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Black-hole binaries

1 INTRODUCTION

The black hole is the most exotic object in the universe predicted as a direct consequence of general relativity. Research of stellar mass black holes dates back to 1939, when Oppenheimer and Snyder (1939) predicted the possible presence of black holes. They discovered that, based on general relativity, a sufficiently massive star would collapse indefinitely when all thermonuclear energy was exhausted and disappear inside a sphere of a limiting radius from which even photons could not come out (the "event horizon"). This limiting radius, called the Schwartzschild radius, equals twice the gravitational radius, r_g ($= MG/c^2$, where M, G and c are the mass, the gravitational constant and the light velocity, respectively). Such an object is what is later called a black hole. However, black holes remained merely theoretical objects for a long time.

The actual existence of stellar-mass black holes came to light for the first time in the early seventies, as described below. At present, the presence of stellar mass black holes in a certain type of X-ray binaries has become beyond doubt. The "discovery" of black holes was a great victory for general relativity theory, and was certainly one of the highlights of astronomy in the twentieth century. However, the presence of stellar mass black holes in our Galaxy has not been established by a single indisputable discovery (unlike the discovery of neutron stars with radio pulsars). In actuality, their real existence has become convincing as a result of steadily growing evidence accumulated over a length of time.

It is not straightforward to identify black holes observationally. The most direct proof for a black hole would be

1. to demonstrate the presence of an event horizon in a compact (gravitationally collapsed) object.

However, this demonstration is extremely difficult. The next best thing is

2. to find the general relativistic effects (particle motion near the speed of light, a large gravitational redshift, etc.) that are events unique to close vicinities of event horizons.

For the reasons discussed later, attempts along this line have not been as yet successful (although successful for some Seyfert galaxies). So far, the most reliable evidence for a black hole has come from mass determination:

3. showing the mass of a compact object exceeds $3M_\odot$.

To the best of our current knowledge, any compact object more massive than $3M_\odot$, the mass upper limit of a stable neutron star, is believed to have no other fate than to collapse into a black hole.

As of the end of 1999, the compact objects in twelve X-ray binaries have been shown to have a mass greater than $3M_\odot$ (see Table 1, Section 4.1). On this theoretical basis, they are considered to be "reliable" black holes. (It is to be noted that black holes can in principle have any mass, hence black holes of $<3M_\odot$, if they exist, are not recognized using this criterion.) Yet, genuine general relativistic tests such as the above-mentioned (1) and/or (2) are still lacking. In this sense, one can say that the presence of stellar mass black holes in some X-ray binaries is virtually certain, but rigorously speaking the observational proof is not yet perfect.

A wealth of observational results on X-ray binaries has become available in the last few decades. Accordingly, studies of the X-ray properties of these sources have made great progress, and we have acquired a fair understanding

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of the nature of X-ray emission. In particular, we find that in certain circumstances, X-ray binaries containing a black hole (hereafter referred to as "black-hole X-ray binaries") show X-ray properties distinctly different from those containing a neutron star ("neutron-star X-ray binaries"), a point to which we will return in a later section. Based on these properties, one can identify the most probable black holes with the X-ray observations alone. As a result, it has become certain that many more black-hole binaries exist in our Galaxy. Interestingly enough, most of the black-hole binaries are not bright in X-rays all the time, but they are transient sources. The current observational facts on these transients make us suspect that there exist as many as several hundred or even more black-hole binaries (though most of them are X-ray quiet) in our Galaxy.

It is worth emphasizing that X-ray observations, which are only possible from space, have played a unique role in the investigation of black holes. The currently known stellar-mass black holes have all been discovered among bright X-ray binaries. There are good reasons for this, since, explained later, X-ray observation is practically the only means to discover stellar-mass black holes. Thus, one can say that without the development of observations from space, this fundamentally important field could not have been opened.

The above summarizes the present status of observational research into black-hole binaries *as of the end of 1999*. We shall discuss these topics in detail in the rest of this chapter. For previous reviews, see e.g. Tanaka and Lewin (1995), Tanaka and Shibazaki (1996), and references therein. The Research in this field has been long and is expanding rapidly. A great many investigators have been involved in the course of development. However, it is beyond the capability of the author to cover all the important contributions and giving them their credit due. Readers must be aware that this article is not intended to be a complete review of the subject and that the coverage of topics and the assessment of the results and interpretations may well be subject to the author's personal bias.

Following this introduction, we begin with a brief history of the early developments that led to the discovery of stellar-mass black holes.

2 EARLY DEVELOPMENTS

Soon after the discovery of X-ray stars in 1962 (Giacconi *et al.* 1962), the concept of an accreting compact object emerged in order to account for the large X-ray luminosity. If a compact object is in a binary system and accretes matter from a companion star, the matter falling into a deep gravitational potential well of the compact object would be heated to a very high temperature and efficiently emit X-rays. Shklovsky (1967) argued that the compact object of Sco X-1 (the first discovered and the brightest X-ray source in the sky) must, on observational grounds, be a neutron star, which later turned out to be the case. This speculation occurred even before the discovery of neutron stars. Neutron stars were discovered in 1967 by Hewish and Bell (Hewish *et al.* 1968) as radio pulsars. Soon, a rapidly spinning neutron star was found in the center of the Crab Nebula. This discovery provided direct evidence for the birth of a gravitationally collapsed object as a consequence of supernova explosions, a phenomenon predicted earlier by Baade and Zwicky in 1934. These discoveries re-excited interest in black holes, another class of gravitationally collapsed object, that might exist in reality. X-ray sources were considered to be the best locations to look for black holes because the deep gravitational potential of the latter make them strong X-ray emitters. However, in early days of X-ray astronomy there was no observational clue to identify black holes.

An epoch-making development concerning black holes took place in 1972. This was with Cyg X-1. It is worth a brief account here. Cygnus X-1 was one of the bright X-ray sources known from the earliest X-ray observations in sixties. From the early days, this source drew much attention because of its distinct characteristics among then known X-ray sources. It showed a hard X-ray spectrum much harder than others, and also irregular time variabilities. (For those who are not familiar with the expression "hard" or "soft", see explanation in Section 4.3.) The first X-ray astronomy satellite, *UHURU* launched in 1969, found that Cyg X-1 had a bimodal behavior switching between a low-intensity hard state and a high-intensity soft state (see Section 4.3). This added another peculiarity to the source. Various efforts had been made to localize the position of the source, but they were not yet precise enough to allow optical identification. In 1971, a new radio source was detected within this error region by Braes and Miley (1971) and Hjellming and Wade (1971). It became convincing that this radio source was Cyg X-1 itself, since the radio source had emerged in coincidence with the epoch when Cyg X-1 had changed from a high/soft state into a low/hard state. The accurate position of the radio source immediately led to an identification of the optical counterpart of Cyg X-1 with the O-type supergiant (O9.7I_{ab}) HDE226868.

A big surprise soon followed, when Webster and Murdin (1972) and Bolton (1972) discovered a sinusoidal variation with a 5.6-day period in the optical Doppler curve of HD 226868 (Figure 1), clearly indicating that it is a binary system. This was the first discovery of the binary nature of Galactic X-ray sources, and was prior to the discoveries of binary X-ray pulsars. The invisible companion must be a compact object accreting matter from the supergiant and emitting strong X-rays. Not only that, but the mass function (see equation below) obtained by them indicated that the mass of the compact object probably exceeded $3M_\odot$ (more recent results listed in Table 1). They independently considered that this binary system contained a black hole, Webster and Murdin wrote, "it is inevitable that we should also speculate that it might be a black hole". Bolton wrote, "this raises the distinct possibility that the secondary is a black hole".

Because of the great impact on the astronomy community, this discovery excited various critical discussions. However, none of the suggested alternatives to exclude the black hole hypothesis (e.g. invoking an equation of state with strange matter, or a three-body system, etc.) survived. Thus, Cyg X-1 remained as a strong candidate for a black-hole binary. Details of these accounts on Cyg X-1 are found in a review by Oda (1977).

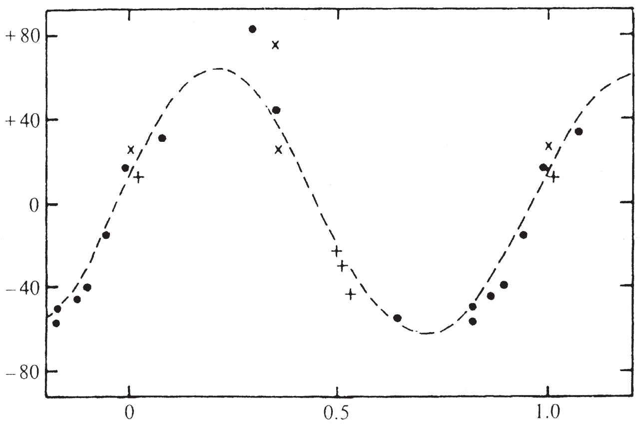

Figure 1 The radial velocity curve of HD 226868 plotted against the phase of 5.6-day orbital period. The vertical scale is in units of km s^{-1}. (From Webster and Murdin 1972.)

It is to be cautioned, however, that the above-mentioned X-ray properties of Cyg X-1 are no longer unique, nor are they signatures of black holes. Similar properties are observed from many other X-ray binaries regardless of whether the compact object is a black hole or a neutron star.

3 BLACK HOLES IDENTIFIED FROM MASS FUNCTIONS

During the following ten years, Cyg X-1 was the only black hole candidate until two bright X-ray sources in the Large Magellanic Cloud, LMC X-3 and LMC X-1, were discovered. Both of them were optically identified as early-type stars (Cowley *et al.* 1983 for LMC X-3, and Hutchings *et al.* 1983 for LMC X-1). The mass functions obtained indicated that the masses of the compact objects in these sources were also larger than $3M_\odot$. (The result for LMC X-1 in Table 1 was taken from the follow-up work by Hutchings *et al.* 1987).

The mass function $f(M)$ is given by the following equation:

$$f(M) = \frac{M_x^3 \sin^3 i}{(M_x + M_c)^2} = \frac{PK^3}{2\pi G}$$

where M_x and M_c are the masses of the X-ray emitting compact object and of the companion star, respectively, and i is the inclination angle of the binary orbit. P is the orbital period, and K denotes the amplitude of the Doppler curve (giving the line-of-sight component of the radial velocity) of the companion, which are both optically measurable quantities.

Table 1 Black-hole binaries established from the mass functions

Source name	Spectrum[a]	Companion	$F(M)$ ($M_\odot$)	BH mass ($M_\odot$)	Ref.[b]
Cyg X-1	S+PL	O9.7I_{ab}	0.241 ± 0.013	~16 (>7)	1
LMC X-3	S+PL	B 3 V	2.3 ± 0.3	>7	2
LMC X-1	S+PL	O 7–9 III	0.14 ± 0.05	~6	3
J0422+32 XNova Per '92	PL	M 2 V	1.21 ± 0.06	>3.2	4
0620−003 XNova Mon '75	S+PL	K 5 V	3.18 ± 0.16	>7.3	5
1009−45 XNova Vel '93	S+PL	K 7–8	3.17 ± 0.12	~4.4	6
1124−684 XNova Mus '91	S+PL	K 0–4 V	3.1 ± 0.4	~6	7
1543−475 XNova '71, '83, '92	S+PL	A 2 V	0.22 ± 0.02	2.7–7.5	8
J1655−40 XNova Sco '94	S+PL	F 3–6	3.24 ± 0.09	7.02 ± 0.22	9
1705−250 XNova Oph '77	S+PL	K ~3 V	4.0 ± 0.8	~6	10
2000+251 XNova Vul '88	S+PL	early K	4.97 ± 0.10	6–7.5	11
2023+338 XNova Cyg '89	PL	K 0 IV	6.26 ± 0.31	8–15.5	12

[a] X-ray spectrum at high luminosities, S+PL: soft + power-law, PL: power law.

[b] References:
1. Gies and Bolton 1982
2. Cowley *et al.* 1983
3. Hutchings *et al.* 1987
4. Filippenko *et al.* 1995a
5. McClintock and Remillard 1986
6. Filippenko *et al.* 1999
7. McClintock, Bailyn and Remillard 1992
8. Orosz *et al.* 1998
9. Orosz and Bailyn 1997
10. Remillard *et al.* 1996
11. Filippenko *et al.* 1995b
12. Casares *et al.* 1992

It is clear from the equation that $f(M)$ gives an absolute lower limit of the mass of the compact object. Once $f(M)$ is obtained, the actual mass of the compact object can be estimated if i and M_c are known by some means. These quantities are however subject to a fair amount of uncertainty. In particular, the possible systematic effects in the early type systems (large M_c), where the $f(M)$ values are usually much smaller than M_x (see Table 1), complicates the setting of a firm mass lower limit for the compact object. For instance, the companion mass M_c is usually estimated from the optical spectral type and our knowledge of the masses of those stars of the same spectral type. However, such an estimate might not be correct for the stars in close binary systems such as X-ray binaries that transferred a large amount of mass and might have experienced an unusual evolutionary process. According to the critical discussions, e.g. McClintock *et al.* (1992), $M_x > 3M_\odot$ is secure for Cyg X-1 and LMC X-3, but less secure for LMC X-1. (Yet, we shall see later that the X-ray spectrum of LMC X-1 supports the proposition that it is a black-hole binary.)

Up until 1986, these three were the only known black hole binaries, and they were all high-mass ($M_c \gg M_\odot$) systems. Since 1986, research on black hole binaries entered into a new era of rapid development. It began with

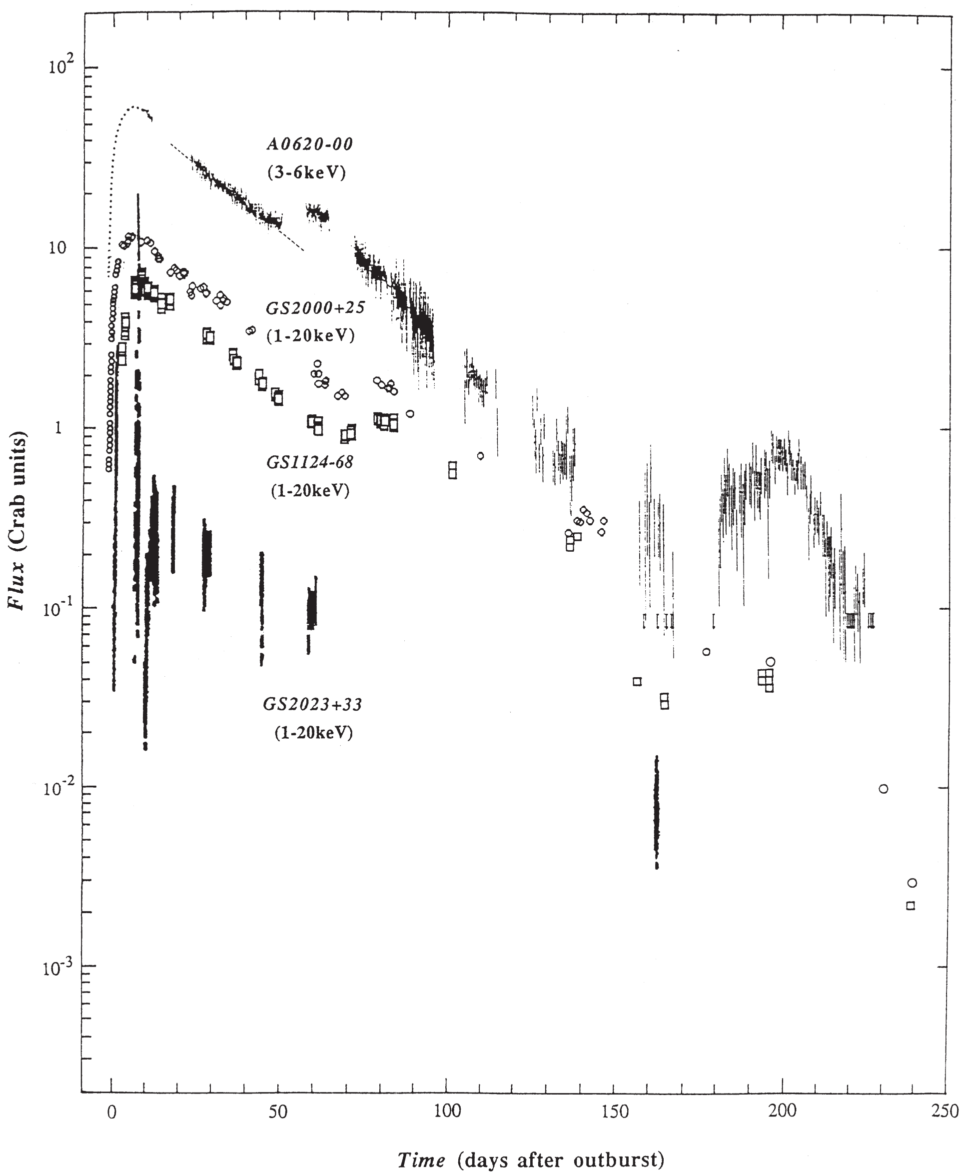

Figure 2 X-ray light curves of the transient outbursts of four black-hole binaries. The observed fluxes are shown in units of the Crab Nebula flux in an energy band indicated for each source. (Tanaka and Shibazaki 1996.)

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