot$. For the secondaries with lower initial masses, the mass loss starts further on the main-sequence or even at the moment when the secondary is already crossing the Hertzsprung-gap. Since the radius is expanding at a much higher rate, the time scale for mass loss is now smaller than the nuclear time scale, but still a factor of 10 larger than the thermal time scale. For an initial mass of the secondary $\lesssim 4.0 M_\odot$, the present mass and orbital period for all tracks of the mass-losing star that cross the center of the error box shown in Fig. 7.10 are between 2.0–2.3 $M_\odot$ and 2.6–3.1 days, respectively. Therefore, we conclude that the binary nature of Nova Sco 1994 is not very important for the determination of the present mass of the secondary based on evolutionary tracks.

From standard evolutionary calculations for single stars, we find that the tracks of stars with a mass in the range 2.1–2.4 $M_\odot$ are consistent with the current position of the secondary of Nova Sco 1994 in the HRD (see Fig. 7.10). This method to determine the mass of the secondary star is entirely independent of the constraints derived in Section 7.3.3 from modeling the light curves of Nova Sco 1994. We emphasize that the mass range derived from evolutionary arguments is consistent with that obtained from modeling the light curves.
7.4.4 Comparison with Orosz & Bailyn (1997)

Our results are consistent with those obtained by Orosz & Bailyn (1997). These authors describe the quiescence light curve of Nova Sco 1994 (obtained during the same period as our data) in terms of an ellipsoidal model and an accretion disk. The main differences between their analysis and the one discussed here are the value of the power-law exponent of the radial temperature distribution on the accretion disk (fixed to $-0.75$ in this work, free parameter in the analysis by Orosz & Bailyn 1997), and the use of the temperature at the pole of the secondary star as input parameter (fixed to 6500 K, Orosz & Bailyn 1997), in contrast to a range of intrinsic luminosities (31, 41, and 54 $L_\odot$, this work) as input to our model.

The best fitting $(i, q)$ values of $69.50 \pm 0.08$ and $2.99 \pm 0.08$ (1$\sigma$ statistical errors) found by Orosz & Bailyn (1997), combined with the mass function imply a secondary and black-hole mass of $2.34 \pm 0.12$ and $7.02 \pm 0.22 M_\odot$, consistent with our results. Also, the values for the fractional disk size (0.747 $\pm 0.010$), and angular thickness of the disk (2°18 $\pm 0.18$) derived by Orosz & Bailyn (1997) are consistent with the results discussed here for the case of a thin (2°) accretion disk. However, our analysis shows that models with an accretion disk of 10° angular thickness are also able to describe the data well. The contribution of the accretion disk to the total luminosity is governed by its fractional size and mean temperature, and therefore, by the temperature at the outer edge of the disk and the radial temperature distribution on the disk. Orosz & Bailyn (1997) derived an outer edge temperature of 4317 $\pm 75$ K, significantly larger than the value we derived from our analysis. This probably reflects the different value of the power-law exponent between both analyses; in our analysis the exponent was kept fixed to $-0.75$ (Pringle 1981), while Orosz & Bailyn (1997) treated the exponent as a free parameter and obtained a value of $-0.12 \pm 0.01$. However, it should be noted that in both analyses the contribution of the disk to the total luminosity of the system is less than 5%, consistent with the value derived from spectroscopy during 1996 February (Orosz & Bailyn 1997).

The errors quoted by Orosz & Bailyn (1997) are 1$\sigma$ internal statistical errors, derived from fitting the light curves of Nova Sco 1994. Note however, that in our analysis we have included errors caused by systematic uncertainties in the properties of the system, e.g., in the interstellar absorption its light suffers. Therefore, we allow for a range of intrinsic luminosities of Nova Sco 1994 (31–54 $L_\odot$). We also allow a range of values for the parameters describing the size and temperature of the accretion disk ($0.7 \leq \alpha \leq 0.9$, $2^\circ \leq \gamma \leq 10^\circ$, and $100 \leq T_{\text{eff}} \leq 1000$ K), and adopt the 3$\sigma$ confidence contours (see Fig. 7.6). Therefore, the limits to the system parameters we have derived in this study are somewhat larger compared to those obtained by Orosz & Bailyn (1997).

7.4.5 Systematic effects

In our modeling of the light curve of Nova Sco 1994 we have made a number of implicit assumptions, e.g., with respect to the geometry of the disk, and such assumptions may affect the results of our analysis systematically. There is one assumption whose systematic effect is particularly strong, i.e., that the non-uniform temperature distribution across the surface of the secondary can be described by a standard gravity darkening coefficient $\beta = 0.25$. This value applies in a situation where the outer layers of a star are in radiative equilibrium. For stars with convective outer layers Lucy (1967) derived a gravity darkening coefficient of 0.08. At its spectral type (F3–F6) the secondary of Nova Sco 1994 is near the boundary in the Hertzsprung-Russell diagram separating hot stars with radiative envelopes and cool stars with convective
envelopes. Therefore, it may contain a shallow convective layer. We have investigated the applicability of standard gravity darkening by computing light curves for \( \beta \) in the range 0.08 to 0.25 (in steps of 0.01). Decreasing \( \beta \) leads to a decrease in the brightness contrast over the secondary’s surface, and therefore to a decrease of the amplitude of the light curve. Since the amplitude increases with \( i \) the strongest limits on \( \beta \) are obtained for \( i = 90° \). For an assumed \( M_2 = 2.2 \, M_\odot \) and \( L_{\text{opt}} = 41 \, L_\odot \) (near the center of our solution space) we derive a lower limit \( \beta \geq 0.18 \) on the gravity darkening coefficient. This suggests that the assumption \( \beta = 0.25 \) is justified.

### 7.5 Conclusion

We conclude that during our 1996 March observations Nova Sco 1994 was in a state of true X-ray quiescence. We derive a refined ephemeris for inferior conjunction of the secondary star with respect to the compact star of HJD 244 9838.4198(52) + 2.62168(14) \times N. We calculated theoretical light and color curves, which constrain the binary inclination and mass of the secondary star to lie in the range 63°7–70°7 and 1.60–3.10 \( M_\odot \), respectively. The implied mass of the black hole is in the range 6.29–7.60 \( M_\odot \). We find that an accretion disk is required to model the light and color curve of Nova Sco 1994. The disk does not contribute significantly to the luminosity, and therefore, acts as body of obscuration only. The mass range we obtained for the secondary star is supported by the results of stellar evolution calculations.

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Summary

This thesis reports on the research of four recently discovered black-hole X-ray transients, GRO J0422+34 (Nova Per 1992), GRS 1009–45 (Nova Vel 1993), GRO J1655–40 (Nova Sco 1994), and GRO J1719–24 (Nova Oph 1993), based on both X-ray and optical observations using the Burst And Transient Source Experiment (BATSE) on board of the Compton Gamma Ray Observatory (CGRO) and ground-based telescopes at the European Southern Observatory (ESO), La Silla, Chile, and the University of Tasmania, Australia.

8.1 X-ray observations

The Compton Gamma Ray Observatory was launched on the Space Shuttle Atlantis on 1991 April 5, as one of the heaviest scientific payloads ever: 15 900 kg. The mission goals of CGRO included performing broad-band gamma-ray observations of supernovae, novae, pulsars, black holes, active galaxies, and gamma-ray bursts with better angular resolution and sensitivity than previous missions, and to perform the first gamma-ray full sky survey. The observatory consists of four different instruments to cover the hard X-ray and gamma-ray regimes from 20 keV to 30 GeV. The Oriented Scintillation Spectrometer Experiment (OSSE) was designed for spectral observations in the 50 keV to 10 MeV energy range; its design enables a rapid response to target of opportunity observations. The Imaging Compton Telescope (COMPTEL) was the first space-born imaging telescope in the Mev range. Comptel is sensitive at energies from 1 to 30 MeV and its accuracy to locate point sources is of the order of 1°. The highest-energy instrument on board CGRO is the Energetic Gamma Ray Experiment Telescope (EGRET). It images gamma-rays in the broad 20 MeV to 30 GeV energy range, has a wide field of view, good angular resolution and a low background.

The fourth instrument on board CGRO is the Burst And Transient Source Experiment (BATSE). BATSE is an all sky monitor in the 20 keV to 2 MeV energy range and consists of eight separate detector modules arranged in an octahedral geometry at the corners of CGRO. The Large Area Detector (LAD) in each module is a 50.8 cm diameter \times 1.27 cm thick sodium iodide crystal. These are passively shielded from behind but uncollimated in front, such that the response of each detector is approximately given by the projected area, i.e., roughly as the cosine of the angle between a source and the detector axis. This configuration results in an effective detector area of \( \sim 2000-4200 \, \text{cm}^2 \), depending on the direction to the source. Each LAD provides ‘continuous data’ (CONT), which are counting rates with a 2.048 sec time resolution in 16 spectral
channels between 20 keV and 2 Mev, and 'discriminator data' (DISCLA), i.e., counting rates in 4 broad energy channels with 1.024 sec time resolution. To each of the LADs, a smaller Spectroscopy Detector is associated, optimized for a broad energy coverage (15 keV to 110 MeV), and with enhanced energy resolution.

The primary scientific objective of BATSE was the study of gamma-ray bursts. Since the launch of CGRO, BATSE has observed over 2000 gamma-ray bursts and shown their isotropic and inhomogeneous distribution in space. From geometrical arguments alone, galactic-disk models of gamma-ray bursts can be excluded. Galactic halo models are severely constrained and highly contrived by the global properties of gamma-ray bursts. The all sky monitor capabilities of BATSE make the instrument ideally suited for continuous monitoring of all transient and bright persistent sources in the hard X-ray and gamma-ray sky. BATSE is able to monitor these sources by way of the Earth occultation technique, in which the intensity of a source is determined by measuring the count rate differences as a source sets below, or rises above the Earth horizon. The CGRO orbital geometry is such that ~ 95% of the sky undergoes occultations during a given orbit; the orbital precession enables eventual monitoring of the full sky.

For the study of the temporal variability of black-hole candidates (BHCs) with BATSE, we made use of the 1.024 sec time resolution DISCLA data. We applied an empirical model to subtract the signal due to the hard X-ray and gamma-ray background. This model describes the background by a harmonic expansion in satellite orbital phase (with parameters determined from the observed background variations), and includes the risings and settings of the brightest X-ray sources in the sky. It uses eight orbital harmonic terms, and its parameters were updated every three hours. Based on a study of the distribution of the length of data-gap free intervals we decided to apply fast Fourier transforms to uninterrupted intervals of 512 successive time bins. We obtained on average ~ 30–40 of such intervals per day during which a source is above the Earth horizon. The corresponding frequency range of the power density spectra (PDSs) is 0.002–0.488 Hz; this range contains much of the interesting phenomenology seen in the PDSs of BHCs.

### 8.1.1 GRO J0422+34 / Nova Per 1992

The soft X-ray transient (SXT) GRO J0422+32 (Nova Persei 1992) was detected with BATSE on 1992 August 5. The hard X-ray intensity of GRO J0422+32 increased rapidly, reaching a maximum flux of ~ 3 Crab (20–300 keV) within three days after its first detection. Thereafter, the 40–150 keV X-ray intensity of the source decreased exponentially with a decay time of 43.6 days. GRO J0422+32 had a hard X-ray spectrum with a power-law index of ~ 2, detected up to 600 keV. COMPTEL observations during X-ray maximum showed that the source was detected up to energies of 1–2 MeV. About 140 days after its first detection, the X-ray flux of GRO J0422+32 reached a secondary maximum, after which the X-ray source continued to decrease with approximately the same decay time. The full X-ray outburst of GRO J0422+32 lasted for ~ 200 days.

The optical counterpart to GRO J0422+32 was identified with a star which had brightened by about 9 mag in V, the largest outburst amplitude observed in any SXT to date. The optical light curve of this source declined initially as an exponential. Two optical mini-outbursts (with an amplitude of ~ 4 mag each) were observed, before the source finally reached quiescence ~ 800 days after the start of the X-ray outburst at V= 22.35. Based on observations performed with the W.M. Keck 10m telescope, the orbital period and mass function of GRO J0422+32 were
determined to be $5.08 \pm 0.01$ hr and $1.21 \pm 0.06$ M$_\odot$, respectively. An upper limit of 45° to the binary inclination, estimated from the 0.03 mag modulation of the optical light curve, implies a mass of $\geq 3.4$ M$_\odot$ for the compact star, slightly above the (theoretical) maximum mass of a neutron star. Therefore, GRO J0422+32 likely contains a black-hole primary.

In Chapter 4 we report on a temporal analysis of BATSE data of GRO J0422+32 during 180 days following its first X-ray detection in 1992 August. We obtained PDSs of the data in the 20–100 keV energy band, covering the frequency interval 0.002–0.488 Hz. The PDSs of GRO J0422+32 are approximately flat up to a break frequency, and decay as a power law above, with index $\sim 1$. During the primary X-ray outburst of GRO J0422+32 the break frequency occurs at $0.041 \pm 0.006$ Hz; during the secondary outburst the break is at $0.081 \pm 0.015$ Hz. The power density at the break during these episodes ranged between 44 and 89% Hz$^{-1/2}$ (20–100 keV). Therefore, the canonical anticorrelation between the break frequency and the power density at the break, as observed in Cyg X-1 and other BHCs in the low state, is not observed in the PDSs of GRO J0422+32. During the first 70 days of the X-ray outburst, the PDSs of GRO J0422+32 show a significant quasi-periodic oscillation (QPO) peak near $\sim 0.2$ Hz, superposed on the power-law tail.

The results of this temporal analysis are compared with those of similar studies of Cyg X-1. The relation between the spectral slope and the amplitude of the X-ray variations of GRO J0422+32 is similar to that of Cyg X-1; however, the relation between the hard X-ray flux and the amplitude of its variation is opposite to what has been found in Cyg X-1.

We computed cross spectra from the Fourier amplitudes to derive the phase (or, equivalently, time) lags between the X-ray variations in the 20–50 keV, and 50–100 keV energy bands of GRO J0422+32. Statistical significant phase lags could be derived during the first 30 days of the outburst of GRO J0422+32 only. During this episode, the variations in the 50–100 keV, lag those in the 20–50 keV energy band by an approximately constant phase difference of $0.039(3)$ rad in the frequency interval $0.02$–$0.20$ Hz. The time lags of GRO J0422+32 during the first 30 days of the outburst, decrease with frequency as a power law, with index 0.9 for $\nu > 0.01$ Hz.

8.1.2 GRO J1719–24/Nova OpH 1993

GRO J1719–24 was detected independently with BATSE and the SIGMA telescope on board GRANAT on 1993 September 25, and reached a maximum brightness of $\sim 1.4$ Crab (20–100 keV) within a few days. In contrast to the X-ray light curve of GRO J0422+34, that of GRO J1719–24 showed a decay by $\sim 0.3\%$ per day only over a period of about 2 months, followed by a sudden decrease below the BATSE detection limit. The full 1993 X-ray outburst lasted $\sim 80$ days. The 2–300 keV X-ray spectrum, obtained within a few days after first detection of the source by combining SIGMA data with quasi-contemporaneous data taken with TTM on board Mir-Kvant, suggests that during the 1993 outburst GRO J1719–24 was likely in the low (or hard) state; the spectrum has a power law shape, exhibits no soft component and cuts off at energies above 100 keV. Starting 1994 September, several X-ray flares were detected from GRO J1719–24. Following a strong X-ray flare in 1995 February, a rapidly decaying radio flare was detected, followed by recurrent radio flaring activity. The relation between the X-ray and radio events is similar to that observed in GRO J1655–40, a superluminal radio jet SXT. A possible optical counterpart to GRO J1719–24 was identified soon after first X-ray detection, Quiescent optical photometry and/or spectroscopy of this source has not been reported. Therefore, GRO J1719–24 is considered a black-hole candidate on the basis of its X-ray and radio analogies to dynamically proven BHCs.
The rapid X-ray variability of the 1993 X-ray outburst of GRO J1719–24 is studied in Chapter 2. We obtained PDSs of the data in the 20–100 keV energy band, covering the frequency interval 0.002–0.488 Hz. A significant low-frequency QPO peak is found in the PDSs of GRO J1719–24, whose centroid frequency increases during the course of the outburst from ~0.04 Hz to ~0.3 Hz. Two additional peaked noise components are present in the PDSs, whose centroid frequencies are linearly related to the frequency of the QPO. We found that the evolution of the PDSs of GRO J1719–24 can be described by a single characteristic profile, the frequency scale of which is being stretched during the outburst. The total power in each spectrum, integrated over corresponding (but relatively scaled) frequency intervals, remained constant throughout the outburst. Therefore, it is likely that the X-ray variability during the entire outburst of GRO J1719–24 can be described by a single process, the characteristic time scale of which becomes shorter, but the fractional amplitude of which is invariant.

Phase (or, equivalently, time) lags between the hard and soft X-ray variations of GRO J1719–24 are estimated in Chapter 3. We find that the X-ray variations in the 50–100 keV band, lag those in the 20–50 keV energy band by an approximately constant phase difference of 0.072 ± 0.010 rad in the frequency interval 0.02–0.2 Hz. These results are discussed together with those obtained in similar studies of the black-hole candidates Cyg X-1 and GRO J0422+32.

8.2 Optical observations

8.2.1 GRS 1009–45 / Nova Vel 1993

The WATCH instrument on board GRANAT discovered GRS 1009–45 on 1993 September 12; the presence of this new X-ray source was confirmed with BATSE on the same day. The X-ray spectrum of GRS 1009–45 consisted of two components; a soft thermal component that could be approximated by a blackbody spectrum with a temperature of ~0.5 keV, and a hard power-law tail with spectral index 2.5 at 10–100 keV. The 2–200 keV X-ray spectrum of GRS 1009–45 was similar to those of GS 2000+25 and GS 1124–68, both dynamically proven BHCs (see, e.g., Table 1.1). The X-ray light curve of GRS 1009–45 resembled that of GS 1124–68: a bright primary X-ray outburst followed by two later maxima. However, both maxima occurred sooner than the secondary maximum observed in GS 1124–68. The optical counterpart of GRS 1009–45 was discovered in 1993 November as a blue object with \( V = 14.6 \). Subsequent optical observations between 150 and 205 days after the start of the X-ray outburst provided evidence for a secondary optical outburst and repeated mini-outbursts, similar to those observed from the BHC GRO J0422+32. The brightness of GRS 1009–45 varied between \( V \approx 16 \) and \( \approx 20 \) during these observations.

We performed optical photometry and spectroscopy of Nova Vel 1993 during 1995 and 1996, when the source had returned to its quiescent brightness \( R = 20.6 \) (Chapter 5). Unfortunately, Nova Vel 1993 is located 1"4 South-East to a star of \( R = 17.4 \), which makes the analysis of the data difficult. Observing conditions during part of the 1995 May observations were excellent, enabling us to separate the source from its close companion. We applied relative photometry to Nova Vel 1993 and nearby comparison stars using a point spread function fitting algorithm, to determine the \( R \)-band light curve of the source. The optical light shows an orbital, ellipsoidal modulation at a period of 6.86 ± 0.12 hr. The amplitude of the modulation is 0.23 mag. By modeling the optical ellipsoidal modulations of the secondary star we determine a firm 95% lower limit to the binary inclination of 37°.
Optical spectra of Nova Vel 1993 were obtained in 1995 June and 1996 March with the 3.5m New Technology Telescope, using the ESO Multi Mode Instrument, in Chile, remotely operated from ESO headquarters in Garching, Germany. The spectra show a broad, double-peaked Hα emission line presumably arising from the accretion disk, superimposed on a red featureless continuum. The zero-intensity full width at the base of the Hα emission line is $\sim 2750 \text{ km s}^{-1}$, and the separation between both Hα components in the 1995 spectra is 1020 km s$^{-1}$. We estimate the spectral type of the secondary to be late-G/early-K. Radial velocity measurements of the secondary star have yet to be performed.

8.2.2 GRO J1655—40/Nova Sco 1994

GRO J1655—40 was discovered with BATSE on 1994 July 27 and was quickly identified with an optical star which had brightened by about 3 mag. The initial X-ray outburst lasted for three weeks, and the source became as bright as 0.7 Crab in the 20–100 keV energy range. Following this X-ray outburst, GRO J1655—40 remained active, and showed repeated X-ray outbursts separated by about 120 days, each typically lasting many weeks. Radio outbursts were observed from GRO J1655—40 shortly after the first X-ray detection, during which material was ejected in opposite directions from the central source at apparent superluminal speeds. Therefore, GRO J1655—40 is the second superluminal radio jet source in our Galaxy, and the only one to be identified optically (see Section 1.5.6).

Chapter 6 describes the analysis of 40 nights of photometry on Nova Sco 1994 obtained during the period 1995 May–July at La Silla and Tasmania. During the course of our 1995 observations, the brightness of Nova Sco 1994 increased steadily by about 1 mag, the extra light probably arising from X-ray heating of the secondary star and the accretion disk. Nevertheless, when we removed this long term trend from the data, we were able to confirm the 2.6 day period of Nova Sco 1994 reported earlier. We modeled the R-band light curve as primarily being due to an X-ray heated secondary, which constrained the inclination of the system to 65–76°, and its mass ratio $q = M_1/M_2$ to 3.8–5.5.

In Chapter 7 we report on 28 consecutive nights of photometry on Nova Sco 1994 obtained during 1996 March with the Dutch 0.91m telescope at La Silla. During these observations the source was close to its quiescent pre-outburst optical brightness $V = 17.3$, and remained so until the end of 1996 April. The $V, R,$ and $i$ light curves of Nova Sco 1994 (spanning 11 consecutive cycles) are remarkably smooth in comparison with several other quiescent SXTs, which show cycle-to-cycle variations of the order of a few percent. The light curve of Nova Sco 1994 shows a modulation with two equal maxima and unequal minima, whose depths are 0.31 and 0.48 mag. From our observations and data taken from the literature we refine the orbital period to be 2.62168(14) days. We have calculated $\sim 30,000$ theoretical light- and color curves for a wide range of parameters of a model describing a Roche lobe filling secondary star supplemented with a model of an accretion disk around the compact star. From the shape of the light curve of Nova Sco 1994 we derive constraints on the binary inclination ($63.7°–70.7°$) and mass ratio of the system. Together with the mass function the limits to the secondary ($1.60–3.10 \text{ M}_\odot$) and black-hole mass ($6.29–7.60 \text{ M}_\odot$) are obtained. Apart from accurately determining the mass of the black-hole primary, an important conclusion is that an accretion disk orbiting the black hole in Nova Sco 1994 is required to model the quiescent light- and color curves satisfactorily. This quiescent disk does not contribute significantly to the luminosity, but acts as body of obscuration only.
Zwarte gaten in dubbelsterren

Deze studie beschrijft observationeel onderzoek aan vier dubbelsterrintensystemen, gebaseerd op röntgen- en optische waarnemingen. Verreweg de meeste sterren in het heelal maken deel uit van een dubbel- of meervoudig sterrintensysteem. De hier bestudeerde dubbelsterren zijn echter van een heel bijzonder type: voor elk van deze systemen bestaat een geharmooged dat een van de beide sterren een zwart gat is. De andere ster in het systeem is een 'gewone ster', met eigenschappen die vergelijkbaar zijn met die van de zon. Beide componenten van de dubbelster bewegen rond het gemeenschappelijke zwaartepunt en kunnen, indien de onderlinge afstand voldoende klein is, elkaars evolutie beïnvloeden.

In ons Melkwegstelsel bevinden zich naar schatting circa 1000 nauwe dubbelsterren die bestaan uit een zwart gat en een begeleider met een gewicht van ongeveer één zonmassa (1 M☉). De beschikbaarheid van steeds gevoeliger detectoren op een groeiend aantal telescopen en satellieten gedurende de jaren negentig, heeft een doorbraak in het observationeel onderzoek aan zwarte gaten teweeggebracht. Voor acht dubbelsterren is nu aangetoond dat één der beide sterren hoogst waarschijnlijk een zwart gat is; voor nog eens ruim een dozijn systemen bestaat het vermoeden dat zij mogelijk een zwart gat bevatten. Nader onderzoek kan hierover uitsluitend geven.

Zwarte gaten zijn zeer bijzondere objecten en worden gekarakteriseerd door het sterke zwaartekrachtsveld dat zij veroorzaken. Het zwaartekrachtsveld van een object wordt bepaald door de massa en de straal van het object. De sterkte van het veld neemt toe bij grotere massa en kleinere straal, met andere woorden, zwarte sterren met een kleine straal hebben een sterk zwaartekrachtsveld. Op het oppervlak van de aarde is de versnellingsnormale van de zwaartekracht 9.8 m sec⁻²; op de maan (81 maal lichter en 4 maal kleiner dan de aarde) is de zwaartekrachtsversnelling ongeveer 5 maal kleiner dan op aarde. Tengevolge van hun grote massa is de zwaartekrachtsversnelling aan het oppervlak van de meeste sterren vele malen groter dan die aan het aardoppervlak. Ze bedraagt aan de rand van de zon 274 m sec⁻², 28 maal groter dan op het aardoppervlak. Voor zogenaamde 'compacte sterren' is het zwaartekrachtsveld extreem sterk; deze sterren combineren een grote massa met een zeer kleine straal. Materie in deze sterren is daarom extreem dicht opeengepakt. Compacte sterren kunnen worden onderscheiden in witte dwergen, neutronensterren en zwarte gaten. Witte dwergen hebben een massa die ongeveer gelijk is aan die van de zon, en een straal die vergelijkbaar is met de straal van de aarde. Neutronensterren zijn iets zwaarder dan de zon (ongeveer 1.4 M☉), maar hebben een straal van slechts ongeveer 10 km. De zwaartekrachtsversnelling aan het oppervlak van een neutronenster is daarom ongeveer 200 miljard maal groter dan die aan het oppervlak van de aarde!

De snelheid die een deeltje minimaal moet bezitten om aan het zwaartekrachtsveld van een planeet of ster te ontkomen wordt de ontsnappingssnelheid genoemd. Een sterk zwaartekrachtsveld vereist een grote ontsnappingssnelheid: voor de aarde bedraagt de ontsnappingssnelheid 11.2
Zwarte gaten in dubbelsterren

km sec\(^{-1}\) en voor de maan 2.4 km sec\(^{-1}\). De ontsnappingssnelheid van compacte sterren is enorm groot: van een witte dwerg bedraagt hij ongeveer 6500 km sec\(^{-1}\), en van een neutronenster ongeveer 190000 km sec\(^{-1}\). Een zwart gat wordt gekenmerkt door een zwaartekrachtsveld dat zo sterk is, dat de vereiste snelheid om te ontsnappen groter zou moeten zijn dan de lichtsnelheid: 300000 km sec\(^{-1}\). Het is echter niet mogelijk om te bewegen met een snelheid groter dan die van het licht, en het directe gevolg hiervan is dat het onmogelijk is om uit een zwart gat te ontsnappen. Een zwart gat kan zelfs geen licht uitzenden.

Zwarte gaten zijn oneindig klein, alle materie is in één punt geconcentreerd. De afmeting die veelal met de grootte van een zwart gat wordt geassocieerd is de straal van de ‘horizon’ van een zwart gat. Deze horizon is een denkbeeldig boloppervlak rond het zwarte gat, met in het centrum de totale massa. Het bestaan van de horizon volgt uit de wiskundige beschrijving van de ruimte in de buurt van een zwart gat. De horizon is echter geen fysieke begrenzing aan de grootte van een zwart gat. De horizon is te beschouwen als een enkelzijdig membraan: alle materie die in de richting van een zwart gat stroomt en de horizon bereikt zal onvermijdelijk naar het centrum van het zwarte gat vallen. Dit proces is onomkeerbaar: niets van wat zich binnen de horizon bevindt kan ooit nog naar buiten de horizon worden getransporteerd. De straal van de horizon wordt bepaald door de massa van het zwarte gat en bedraagt voor een zwart gat met een massa van één zonsmassa ongeveer 3 km.

De massa van een zwart gat is in principe niet gelimiteerd. Elke gasbol van willekeurige massa die voldoende compact is kan een zodanig sterk zwaartekrachtsveld veroorzaken dat de ontsnappingssnelheid groter is dan de lichtsnelheid. Zwarte gaten in dubbelsterren, zoals bestudeerd in dit proefschrift, hebben een massa ter grootte van enige zonsmassa's. Deze zwarte gaten worden gevormd tijdens de laatste evolutiestadia van een zware ster. Elke ster bestaat aan het begin van zijn evolutie voornamelijk uit waterstof en helium. Door kernfusie van waterstof tot helium in het binnenste van een ster wordt energie vrijgemaakt, die vervolgens aan de rand wordt uitgestraald. Zware sterren blijken tevens zeer heldere sterren te zijn, waarvoor veel energie vereist is; de waterstofvoorraad neemt dan in hoog tempo af. Een zwaardere ster heeft weliswaar een grote energievoorraad, maar dit weegt niet op tegen de grotere helderheid: een zware ster evolueert sneller dan een lichte ster. In het binnenste van een zware ster wordt daarom in relatief korte tijd waterstof omgezet tot helium, en vervolgens helium tot koolstof. Voor de allerzwaarste sterren is de temperatuur in het binnenste hoog genoeg om de kernfusieprocessen voort te zetten totdat de kern van de ster volledig bestaat uit ijzerkerne. Verdere kernfusieprocessen zijn onmogelijk, omdat bij de fusie tot nog zwaardere atoomkernen geen energie meer kan worden vrijgemaakt. Omdat de ster geen andere energiebronnen bezit, stort de kern van de ster ineens naar een extreem compact restant, waarbij de buitenlagen worden weggeslingerd. Voor voldoende zware sterren, zwaarder dan ~ 40–60 \( M_\odot \) bij aanvang van hun evolutie, is dit extreem compacte restant van de oorspronkelijk zeer zware ster een zwart gat.

Het is onmogelijk om een zwart gat direct waar te nemen: een zwart gat zendt immers geen licht of andere straling uit. Waarnemingen van zwarte gaten zijn daarom altijd indirect. Wanneer een zwart gat een component is van een dubbelstersysteem bestaan er verschillende mogelijkheden om zijn aanwezigheid in het systeem te constateren. Zijn begeleider is in de meeste gevallen een gewone ster, die materie overdraagt naar het zwarte gat wanneer de onderlinge afstand voldoende klein is. Als gevolg van de baanbeweging rond het gemeenschappelijke zwartepunt valt de overgedragen materie niet zonder meer in het zwarte gat, maar vormt een platte gasschijf er omheen, waarin de materie geleidelijk naar binnen spiralisert: de accretieschijf. Tijdens het naar binnen bewegen verliest: de materie potentiële energie, die door wrijving gedeeltelijk wordt
omgezet in warmte. In het geval van massa-overdracht naar een zwart gat of een neutronenster worden de binnenste gedeelten van de schijf hierdoor zodanig verhit dat deze (harde) röntgenstraling uit gaan zenden. Dergelijke systemen worden röntgendubbelsystemen genoemd.

De intensiteit van de röntgenstraling afkomstig van dit soort dubbelsterren blijkt zeer snelle fluctuaties in de tijd te vertonen. Het feit dat variaties in de orde van 0.1 sec en korter waarneembaar zijn in de röntgenintensiteit impliceert dat de straling voornamelijk wordt uitgezonden in een gebied dat relatief klein is. Immers, snelle variaties in de röntgenintensiteit zullen versmoeid raken als het reistijdsverschil (tengelijke van de eindige lichtsnellheid) van straling afkomstig van verschillende delen van het stralingsgebied van dezelfde grootte wordt als de tijdspanne van de variaties. De aanwezigheid van snelle variaties in de röntgenintensiteit van een dubbelster duidt echter niet noodzakelijk op de aanwezigheid van een zwart gat in het systeem. Vergelijkbare variaties kunnen zich ook voordoen in de röntgenintensiteit afkomstig van neutronensterren. Het aantonen van snelle variaties in de röntgenintensiteit van een röntgendubbelsysteem is daarom slechts een onderdeel van het bewijsmateriaal voor de aanwezigheid van een zwart gat in het systeem.

De meest betrouwbare methode om een zwart gat van een neutronenster te onderscheiden is het bepalen van zijn massa. De massa van de compacte ster kan worden afgeleid uit fotometrische en spectroscopische waarnemingen. Uit optische waarnemingen aan de begeleider van de compacte ster wordt de baanperiode van het systeem bepaald. Tevens is het mogelijk om de grootte van de snelheid van de begeleidende ster rond het gemeenschappelijke zwaartepunt vast te stellen. Met behulp van deze gegevens kan een groothed worden berekend die de massafunctie wordt genoemd. De massafunctie geeft een verband tussen enerzijds de baanperiode en de snelheid van de begeleider, en anderzijds tussen de massa's van beide sterren in het systeem en de hoek waaronder het baanvlak van het systeem wordt waargenomen. De waarde van de massafunctie geeft direct een ondergrens aan de massa van de compacte ster; als bovendien de massa van de begeleider en de hoek waaronder het systeem zichtbaar is voldoende nauwkeurig bekend zijn, kan de massa van de compacte ster uit de massafunctie worden opgelost.

Uit modellberekeningen volgt dat de massa van een neutronenster tamelijk nauw begrens is. Op basis van algemene fysische gronden kan worden afgeleid dat de maximale massa van een neutronenster ongeveer 3 M⊙ bedraagt. Massabepalingen van neutronensterren die deel uit maken van een dubbelstersysteem, tonen aan dat de massa van al deze sterren in het interval 1.3-1.9 M⊙ ligt. Wanneer uit de massafunctie volgt dat de compacte ster in een röntgendubbelsysteem zwaaider is dan 3 M⊙, wordt daarom aangenomen dat de compacte ster een zwart gat is. Immers, een neutronenster kan onmogelijk zo zwaar zijn en een zwart gat is het enige overgebleven alternatief. Een massabepaling leverd dus geen direct bewijs voor de aanwezigheid van een zwart gat in de dubbelster, maar komt neer op het uitsluiten van andere mogelijkheden en het vervolgens accepteren van het enige ons bekende alternatief. In correct taalgebruik dient voor dergelijk compacte sterren in röntgendiffelsystemen dan ook te worden gesproken van een 'kandidaat zwart gat'. De aanwezigheid van een zwart gat in het systeem is weliswaar hoogst waarschijnlijk, maar direct bewijs is niet geleverd.

De eerste röntgenbron waarvan werd vastgesteld dat deze zich in een dubbelster bevond verschafte tevens het eerste observationale bewijs van het bestaan van (kandidaat) zwarte gaten. Dit is Cyg X-1, de eerste röntgenbron (X-1) in het sterrenbeeld Zwaan (Cygnus). Deze röntgenbron werd in 1965 ontdekt en is de helderste persistente bron van harde röntgenstraling aan de gehele hemel. In 1971 volgde uit optische waarnemingen het bewijs dat de compacte ster zwaaider is dan de maximaal mogelijke massa van een neutronenster. Hieruit werd geconcludeerd dat de compacte ster in Cyg X-1 een zwart gat is.
Röntgendubbelsterren worden onderscheiden op basis van de massa van de ster die de compacte ster begeleidt. In zware röntgendubbelsterren heeft de begeleidende ster een massa groter dan 10 M\(_{\odot}\); in lichte röntgendubbelsterren bedraagt de massa van de begeleider minder dan 1 M\(_{\odot}\). De begeleider in Cyg X-1 is een zware ster, Cyg X-1 behoort daarom tot de eerste categorie. De meest veelbelovende systemen om een zwart gat aan te treffen behoren tot een subklasse van de lichte röntgendubbelsterren. Deze systemen worden gekenmerkt door plotselinge, extreem heftige uitbarstingen van röntgenstraling. In korte tijd neemt de röntgenintensiteit van het systeem toe van onwaarnembaar tot soms groter dan die van de helderste röntgenbronnen aan de hemel. Tijdens de röntgenuitbarsting neemt tevens de optische helderheid van het systeem sterk toe. Dergelijke röntgenuitbarstingen duren een aantal weken tot maanden. Ze worden afgewisseld met perioden van één tot tientallen jaren waarin niet of nauwelijks röntgenstraling wordt uitgezonden. Deze systemen zijn om verschillende redenen ideaal voor het onderzoek aan zwarte gaten in dubbelsterren. De toegenomen optische helderheid na aanvang van de röntgenactiviteit maakt identificatie van het systeem met een optische ster eenvoudiger. Tijdens de periode van röntgenactiviteit, die wordt toegeschreven aan instabiliteiten in de massa-overdracht naar de compacte ster, domineert de accretieschijf de optische helderheid en is de begeleider volkomen overstroomd. Wanneer de röntgenactiviteit is afgenomen en tevens de optische helderheid van het systeem weer op het niveau van voor de röntgenuitbarsting is gekomen, kunnen vervolgens de eigenschappen van de begeleidende ster worden bestudeerd. Dat wil zeggen, de massa en dus de massa van de compacte ster kunnen worden bepaald.

De eerste bron waarvan aangetoond werd dat deze tot de subklasse zwart-gat lichte röntgendubbelsterren behoorde is A 0620-00. De röntgenbron in dit systeem werd in 1975 ontdekt en spoedig geïdentificeerd met een optische ster. De massafunctie van A 0620-00 werd in 1985 bepaald en dit leidde direct tot de conclusie dat het systeem een zwart gat moet bevatten: de massafunctie van A 0620-00 bedraagt 3.18 M\(_{\odot}\). Sinds 1985 is voor nog eens zeven andere lichte röntgendubbelsterren aangetoond dat zij hoogst waarschijnlijk een zwart gat bevatten.

Dit proefschrift beschrijft studies van vier zwart-gat lichte röntgendubbelsterren gebaseerd op röntgen- en optische waarnemingen. Hiervoor werd gebruik gemaakt van drie optische telescopen van de Europese Zuidelijke Sterrenwacht op La Silla (Chili) en een telescoop van de Universiteit van Tasmanië (Australië). De röntgenwaarnemingen werden verricht met het 'Burst And Transient Source Experiment' (BATSE), aan boord van de 'Compton Gamma Ray Observatory', een Amerikaanse satelliet speciaal ontwikkeld voor het verrichten van waarnemingen in harde röntgen- en gammastraling. Deze satelliet werd in 1991 door de Space Shuttle in een baan om de aarde gebracht en bevat vier verschillende instrumenten. BATSE is één van deze instrumenten; het bestaat uit acht identieke detectoren die bevestigd zijn op de hoekpunten van de satelliet. Hierdoor is BATSE in staat om voortdurend de gehele hemel waar te nemen. Dit maakt BATSE tot een geschikt instrument om de maandenlange uitbarstingen van röntgendubbelsterren te bestuderen.

In de Hoofdstukken 2, 3, en 4 worden de bronnen GRO J1719-24 en GRO J0422+32 bestudeerd met behulp van BATSE data. De naam van deze systemen duidt op zowel de satelliet die de röntgenbron ontdekte (GRO), als de positie aan de hemel (rechte klimming 17 hr 19 min, declinatie -24°), als de epecho (J). Het is gebruikelijk dat een systeem tevens een naam krijgt die aangeeft in welk jaar de röntgenuitbarsting plaatsvindt, en in welk sterrenbeeld de bron staat. GRO J1719-24 en GRO J0422+32 zijn daarom eveneens bekend onder de namen Nova Ophiuchi 1993 en Nova Persei 1992. De röntgenintensiteit van GRO J1719-24 en GRO J0422+32 is onderzocht op variaties op tijdschalen van de orde van één tot enige honderden seconden.
De röntgenintensiteit van GRO J1719–24 vertoont sterke variaties op een tijdschaal van ~25 sec; gedurende de uitbarsting van de bron neemt deze geleidelijk af tot ~3 sec. In Hoofdstuk 2 laten we zien dat de variabiliteit van GRO J1719–24 gedurende de gehele röntgenuitbarsting beschreven kan worden door één proces waarvan de karakteristieke tijdschaal afneemt, maar waarvan de mate van variabiliteit gelijk blijft. De röntgenuitbarsting van GRO J0422+32 duurde ongeveer een half jaar. Gedurende het begin van de uitbarsting vertoonde de röntgenintensiteit sterke variaties op een tijdschaal van ~10 sec; tijdens latere stadia van de uitbarsting zijn deze niet meer waarneembaar. In Hoofdstuk 4 bestuderen we de variabiliteit van de röntgenstraling van GRO J0422+32 in drie verschillende energiebanden en vergelijken de eigenschappen van de röntgenvariabiliteit van GRO J0422+32 met die van Cyg X-1. Het blijkt dat GRO J0422+32 een aantal van de eigenschappen vertoont die specifiek zijn voor zwarte gaten, maar in andere opzichten in detail verschilt van de snelle variabiliteit zoals waargenomen in Cyg X-1.


De optische variabiliteit van GRO J1655–40 werd bestudeerd gedurende twee omvangrijke waarnemingscampagnes in 1995 en 1996. Hoofdstuk 6 beschrijft de analyse van waarnemingen gedurende mei tot en met juli 1995. Helaas was gedurende deze periode de röntgenbron in GRO J1655–40 actief, waardoor tevens de optische helderheid van het systeem was toegenomen. Dit maakte de analyse van de optische data gecompliceerd. Desalniettemin slaagden we erin om uit deze data de baanperiode van het systeem af te leiden en sterk verbeterde limieten te bepalen voor de hoek waaronder het baanvlak van het systeem wordt waargenomen. Gedurende de optische waarnemingen in maart 1996 was röntgenactiviteit van GRO J1655–40 afwezig; deze waarnemingen worden gepresenteerd in Hoofdstuk 7. We bestuderen de optische ster in GRO J655–40 in drie kleuren en bevestigen de eerder bepaalde baanperiode. De variaties in de optische helderheid van GRO J1655–40 worden vergeleken met modelberekeningen. Op basis hiervan kunnen we de verhouding van de massa's van beide sterren in het systeem en de hoek van het baanvlak zeer nauwkeurig bepalen. Met deze gegevens kan vervolgens de massafunctie worden opgelost en de massa van beide dubbelster componenten worden bepaald. We vinden dat de compacte ster in GRO J1655–40 een massa heeft van ~7 M☉, en we concluderen dat GRO J1655–40 een zwart gat bevat.
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GRO J1744–28

Correlation between BATSE hard X-ray spectral and timing properties of Cygnus X-1

Search for rapid X-ray variability from the black-hole candidate GRO J1655–40

V485 Centauri: a dwarf nova with a 59 min orbital period

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Rapid X-ray variability in GRO J0422+32 (Nova Per 1992)

The quiescent optical light curve of Nova Scorpii 1994 (= GRO J1655-40)

Hard X-ray lags in Cyg X-1

Phase-resolved spectroscopy of the atoll sources 1636-536/V801 Ara and 1735-444/V926 Sco

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Pulsar timing and general relativity

Hard X-ray time lags in GRO J1719-24

The mass of X-ray Nova Scorpii 1994 (= GRO J1655-40)

The rotation speed of the companion star in the Halo source V395 Car (= 2S 0921-630)
Nawoord

Het zit er bijna op! Nu, na ruim vier jaar besteed te hebben aan onderzoek en schrijven, rest mij nog slechts dit nawoord. Het is een bijzonder leerzame en veeleisende periode geweest, met succes en tegenslag, maar vooral ook een periode met heel veel plezier. Immers, hoe veeleisend sommige klusjes ook bleken te zijn, een geslaagde waarnemnacht of een mooi resultaat na maanden van data reductie en analyse maakten veel goed. Een prettig en leerzaam aspect van dit onderzoek was dat ik in de gelegenheid was om veel te reizen en intensief samen kon werken met wetenschappers in de Verenigde Staten en Groot-Brittannië.

Om verschillende redenen zijn dit de laatste anderhalf jaar niet zo heel erg eenvoudig geweest. Hoewel er wellicht momenten waren dat het afroden van het onderzoek eindeloos ver weg leek, en de waarde van een voltooid proefschrift soms minder belangrijk was dan ooit, heb ik nooit echt getwijfeld aan de goede afloop. Welnu, het boekje is inderdaad gereed. Hiermee besluit ik niet alleen dit promotie onderzoek, maar tevens mijn loopbaan in de sterrenkunde. Een moeilijke en ingrijpende beslissing want sterrenkunde is uiteraard één van de mooiste wetenschappen met onwaarschijnlijk veel interessante problemen en vragen die op een oplossing wachten. Het was een fantastische periode, met mooie herinneringen, maar nieuwe uitdagingen wachten buiten de sterrenkunde.

Jan, bedankt voor de prettige samenwerking. In binnen- of buitenland, jouw begeleiding bleef altijd enthousiast en gedreven. Het passeren van de 80000 mijl op de parkeerplaats van Bruno in Huntsville zal ik niet snel vergeten!

Part of this thesis is based on data obtained with BATSE. I have visited the BATSE-team at NASA's Marshall Space Flight Center in Huntsville for a period of nearly four months. It is a pleasure to thank Jerry Fishman, Chryssa Kouveliotou, David Crary, Bill Paciesas, Brad Rubin, Mark Finger, Tom Koshut, Alan Harmon and Susan Morris for their help with data and computers, and driving me through town whenever I was without transport. Chryssa, your presence in Huntsville really makes a difference. Thank you for your fabulous cooking and warm hospitality: ευχαριστώ πολύ! For the optical observations I collaborated with Phil Charles, Jorge Casares, Tariq Shahbaz and Andy Martin of Oxford University. We have spent quite some nights at the control of telescopes in Garching and La Silla: thanks for your help and stimulating discussions! These observations would not have been as successful without the excellent assistance of staff and night assistants of the ESO facilities in Germany and Chile.

Nathalie, gedurende 10 jaar hebben we gelijktijdig gestudeerd en aan ons proefschrift gewerkt. Hoewel we het nooit inhoudelijk over onze proefschriften hadden, zijn er toch heel wat avonden geweest waarbij de promotie ter sprake kwam. Bedankt voor alle vriendschap en steun tijdens de afgelopen jaren Nathalie; op naar het volgende project!

Velen hebben de unieke sfeer en tradities van het Anton Pannekoek instituut proberen te beschrijven, maar feit is dat je het moet ondergaan alvorens het echt te kunnen begrijpen. Ik ben blij een API te zijn geweest, en zal het schaatsen, Sinterklaas, buiten lunchen, carmen, de kerstborrel, cake-club, theater, film, diners, TV kijken bij het NIKHEF, goochelen, het koffieplein en The Pyramid zeker missen. Daarom wil ik alle API’s bedanken voor de leuke tijd, in het bijzonder Martin, Mariano, Martijn, Jane, Erica, Paul, Michiel, Rudi, Marnix, Hammi, Peer, Jeroen, Ankie, Tim, Thomas, Martin, Nicole en Onno. Dirk, bedankt voor je hulp; je kan de VAXen nu met gerust hart uit het raam kieperen.

Het belang van broers en roeien kan niet voldoende worden benadrukt. Zie ik je zaterdag om half tien op het botenhuis Rob?
Stellingen

behorende bij het proefschrift

X-ray and Optical Observations of Black-Hole X-ray Transients

1. De variabiliteit van de röntgenflux van GRO J1719-24 gedurende de uitbarsting in 1993 kan beschreven worden door één proces waarvan de karakteristieke tijdschaal afneemt, maar waarvan de mate van variabiliteit gelijk blijft.
   (Hoofdstuk 2 van dit proefschrift)

2. De kanonieke anticorrelatie tussen de break frequency en de power density bij deze frequentie, zoals waargenomen in de power density spectra van Cyg X-1 en andere BHCs, is niet aanwezig in de power density spectra van GRO J0422+32.
   (Hoofdstuk 4 van dit proefschrift)

   (Hoofdstuk 7 van dit proefschrift)

4. Onwaarschijnlijk kleine foutenmarges worden beter gewaardeerd dan een reële schatting van de onnauwkeurigheid.
   (zie Orosz & Bailyn (1997) en Hoofdstuk 7 van dit proefschrift)

5. Het is lastig navigeren in een multi-dimensionale $\chi^2$ ruimte.


7. Hoewel een goed geollieerde publiciteitsmachine ook in de wetenschap van onschattbare waarde is, schetst de uitspraak 'Helaas vergt het tegenwoordig de communicatieve vaardigheden van een autoverkoper om in de academische wereld te overleven.' een onjuist beeld.
   (zie S. Bais, in de Volkskrant, 28 maart 1998)


10. Het aanbrengen van strips op armen en benen, zoals geïntroduceerd tijdens de Olympische schaatswedstrijden in Nagano, heeft voornamelijk effect tussen de oren.

11. De zon schijnt!
    (zie M.H.M. Heemskerk, proefschrift, Universiteit van Amsterdam, 1994)

Amsterdam, 20 oktober 1998

Frank van der Hooft