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Evolutionary concepts of binaries with compact objects

In 1962 the first extrasolar X-ray source, Sco X-1, was discovered (Giacconi *et al*. 1962) and by the end of the 1960s several dozen such strong point X-ray sources had been discovered with rocket and balloon experiments.

Their marked concentration in the direction of the galactic center made clear that the distances of a number of them must be of the order of 8 kpc, implying a very large energy output in the form of X-rays, of the order of 10^{37} to 10^{38} ergs s^{-1} (some 10^4 times the total energy output of the Sun). What could be the mechanism generating these enormous X-ray luminosities? Largely thanks to the Russian team of Zel'Dovitch and co-workers, since the mid-1960s the idea arose that in a binary system the process of accretion of matter flowing over from a normal companion star to a neutron star or a black hole might power these strong galactic X-ray sources. Indeed, the simple process of accretion of an amount of mass m onto a neutron star (black hole) releases some $0.15\,mc^2$ (0.06 to $0.42\,mc^2$) of gravitational binding energy which, converted into heat, is available for emission in the form of X-rays. (The process of mass accretion onto a supermassive black hole had already been suggested as the energy source for quasars and active galaxy nuclei by Salpeter (1964), Zel'Dovitch (1964), and Zel'Dovitch and Novikov (1964).)

It should be kept in mind, however, that the existence of neutron stars in nature was not known before the end of 1968 – the year in which the discovery of radio pulsars was announced (Hewish *et al*. 1968). The discovery of the Crab Nebula pulsar in November 1968 (Staelin and Reifenstein 1968) and the detection of its large spindown rate made clear that pulsars are neutron stars and that neutron stars are born in a supernova event (Gold 1969; Monaghan 1969) just as had been predicted 34 years earlier by Baade and Zwicky (1934). Before 1968 neutron stars and black holes had been purely theoretical concepts, based on theoretical insights developed in the pioneering studies by Oppenheimer and Volkoff (1938) and Oppenheimer and Snijder (1939), respectively, and subsequently studied by various groups, notably those of J.A. Wheeler in the USA and Ya.B. Zel'Dovitch in the USSR. The first to search for black holes in binary systems were Zel'Dovitch and Guseinov (Guseinov and Zel'Dovitch 1966; Zel'Dovitch and Guseinov 1966), who searched for spectroscopic binaries with massive unseen secondary stars. They did not yet, however, mention the possibility that such binaries might emit X-rays, but Novikov and Zel'Dovitch (1966) did so slightly later. Following the discovery of the faint blue optical counterpart of Sco X-1 (Sandage *et al*. 1966) this early work culminated in Shklovskii's (1967) neutron star binary model for Sco X-1. This author showed that the optical light in the system could not arise from the same source as the X-rays, and that the X-ray energy distribution is consistent with thermal bremsstrahlung from an optically thin plasma accreting onto a neutron star. Since the optical spectrum of the source resembles that of a cataclysmic variable (CV: these are binary systems consisting of an accreting white dwarf and a low-mass ordinary star; Chapter 33) and since no stellar spectrum is seen (implying that the companion star is faint) it was postulated that the neutron star is in a binary and accretes matter from a low-mass companion star. It took another nine years before this "low-mass X-ray binary" model for Sco X-1 was confirmed by the detection of its 0.86-day orbital period by Gottlieb *et al*. (1975).

Before that, however, the first X-ray satellite Uhuru (USA, 1970) had, in 1971, discovered the existence of the

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pulsating and eclipsing binary X-ray source Cen X-3, which left no doubt about the existence of neutron stars moving in orbits around massive ordinary stars (Schreier *et al.* 1972). Shortly before this, earlier in 1971, the Uhuru group had discovered rapid X-ray variations in Cyg X-1, with timescales down to 50 ms, with no obvious periodicity (Oda *et al.* 1971). This rapid variability indicated that the X-ray source in the system cannot be larger than about 10^4 km. Webster and Murdin (1972) and Bolton (1972) independently that same year identified the bright O9.7 supergiant star HD 226868 as the optical counterpart to this source. This identification was an indirect one, through the accurate arc second position of a radio source that had been discovered independently by Braes and Miley (1971) and Hjellming and Wade (1971) in the X-ray error box of Cyg X-1. Webster and Murdin and Bolton found the blue supergiant to be a 5.6-day single-lined spectroscopic binary with a large velocity amplitude (72 km s^{-1}) indicating, if the O 9.7 supergiant has a normal mass ($\geq 15M_{\odot}$) for its spectral type, the presence of a companion of mass $>3M_{\odot}$. As this is above the upper mass limit of a neutron star (Nauenberg and Chapline 1973; Rhoades and Ruffini 1974; Kalogera and Baym 1996) they suggested Cyg X-1 to be a black hole – a suggestion that nowadays has been fully accepted. However, at the time this was, like that for Sco X-1, a rather indirect indication for the existence of X-ray binaries, and not yet completely convincing. For example, Kristian *et al.* (1971) dismissed the blue supergiant as the optical counterpart of the X-ray source. On the other hand, there could be little doubt that the X-ray source and the radio source were connected, as the radio source appeared just at the time when a dramatic change in the spectrum of the X-ray source occurred (Tananbaum 1973). Since the radio source coincided within a few arc seconds with the blue supergiant star, it seemed quite likely that the star, the radio source, and the X-ray source were connected. However, the X-ray source did not eclipse and neither the X-ray source nor the radio source showed a trace of a 5.6-day period variability that might connect them with the 5.6-day blue supergiant binary (only recently such periodic variability has been established at radio wavelengths (Pooley *et al.* 1999)).

For these reasons it was only with the discovery of the eclipsing pulsating binary X-ray source Cen X-3 by Schreier *et al.* (1972) that this collection of observations found a definitive explanation. Here one observed for the first time an X-ray pulsar (neutron star) that shows a beautiful 2.087-day sinusoidal Doppler modulation of its 4.84 s pulse period and is eclipsed every orbit for about 0.5 days. From the Doppler effect a projected orbital velocity of 415.1 ± 0.4 km s^{-1} was derived leading to a minimum companion mass of about 17 solar masses. The presence of this massive companion made it immediately clear that Cyg X-1 might form a similar system with the massive blue supergiant star HD 226868. Thus, by 1972 the existence of both neutron stars and black holes in close orbits around massive companion stars appeared well established. In the same year, Uhuru discovered the second pulsating and eclipsing binary X-ray source Her X-1, in which the 1.2 s period X-ray pulsar orbits in 1.7 days a star of rather low mass, about $2.0M_{\odot}$ (Tananbaum *et al.* 1972). In the 1970s and 1980s more and more X-ray binaries were discovered. They were found to fall into two broad categories: the high-mass X-ray binaries (HMXBs) like Cen X-3 and the low-mass X-ray binaries (LMXBs) like Her X-1 and Sco X-1 (Chapters 34–36).

The recognition that neutron stars and black holes can exist in close binary systems came at first as a surprise, as it did not seem to fit with the then current ideas about the evolution of binary systems. It was known from stellar evolution that the more massive a star is, the shorter its lifetime. Thus, the more massive component of a binary will be the first one to undergo a supernova explosion. If more than half the mass of a circular-orbit binary system is explosively ejected, the orbit of the system becomes hyperbolic and the system is disrupted (Blaauw 1961). This is a simple consequence of the virial theorem (Van den Heuvel 1994a). In a massive binary the mass of the neutron star remnant ($\sim 1.4M_{\odot}$) is negligible with respect to the masses of the two components (and to the amount of mass ejected in the supernova), so at first sight one would always expect these systems to be disrupted by the first supernova explosion. Still more puzzling were the almost perfectly circular orbits of Cen X-3 and Her X-1, apparently showing no trace of the effects of the supernova (although Cyg X-1 still has a slightly eccentric orbit). For the HMXBs like Cen X-3, it was soon realized (Van den Heuvel and Heise 1972) that the survival of the systems was due to the effects of large-scale mass transfer that must have occured prior to the supernova explosion. This caused the initially more massive star in the system to have become much less massive than its companion at the time of the explosion, and prevented the system from being disrupted. Tidal effects subsequently circularized the orbits during several millions of years, before the reverse mass transfer began and the system became an X-ray source. (Several other authors somewhat later independently came to similar conclusions: Börner *et al.* (1972); Tutukov and Yungelson (1973)). The model of Van den Heuvel and Heise (1972) built on earlier work on close binary evolution developed primarily in the 1960s. Morton (1960) had been the first one to show that large-scale mass transfer may explain why the more evolved (sub-giant) component of a close binary system like Algol (β Persei) may be less massive than its brighter and less evolved companion star. The reason is that in the course of its evolution the envelope of a star gradually expands, and after the exhausion of the hydrogen fuel in the stellar core, swells up to giant dimensions. However, in a close binary system there is no room for a giant star: the sizes of the stars are limited by the dimensions of their so-called Roche lobes, pear-shaped critical equipotential surfaces, surrounding the stars (Section 2). As soon as a star becomes larger than its Roche lobe, the matter outside the Roche lobe will flow over to its companion. The more massive star in a binary will be the first one to overflow its Roche lobe. Evolutionary calculations by Kippenhahn and Weigert (1967), Plavec (1967), and Paczynski (1966, 1971a) in the 1960s showed that this leads to the transfer of most of the star's hydrogen-rich envelope ($\geq$70% of its mass) to its companion, reversing the mass ratio of the system.

This type of "conservative" evolution (in which mass and orbital angular momentum of the system are conserved) appears to be able to explain the formation of the HMXBs.

However, for the LMXBs it was much harder to understand how the system survived the supernova explosion. The same holds for the close double neutron stars, such as the Hulse–Taylor binary pulsar PSR 1913+16 (Hulse and Taylor 1975), which has an orbital period of only 7.75 hours and an orbital eccentricity of 0.615. These systems must have survived two supernova explosions! In the LMXBs and their close relatives the cataclysmic variables the companion of the compact object is a low-mass ordinary star like our Sun, and the orbital periods are in general very short: mostly between 11 minutes and about half a day (Chapter 34). All these systems must in the course of their lives (and, in the case of LMXBs and binary pulsars, before the last supernova in the system) have lost a very large amount of mass and orbital angular momentum. The evolution of these systems was therefore much more complicated than that of the HMXBs. The first models for the evolution of binaries with a large loss of mass and orbital angular momentum were made by Van den Heuvel and De Loore (1973) who showed that a HMXB may later in life turn into a very close binary system consisting of a helium star (the helium core of the massive star) and a compact star. They suggested that the 4.8 hour X-ray binary Cyg X-3 is such a helium-star system, which was confirmed almost 20 years later (Van Kerkwijk *et al*. 1992). The Hulse–Taylor binary pulsar is a logical later evolutionary product of such a system (Flannery and Van den Heuvel 1975; De Loore *et al*. 1975). The first model for explaining the origin of an LMXB was that of Sutantyo (1975a) for the origin of Her X-1. He showed that in order to obtain such a system one should start out with a binary with components that differ very much in mass. In this case, due to the large difference between the thermal timescales of the envelopes of the stars, the low-mass component can hardly accept any mass from its more massive companion, once that star begins to overflow its Roche lobe. As a result most of the overflowing matter is lost from the systems, together with its orbital angular momentum, and only the helium core of the more evolved star is left, together with the practically unchanged low-mass companion. Still, in order to not disrupt the system when this helium star explodes, the initial conditions must have been very fine-tuned. Therefore, the formation of a LMXB is a much rarer event than the formation of HMXBs (Van den Heuvel 1983, 1994a; Webbink and Kalogera 1994; Kalogera 1998a,b), and the same holds for double neutron stars.

An important new ingredient that has been introduced in these binary evolution models since 1975 (Flannery and Van den Heuvel 1975) is the occurrence of velocity "kicks" of the order a few hundred kilometers per second that are imparted to the neutron stars in their birth events. Ample evidence for the occurrence of such kicks has been inferred in the last decade from the space and velocity distribution of radio pulsars and from a variety of other observational facts (Dewey and Cordes 1987; Tauris *et al*. 2000; Hartmann 1996, 1997; Van den Heuvel and Van Paradijs 1997). Without the occurrence of these kicks a variety of properties of the X-ray binaries and the binary radio pulsars, including their birth rate in the galaxy, would be difficult to understand (Verbunt and Van den Heuvel 1995; Kalogera 1998a,b; Kalogera and Webbink 1998).

As mentioned above, in the mid-1970s a link was suggested between the massive X-ray binaries and the Hulse–Taylor binary pulsar. The magnetic field of this pulsar is relatively weak ($\sim 10^{10}$ G, some two orders of magnitude lower than the average of pulsar magnetic fields) and its spin period is very short (0.059 s). As it was believed at the time that neutron star magnetic fields decay spontaneously on a relatively short timescale ($\sim 10^7$ yr) the weak field suggested that this neutron star is old. Since in X-ray binaries with accretion disks angular momentum is fed to the neutron star, one observes the X-ray pulsars in these systems to show a gradual decrease of their pulse periods in the course of time (Chapter 35; Section 1.4), so-called "spin-up." Bisnovatyi-Kogan and Komberg (1975) suggested that if the binary system is disrupted in the second supernova, this spun-up neutron star may again become observable as a radio pulsar. It was suggested by Smarr and Blandford (1976) that PSR 1913+16 is the old "spun-up" neutron star in the system (due to its weak magnetic field it now spins down only very slowly, on a timescale of the order of 10^8 yr). The other neutron star in the system was then produced by the second supernova explosion, and must be a young, strong-field neutron star. It is not observable, either because it has already rapidly spun down (Srinivasan and Van den Heuvel 1982), or because the Earth is outside of the pulsar beam. Old neutron stars spun-up by accretion in X-ray binaries, which are now observable as radio pulsars, are called "recycled pulsars" (Radhakrishnan and

Srinivasan 1982, 1984). In order to become observable as a radio pulsar, there should no longer be gas in the system, so accretion should have terminated. The companions of recycled pulsars should therefore either be white dwarfs or neutron stars. The system may also have been disrupted, resulting in a single recycled pulsar. The discovery of the first millisecond radio pulsar in 1982 gave the recycling idea an enormous boost: Alpar *et al*. (1982) and Radhakrishnan and Srinivasan (1982) suggested that millisecond pulsars are very old neutron stars which were spun-up by accretion in LMXBs. Because of the very long duration of the accretion phase in LMXBs ($\gtrsim 10^8$ yr), a lot of angular momentum can be fed to these neutron stars, leading to spin-up to millisecond periods. This recycling model has recently been beautifully confirmed by the discovery of the first millisecond X-ray pulsar in the LMXB system SAX 1808.4-3658 (Wijnands and Van der Klis 1998). In order to spin-up a neutron star to a millisecond period, its magnetic field should have decayed to below 10^9 G (Section 6). The general idea now is that the decay of the magnetic field in accreting neutron stars is somehow related to the accretion process (Taam and Van den Heuvel 1986), although the precise mechanisms for field decay are still being debated (Konar and Bhattacharya 1999).

This chapter is organized as follows. In Section 1 an overview is given of the various observed types of binaries with one or two compact components. In Section 2 the orbital dynamics of binary systems is described, including the main effects of mass exchange and mass loss on the orbits. In Section 3 the reasons for the existence of the two main classes of X-ray binaries, high- and low-mass systems, are discussed. In Section 4 an overview is given of the evolution of single stars, and of close binaries leading to the formation of X-ray binaries and CVs. In this section the further evolution of X-ray binaries until their final stages is also discussed. Section 5 deals with the globular cluster X-ray sources and their formation and Section 6 with the formation of binary radio pulsars as the final products of the evolution of X-ray binaries.

1 TYPES OF BINARIES WITH COMPACT OBJECTS

1.1 Introduction

The binaries with compact objects can be divided into the categories and types listed in Table 1. Basically they fall into the categories "compact star plus ordinary star" and "two compact stars." The first category consists of the X-ray binaries and the CVs, the second of the binary radio pulsars and the double white dwarfs. Each of these categories can be divided into a few main types, that can be further divided into sub-types, as indicated in the table, where examples of the different sub-types are also given. A few binaries with compact objects do not fit into the above four categories, notably the so-called "ante-deluvian" binary radio pulsars, which are young pulsars in an eccentric orbit around a massive star, which presumably are the progenitors of HMXBs. Four such systems are presently known, also indicated in the table: PSR 1259–63 ($P_{orb} = 3.4$ yr), PSR 1820-11 ($P_{orb} = 357.8$ d), PSR J1740-3052 ($P_{orb} = 231$ d), and PSR J0045-7319 ($P_{orb} = 51$ d) in the Large Magellanic Cloud. In the first system and the last-mentioned two systems the companion of the young pulsar is a B-type star, in PSR 1820-11 the companion is not known. Furthermore, there are the two peculiar X-ray binaries with relativistic jets, SS433 and Cyg X-3. In SS433 ($P_{orb} = 13$ d) the companion of the jet-producing compact object is probably an early-type hydrogen-rich star (Margon 1983). In Cyg X-3 ($P_{orb} = 4.8$ h) it is a Wolf–Rayet star (helium star; Van Kerkwijk *et al*. 1992).

I now briefly describe the main characteristics of each of the various types of neutron star and black hole binary systems listed in the table. In this review I will concentrate mainly on these systems as these are the ones that have primarily been discovered thanks to observations from space. Only where this is appropriate will I also mention the CV systems and double white dwarfs.

1.2 X-Ray Binaries

High- and low-mass X-ray binaries

The X-ray binaries can, broadly speaking, be divided into two main groups, the HMXBs and LMXBs, which differ in a number of important characteristics, listed in Table 2, and graphically depicted in Figure 1. (The characteristics listed and depicted are for systems containing neutron stars but most of them also hold for the X-ray binaries that contain black holes; also these can be divided into HMXBs and LMXBs, see Figure 3.) For further details we refer here to the reviews of these two types of systems in Chapters 34 to 36. In HMXBs the companion of the X-ray source is a luminous early-type star of spectral type O or B, like in the Cen X-3 system, with a mass typically between 10 and $40M_\odot$. In LMXBs it is a faint star of mass $\leq M_\odot$; in most cases the stellar spectrum is not even visible, as the light of the systems is dominated by that of the accretion disk around the compact star. The orbital periods of the LMXBs are generally short (mostly ≤ 0.5 d), though on average somewhat longer than those of the CVs.

Intermediate-mass X-ray binaries

Only recently it was realized that apart from these two main groups of X-ray binaries, which each contain some 10^2 known systems in our Galaxy (Van Paradijs and McClintock 1995), there are a few X-ray binaries in which the companion

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