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Accreting neutron stars and black holes: a decade of discoveries

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1.1 Introduction

Since their discovery in 1962 (Giacconi *et al.* 1962), accreting compact objects in the Galaxy have offered unique insights into the astrophysics of the end stages of stellar evolution and the physics of matter at extreme physical conditions. During the first three decades of exploration, new phenomena were discovered and understood, such as the periodic pulsations in the X-ray lightcurve of spinning neutron stars (Giacconi *et al.* 1971) and the thermonuclear flashes on neutron-star surfaces that are detected as powerful X-ray bursts (see, e.g., Grindlay *et al.* 1976; Chapter 3). Moreover, the masses of the compact objects were measured in a number of systems, providing the strongest evidence for the existence of black holes in the Universe (McClintock & Remillard 1986; Chapter 4).

During the past ten years, the launch of X-ray telescopes with unprecedented capabilities, such as RXTE, BeppoSAX, the Chandra X-ray Observatory, and XMM-Newton opened new windows onto the properties of accreting compact objects. Examples include the rapid variability phenomena that occur at the dynamical timescales just outside the neutron-star surfaces and the black-hole horizons (van der Klis *et al.* 1996; Strohmayer *et al.* 1996; Chapters 2 and 4) as well as atomic lines that have been red- and blue-shifted by general relativistic effects in the vicinities of compact objects (Cottam *et al.* 2001; Miller *et al.* 2002b). Accreting neutron stars and black holes have been monitored in broad spectral bands, from the radio to gamma rays, leading to the discovery of highly relativistic jets (Mirabel & Rodriguez 1994; Chapter 9), to the indirect imaging of accretion flows (Horne 1985; Chapter 5), and to the possible identification of neutron stars with masses close to the maximum value allowed by general relativity (Barziv *et al.* 2001). Finally, the theoretical modeling of accretion flows also experienced significant advances, such as the identification of a whole suite of stable solutions for accretion flows beyond the standard model of geometrically thin accretion disks (e.g., Narayan & Yi 1994) and of the most promising avenue towards explaining the very efficient transport of angular momentum in accretion flows (e.g., Balbus & Hawley 1991).

The aim of this chapter is to provide a general overview of these recent advances in the astrophysics of X-ray binaries in our Galaxy. The basic concepts have been reviewed in a number of textbooks (e.g., Shapiro & Teukolsky 1983; Glendenning 2003) and review articles (e.g., White *et al.* 1995) and will only be briefly mentioned here. Several other classes of compact stellar X-ray sources that do not involve accretion onto a neutron star or black hole will also not be discussed in this chapter but are reviewed elsewhere in this volume. These systems include: isolated neutron stars (Chapter 7); cataclysmic variables (CVs; Chapter 10); super-soft sources (SSS; Chapter 11); soft gamma-ray repeaters and

Compact Stellar X-Ray Sources, eds. Walter Lewin and Michiel van der Klis.

Published by Cambridge University Press.

anomalous X-ray pulsars (SGRs and AXPs; Chapter 14); and Gamma-ray bursts (GRBs; Chapter 15). Finally, accreting compact objects in other galaxies will be reviewed in Chapter 16.

1.1.1 X-ray binary systems

Whether a compact object in a binary system is accreting mass in a stable long-lived phase or not depends mostly on the mode of mass transfer, the ratio of the mass of the compact object to that of the companion star, and their orbital separation. For example, in the case of a neutron star (with a mass $\sim 1.4-2.0\,M_\odot$), stable mass transfer through the inner Lagrangian point occurs only when the companion fills its Roche lobe and has a mass smaller than that of the neutron star. In such systems, mass is driven by angular momentum losses due to gravitational radiation (for very small masses and orbital separations) and magnetic braking (for orbital periods ≤ 2 day) or by the evolution of the companion star (for orbital periods ≥ 2 day). These sources are significantly brighter in the X-ray than in the optical wavelengths, with the flux at the latter spectral band being mostly due to reprocessing of the X-ray flux from the outer accretion flows. Binary systems with low-mass companions to the neutron stars or black holes are called low-mass X-ray binaries (LMXBs).

A compact object can also accrete matter from a companion star that does not fill its Roche lobe, if the latter star is losing mass in the form of a stellar wind. For this process to result in a compact star that is a bright X-ray source, the companion star has to be massive ($\gtrsim 10\,M_\odot$) in order to drive a strong wind. In this configuration, the optical luminosity of the companion star dominates the total emission from the system and the rate of mass transfer is determined by the strength and speed of the wind and the orbital separation. Such systems are called high-mass X-ray binaries (HMXBs).

The large difference in the companion masses between low- and high-mass X-ray binaries leads to a number of additional differences between these two classes of systems. The lifetimes of HMXBs are determined by the evolution of the high-mass companions and are short ($\sim 10^5-10^7$ yr), whereas the lifetimes of the LMXBs are determined by the mass-transfer process and are longer ($\sim 10^7-10^9$ yr). For this reason, HMXBs are distributed along the galactic plane, as young stellar populations are, whereas LMXBs are found mostly towards the galactic center and in globular clusters (Fig. 1.1). Moreover, because neutron stars in HMXBs accrete for a relatively short period of time, their magnetic fields do not evolve away from their high birth values, and hence these neutron stars appear mostly as accretion-powered pulsars. On the other hand, the prolonged phase of accretion onto neutron stars in LMXBs is believed to be responsible for the suppression of the stellar fields and the absence of periodic pulsations in all but a handful of them.

Finally, in LMXBs, the very small sizes of the companion stars can lead to a number of interesting configurations in systems that are viewed nearly edge on. For example, in the accretion-disk corona (ADC) sources, the X-rays from the central object are scattered towards the observer by electrons in a hot corona that has a size larger than that of the companion, e.g., smoothing out the lightcurves of the X-ray eclipses (White & Holt 1982). On the other hand, in the so-called dippers, the shallow X-ray eclipses may not be caused by the companion star but rather by the stream of mass transfer from the companion star to the accretion disk (see, e.g., White & Swank 1982).

Overall, there are believed to be only a few hundred accreting high-mass and low-mass X-ray binaries in the whole Galaxy. Consequently, these binaries are extremely rare among

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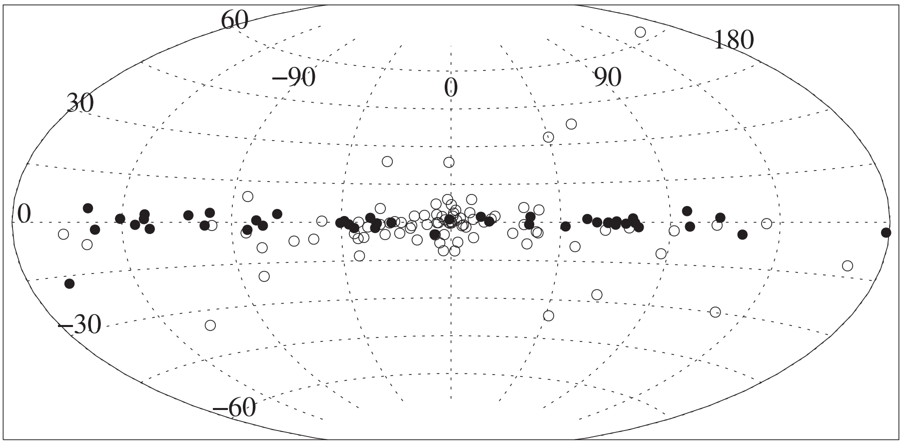

Fig. 1.1. Distribution of low-mass X-ray binaries (open symbols) and high-mass X-ray binaries (filled symbols) in galactic coordinates (Grimm *et al.* 2002).

stellar systems. This is in accord with the large number of improbable evolutionary steps a primordial binary needs to follow in order to become an X-ray source with an accreting compact object. Indeed, the progenitors of the compact objects are believed to be too large to fit in the tight orbits of most X-ray binaries. Moreover, the supernova explosions that precede the formation of the compact objects may disrupt most systems at the phase prior to the formation of the X-ray binary. The resolutions to these and other puzzles on the formation and evolution of X-ray binaries involve exotic and poorly understood binary-evolution processes such as common-envelope evolution of binary stars (Taam & Sandquist 2000), asymmetric supernova explosions that impart recoil velocities to the newborn compact objects, and two- and three-star interactions in the dense stellar fields of globular clusters (see Chapter 8) . The processes that lead to the formation and evolution of X-ray binaries are reviewed in detail in Chapter 16.

1.1.2 Accretion onto compact objects

An X-ray binary is formed when either the companion star transfers matter onto the compact object through the inner Lagrangian point or the compact object captures mass from the wind of the companion star. In both cases, the fate of the transferred mass depends on the amount of angular momentum it possesses, on the physical processes by which it loses angular momentum, and, most importantly, on the radiation processes by which it cools (see Frank *et al.* 2002 for a comprehensive review of this subject).

Beginning in the early 1970s and for the next two decades, most of the modeling effort of accretion flows onto neutron stars and black holes was based on two restrictive assumptions. First, accretion flows were assumed to be losing angular momentum at high rates because of an unspecified process, typically taken to be proportional to the pressure (see, e.g., Shakura & Sunyaev 1973; these solutions are often called α-disks, named after the constant of proportionality). Second, radiation processes were assumed to be very efficient, so that the resulting accretion flows were relatively cool, in the form of geometrically thin accretion disks. The first of these assumptions stemmed from calculations that showed the inefficiency of microscopic viscosity to account for the high inferred rates of mass accretion in the observed sources

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(see Pringle 1981 for a review). The second assumption, on the other hand, was relaxed in a number of studies (e.g., Shapiro *et al.* 1976) but the resulting solutions were shown to be unstable (e.g., Piran 1978).

During the past decade, theoretical models of accretion flows onto compact objects became increasingly more sophisticated and diverse because of two major developments. First was the identification of a magnetohydrodynamic instability in differentially rotating flows (the magneto-rotational instability, or MRI; Balbus & Hawley 1991, 1998), which allows seed magnetic fields of infinitesimal strength in the flow to get enhanced and tangled. This was shown to lead to a fully developed magnetohydrodynamic turbulence and provide an efficient mechanism of angular momentum transport, as envisioned in the earlier empirical models (Balbus & Papaloizou 1999). Studies of the non-linear development of the instability, its level of saturation (e.g., Sano *et al.* 2004), as well as of its effect on the overall properties of accretion disks (e.g., Armitage *et al.* 2001; Hawley & Krolik 2001; Krolik & Hawley 2002; McKinney & Gammie 2002) require large-scale numerical simulations and are all subjects of intense research efforts.

The second development is related to the discovery of new stable inefficient accretion flows (e.g., Narayan & Yi 1994). In these solutions, the electrons and ions have different and high temperatures, the accretion flows are geometrically thick, and most of their potential energy is not radiated away but is rather advected towards the compact objects; these are the so-called advection-dominated accretion flows (ADAFs). Besides being interesting new theoretical solutions to the hydrodynamics equations, advection-dominated flows provide a framework within which the anomalously low efficiency of accretion onto several black holes in the centers of galaxies (Narayan *et al.* 1995) and in the quiescent states of X-ray transients (Narayan *et al.* 1996) can be understood.

Recently, a number of basic properties of these advection-dominated solutions have been scrutinized. The basic assumption that electrons and ions are coupled inefficiently, mostly due to Coulomb scattering, has been revised, taking into account the effects of magnetic fields (e.g., Quataert & Gruzinov 1999). Advection-dominated flows were shown to be capable of launching strong outflows (advection-dominated inflow/outflow solutions or ADIOS; Blandford & Begelman 1999). Moreover, for a wide area of the parameter space, numerical (Stone *et al.* 1999; Igumenshchev *et al.* 2000) and analytical studies (Narayan *et al.* 2000) showed that the solutions are convectively unstable (convection-dominated accretion flows or CDAFs). Finally, the effects of the magneto-rotational instability on the properties of radiatively inefficient flows have also been investigated recently both in the Newtonian regime (see Fig. 1.2; Stone & Pringle 2001; Igumenshchev *et al.* 2003) and in the general relativistic regime (DeVilliers *et al.* 2003; Gammie *et al.* 2003).

The final ingredient in the models of accretion flows onto compact objects is the interaction of the flows with the objects themselves. This is the region in the accretion flows where most of the high-energy radiation is produced and hence is the one that is probed by observations with X-ray and gamma-ray telescopes. Clearly, the interaction depends on whether the compact object is a black hole or a neutron star, and in the latter case, on whether the neutron star is strongly or weakly magnetic. The main observational manifestation of these differences is the presence or absence of pulsations in the X-ray lightcurves of the systems, which reflects the strength of the magnetic fields of the central objects. In the rest of this chapter the observational properties of the pulsating and non-pulsating X-ray binaries, as well as the current efforts for their theoretical modeling, will be reviewed.

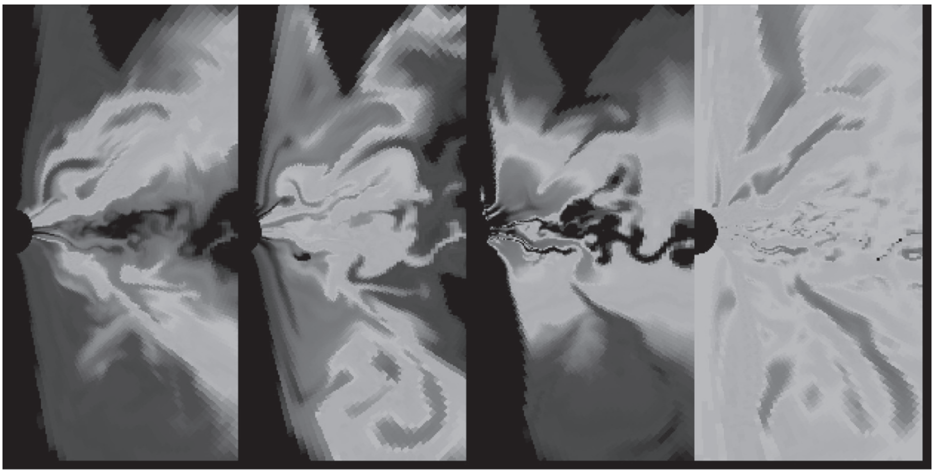

Fig. 1.2. Results of a numerical simulation of a magnetohydrodynamic accretion flow onto a black hole. The panels show the logarithm of the density, specific entropy, square of the toroidal magnetic field, and the $r-\phi$ component of the Maxwell stress tensor (Stone & Pringle 2001).

1.2 Pulsating neutron stars

Neutron stars possess some of the strongest magnetic fields observed in nature. The origin of these magnetic fields is only poorly understood, mostly due to our inability to observe directly the magnetic fields of the cores of pre-supernova stars, which collapse to form the neutron stars, and model their amplification. However, observations of isolated radio pulsars (Chapter 7) and magnetars (Chapter 14) provide strong evidence that neutron-star magnetic fields range between $\sim 10^8$ G and $\sim 10^{15}$ G.

When a strongly magnetic neutron star accretes plasma from a companion star or the interstellar medium, its magnetic field becomes dynamically important close to the stellar surface and determines the properties of the accretion flow. The radius at which the effects of the magnetic field dominate all others is called the Alfvén radius and its precise definition depends on the mode of accretion (i.e., thin-disk vs. quasi-radial), the topology of the magnetic field (i.e., dipolar vs. multipolar), etc. For thin-disk accretion onto a neutron star, the Alfvén radius is defined as the radius at which magnetic stresses efficiently remove the angular momentum of the accreting material (see Ghosh & Lamb 1991 and references therein). For a surface magnetic field strength of 10^{12} G and a mass-accretion rate comparable to the Eddington critical rate, the Alfvén radius is of order 100 neutron-star radii.

The fate of the accreting material after it interacts with the stellar magnetic field near the Alfvén radius depends on the spin frequency of the neutron star. If the stellar spin frequency is smaller than the orbital frequency of matter at the interaction radius, then the accreting material is forced into corotation with the star and is channeled along field lines onto the magnetic poles. As the neutron star spins and the observer sees a different aspect of the hotter magnetic poles, the X-ray flux received is modulated at the stellar spin frequency and an accretion-powered pulsar is produced. On the other hand, if the stellar spin frequency is larger than the orbital frequency of matter at the interaction radius, then the material cannot overcome the centrifugal barrier in order to accrete onto the star. The fate of matter in this case is presently unknown, but it is often assumed that matter eventually escapes the neutron

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star in the form of a wind. Magnetic neutron stars in this configuration are often said to be in the propeller regime (after Illarionov & Sunyaev 1975).

The neutron star itself also reacts differently to the accretion of matter depending on its magnetic field strength, its spin frequency, and the mass accretion rate. Magnetic field lines rotate at the spin frequency of the star and couple the stellar surface to the accreting material. As a result, they transfer angular momentum from the accreting material to the neutron star, if the former is spinning faster than the latter, or from the neutron star to the accreting material, in the opposite situation. Both situations occur simultaneously in an accreting system, since the orbital frequency of matter decreases with increasing radius. The overall effect is a net torque on the neutron star, which can be either positive (spin-up) or negative (spin-down). The magnitude of the torque on the star is expected to increase with increasing mass accretion rate and with increasing magnetic field strength (see Ghosh & Lamb 1979, 1991). Clearly, for every magnetic field strength and mass accretion rate, there is a critical spin frequency at which the net torque on the star is zero. This frequency corresponds to an equilibrium, towards which the neutron star evolves in its lifetime. For a surface dipolar magnetic field with a strength of 10^{12} G and a mass accretion rate comparable to the Eddington critical rate, the equilibrium spin frequency is of the order of a few tenths of a hertz (Ghosh & Lamb 1992).

Accretion-powered pulsars currently provide the best systems in which the spin frequencies and magnetic field strengths of accreting neutron stars can be studied. Two distinct classes of such pulsars are known: pulsars with periods of order a second, which are found mostly in high-mass X-ray binaries, and pulsars with millisecond spin periods, which are found in binary systems with very short orbital periods (see Section 1.2.2).

1.2.1 Classical (slow) accretion-powered pulsars

The detection of coherent pulsations from an accreting X-ray source, in 1971 (Giacconi *et al.* 1971), provided the strongest evidence, at the time, that the compact objects in many of these sources were neutron stars. Since then, accretion-powered pulsars with periods of the order of one second or more have been studied extensively with every X-ray satellite. In recent years, the long-term monitoring of such pulsars with BATSE as well as the detailed spectral studies with RXTE and BeppoSAX provided a remarkable look into the properties of these systems, resolving some long-standing questions and posing a number of new ones (see Bildsten *et al.* 1997 and Heindl *et al.* 2004 for comprehensive reviews of the accretion-powered pulsars discussed in this section).

The vast majority of slow accretion-powered pulsars are found in high-mass X-ray binaries; only five of them (Her X-1, 4U 1626−67, GX 1+4, GRO J1744−28, and 2A 1822−371) have low-mass companions. Indeed, most low-mass X-ray binaries are old systems and their prolonged phase of accretion is thought to have suppressed the magnetic fields of the neutron stars and to have spun them up to millisecond periods (see Section 1.2.2). On the other hand, high-mass X-ray binaries are younger systems and the neutron stars in them are expected to have magnetic fields that are dynamically important.

The properties of the high-mass binary systems in which slow pulsars reside can be described more easily on the diagram that correlates their spin to their orbital periods (the Corbet diagram; Fig. 1.3). About half of the slow pulsars are orbiting main-sequence Be stars, whereas the remaining pulsars are orbiting evolved OB supergiants. The systems with Be companions are generally eccentric transient systems, in which the companion stars are not filling their Roche lobes and the pulsars become detectable during periastron passages

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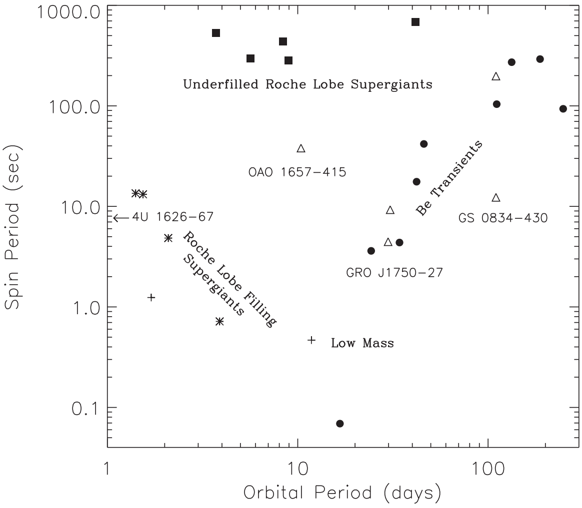

Fig. 1.3. The spin and orbital periods of classical accretion-powered pulsars (the Corbet diagram; after Bildsten *et al.* 1997).

(Chapter 5). The properties of the systems with supergiant companions depend on whether these stars fill their Roche lobes or not. If they do, matter is transfered onto the neutron stars via the inner Lagrangian point of their binary potential possessing significant angular momentum and forming a geometrically thin accretion disk. On the other hand, for companion stars that do not fill their Roche lobes, mass lost via a radiation-driven wind is captured by the neutron star at rates that are typically lower than the disk-fed systems.

1.2.1.1 Spin-period evolution

The mode of mass transfer onto the neutron stars, which depends on the properties of the binary systems, also determines the spin evolution of the neutron stars. The long-term aspect of this dependence is clearly visible in Fig. 1.3. The systems with Roche-lobe filling supergiants have short spin periods that are anticorrelated with the orbital periods; the systems with underfilling supergiants have long spin periods that do not show any correlation with orbital periods; and the Be transient systems have long orbital periods that are positively correlated to the orbital periods. These correlations are believed to depend strongly on the mode and efficiency of mass transfer from the companion stars to the neutron stars but are only poorly understood (see, e.g., Waters & van Kerkwijk 1989).

A clear look into the short-term dependence of the spin periods of neutron stars on the properties of the accretion flows was made possible because of the intense monitoring of several accretion-powered pulsars with the BATSE experiment onboard CGRO. Contrary to earlier results, the measurements with BATSE revealed that transient and persistent sources show two different types of spin-period evolution (Bildsten *et al.* 1997).

Transient accretion-powered pulsars in outburst show a positive dependence of the accretion torque (as measured by the spin-up rate) on the inferred accretion luminosity (Fig. 1.4; left panel). This is consistent with the simple model of disk–magnetosphere interaction (e.g., Ghosh & Lamb 1992), in which, as the accretion rate increases, the rate of angular momentum transfer from the accretion flow to the neutron star increases. At the limit of very low mass accretion rate, the neutron stars are expected to spin down, because the magnetic

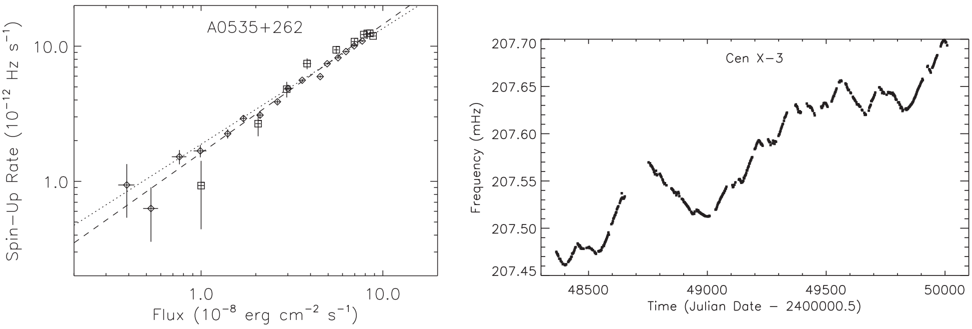

Fig. 1.4. (*Left*) The dependence of the spin-up rate on the pulsed flux for the source A 0535+262, as observed by BATSE; the dashed and dotted curves show the best-fit line and the theoretical prediction, respectively (see text). (*Right*) The evolution of the spin frequency of Cen X-3 as observed by BATSE (Bildsten *et al.* 1997).

field lines that couple to the outer, slower accretion flow remove spin angular momentum from the neutron star. Such spin-down episodes have not been detected by BATSE, although evidence for spin-down in the pulsar EXO 2030+375 has been previously reported based on EXOSAT data (Parmar *et al.* 1989). The very low fluxes down to which the transient sources continue to spin up place strong constraints on the relative importance of angular momentum transfer between the accretion disk and the neutron star via anchored magnetic field lines.

In sharp contrast to the transient sources, persistent disk-fed pulsars show a bimodal behavior in their accretion torques (Bildsten *et al.* 1997; see also Fig. 1.4; right panel). Episodes of spin-up and spin-down of approximately equal accretion torques alternate at timescales that vary from ∼10 days (e.g., in Cen X-3) to ≥10 yr (e.g., in GX 1+4). The transition between spin-up and spin-down is rapid (≤ a few days) and cannot be resolved with BATSE measurements. Current models of the disk–magnetosphere interaction in accretion-powered pulsars can account for the observed bimodal torques only if one of the physical properties of the accretion flow is also assumed to show a bimodal behavior. Such assumptions include a bimodal distribution of the mass transfer rate onto the pulsar, or a bimodal dependence on accretion rate of the orientation of the disk (Nelson *et al.* 1998; van Kerkwijk *et al.* 1998), of the orbital angular velocity of the accreting gas (Yi & Wheeler 1998), or of the strength and orientation of any magnetic field produced in the disk (Torkelsson 1998). Alternatively, for any given mass accretion rate onto the neutron star, two equilibrium solutions may be possible, one in which the star is spinning up and one in which it is spinning down (Lovelace *et al.* 1999). It is not clear at this point which, if any, of these alternatives is responsible for the observed torque reversals in accreting neutron stars and this remains one of the puzzles of the BATSE monitoring of slow accretion-powered pulsars.

1.2.1.2 Quasi-periodic oscillations

In several accretion-powered pulsars, the power-density spectra in X-rays or in longer wavelengths show a number of quasi-periodic oscillations, in addition to the period of the pulsars (Table 1.1; Fig. 1.5). The frequencies of these oscillations range from ∼1 mHz

Table 1.1. *Quasi-periodic oscillations in accretion-powered pulsars*[a]

Source	Spin frequency (mHz)	QPO frequency (mHz)
4U 1907+09	2.27	55
XTE J1858+034	4.5	111
A 0535+26	9.71	27–72
EXO 2030+375	24	187–213
LMC X-4	74	0.65–1.35, 2–20
4U 1626−67	130	1, 48
Cen X-3	207	35
V 0332+53	229	51
4U 0115+63	277	2, 62
Her X-1	807.9	8, 12, 43
SMC X-1	1410	60?
GRO 1744−28[b]	2140	40000

[a] Compilation after Shirakawa & Lai 2002; [b] Zhang *et al.* 1996.

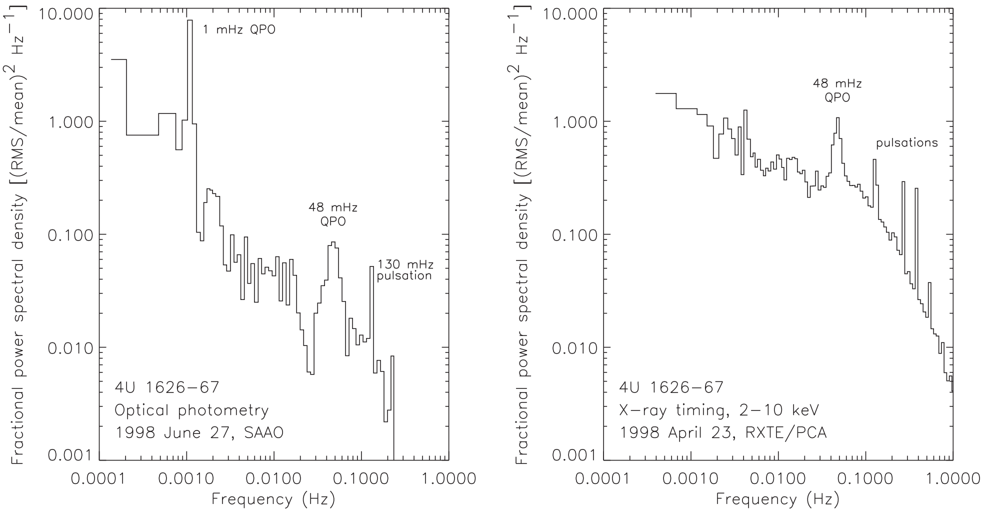

Fig. 1.5. The optical (*left*) and X-ray (*right*) power spectrum of the accretion-powered pulsar 4U 1626−67 showing mHz quasi-periodic oscillations (Chakrabarty *et al.* 2001).

to ∼40 Hz and they can be from ∼100 times smaller to ∼100 larger than the pulsar spin frequencies.

The frequency of the fast oscillations in the transient pulsar EXO 2030+375 was found to be in good agreement with beat-frequency models (Finger *et al.* 1996), in which oscillations occur at the beat frequency between the orbital frequency of matter at the Alfvén radius and the stellar spin frequency (Alpar & Shaham 1985). On the other hand, the low-frequency oscillations observed in 4U 1626−67 appear also as asymmetric sidebands to the pulse period (Kommers *et al.* 1998) and are probably related to a low-frequency modulation of

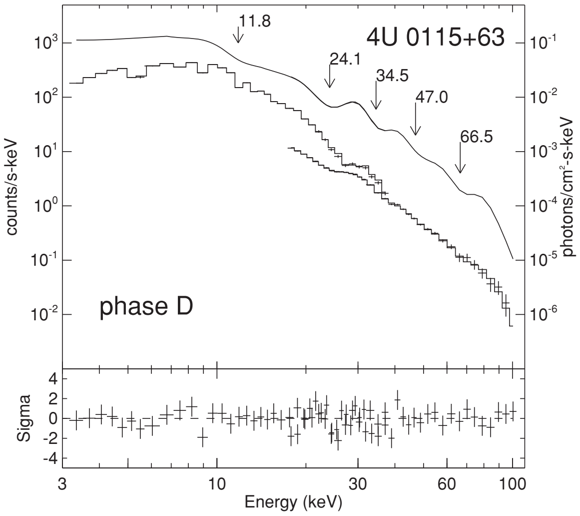

Fig. 1.6. The observed (histogram) and model spectrum (solid line) of the accretion-powered pulsar 4U 0115+63 showing evidence for cyclotron lines with as many as four overtones (Heindl *et al.* 1999).

the accretion flow, possibly due to the presence of a precessing disk warp (Shirakawa & Lai 2002). It is unclear at this point whether all of these quasi-periodic oscillations are related to the same phenomenon or not and what is their physical origin.

1.2.1.3 Cyclotron lines

The X-ray spectra of accretion-powered pulsars are typically described in terms of relatively flat power laws with exponential cutoffs at energies $\geq$ 10 keV. These continuum spectra are believed to be the result of upscattering of soft photons by the hot electrons in the accretion columns above the magnetic polar caps (Meszaros 1992). For neutron-star magnetic field strengths of $\sim 10^{12}$ G, the cyclotron energy on the stellar surface is $\sim$11.6 keV and the continuum spectra are expected to show evidence for harmonically related "cyclotron resonance scattering features" (or simply cyclotron lines) in the X-rays. Observation of such features was anticipated from the early days of X-ray astronomy and expected to lead to direct measurements of the magnetic field strengths of accreting neutron stars (e.g., Trumper *et al.* 1978).

The broadband spectral capabilities of RXTE and BeppoSAX made possible the unequivocal detection of harmonically related features in four accretion-powered pulsars, as well as the detection of single features in ten more sources (Fig. 1.6 and Table 1.2). The widths of the resonance features appear to be correlated to the energies of the continuum cutoffs and to be proportional to their central energies and to the inferred scattering depths (Coburn *et al.* 2002). The central energies of these features provided direct measurements of the surface magnetic fields of accreting pulsars, which can be used in constraining the models of disk–magnetosphere interaction. Future observations of the pulse-phase dependence of the scattering features is also expected to provide more detailed constraints on the geometries of the accretion columns in slow accretion-powered pulsars.