12 Black Holes and Neutron Stars

Thomas J. Maccarone
School of Physics and Astronomy, University of Southampton,
Southampton, Hampshire, United Kingdom

T.D. Oswalt, M.A. Barstow (eds.), *Planets, Stars and Stellar Systems. Volume 4: Stellar Structure and Evolution*,
DOI 10.1007/978-94-007-5615-1_12, © Springer Science+Business Media Dordrecht 2013

Abstract: Black holes and neutron stars are the compact remnants of massive stars. They represent one of the key intersections between astronomy and fundamental physics – both are classes of objects which are sufficiently compact that Newtonian gravity cannot be used to describe the forces near their surfaces. The structure of neutron stars furthermore presents one of the few key tests of the equation of state of nuclear matter. This chapter will review some of the key theoretical results underpinning the current understanding of neutron stars and black holes. It will also describe the observations of neutron stars and black holes both in isolation (as thermal emitters and as radio pulsars for the case of neutron stars) and in close binaries, where accretion processes can make these objects bright X-ray sources. Additionally, this chapter will detail the formation processes of both neutron stars and black holes in general, and also the formation of close binaries containing such objects.

Keywords: (Including multiple): close, Pulsars: general, Radio continuum: stars, (Stars:) binaries, Stars: neutron, X-rays: binaries, X-rays: bursts

1 Introduction

The observational study of neutron stars and black holes has developed almost entirely in the past 50 years; the articles for the first edition of "Stars and Stellar Systems" were set to press just as the first cosmic X-ray sources were being discovered. These soon came to be understood to provide the first observational evidence for neutron stars and black holes in the Galaxy. More than 5 years later came the first publication of the discovery of radio pulsars. Some observation evidence for the existence of supermassive black holes had been found already by that time [for example, the discovery of strong, extremely broad optical emission lines from some galactic nuclei, seen by Seyfert in 1943, and an optical jet being ejected by the supermassive black hole in M87 has been known even further back (Curtis 1918)]. However, the interpretation of the active galactic nuclei as accretion onto black holes did not gain traction until well into the 1960s (Salpeter 1964) nor did it achieve a consensus until the 1970s. Over the past several decades, the wealth of data from across the wavelength spectrum, from radio through gamma-rays, has greatly increased the level of understanding of how matter behaves near compact objects.

Black holes and neutron stars are astrophysically important objects for a variety of reasons. Both classes of objects represent the end stages of stellar evolution of massive stars – the stars that form the bulk of the heavy elements in the Universe. Understanding the formation of black holes and neutron stars is thus an essential part of understanding how the Universe is chemically enriched to the point in can produce life. After all, matter locked up in a black hole or a neutron star represents core material which has not been injected into the interstellar medium.

Both classes of compact objects also represent objects which can be used to test ideas about fundamental physics. Black holes can be used to determine whether general relativity is, indeed, the correct formulation of gravity. General relativity is also important for understanding the structure of neutron stars, and neutron stars also provide one of Nature's opportunities to study the properties of matter at nuclear density. Both pulsars and black hole X-ray binaries have been associated with high-energy gamma-ray emission, and, more tenuously, with cosmic rays – they may thus also serve as particle accelerators more powerful than any yet built on Earth. These objects are also strong candidates for producing the low-energy positron background seen from the Galactic Center region.

Comparisons between the accretion process onto stellar-mass black holes and that seen onto the supermassive black holes in active galactic nuclei can yield important information about which parts of the accretion process are "scale-free," and which show significant differences as a function of the accretor mass. There are also facets of the accretion process which can be studied only with stellar-mass black holes because of the higher signal-to-noise ratio one can obtain from them and because the characteristic timescales of accretion are generally proportional to black hole mass, making some variability features inaccessible in supermassive black holes on timescales shorter than the lifetimes of typical astronomers. Accretion onto neutron stars can be used to compare with accretion onto black holes. Since the mass differences between neutron stars and stellar-mass black holes are relatively small and the gravitational potential well depths are nearly the same for both cases, the differences can often be ascribed to the presence of a surface and/or a magnetic field in the neutron star accretors.

More speculatively, both neutron stars and black holes may be important sources of gravitational radiation. Mergers involving two black holes, two neutron stars, or a black hole and a neutron star are among the few candidate classes of event that should be able to produce gravitational radiation both strong enough and in the right frequency range for detection by ground-based gravitational wave detectors. Pulsar binaries already represent the best evidence to date for indirect gravitational radiation as their excellent clocks can be used to measure their orbital period derivatives to a precision greater than other techniques.

This article will start with an introduction of the general properties of neutron stars and black holes, followed by a discussion of the mechanisms which allow them to cause the emission of radiation (either directly from neutron stars themselves, or from accretion disks surrounding compact objects from either class), and will close with a discussion of their formation and evolution. While this approach may seem counterintuitive, given that, obviously, a compact object must form before it can emit, an understanding of the emission processes from compact objects is necessary for understanding the selection effects that come into population studies of these classes of objects.

2 Neutron Stars

The first suggestion that neutron stars might exist came from the work of Baade and Zwicky (1934), who showed that the total energy radiated in a supernova was about 10^{51} ergs and argued that one of the few plausible sources of such an amount of energy would be from collapsing a star down to a very small radius, at which point it would have nuclear density, and consist primarily of neutrons. It has since been realized that the total energy release from supernovae is dominated by neutrinos, rather than radiation or kinetic energy, and hence that the total energy release from a supernova is about an order of magnitude larger than Baade and Zwicky had estimated. On the other hand, it has become more widely accepted that the means by which this energy is generated is the gravitational collapse of the core of a massive star into a neutron star or a black hole.

Neutron stars are upheld by degeneracy pressure between nucleons (and, perhaps, free quarks) in their cores. The term "neutron star" implies that these objects are composed almost entirely of neutrons. However, there is strong evidence that these stars contain thin envelopes of normal matter, and there are speculative suggestions that these stars may contain substantial components of other more exotic forms of matter, such as free quarks. The density inside a neutron star is large enough that protons and electrons can combine to form neutrons.

2.1 Structure of Neutron Stars

A full understanding of the structure of neutron stars requires an in-depth knowledge of nearly all areas of modern physics. Neutron stars have combinations of masses and radii that leave them within a factor of a few of becoming black holes. Their structure depends heavily on the interactions between nucleons at densities slightly higher than those in atomic nuclei. Their inner cores are often thought to be superconducting, and in some cases, they may contain substantial numbers of "free" quarks.

One of the key reasons that studies of neutron stars are important is that the neutron star equation of state places important constraints on how matter behaves at nuclear densities. Equations of state are referred to as "hard" if they have a weak dependence of radius on mass, and "soft" if they have a stronger dependence of radius on mass. Both the maximum and minimum masses of neutron stars are of considerable interest. The maximum mass of a neutron star is determined by the stiffness of the equation of state of the neutron star. An equation of state is referred to as soft if density depends strongly on pressure, while it is referred to as stiff if density depends weakly on pressure. Soft equations of state therefore can be ruled out if high-mass neutron stars can be observed.

The minimum mass of a neutron star comes from the requirement that β-decay of neutrons in the star is not effective. Under normal densities, free neutrons *will* decay via β emission. However, at very high matter densities, all electron energies levels up to the energy of the electron to be emitted can be filled (see, e.g., Shapiro and Teukolsky 1983 reference work for a more detailed discussion). If the density of a star is below this critical density, it cannot contain the number of free neutrons seen in neutron stars; the neutrons will decay via β emission into electrons and protons. The star will then be supported by electron degeneracy pressure rather than nucleon degeneracy pressure. Under normal conditions of stellar evolution, this minimum mass for a neutron star is not physically relevant – the minimum mass for a neutron star is smaller than the maximum mass for a white dwarf, and normal stellar evolutionary processes will not pass through the region of parameter space with very small radius and medium core mass, where a low mass neutron star might exist. However, under some circumstances, binary evolution might produce an object which starts out as a neutron star but eventually falls below the minimum neutron star mass. This could happen, for example, if the neutron star is in a close binary with either a black hole or a heavier neutron star, and is transferring matter onto that object by Roche lobe overflow (see below). This transformation would be likely to result in a neutrino-rich explosion.

3 Black Holes

Black holes are in many ways Nature's simplest objects. Like fundamental particles, they can be described by only three numbers – charge, mass, and spin. Unlike fundamental particles, only their charges are likely to be effectively quantized – the spins and masses of black holes should reside in the fully "classical" limit. Charge of black holes is generally neglected for astrophysical purposes as a charged black hole should quickly acquire a particle of the opposite charge and neutralize itself.

A few key results from general relativity are important for understanding observable effects see from the region near black holes. In general relativity, gravitational redshifts exist – changes in the wavelength of light for observers located at different depths in gravitational potential wells. A black hole is an object which is sufficiently dense that it has a surface where the gravitational redshift becomes infinite. This surface is called the event horizon.

The equations for a nonrotating black hole were solved by Karl Schwarzschild in 1916, relatively soon after Einstein published his theory of general relativity. As a result, nonrotating black holes are often referred to as "Schwarzschild black holes." The radius of the event horizon is called the Schwarzschild radius and is $R_{SCH} = 2GM/c^2$. A related scale parameter called the gravitational radius, defined to be GM/c^2, is often used in relativity. It is an interesting curiosity that this expression can be obtained correctly, albeit through incorrect reasoning, by setting the Newtonian escape velocity equal to the speed of light and solving for radius.

More than about 20 Schwarzschild radii from a black hole, the general relativistic corrections to Newtonian gravity are quite small. However, close to a black hole, there are some fundamental differences between general relativity and Newtonian gravity, apart from just the gravitational redshift. One important such effect with observable consequences is that there exists an innermost radius, inside which no stable circular orbits can exist. It is generally presumed that emission from an accretion disk will also be truncated at this radius as the orbits will be "plunging orbits" over which viscosity is unlikely to be important. Some debate has existed in recent years about whether magnetic coupling across this boundary could lead to significant emission from inside the innermost stable circular orbit, but the most recent work on the topic indicates that such effects are likely to be quite small (Shafee et al. 2006).

Rotating black holes have presented a greater challenge to theorists. The solution to Einstein's equations for rotating black holes was first presented by Kerr (1963) – it is called the Kerr metric, and rotating black holes are often referred to as "Kerr black holes." In fact, given the difficulty in obtaining the solution, it is surprising how simply one can express the key observable results of the Kerr metric. The dimensionless angular momentum a is defined to be the angular momentum J divided by Mc. If one expresses the Schwarschild radius as r_s in gravitational radii, then the event horizon of a Kerr black hole can be given as $\frac{r_s+\sqrt{r_s^2-4a^2}}{2}$. Therefore, as a approaches unity, the event horizon radius approaches the gravitational radius.

A second important characteristic radius for Kerr black holes is the radius of the "ergosphere." The ergosphere is defined as the region within which a stationary particle would not experience a proper time. Within this region, particles are "dragged" by the inertia of the black hole to rotate in the same direction as the black hole. The radius of the ergosphere is given by $\frac{r_s+\sqrt{r_s^2-4a^2\cos^2\theta}}{2}$.

Finally, we can consider the innermost stable circular orbits around Kerr black holes. As a result of the inertia effects of the black hole on the spacetime around it, the innermost stable circular orbit differs for prograde and retrograde rotation. For prograde rotation about a maximally rotating black hole, the innermost stable circular orbit is at the event horizon, while for counter-rotating orbits, the innermost radius is at nine gravitational radii.

The case of rotation with an axis which is misaligned from the spin axis of the black hole is an interesting one. Exactly what happens in such circumstances is rather difficult to calculate. For a viscous disk of gas, there should be some radius within which the inertial frame dragging due to the black hole's spin forces the accretion disk to become warped, such that it is forced to rotate with an axis closer to that of the black hole's at smaller radii (Bardeen and Petterson 1975). The details of how that happens depend not just on general relativistic effects, but also on more complicated disk physics.

4 X-Ray Binaries

Much of what is currently known about neutron stars, and nearly all that is currently known about stellar-mass black holes comes from observations of X-ray binaries (additional knowledge about black holes comes from studies of active galactic nuclei, covered in another volume of this series). An X-ray binary is a system containing either a neutron star or a black hole in a close binary system with a "normal star" (including, in some cases, white dwarf donor stars and objects of insufficient mass to support hydrogen fusion). The system must be close enough for mass to be transferred from the "normal" star onto the black hole or neutron star. ➋ *Fig. 12-1* shows a computer-generated visualization of an X-ray binary.

4.1 Classes of X-Ray Binaries

X-ray binaries can be classified both by the nature of the compact accretor (black hole or neutron star) and by the nature of the donor star. There exists a broader variety of classes of donor stars than accretors. Two broad classes, high-mass X-ray binaries (with mass donors of $> 8M_\odot$) and low-mass X-ray binaries (with mass donors less than about 1 $M_\odot$) have been used broadly in the literature. This classification obviously ignores the existence of X-ray binaries whose donor

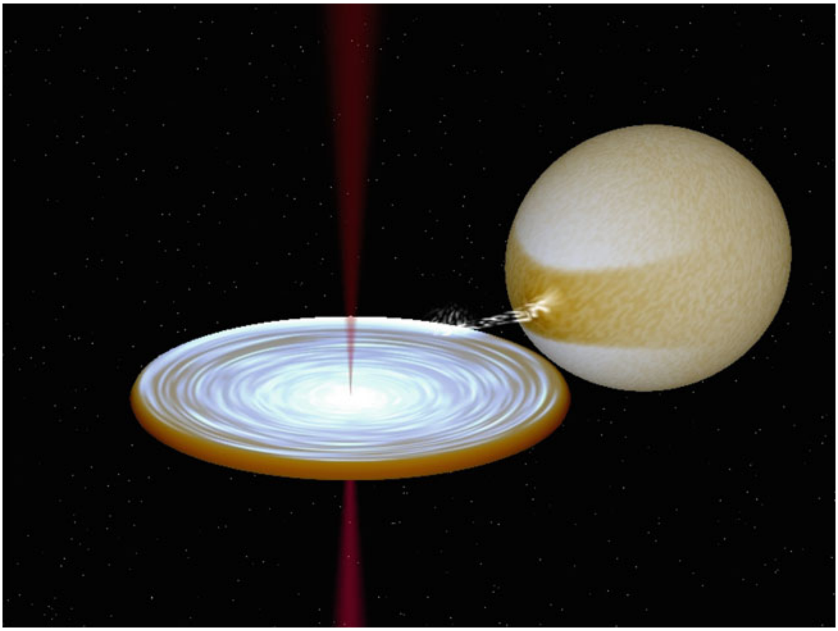


Fig. 12-1
A computer-generated visualization of an X-ray binary, made using Rob Hynes' BinSim tool (Hynes 2002). The figure illustrates the key features of accreting binaries – a deformed donor star, overflowing its Roche lobe and transferring material through an accretion stream into an accretion disk, with some matter and power expelled from the system in the form of a jet

stars are in the intermediate range of 1–8 $M_\odot$, a class whose membership in catalogs of known objects has expanded significantly in the past decade or so. These systems are sometimes classified as low-mass X-ray binaries, but in other cases, they are classified, more appropriately, as intermediate-mass X-ray binaries.

As is traditional when astronomers break objects into two classes, the need for subclasses of X-ray binaries has become apparent. Both the high-mass and low-mass X-ray binaries can contain either black holes or neutron stars as accretors. Additionally, there are subclasses based on the specifics of the type of donor star, and properties of the accretion.

5 The Basics of Accretion

It is first noted that much of the material in this section is drawn from the excellent reference work by Frank et al. (1995), which covers the basics of accretion in considerable detail. There are two major processes by which accretion can take place. The first is Roche lobe overflow, where matter spills from a donor star onto an accretor, because some of the matter in the outer regions of the donor star is more strongly gravitationally attracted to the accretor than to the donor. The second is wind accretion, where a star captures material being ejected from another star.

Let us first consider the case of Roche lobe overflow. The Roche lobe of a star is a roughly teardrop–shaped surface of equipotential in a binary star system, calculated by taking into account both the gravitational and rotational effects on the potential. The inner Lagrangian point, L_1, is the location where the two Roche lobes meet. It is a saddle point for the Roche potential. When a star is larger than its Roche lobe matter will be transferred from it onto is binary companion through the L_1 point.

A few key rules of thumb regarding Roche lobe overflowing systems are important. First, there are a few well-established analytic approximations for the sizes of Roche lobes:

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \tag{12.1}$$

which comes from Eggleton (1983), and $R_2/a = \mathrm{Max}(0.462[1/(1+q)]^{1/3}, 0.38 + 0.2\log_{10} q)$, which comes from Paczynski (1971). In both formulae, $q = M_2/M_1$, where M_2 is the mass of the donor star, and M_1 is the mass of the accretor. Eggleton's formula is accurate to higher precision over a wider range of mass ratios.

Paczynski's formula, at least for low-mass ratios, where the first term will dominate, is more convenient for use in analytical approximations. One of the more well-known and useful applications of Paczynski's formula is the derivation of the mass-period relation for X-ray binaries. For low-mass main-sequence stars, it can be shown that the mass of the donor star in a Roche lobe overflowing system will be 0.11 times the orbital period in hours. The orbital periods of binary systems are generally much easier to measure than the masses of their secondary stars. It should be noted that evolved stars will be considerably less dense than main-sequence stars of the same mass, so the period-mass relation should normally be taken as a useful means of estimating an upper limit to the donor star mass.

Accretion will not take place merely because a star fills its Roche lobe; it must overflow the Roche lobe. The accretion process is thus continually driven by three processes in Roche lobe overflowing binaries, with the dominant process depending on the mass and evolutionary state of the donor star. For relatively high-mass stars, the nuclear evolution of the donor star leads to its expansion and, hence, to continued accretion.

In the absence of substantial evolution in the radius of the donor star, angular momentum loss is required to keep the two stars in contact. For stars in very short-period orbits, gravitational radiation will provide a substantial loss of angular momentum. This can be especially important in systems where the mass donor is a white dwarf star, since white dwarfs can be quite massive even for very short orbital periods. For stars in intermediate period orbits, magnetic braking will be the dominant source of angular momentum loss. Magnetic braking occurs when the wind of the mass donor is forced to move through its magnetic field. The details of how the magnetic braking process works and what is an appropriate prescription for the magnetic braking angular momentum loss are still areas of active research.

The other major process by which mass transfer can take place is through wind accretion. Typically, for X-ray binaries, wind accretion comes from the winds of massive stars. Among these systems, the overall number of X-ray binaries where the donor star is a Be star, rather than a more "normal" O/B star dominates. In any given epoch, however, the majority of the wind-fed X-ray binaries will be those fed by the more spherically symmetric winds of massive stars, rather than from the excretion disks of Be stars. There also exists a small class of objects called symbiotic stars, where accretion takes place from a red giant donor's wind. A much larger population of symbiotic stars with white-dwarf accretors is known to exist as well.

The problem of wind mass transfer can be modelled in a manner very similar to the Bondi–Hoyle accretion problem. The compact object in a binary system is assumed to accrete any gas that becomes gravitationally bound to it. This leads to a rather strong dependence of the mass accretion rate on the wind speed of the donor star and, hence, to large uncertainties in the predicted accretion rate.

Once mass transfer has started, an important question is why the gas falls in toward the compact object. Early models of accretion disks posited the existence of a form of viscosity that could lead gas to fall inward. They parameterized the viscosity in terms of a parameter α, such that:

$$\nu = \alpha c_s H, \tag{12.2}$$

where ν is the viscosity, c_s is the sound speed in the gas, and H is the scale height of the accretion disk.

The magnetorotational instability (Balbus and Hawley 1991) is the most commonly invoked mechanism for producing this viscosity. This instability requires only a small vertical magnetic field to work. The magnetic forces act toward forcing rigid body rotation in the disk. The effect, then on a fluid element which is displaced outward is that the magnetic field forces it to rotate faster than the Keplerian speed at its new radius, pushing it still further outward. This hence enables a small amount of gas to transport a large amount of angular momentum outward through the disk, allowing the rest of the gas to flow inward.

The efficiency of accretion is an important parameter. Apart from matter-anti-matter annihilation, accretion onto black holes and neutron stars is the most efficient process in the universe in terms of the amount of energy that can be produced per unit matter. Nuclear fusion can produce about 9 MeV per nucleon, if one considers the fusion of hydrogen all the way into iron. If one defines the efficiency of energy production of a process, η to be $E/(Mc^2)$, this corresponds to an efficiency of about 10^{-2} for nuclear fusion. For fusion of hydrogen into helium, the efficiency is a factor of about 10 lower than this value. In the Newtonian limit, the efficiency of accretion is $GM/(R_*)$. For a white dwarf, this yields a value of about 10^{-4} – smaller than the efficiency of nuclear fusion – while for accretion onto a neutron star, this yields about 0.2. However, only half the gravitational energy of a Keplerian disk is radiated, with the other half going into the increase in the rotational energy of the material as it falls inward.

At the surface of the neutron star, a boundary layer is formed. Some of the rotational energy in the boundary layer will be radiated away, and some will go into increasing the rotational velocity of the neutron star. Therefore, typically, $GM/(2R_*)$ is often taken as the radiative efficiency of a neutron star.

For a black hole, the situation is much more complicated. Newtonian gravity clearly does not apply, and a fully relativistic calculation must be done. It can be shown that the radiative efficiency of a nonrotating black hole's accretion disk will be about 0.06, while that for a prograde disk around a maximally rotating black hole will be about 0.42 (Shapiro and Teukolsky 1983). These values are derived by taking the inner radius of the disk to be the radius at which the innermost stable circular orbit of the disk is found and applying the relativistic corrections due to gravitational redshifts from that radius. However, it bears mention that black holes, due to the presence of the event horizon, need not radiate away all the power released by the gravitational fall of material into them. This is especially true if the gravitational energy is locked up in protons, rather than in electrons. Furthermore, in nearly all classes of accreting objects, there exists evidence for jets launched from somewhere in the inner accretion flows. There are some indications that the jets may, in some cases, carry away more kinetic power than the radiated luminosity of the accretion flow.

Spectral modelling of X-ray binaries has typically focused (not surprisingly) on their X-ray and γ-ray emission, although in recent years, a growing number of simultaneous or nearly simultaneous monitoring campaigns have been undertaken including radio, infrared, and optical data, in addition to the high-energy data. Several components are frequently required to fit the spectra of X-ray binaries. The physics behind these components will be described in this section, with the details of the spectra of real accreting objects described in ➋ Sect. 6.3.

5.1 Geometrically Thin Accretion Disks

The "standard" model of an accretion disk around a relativistic star comes from Shakura and Sunyaev (1973). In the context of the Shakura–Sunyaev model, the X-ray spectrum of a geometrically thin, optically thick accretion disk can be described very well as the sum of a series of annuli, each of which emits as a black body with a temperature scaling as $R^{-3/4}$. Some corrections are made for relativistic effects and for the effects of scattering of the photons in the atmosphere of the accretion disk so that estimating the best-fitting inner disk radius, as naively estimated from model fits underestimates the real inner disk radius, typically by a factor of about 3 (see for example, Merloni et al. 2000).

5.2 Comptonization Regions

It was realized early on in the history of high-energy astrophysics that some X-ray binaries showed power in the soft γ-rays at luminosities far in excess of what could be explained from purely thermal models for energy production, and that some sources would switch between being dominated by soft X-rays and dominated by soft gamma-rays (e.g., Tananbaum et al. 1972). A natural explanation of such emission is Compton scattering in a geometrically thick, optically thin cloud of hot gas (Thorne and Price 1975). Such clouds can be maintained as hot if there is weak Coloumb coupling between the protons and electrons in the plasma so that most of the energy is advected by the black hole, rather than radiated away (Ichimaru 1977; Narayan and Yi 1994).

Compton scattering can be expected to produce power-law spectra, even if the energies of the electrons off which the scattering takes place do not follow a power-law distribution. Each Compton scattering event will, statistically speaking, result in the multiplication of the photon energy by a constant (presuming that the initial photon energy is small relative to the typical electron energy). This will be $\frac{4kT}{m_e c^2}$ in the nonrelativistic regime, and $(\frac{4kT}{m_e c^2})^2$ in the highly relativistic regime. The number of scatterings will follow $\mathrm{Max}(\tau, \tau^2)$ to good approximation for scattering in a homogeneous, spherical medium, where τ is the optical depth of the medium (there will be some deviations from the latter law due to the fact that Compton scattering has some directional dependence and due to the fact that the scattering medium cannot be infinite in size). This leads to a power-law distribution of photons since the number of photons at high energies will be the fraction of photons at low energies multiplied by the probability that enough amplifications take place to reach the high energy. As the photon energies approach the kT of the electrons, the amplification will become weaker, leading to a cutoff in the energy spectrum.

Additionally, the results above can be used, in some cases, to rule out thermal Comptonization as an emission model. For sufficiently high electron temperatures, $4kT >> m_e c^2$. This can then lead to substantial amplification of the photon energy per scattering. A result of Compton scattering in such a high-temperature medium would then be to produce "bumps" in the spectrum, rather than a smooth power law. Therefore, a smooth power-law spectrum with no cutoff in the power law out to energies of ~1 MeV is a strong indicator that thermal Comptonization is not the dominant energy production mechanism for the power law (see, e.g., Coppi 1999). It can be, in such cases, that the electrons have a nonthermal energy distribution, as might be expected if they are accelerated in magnetic reconnection events, for example. This may represent a good explanation of what is happening in the handful of systems with power laws out to several MeV, with no discontinitiuities in the soft X-rays, as would be expected for thermal Comptonization from a kT~300 keV plasma.

5.3 Reprocessing Components

Some additional components are often seen in the spectra of X-ray binaries which are best explained as reprocessing of hard X-rays producing in the Comptonizing region by the optically thick, geometrically thin accretion disk. Notably, these include emission lines (the strongest being from iron Kα at 6.4–6.7 keV, depending on the ionization state of the disk), and a "reflection bump" which is a continuum component peaking around 30 keV, as well as some edges, primarily due to partially ionized states of oxygen and iron. The first discussions of the effects of photoionization of cold gas by X-ray sources can be found in Basko et al. (1974), while the most commonly used spectral models for this effect are presented in Magdziarz and Zdziarski (1995).

Additionally, in many low-mass X-ray binaries, much of the emission from the geometrically thin, optically thick accretion disk is thought to be reprocessed X-ray emission, rather than energy produced from viscous heating of the disk (in most high-mass X-ray binaries, the optical luminosity of the donor star will dominate over that of the accretion flow components). Support for this idea comes largely from the evidence that the optical luminosities of X-ray binaries increase both with X-ray luminosity and with orbital period, following well what is expected for a model in which the optical emission is reprocessed X-ray emission (van Paradijs and McClintock 1994), but there exists also additional timing information that indicates this in many cases.

5.4 Emission from Relativistic Jets

Some X-ray binaries show strong radio emission. An excellent review of jets from X-ray binaries is that of Fender (2006). It can be shown easily that the radio emission from X-ray binaries must come from an outflow, rather than from the accretion inflow. The brightness temperature of a radio source can be defined as:

$$T_B = \frac{c^2}{k_b \nu^2} I_\nu \tag{12.3}$$

Note that this is referred to as a brightness temperature because it is the temperature required for the flux to be produced in the Rayleigh–Jeans part of blackbody emitter's spectrum. Where the brightness temperature is above 10^{13} K, the emission mechansism cannot be unbeamed incoherent synchrotron radiation. One can thus use this argument to infer that the radio emission region in many systems is likely to be considerably larger than the binary separation, thus requiring the emission come from an outflow.

In many systems, the jet emission shows a flat spectrum, all the way from the radio through the infrared. This flat spectrum radio emission is most commonly explained as the emission from a compact, conical jet (e.g., Blandford and Konigl 1979; Hjellming and Johnston 1988). In the context of these models, the flat spectrum occurs due to the superposition of a series of synchrotron self-absorbed peaks, with the self-absorption frequency varying as a function of radius.

In other systems, where the jet power is emitted over a more spatially extended region, the jet spectrum is a $f_\nu \propto \nu^{-0.7}$ power law. This power law is what is expected from synchrotron emission from a distribution of relativistic electrons with a power-law index of 2.4 (i.e., $\frac{dN}{dE} \propto E^{-2.4}$). In a few cases, emission has also been seen from an interaction site far from the X-ray binary, where the jet presumably collided with an overdensity in the interstellar medium.

The historically best well-known radio emitting X-ray binaries are all high-mass X-ray binaries – Cygnus X-1, Cygnus X-3, and SS 433. The latter two, in particular, have very dense stellar winds in the vicinity of where the jet is launched, and it is likely in both cases that the radiative power of the jet in enhanced by interactions with the stellar wind. In SS 433, emission lines are seen in both the optical and X-rays (Margon et al. 1979; Kotani et al. 1994), indicating that the jet is likely to be entraining material from a thick accretion disk.

5.4.1 Emission from the Neutron Star Surface and Boundary Layer

Finally, in the neutron star systems, there can also be emission from either the surface of the neutron star or from a boundary layer very close to it. In some systems, where the accretion rate is high and the boundary layer is optically thick, this emission is rather straightforward and is well fitted by a black-body component in the X-ray spectrum. In some other cases, there exists little evidence for boundary layer emission in the X-rays – although this can indicate either a low-temperature boundary layer, emitting at sub-X-ray energies, or a higher temperature, optically thin boundary layer, merged in with the Comptonizing component.

Emission directly from the surface of a neutron star in an X-ray binary is especially important. It is believed that during outbursts of X-ray transient systems, the neutron star itself can be heated by the accretion energy. Understanding the rate of cooling of the neutron star can be important for understanding the internal structure of the neutron star – if the neutron star's internal energy, as estimated from its surface temperature, varies more quickly than the intergration of its thermal emission over time, then one needs to invoke other cooling mechanisms, such as, for example, neutrino cooling (see, e.g., Rutledge et al. 2002; Wijnands et al. 2004).

5.5 Variability Measurement Techniques

For a comprehensive review of variability of X-ray binaries, see van der Klis (2006). Variability studies hold an important place in the current state of understanding of black hole and neutron star accretion disks. X-ray binaries frequently show variability with ~30% root-mean squared amplitudes on timescales of seconds and can show variability of factors of about 10^7 on timescales of years. Results from variability studies are, in general, much more constraining than spectral observations. Most spectroscopic results, especially for continuum components, can be explained by a wide range of source geometries. In contrast, many variability phenomena have been well known for decades without satisfactory theoretical explanations. At the same time, calibration of variability data is far easier than calibration of spectroscopic data, meaning that any well-understood results from X-ray timing is likely to be far more robust than an equally well-understood results from X-ray spectroscopy.

A wide range of timescales of variability can be seen from X-ray binaries. A major part of the reason for this is that the range of radii which can play a relevant role in an X-ray binary is larger than in most other classes of systems. Indeed, the radius of a neutron star is about 10 km, and the Schwarzschild radius of a 10 $M_\odot$ black hole is about 30 km. The light crossing times at these radii represent the shortest timescales on which one would expect to see variability from an X-ray binary. At the same time, the radius of the accretion disk can often be as large as 10^{12} cm, a factor of about 10^6 larger than the smallest spatial scale. The viscous timescale – the timescale on which matter will flow from the outer disk to the black hole's event horizon or the neutron star's surface – at this radius can be weeks.

The power spectrum (the squared magnitude of the Fourier spectrum) represents the major tool used in rapid variability studies of X-ray binaries. The power spectra of accretion disks are rather unlike the power spectra of most other astronomical objects and, hence, bear some specific discussion. In most areas of astronomy, time series are searched for periodicities – for example, those of stellar pulsations and of orbits. Searches for periodicities are important in undestanding accretion flows, as well, but the power spectra made in the X-rays and in the few cases studied to date of the optical and infared, time series of X-ray binaries often show broader features. These features can usually be well-fitted by Lorentzian components. If the Q value of the Lorentzian is very small, the feature is generally referred to as a "noise component." Noise components are also often well fitted with power laws. Higher Q Lorentzians are usually referred to as "quasi-periodic" oscillations. Coherent oscillations have also been found and in all cases to date, these oscillations have been associated with the rotational frequency of an accreting neutron star or the orbital period of the binary system. For longer time-scale variability (i.e., the variability on timescales much longer than seconds), there has generally not been good sampling of most sources, and less rigorous analysis techniques are generally used.

Time lags are another tool used to try to understand X-ray variability in X-ray binaries. One can make light curves in different X-ray energies and then look either with a cross-correlation function or a cross-spectrum for time lags between the different bands. These can, for example, be used to constrain the size of a region in which Compton scattering is taking place as the Compton scatterings will increase the path lengths which must be followed by higher-energy photons relative to the path lengths followed by the lower-energy "seed" photons. In fact, models which explain the time lags solely through light travel times often fail to reproduce the observed light curves of X-ray binaries in detail (see, e.g., Maccarone et al. 2000), so these lags represent only upper limits on the size of the emission regions in most cases.

5.6 Disks: Formation and Stability

Accretion frequently occurs in accretion disks. However, the fact that accretion takes place in a system does not immediately imply that an accretion disk will form. In some cases, the accretion stream will impact the accretor directly or will be channeled by the accretor's magnetic field before a disk forms. Disks form only when the angular momentum of the accreted material is larger than that of a circular orbit either at the radius of either the innermost stable circular orbit around a relativistic object or the radius around a less relativistic object. The radius for which the angular momentum of the accreted gas equals the angular momentum of a Keplerian orbit is called the circularization radius. This will typically be quite similar to the outer radius of the disk, but in some cases, the angular momentum transported outward by the accretion process will lead to a somewhat larger outer disk radius. In some cases, there will also be large magnetic fields with which to contend; the high magnetic field neutron star accretors are mostly fed by the fast winds of massive stars, and often the magnetic pressure of the neutron star is larger than the ram pressure of the gas at the circularization radius so that a disk does not form, and instead, what material is accreted by the neutron star is chanelled along its magnetic field lines to the magnetic poles. See again, Frank et al. (1995) and references within for more details of disk formation.

Accretion disks around all sorts of compact objects – white dwarfs, neutron stars, and black holes – are subject to instabilities. The most prominent of these instabilities is the ionization instability. Many aspects of disk stability were first studied in cataclysmic variable stars (e.g., Smak 1984). Much can be learned from such studies, but there are some fundamental differences between the properties of CVs and of X-ray binaries. In particular, the irradiation of the outer accretion disk by the inner accretion disk is far more important in X-ray binaries, where the overall efficiency of accretion is orders of magnitude larger (e.g., Dubus et al. 1999). The essence of the irradiation instability model is that the effective viscosity of gas is larger when the gas is highly ionized than it is when gas is largely neutral. Other sorts of disk instabilities may be relevant as well. Several X-ray binaries show precession, also thought to be due to radiation driven warping of the accretion disk.

Most of the known X-ray binaries are X-ray transients, in the sense that they have been seen to vary in X-ray luminosity by several orders of magnitude over the history of X-ray astronomy. They belong, broadly speaking, to two classes, known as soft X-ray transients (in which the accretors are either black holes or low magnetic field neutron stars, and the spectra near the peak of the outbursts are hence usually dominated by emission at about 1–3 keV) and hard X-ray transients (in which the accretors are high magnetic field neutron stars, and the spectra typically peak at about 15 keV). It is also likely that among the low-mass X-ray binary systems thought to be persistent, there are probably some sources in transient systems with long outbursts, rather than being bona fide persistent systems, given that some systems like GRS 1915+105 have been known to be bright and apparently persistent for about half the history of X-ray astronomy.

Hard X-ray transient behavior is seen only from neutron stars in Be X-ray binaries. In these systems, the accretion onto the neutron star is fed by the decretion disk of the Be star. The orbits of the neutron stars are usually highly eccentric and do not appear to be coplanar with the decretion disk (see the section on neutron star natal kicks below for a discussion of why), and strong X-ray emission is observed primarily during passages through the plane of the excretion disk. The outbursts thus typically occur periodically, although additional outbursting is sometimes seen which is generally attributed to variations in the excretion disk itself.

Soft X-ray transient behavior is seen from a subset of low-mass X-ray binaries, in which the ionization instability acts. Because the radii of black hole accretion disks will be larger than those of neutron star accretion disks at the same orbital period, and because the ionization instability depends on the temperature of the outer accretion disk, it is expected that a larger fraction of black hole X-ray binaries should be transients than neutron star X-ray binaries. It should also be noted that the lowest-mass black holes would be most likely to end up as persistent sources.

Testing this idea is difficult due to selection effects. Neutron star X-ray binaries can clearly by identified in many cases when Type I X-ray bursts (large increases in luminosity for about 100 s, which are thought to be due to thermonuclear runaway on the surface of a neutron star) are seen. Black hole X-ray binaries have no such clear signature in the X-rays. Measurement of a mass is difficult when a source is in outburst since doing so requires spectroscopic observations of the companion star, which is typically swamped by the optical emission from the outer disk during outbursts. Despite these selection effects, there is still reasonably good evidence that all or nearly all of the persistent low mass X-ray binaries have neutron star primaries – most have shown Type I X-ray bursts or some other variability phenomena (e.g., kilohertz quasi-periodic oscillations, discussed below) seen in bursters, but not seen from any dynamically confirmed black hole candidate. There exists one persistent system, 4U 1957+11, which has never shown Type-I X-ray bursts, and has never shown kilohertz quasi-periodic oscillations. It is considered a strong candidate for being a black hole X-ray binary, but is far from confirmed as such.

The behavior of X-ray transients in outburst is complex. A relatively large fraction of the transients follow a "fast rise, exponential decay" profile in time, but a significant fraction show quite different behavior (Chen et al. 1997). A few qualitative statements can be made about the properties of the outbursts as a function of orbital period. Longer period systems have, as a class, higher peak luminosities and longer outbursts than shorter period systems. These can both be explained as a consequence of their having physically larger accretion disks, which have stored up a larger mass reservoir at the time they reach a critical ionization level to start a new outburst.

More recently, using monitoring campaigns made by the pointed instruments on Chandra and XMM, it has been shown that there exists a population of transient X-ray sources whose outburst are quite faint (e.g., Wijnands et al. 2006). The campaigns which have found these objects have been focused either on the Galactic Center region or on globular clusters – regions expected to contain relatively large numbers of mass-transferring binary systems within a field of view of a pointed X-ray instrument. In globular clusters, the evolutionary processes by which X-ray binaries form are very different than elsewhere in the Galaxy, while the Galactic Center region sources are difficult to followup in other wavelengths. There thus remains considerable uncertainty about the properties of X-ray transients which peak at fluxes below the sensitivity of current and past all-sky monitors.

6 High Magnetic Field Neutron Star Accretors

One class of X-ray binaries contains neutron stars whose magnetic fields are sufficiently large as to channel the accretion flows down the magnetic poles. This class consists predominantly but not entirely of systems with high-mass donor stars. It is generally believed that the accretion process can bury the magnetic field of the neutron star and, perhaps, that it can cause the neutron star's magnetic field to decay (e.g., Cumming et al. 2001). As a result, high-mass X-ray binaries, over whose lifetimes relatively little total accretion occurs, should have predominantly high magnetic field neutron star companions, while only the fraction of low-mass X-ray binaries in which accretion has started recently should have very high magnetic fields.

While the primary distinguishing characteristic of high magnetic field neutron stars is the presence of pulsations, there are properties of the X-ray spectra of this class of objects which also clearly distinguish these objects from low magnetic field neutron star accretors or from black hole accretors. The typical X-ray spectral shape of a high magnetic field neutron star is reasonably well modelled by a broken power law with a very flat spectrum below about 15 keV and a very steep spectrum above about 15 keV.

Additionally, the high magnetic field systems often show cyclotron resonance lines in their spectra. These lines are seen at:

$$E = 11.6 \frac{B}{10^{12}\mathrm{G}} (1 + z_g)^{-1} \mathrm{keV}, \tag{12.4}$$

where E is the energy of the cyclotron line, B is the neutron star's magnetic field, and z_g is the gravitational redshift of the neutron star. As a result, these lines are useful for making estimates of neutron star magnetic fields. The lines tend to be broad because they are usually formed over a finite sized region near the surface of the neutron star, rather than at the surface of the neutron star. See Wilms et al. (2009) for a detailed review of the detections of cyclotron lines from neutron stars.

6.1 Low Magnetic Field Neutron Star Accretors

Most neutron stars in low-mass X-ray binaries have low magnetic fields. There is no definitive evidence for the magnetic field being dynamically important in these systems, but there are suggestions that some of the quasi-periodic oscillations seen in neutron star X-ray binaries may require magnetic effects from the star itself. There is nearly a one-to-one correspondence between a neutron star in X-ray binary having a low magnetic field and its being in a low-mass X-ray binary; only a handful of low-mass X-ray binaries contain X-ray pulsars.

An intermediate class of neutron star accretors is the class of millisecond X-ray pulsars (see Wijnands 2004 for a review). These systems show pulsations with periods in a range similar to that seen from millisecond radio pulsars (i.e., a few hundred Hz) but otherwise show X-ray properties that are similar to those see in low-luminosity, low magnetic field neutron stars. The known millisecond X-ray pulsars are all short period systems, with very low-mass donor stars. They all have low mean accretion rates. A few recent observations have found intermittent coherent pulsations from neutron star X-ray binaries, clouding the distinction between millisecond X-ray pulsars and other classes of low magnetic field neutron stars (e.g., Casella et al. 2008).

The low magnetic field neutron stars exhibit a phenomenon known as Type-I X-ray bursts, first discovered by Grindlay et al. (1976). These bursts are increases in X-ray luminosity typically lasting a few seconds. They are often, but not always Eddington limited. Their X-ray spectra are typically well fitted by modified blackbody models. These bursts are thought to be caused by runaway thermonuclear burning in a layer on the surface of the neutron star (e.g., Woosley and

Taam 1976; Swank et al. 1977). During the bursts, sometimes coherent oscillations can be seen in the X-ray flux (e.g., Strohmayer et al. 1996). A subclass of thermonuclear bursts, called superbursts, has also been seen. These bursts typically last 3–5 h. They are most frequently associated with runaway carbon burning, but alternatively, it has been suggested that they may be associated with electron capture by protons in the neutron star's atmosphere. At present, superbursts have been seen only from sources with accretion rates from 10–30% of the Eddington rate. See Kuulkers (2004) for a review of the superbursts.

6.2 Black Holes in X-Ray Binaries

Relatively early in the history of X-ray astronomy, some good candidates were found for containing black holes. Traditionally, the level of proof required for astronomers to call an object a black hole is to demonstrate that it produces no fusion-based optical light (i.e., that all its optical light can be well explained as coming from some combination of the accretion disk and the companion star) and to demonstrate that its mass is significantly larger than the maximum mass for a neutron star under any reasonable equation of state. In other cases, a much higher burden of proof is invoked, and it is required that an event horizon be shown to exist. This requirement is nearly impossible to satisfy through electromagnetic observations as an object with a sufficiently large gravitational redshift will be indistinguishable from a bona fide black hole (Abramowicz et al. 2002).

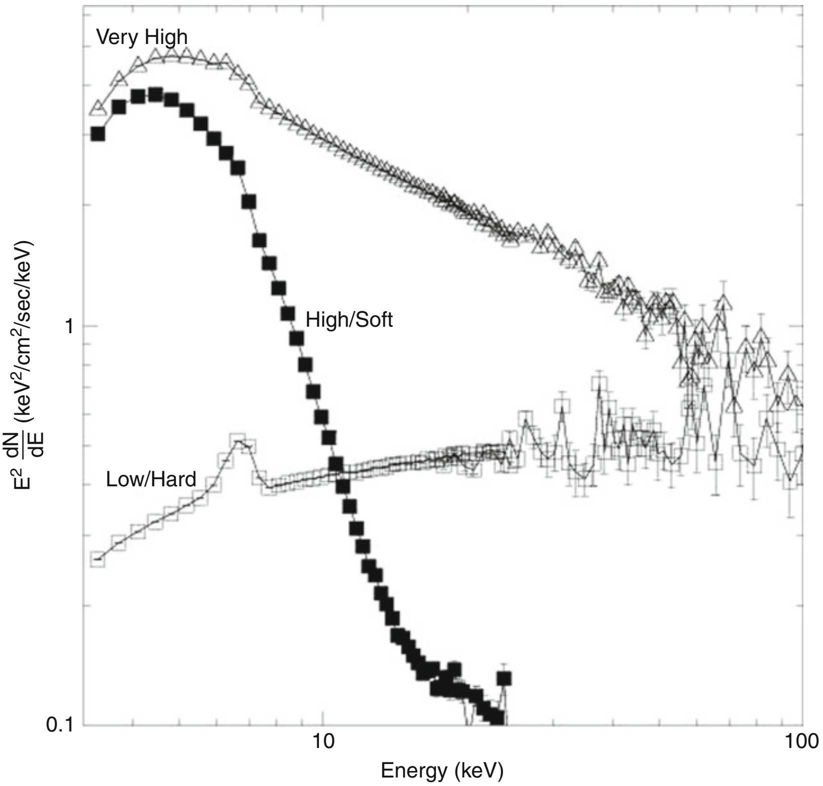
6.3 Spectral States

Accreting black holes and accreting low magnetic field neutron stars both exhibit what is known as spectral state phenomenology. Across a wide range of objects, certain patterns in behavior of the spectral energy distribution and the power spectral densities of sources are found to be well correlated with one another. Historically, different nomenclature has been used to describe the spectral states of black holes and the spectral states of neutron stars, but the basic phenomenology of the spectral state behavior seems to be nearly independent of the nature of the compact object.

The state in which an X-ray binary will find itself is mostly a function of the mass accretion rate but also must depend on other parameters. It is customary to discuss luminosities of X-ray sources in terms of the fraction of the Eddington luminosity at which they are emitting. The Eddington luminosity is defined as the luminosity at which the gravitational force inward on a spherically symmetric, fully ionized accretion flow is equal to the radiation pressure outward. The value of the Eddington luminosity is $4\pi G M m_p c/\sigma_t$, where G is the gravitational constant, M is the mass of the accretor, m_p is the proton mass, c is the speed of light, and σ_t is the Thompson cross section. Numerically, the Eddington luminosity is $1.38 \times 10^{38} (M/M_\odot)$ ergs/s. The Eddington limit may be violated if, for example, an accretion flow is not spherically symmetric or if the emission is coming from a region that is moving relativistically toward the observer so that doppler boosting is important.

The current state of understanding of how X-ray binaries behave is best at intermediate fractions of the Eddington luminosity. In particular, at a few percent of the Eddington luminosity, X-ray binaries are frequently found in what is known as a high/soft state. In this state, the accretion flow is well described by classical models of geometrically thin, optically thick accretion disks. The high soft state generally has a weak but existent power-law tail to the spectrum. In the soft states, typical root mean squared variability amplitudes, with only the two persistent sources, Cygnus X-1 and LMC X-1, showing stronger variability (e.g., Nowak et al. 2001) – these two sources also show the most luminous power laws in the soft state. It has alternatively been proposed to call the soft state the "thermal dominant state" (McClintock and Remillard 2006) and also to refer to the cases with the very weakest power-law tails as "ultrasoft states" (Done et al. 2007). In ➲ *Fig. 12-2*, we show examples of the spectra of an X-ray transient in the canonical spectral states.

At lower luminosities, X-ray binaries are typically found in what is known in the low/hard state. A well-developed phenomenological picture exists describing the behavior of systems in this state, although the nature of the emission geometry remains a topic of ongoing research. For black holes in the low hard state, the X-ray spectrum is typically well modelled by a cutoff



◘ Fig. 12-2

The X-ray spectra of XTE J1744-288 in the three canonical states, made using data from the Rossi X-ray Timing Explorer. In the low hard, state, one can see power law emission extending over nearly the full energy range, with possible evidence for a cutoff at the highest energies. In the high soft state, it is clear that nearly all the emission is coming from a quasi-thermal component. In the very high state, both a quasi thermal component (below about 7 keV), and a power law component (at the higher energies) can be seen in the spectrum

power law, plus a contribution from a reflection component, with a contribution from a disk at somewhat lower energies than where it is seen in the high/soft state. The root-mean squared amplitude of variability in the hard state is typically about 30%.

A different phenomenology is seen both during state transitions and during some extended episodes of very high luminosity. In these spectral states, sources are seen to have strong emission from both a quasi-thermal component and a power-law component, typically with a spectral index of about 2.5. Strong variability is seen and, frequently, strong quasi-periodic oscillations are seen. Again, varying terminology is used to describe this state. Traditionally, the term very high state has been used to describe these states at high luminosities, and intermediate state to describe them at lower luminosities (Nowak 1995), while the more recent review article of McClintock and Remillard (2006) proposes calling such states "steep power law" states.

We note that there are different sets of terminology sometimes used to describe the spectral states of neutron stars in the literature. In particular, the neutron stars in low/hard type states are often called "island state" systems and, in high/soft states, are often called "banana" state systems. In their very high states, they are often called "Z-sources." This terminology comes from color-color plots of neutron star X-ray binaries made with the EXOSAT observatory. The brightest systems traced out a Z-shaped track in the color-color space, while the fainter systems traced out a track that looked like an atoll, with an island-shaped region and a banana-shaped region. At the time, all known non-pulsing neutron star X-ray binaries fell into one of the two categories, so the sources were broken up into the Z-source and atoll source categories. Since that time, a transient neutron star X-ray binary went through both the atoll states and the Z-source states and returned to quiescence, indicating that the atoll and Z classification is primarily a luminosity classification (Homan et al. 2007).

6.4 Jets and Spectral States

The properties of relativistic jets in X-ray binaries are well correlated with the X-ray properties of the systems. For the most part, the strength of jet emission is correlated with the strength of hard X-ray emission. Additionally, the properties of the jets are different for systems with neutron star accretors than they are for systems with black hole accretors.

In hard-state black hole X-ray binaries, the radio emission from X-ray binaries has a flat spectrum due to synchrotron self-absorption, which typically breaks in the range between the near-infared and near-ultraviolet. It is usually difficult to measure the spectral index of the jet in the non-absorbed part of the spectrum because there is usually only a very narrow range of wavelengths where the jet is both optically thin and significantly brighter than the accretion disk. Most of the black hole X-ray binaries fit on a relation where $L_R \propto L_X^{0.7}$ (Gallo et al. 2003). A few recently discovered sources seem to have radio fluxes significantly below the predictions of this relation, and there are hints at possible parallel tracks in this relation, with similar power-law indices, but different normalization (see, e.g., Fender et al. 2010, whose compilation of data points has been plotted in ➋ *Fig. 12-3*).

Less information is available about neutron star X-ray binaries in low/hard states. The number of radio detections of low/hard state neutron star X-ray binaries is much smaller than the corresponding number of black hole detections. No radio spectra have been measured for these sources which are of sufficient quality to distinguish between a spectral index of 0.0 and one of −0.7 (the two extremes typically seen from black hole X-ray binaries), but the detection

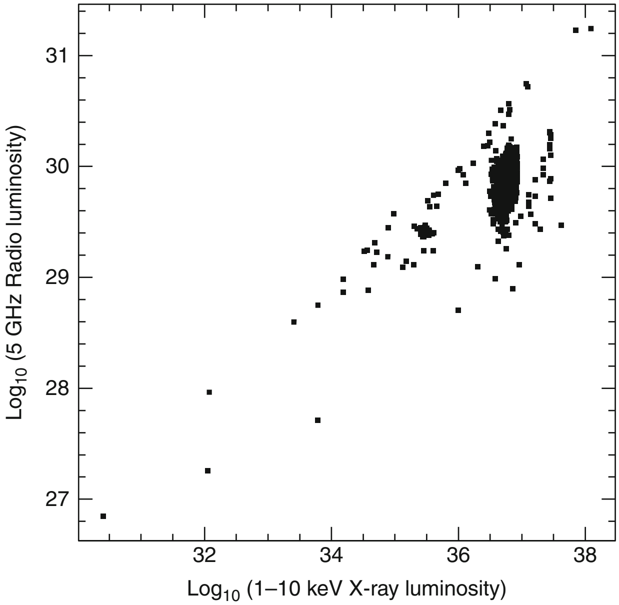


Fig. 12-3

The radio versus X-ray luminosity for a compilation of X-ray binaries, mostly in hard spectral states. The overall trend of $L_X \propto L_R^{0.7}$ can be seen from the data, as well as some considerable scatter. The turndown from this relation at high X-ray luminosities is mostly from data points on Cygnus X-1 as it approaches the high/soft spectral state. This figure uses the same data as that of Fender et al. (2010)

of jet emission in the mid-infrared from the neuton star 4U 0614+091 requires that the spectral index be relatively close to a flat spectrum, given that it has never been seen to be an extremely bright radio source (Migliari et al. 2006). Therefore, it seems likely that the analogy between neutron stars and black holes holds for the spectral shapes of the neutron star jets at low luminosities.

The relationship between X-ray and radio luminosities of neutron star X-ray binaries that best fits the existing data is steeper than the relationship for black hole X-ray binaries – for the neutron star systems, $L_R \propto L_X^{1.4}$ (Migliari and Fender 2006). A consequence of this, plus the generally lower X-ray luminosities of neutron star X-ray binaries is that the neutron star systems are much fainter in the radio and, hence, much harder to detect than are the black hole X-ray binaries. The most likely cause of this different relationship is that the black hole systems advect energy across their event horizons, while the neutron stars have large, optically thin, geometrically thick boundary layers. As a result, in the neutron star X-ray binaries, $L_X \propto \dot{m}$, while in the black hole X-ray binaries, $L_X \propto \dot{m}^2$. If the jet production and radiative efficiency of the jet then scale with $\dot{m}$, the observed correlations can be produced (Körding et al. 2006).

Jets are often seen in very high states and in state transitions. In these states, the jets are often seen to be very bright, to have optically thin radio spectra, and to have measurable proper motions. A rapid growth in studies of radio properties of X-ray binaries begin in the 1990s when the first "microquasars" were seen – that is, X-ray binaries with apparently superluminal jet proper motions (e.g., Mirabel and Rodriguez 1994). The neutron star systems have also shown similar jets. Circinus X-1, which is a peculiar system likely to have a highly eccentric orbit, in particular, has shown evidence for outflows at close to the speed of light (with apparent superluminal motions) during its periastron passages (Fender et al. 2004).

There are many radio observations made during high/soft states, as well, both for neutron stars and for black holes. Most of these observations are non-detections. In a few cases, black holes have been observed to show radio emission in high/soft states, but these have all been cases where it was possible (and, indeed, likely) that the radio emitting plasma was ejected from the accretion flow during a previous state transition, and its emission was still decaying at the time of the high/soft state observation. The upper limits on other radio emission from high/soft state black holes are as stringent as 50 times the expected flux from extrapolating the hard state radio/X-ray correlation (e.g., Corbel et al. 2004).

There are detections of radio emission from at least two soft-state neutron star X-ray binaries, 4U 1820-30 and Ser X-1 (Migliari et al. 2004). In these systems, the radio flux is the same in the high soft state as it was in the peak of the low hard state. Thus, there is still reduced radio emission from what was expected from the extrapolation of the hard-state correlation, but not reduced so much as to make the source undetectable in the radio. A possible explanation is that the radio emission from neutron star X-ray binaries is related to the boundary layer (Maccarone 2008). A boundary layer provides large-scale height differentially rotating plasma. On the other hand, an example of a neutron star with a stringent upper limits on its soft state radio flux also exists (Tudose et al. 2009), so the presence of radio emission in the high soft states of neutron stars is not a universal difference between neutron stars and black holes.

The high-mass X-ray binaries with accretion powered pulsars have not been detected as radio sources. Because of the truncation of their disks at large radii by the magnetic fields of the neutron stars, it is presumed that these systems are poor locations for jet launching. On the other hand, the searches of these systems for radio emission are, to date, quite shallow. One class of binaries which are likely to consist of neutron stars and high-mass stars has shown strong radio emission. These are "gamma-ray binaries," LS 5039, LS I +61 303, and PSR B1259-63. It is generally thought that these systems are composed of a rotation-powered pulsar whose pulsar wind interacts with the stellar wind of the high mass star (e.g., Dubus 2006; Dhawan et al. 2006), although models do exist for explaining the emission from this source through interactions between a black hole–powered jet and a stellar wind (Massi and Kaufman Bernado 2009).

6.4.1 Outbursts and Spectral State Transitions

Most known outbursts of transient low-mass X-ray binaries exhibit multiple spectral states. Outbursting sources typically rise in luminosity in the hard state, and somewhere rather close to their maximum fluxes make a transition to the soft state. They then fade within the soft state and make a transition back to the hard state at a lower luminosity than where they transited from the hard state to the soft. This hysteresis effect in spectral state transitions occurs in both neutron star and black hole systems (Maccarone and Coppi 2003). Typically, the transition from the hard state into the soft state takes place near the peak of the outburst, while the transition from the soft state to the hard state takes place at about 2% of the Eddington limit (Maccarone 2003). A subset of low-mass X-ray binary transient events seems to take place in which the source never enters a soft state. These are all outbursts whose peak luminosities are low and are predominantly from short period systems (Brocksopp et al. 2004).

6.5 Mass Estimates

It is obviously of great importance to have a good understanding of the masses of compact objects in close binaries. Breaking up classes of compact binaries into neutron stars and black holes requires accurate mass estimates so that one can determine which objects have masses larger than the maximum mass for a neutron star, under even the inclusive equations of state.

The first step in determining a compact object's mass is to measure its mass function:

$$f(M_1, M_2) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2}, \tag{12.5}$$

where M_1 and M_2 are the masses of the two stars in the system, P_b is the binary orbital period, G is the gravitational constant, i is the inclination angle of the binary, with $i = 90^\circ$ for an edge on binary, and a is the semimajor axis of the binary. The mass function then sets a lower limit on m_2.

The mass function thus represents a robust lower limit on the mass of an object. For making strong claims that an object is heavier than the maximum mass of a neutron star, the mass function can often be sufficient. Care must be taken to determine where the observed spectral lines are generated, and to ensure that the velocities measured are representative of the velocity of the center of mass of the donor star. Ordinarily, this does not represent a terribly serious issue, but in the case of radial velocity curves measured from emission lines generated in the stellar wind of a high mass donor star, it can be very serious; the X-rays from the X-ray binary may be capable of ionizing the stellar wind in the inner regions of the binary system but not in the regions shielded from the X-rays by the donor star. This can result in a significant overestimate of the radial velocity of the donor star if one does not correct for it. This issue has been discussed in detail for the case of the Galactic wind-fed system Cygnus X-3 (van Kerkwijk 1993), but the basic arguments apply more generally.

For making a reliable census of masses of black holes or of neutron stars, the inclination angle must be estimated in some manner. Eclipses can provide excellent constraints on the inclination angles of systems, and the use of pulsar timing, in the systems where the accretor is a high magnetic field neutron star, can also provide additional constraints on the orbital parameters of the system. For this reason, there exist many HMXB neutron star systems with mass measurements accurate to about 10%, whereas only one black hole, which is in an eclipsing binary, has a mass measurement so precise (Orosz et al. 2007).

In many ways, though, accurate measurements of black hole masses and of the masses of neutron stars in LMXBs are more interesting than accurate mass estimates of the neutron stars in high-mass X-ray binaries. The neutron stars in high-mass X-ray binaries are generally unlikely to accrete much material before the donor star's lifetime ends. If normal stellar evolution leads to the production of neutron stars within a narrow range of masses (i.e., typically just larger than the Chandrasekhar mass), only in low-mass X-ray binaries are the most massive neutron stars likely to be formed. There is even more uncertainty about the masses of black holes. Theoretical work on black hole formation predicts a range of masses (e.g., Fryer and Kalogera 2001).

The inclination angles in low-mass X-ray binary systems are generally estimated using ellipsoidal modulations of the donor stars – the variations in the flux of the donor star as seen from Earth due to the nonspherical shape of the donor star. The sizes of the ellipsoidal modulations seen can then be compared with models based on a Roche geometry of the donor star and converted into an inclination angle. Measurements of the amplitude of the ellipsoidal variations can generally be made quite precisely. A major source of uncertainty can often be the ratio of the flux of the accretion disk and jet in the optical or infrared band used to estimate the size of the modulations. While the measurements are generally made while the black hole or neutron star is "quiescent," the bolometric luminosity of the accretion flow can often still be a substantial fraction of the luminosity of the donor star.

Eccentric radio pulsar binaries can be used to make mass estimates purely through pulse timing behavior. These systems are typically found only in globular clusters, where stellar encounters can induce eccentricities in binaries faster than the binaries will re-circularize themselves. One needs to measure both the relativistic effect of the advance of the periastron, plus the Keplerian motions in order to measure the masses of both objects in a binary system purely from pulsar timing. The details and results of this technique can be found in the review article of Lorimer (2008).

6.6 Constraints on the Neutron Star Equation of State

Understanding the equation of state of nuclear matter is one of the key goals of neutron star research. There are several means to do this. The simplest is simply to find the most massive neutron stars. The softest equations of state can be ruled out by finding sufficiently massive neutron stars, as in the softest equations of state, the threshold mass at which an object must become a black hole, rather than a neutron star, is lowest. The lack of clear evidence for neutron stars more massive than about 1.8 $M_\odot$ favors soft equations of state, but as noted above, the low-mass X-ray binaries' neutron stars are most likely to be the heaviest neutron stars, and the few mass estimates for those objects are generally poorly constrained.

For limiting the range of possible harder equations of state, however, it becomes necessary to limit the available parameter space in the mass-radius relation. This can be done by measuring the gravitational redshift at the surface of the neutron star. At the present time, there exist some controversial measurements of the gravitational redshift of a single neutron star from absorption lines in the X-ray spectrum of a Type I burst (Cottam et al. 2002; Galloway et al. 2009). It can also be done by detailed spectral modelling of the surface emission from Type I X-ray bursts (Özel et al. 2009).

Neutron star X-ray binaries often show "kilohertz quasi-periodic oscillations" – quasi-periodic oscillations at frequencies of about 600–1200 Hz. Combined mass-radius constraints may also be possible if a clear model for kilohertz quasi-periodic oscillations can be found, and the results could be particularly effective for determining the actual masses and radii of specific neutron stars. While considerable debate still exists about what is the correct model for the QPOs (or indeed, whether any currently proposed model is correct), in the long term, the quasi-periodic oscillations are quite likely to provide the strongest constraints on the neutron star equation of state, since the measurements of the QPO frequencies are highly precise (typically accurate to about 1%), and far less susceptible to calibration uncertainties or radiative transfer effects than are spectral signatures.

6.7 Distance Estimates

A variety of techniques are used for measuring distances to black holes and neutron stars in the Galaxy. The most robust of these, the geometric parallax, has been applied for about 20 neutron star sources [one X-ray binaries – Sco X-1 (Bradshaw et al. 1999), about a dozen pulsars (Chatterjee et al. 2009), and one isolated non-pulsing neutron star (Kaplan et al. 2002)]. One black hole's parallax distance has recently been measured as well (Miller-Jones et al. 2009). Apart from parallax distances, there are also cases of firm associations with star clusters and supernova remnants which can be used to make reliable distance estimates. The comparisons between parallax distance estimates and other distance measurement techniques are important for understanding the errors in the other techniques.

Nearly all parallax distance measurements of neutron stars to date have made use of very long baseline radio interferometry, with a much smaller number measured in the optical with the Hubble Space Telescope (Chatterjee et al. 2009). Present instrumentation at other wavelengths lacks the angular resolution needed to make parallax measurements. The ease of measuring the parallaxes of radio pulsars can be improved by "pulsar gating" – taking the known timing solution of the pulsar and making an image only when the pulsar is bright, resulting in a significant reduction of noise with relatively little loss of signal. The limits to radio parallaxes are typically severe at distances of a few kpc, although one parallax measurement has been made of a pulsar at 7.2 kpc. At larger distances, the uncertainties with which one can do phase referencing in radio astronomy – the measurement of positions based on the phase differences seen from different sources – is limited by ionospheric effects. More accurate radio astrometry will be possible with an upgraded bandwidth Very Long Baseline Array because it will allow the use of phase calibrators which are fainter and, hence, closer to the source of interest. Timing parallax measurements can be made for some of the pulsars which act as the most accurate clocks – residuals in the timing solution which correlate with time of year can be used to estimate the position

Where parallax measurements have not been made, the distance measurements techniques generally differ quite strongly between radio pulsars and X-ray binaries. When the distance to a radio pulsar cannot be measured either through a parallax or by an association with a star cluster or other object whose distance is known, dispersion measure distances are often used. The dispersion measure of a pulsar is the number of free electrons between the pulsar and the observer. Dispersion of radio waves as they pass through ionized gas leads to a time delay which is function of photon frequency. By comparing the pulsar's pulse arrival times at different radio frequencies, one can thus measure the column density of free electrons to the pulsar. There exist models of the free electron distribution in the Galaxy which can be used to estimate the distances of these pulsars (e.g., Cordes and Lazio 2003). Distances estimated from dispersion measures are usually accurate to within a factor of about two within the Galactic Plane and fail quite badly for most globular cluster pulsars.

The distances to neutron star X-ray binaries can often be estimated from Type I X-ray bursts. When these bursts show radius expansions over the course of the burst duration, this generally gives a good indication that the burst is Eddington limited. The Eddington limited bursts have often been suggested to be good standard candles, and repeated observations of a large number of Type I bursts in globular clusters have helped to verify this (Kuulkers et al. 2003).

However, not all neutron star X-ray binaries have shown radius expansion bursts, and, of course, no black hole X-ray binaries show Type I bursts. For these objects, usually the best distance estimates come from using the donor star, using the photometric parallax technique.

A crude estimate of the distance to a donor star can be made by measuring the flux of the donor star and comparing it with the luminosity of a star of its spectral type. However, the evolutionary paths followed by the donor stars in low-mass X-ray binaries are often nonstandard, and the stars themselves are always nonspherical and rapidly rotating. More reliable distance estimates come from making an estimate of the radius of the donor star directly from the data, rather than under the assumption that the donor star has the mass and radius typical for its spectral type. The estimation of the stellar radius is most reliably done by measuring the rotational broadening of the lines in the donor star's spectrum, combined with the fact that the star must rotate synchronously with the binary orbit. Absent a reliable estimation of the star's rotational velocity, the relation between the orbital period and the density of the donor star can be used to estimate the donor star's radius – this technique requires an estimate of the donor star's mass, but this can come from the mass ratio between the donor star and the accretor if a rotation curve for the accretion disk can be measured from disk emission lines. The status of distance estimation techniques for X-ray binaries is well discussed in Jonker and Nelemans (2004) and references within.

A few other techniques are sometimes used, but typically place only bounds on the distances to low mass X-ray binaries, rather than giving actual distance estimates. One is the use of two-sided jet proper motions. This technique gives a robust upper limit on the distance to an object based on requiring no motions faster than the speed of light. It has also been shown that sources will typically be at distances very close to the upper limits derived from this technique (Fender 2003).

The other prominently used technique is to look for evidence of absorption, either in the form of interstellar lines such as the Na D line in an optical spectrum or HI absorption in a radio spectrum. One can then use the rotation curve of the Galaxy to estimate the distances of the absorbing material to place a lower limit on the distance to the X-ray source, and somewhat more speculatively, can use the absence of absorption from more distant gas to place an upper limit on the distance (e.g., Hynes et al. 2004). The state transition flux from the high/soft state to the low/hard state can also provide an approximate distance estimator (Maccarone 2003), with an accuracy similar to that from dispersion measure distance estimates of pulsars. While these techniques are less reliable, some of them can provide distance estimates for X-ray binaries with large foreground column densities which make it impossible to make measurements of the donor star.

6.8 Key Phenomenological Differences Between Black Holes and Neutron Stars

The existence of black holes is one of the key predictions of general relativity. A key goal of observational astronomy is then to attempt to prove that black holes do, in fact, exist in Nature. The first step in this process is to find objects heavier than the theoretical maximum mass of a neutron star under equations of state which are not in conflict with nuclear physics experiments. Astronomers have, in fact, found about two dozen such objects, heavier than 3 $M_\odot$.

The next step in this process is to demonstrate that the objects heavier than 3 $M_\odot$ are in some ways qualitatively different from those lighter objects, which are likely to be neutron stars, and to demonstrate that the observed differences are related to the existence of a solid surface in the neutron stars, which is absent in the black holes. Considerable progress has been made in recent years on this topic.

The most prominent surface effects of neutron stars are Type I X-ray bursts, pulsations, and surface emission in quiescence. All are evidence of a surface, but in no case is the absence of these effects clear evidence of the absence of a surface. Pulsations are generally absent in low magnetic field neutron stars. There are objects, known to be neutron stars due to observations of Type I X-ray bursts during their outbursts, but which have shown no surface emission in quiescence. This can be explained by enhanced cooling processes, perhaps related to a relatively high neutron star mass (Jonker et al. 2007). Prior to those observations, there had been a relatively clear picture that the quiescent luminosities of low-mass X-ray binaries with neutron stars were systematically higher than those of black holes with the same orbital periods (e.g., Garcia et al. 2001). Type I X-ray bursts are only expected from low magnetic field neutron stars, and only in a certain range of accretion rates. At low accretion rates, it can take a very long time before enough material piles up to allow runaway nuclear burning to take place, leading to a sufficiently low rate of bursts that one cannot expect to detect bursts. At higher accretion rates, steady nuclear burning is expected to take place. On the other hand, in the intermediate accretion rate range where frequent bursts are expected, they are always seen (Remillard et al. 2006). Therefore, the absence of both bursts and pulsations from a well-observed source may be taken as reasonably good evidence for an event horizon. The above-mentioned point, though, that one cannot rule out observationally the possibility that a mass configuration could exist in which a star could have a surface gravitational redshift of $\sim 1,000$, remains (Abramowicz et al. 2002).

6.9 Evidence for Black Hole Spin

In the past few years, a variety of lines of evidence have all started to indicate that most stellar-mass black holes have substantial angular momentum. This is perhaps not surprising since massive stars routinely have angular momenta in excess of the maximum angular momentum for black holes of the same mass. On the other hand, it is difficult to measure the black hole spin with high precision because its effects are generally relatively minor and are often degenerate with other effects.

The observations of relativistic jets have been suggested in some cases to be strong evidence of black hole spin. This is partly motivated by the work of Blandford and Znajek (1977), who argued that jets could be powered in part by tapping the spin energy of the black hole. However, the observations of jets from other classes of objects which have no event horizons, and from neutron stars, which cannot be rotating quickly in terms of specific angular momentum (their break-up speeds are at about 0.1 times the speed they would need to be at to have angular momentum per unit mass similar to maximally rotating black holes).

Several lines of evidence have been proposed in recent years to show that black holes are spinning. These fall, broadly speaking, into two classes: attempts to make precision measurements of the black hole spins, and attempts to show effects which qualitatively demonstrate that the black holes must be rotating, at least at some speed. In the former category are iron-line measurements, disk spectral fitting measurements, and specific modelling of certain quasi-periodic oscillations, while in the latter are other work on quasi-periodic oscillations, and attempts to demonstrate that frame dragging is taking place in accretion disks.

There are two classes of X-ray spectral evidence for spinning black holes. The first is from the use of broad iron lines. Iron fluorescence lines can be generated as a hard X-ray producing component illuminates the cold neutral material in the inner accretion disk. The profile of the iron line will not be a delta function in energy, but rather will be severely affected by the special relativistic effects due to Doppler motions of the material around the black hole in a rotating accretion disk, as well as by the general relativistic effects of the gravitational redshift due to the fact that most of the iron line flux will be generated very deep in the gravitational potential well of the black hole. Because the orbital motions approach rather close to the speed of light in the inner accretion disk, the Doppler effect not only provide a change in the photon energies, but also provides a strong boosting of the luminosity of the blue wing of the iron line.

The key advantages of using the iron line to fit black hole spin relative to using disk continuum fitting are that the spin measurement is independent of the distance to the black hole and of the mass of the black hole. These advantages remove two of the biggest uncertainties in nearly all measurements of anything for stellar-mass black holes in the Galaxy, which is why proper calibration of this technique is so attractive for understanding black holes.

In detail, the fit results are susceptible to a number of uncertainties, only some of which have been studied in detail in the literature to date. As the iron lines need to be fitted over a very broad range of energies – typically from about 4–8 keV, the continuum must be known to high precision over this energy range, and the instrument being used must be well calibrated within this energy range. The requirements of an accurate continuum model and of an excellent flux calibration in order to study an emission line are rather different than the usual requirements for making reliable, detailed measurements of stellar lines in the optical, but are a consequence of having lines with significant flux over a range of a factor of two in photon energy.

In X-ray binaries in their bright states, the continuum over this range of energies is often affected by the fact that the disk blackbody component and the Comptonized component meet near 4 keV, and the high spectral resolution instruments which can be used to estimate the shape of the iron line usually cut off at about 10 keV, leaving relatively little lever arm for measuring the shape of the power-law component. Additionally, the iron line is accompanied by an iron edge which is also relativistically smeared. Without good coverage of the spectrum up to energies well beyond the edge energy, there can be degeneracies between the shape of the line and the energy of the edge.

There are a few additional free parameters and assumptions in iron-line spin estimates. One parameter is the inclination angle of the inner accretion disk. Another parameter is the emissivity profile of the iron line (i.e., the amount of line emission that comes from the disk as a function of radius). The emissivity profile is usually assumed to be a power law, and its index is fit. The fitting also requires as parameters the inner and outer radius contributing to this emissivity. The ionization parameter of the emission region is usually taken to be a constant, although it is not likely actually to be a constant. Finally, there are assumptions that the disk is planar and tied to the plane of the black hole spin in the inner region. Furthermore, it is also assumed that there are no other components of iron emission, and that the orbits in the accretion disks are circular, rather than elliptical.

Measurements of spins of black holes from continuum spectra have a different set of advantages and disadvantages. From the X-ray continuum, one can attempt to estimate the inner disk radius. However, this method is strongly susceptible to uncertainties in the black hole mass, the black hole distance, and the inclination angle of the inner accretion disk and relies on the assumption that the accretion disk extends in to the innermost stable circular orbit around the black hole. Continuum fitting is susceptible to the same problems with uncertainties in the instrument response matrix that affect iron-line fitting. It is very susceptible to errors in estimating the effects of Compton upscattering of disk photons and, to date, has been attempted only with sources in the ultrasoft state. On the other hand, it can be done with sources which are much fainter than those for which iron-line measurements can be made.

At the present time, the spin estimates from reflection features span the full range of prograde black hole spins possible (Miller et al. 2009). The disk continuum fits also span a large range in a, from about 0.1–0.8 (Shafee et al. 2006; Davis et al. 2006). Unfortunately, at the present time, for the two sources for which both methods have been tried, GRO J1655-40 and 4U 1543-47, only marginal agreement is seen between the two methods, with the iron-line method giving larger spin values.

Using quasi-periodic oscillations to measure black hole spins ultimately has the greatest potential for being used to give reliable and precise spin measurements. Narrow features in power spectra are far easier to calibrate properly than spectral measurements and are not subject to any reprocessing effects (except in that the timing signature can be weakened by photon scattering).

There are two classes of QPO that have been used as evidence for black hole spin. The first is the presence of oscillations at about 1–10 Hz, seen in many black hole X-ray binaries. These have been suggested to be evidence of a Lense–Thirring precession, an effect due to relativistic frame-dragging of tilted accretion disk (e.g., Fragile et al. 2001). Precision spin measurements are not possible from the frequency of the L-T oscillation because the relation between the black hole spin and the QPO frequency will depend rather strongly on details on angular momentum transport in accretion disks.

The other QPOs, which may have potential for providing precision spin measurements, are the high-frequency QPOs seen from several black holes in a 2:3 frequency ratio (e.g., Strohmayer 2001; Abramowicz and Kluzniak 2001). Several mechanisms exist for explaining these QPOs – for example, resonances between relativistic coordinate frequencies (Abramowicz and Kluzniak 2001) and fundamental modes of oscillation of a torus around the black hole (Rezzolla et al. 2003). All QPO-based methods to date can give precision measurements of the black hole spin, but all depend on knowing also the mass of the black hole to high accuracy, and the different models give substantially different spin values. The advantages of using QPOs to measure spin of black holes are then that the method is distance independent, and that the measurements are far less susceptible to non-statistical errors than are the spectral measurements. The key disadvantages are that the measured spins are strongly dependent on both what is the actual correct model and on the black hole mass.

6.10 Isolated Black Holes

Black holes which are not accreting are nearly impossible to detect astrophysically. Searches have been made for evidence of heavy, dark stars in binary systems with no evidence for accretion taking place and have not yielded any strong candidate black holes. A few stellar-mass black hole candidates have been found in microlensing searches (Bennett et al. 2002). It has also been suggested that isolated black holes in very dense regions of the interstellar medium, such as molecular clouds, might be detectable through accretion signatures, either in high energies or in radio (e.g., Armitage and Natarajan 1999; Maccarone 2005).

6.11 Neutron Stars not in Accreting Binaries

Neutron stars, with solid surfaces and magnetic fields, can be detected even when not accreting. There are several classes of such neutron stars known. Two of them, the rotation-powered pulsars and the magnetars, have well-defined characteristics clearly suggested by their names. Additionally, there exist a few neutron stars whose emission is dominated by thermal cooling of the initially hot star. More recently, two new classes of objects have been proposed, which may, in some cases, be objects which can also fit into the already known classes. The term "isolated neutron stars" is often used to refer to a small subset of the known neutron stars not in binary systems, and the "central compact objects" which are distinguished by their locations near the centers of young supernova remnants, rather than any particular physical properties they possess. A review of the state of the art of all classes of isolated neutron stars can be found in Kaspi et al. (2006). More detailed discussion of the rotation-powered pulsars can be found, for example, in Lyne and Graham-Smith 2006 and of binary and millisecond pulsars in Lorimer (2008).

6.12 Pulsars and Other Rotation-Powered Emitters

While the first neutron star to be observed and identified as an unusual object was the X-ray binary Sco X-1, the early observations of radio pulsars half a decade later represented the first truly strong evidence for the existence of neutron stars. The accurate clocks provided by pulsars have allowed measurements to precision higher than any other class of astronomical measurement – in a few cases, the masses of pulsars are known to such high precision that the largest source of error is in the measurement of $GM_\odot$, the product of the gravitational constant times the solar mass, rather than in any of the measurements specific to the pulsar itself. This timing precision provides for an inexpensive technique for searching for gravitational radiation – looking for correlated residuals in the timing behavior of several pulsars. Pulsars are additionally an important source of radiation across all wavelengths and may themselves be sources of gravitational radiation.

6.12.1 Pulsar Emission Mechanisms

Understanding where the power for pulsars comes from is relatively straightforward. Assuming that the rotation axis of a neutron star is misaligned with the magnetic field of the neutron star, one can calculate the expected power due to dipole radiation. More difficult is to understand how that magnetic dipole power is converted into the radiation observed from pulsars. The rotational frequencies of pulsars range from about 0.2–700 Hz. Even at 700 Hz, the direct dipole emission frequency is well below the plasma frequency of the solar system. Therefore, it cannot be the dipole power itself which is observed from the Earth.

On the other hand, the dipole spin down is thought to dominate total energy loss from rotation-powered pulsars. Since the spin-down power is:

$$\dot{E} = I\dot{\Omega}\Omega = 4\pi^2 I\dot{P}P^{-3} = \frac{\Omega^4 R^6 B_0^2 \sin^2\alpha}{6c^3}, \tag{12.6}$$

where Ω is the rotation rate of the neutron star in angular velocity, I is the moment of intertia of the neutron star, usually assumed to be 10^{45} g cm^2, P is the spin period of the neutron star, $\dot{P}$ is the spindown rate of the neutron star, R is the neutron star radius, B_0 is its surface magnetic field, and α is the angle between the neutron star's magnetic field axis and its rotation axis. Under these assumptions, plus the additional assumption that α is 90°, one can estimate the magnetic field of a neutron star as:

$$B_0 = 3.2 \times 10^{19} (P\dot{P})^{1/2} \mathrm{G}. \tag{12.7}$$

Instead, some mechanism must exist for accelerating particles in the pulsar's magnetosphere. It was originally believed that because the gravitational binding energy per particle at the surface of a neutron star is much larger than the thermal energy per particle, that neutron stars should not have substantial atmospheres (e.g., Hoyle et al. 1964; Pacini 1967, 1968). However, it was shown shortly thereafter, by Goldreich and Julian (1969) that a rotating magnetic field leads to a surface layer with charge separation such that the electric force near the surface of the neutron star is larger than the gravitational force at the surface, meaning that a neutron star surrounded by a vacuum would have a surface layer not in dynamical equilibrium.

The minimum number of charged particles in a neutron star atmosphere to satisfy the Goldreich and Julian criterion is insufficient for producing strong radio emission. Instead, it is generally believed that some pair production process must be taking place within the neutron star atmosphere. In agreement with this idea is the observation of the "pulsar death line" – that there exist no pulsars which are sufficiently slowly spinning and sufficiently low in magnetic field (see, e.g., Chen and Ruderman 1993).

The radio emission from rotation-powered pulsars cannot be incoherent synchrotron radiation. There exists a limit on the brightness temperature which can be produced by incoherent sychrotron emission. Above this limit, the "Compton catastrophe" sets in – that is, Compton scattering works to cool electrons more efficiently than does synchrotron emission, and any additional power added to the system serves only to increase the luminosity of the Compton scattering component. A possible solution to this problem is that the radio emission from pulsars is, indeed, synchrotron emission but is coherent emission – electrons move in "bunches." Since the radiated power from the synchrotron process scales as the square of the charge of the radiating particle, this bunching of electrons can lead to significantly higher ratios of synchrotron to Compton emission than can be obtained from single, incoherent electrons. More recently, plasma maser models, and plasma turbulence models have instead been more commonly proposed to explain the high brightness temperatures of pulsars (e.g. Hankins et al. 2003).

Rotation-powered pulsars usually emit most of their bolometric luminosity outside the radio band. The radio luminosities are typically less than about 10^{-6} of the spin-down luminosities, while the X-ray luminosities are typically about 0.1% of the spindown luminosities, although pulsars with more rapid spindown may have higher ratios of X-ray emission to spindown luminosity, reaching 80% for some of the pulsars with the highest spin-down luminosities (Becker and Trümper 1997; Possenti et al. 2002). The Fermi Gamma-ray Large Area Space Telescope has recently succeeded in discovering several of pulsars as γ-ray sources before they were discovered in radio surveys. A few were quickly discovered as radio pulsars as well (Camilo et al. 2009).

6.13 Millisecond Pulsars

It is clear from examining ➲ *Fig. 12-4* that there are two distinct populations of pulsars. Most of the pulars follow a track with inferred magnetic field values of about 10^{12} G and with spin rates of about 1 s. A significant fraction of the pulsars have inferred magnetic fields of about 10^{8} G and spin periods of about 10 ms. This faster subclass of neutron stars is known as the millisecond

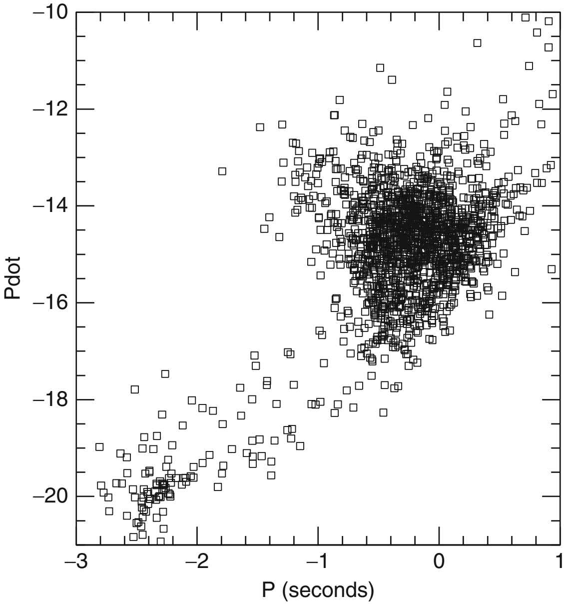


Fig. 12-4

The plot of period derivative versus period for all the pulsars in the Australia Telescope National Facility's pulsar database with period derivative measurements (Manchester et al. 2005). The region in the lower left of the diagram where no pulsars are seen is the "pulsar graveyard", where it is believed that the pulsars are rotating too slowly to produce pair cascades. The millisecond pulsar region includes some globular clusters whose period derivatives may include contributions from acceleration in the gravitational potentials of the clusters

pulsars, the first of which was discovered in 1982 by Backer et al. and collaborators. They are sometimes referred to as "recycled" pulsars because they are thought to be recycled from dead pulsars in low-mass X-ray binaries (Alpar et al. 1982).

The evolutionary scenarios for producing millisecond pulsars usually invoke a normal process of creating a pulsar in a binary system, followed by a phase as a "normal" pulsar. At some point, the neutron star's companion begins to overflow its Roche lobe, and accretion onto the neutron star begins. The accretion process serves to provide a torque to the neutron star, which can increase its spin rate to millisecond periods with only about 0.1 $M_\odot$ of material being added to the neutron star. Recently, a source has been discovered which appears to have spent time as both an X-ray binary and a radio pulsar within the past decade (Archibald et al. 2009).

Accretion is generally thought to reduce the magnetic fields of neutron stars. Most of the observational evidence of isolated neutron stars indicates that they have little or no magnetic field decay. Several theoretical mechanisms exist for explaining why accretion might cause field decay in neutron stars. One possibility is ohmic decay – the magnetic fields in neutron stars are driven by electron motions, and electrical resistivity can lead to a loss of these magnetic fields (see, e.g., Bhattacharya and Datta 1996). The chief alternative possibility is that the magnetic fields do not decay but are merely buried by accreted matter (e.g., Cumming et al. 2001).

Recently, an additional class of radio sources has been detected through the detection of individual pulsars of emission, rather than by Fourier transforming the power received by large radio telescopes. These sources, called rotating radio transients (or RRATs) repeat their pulsations periodically but with a very low duty cycle for detecting the pulses (McLaughlin et al. 2006). It has been suggested that at least some of the RRATs may be relatively normal radio pulsars at large distances but with a larger than typical distribution of pulse heights (Weltevrede et al. 2006).

6.13.1 Anomalous X-Ray Pulsars and Soft Gamma Repeaters

Two classes of isolated neutron stars show properties which share some broad similarities with one another but which are rather different from those seen from other classes of neutron stars. These are the anomalous X-ray pulsars, which are typically detected by showing pulsations in the X-rays and the soft gamma repeaters, which show bursts of gamma-rays which are not too different from those seen in cosmic gamma-ray bursts, except with relatively softer spectra, and with repeated activity coming from single positions on the sky. Both these classes are now thought to have much or all of their emission powered by the magnetic fields of the neutron stars, which are thought to be typically greater than 10^{14} G (Thompson and Duncan 1995).

6.13.2 Old Isolated Neutron Stars

The bulk of the neutron stars in the Galaxy rotate slowly enough to be past the pulsar death line and are not in close binaries. These objects emit thermal radiation from their still-cooling crusts with their emission typically peaking in the far-ultraviolet through soft X-ray band. Because they are both extremely faint, and their emission peaks in the bands most susceptible to interstellar absorption, these neutron stars can generally be observed only if they are very nearby. ROSAT discovered seven such object (see Kaplan 2008 for a review). One particular area of interest with these systems is fitting the spectra produced in their magnetized atmospheres, which can be used both to probe both the properties of highly magnetized matter and to make estimates of the surface gravitational redshifts of these neutron stars (see, e.g., Ho 2007).

7 Populations of Compact Objects

In addition to developing an understanding of how compact objects can produce radiation, it is important to develop an understanding of how they form, and of how often and why they end up in binary systems.

7.1 Observations

Relatively good observational constraints exist for populations of X-ray binaries and of pulsars (although neither is immune from selection effects). Even for these two classes of sources, there is strong evidence that the Galactic population is not well sampled at large distances, especially in the Galactic Plane. For the other classes of compact objects – magnetars, old neutron stars, and isolated black holes – there exist such small numbers of objects that it is difficult to make and global statements about the source populations.

Even the observations of pulsars and of X-ray binaries are limited by selection effects, some of which are not yet well understood. A large majority of the pulsars in the Australia Telescope National Facility's pulsar database are within about 3 kpc. Some have been detected only through scintillation amplification of their brightnesses. The lack of detections of more distant pulsars is likely an effect both of lack of sensitivity of existing radio observatories and the difficulty in finding pulsations of pulsars with large dispersion measures. Most of the known X-ray binaries are on the near side of the Galactic Center, as well. The lack of more distant X-ray binaries is due to the combined effects of lack of sensitivity to large distance objects, especially in the all-sky monitors produced to date and the increasing effects of foreground absorption of soft X-rays in the Galactic Plane.

The interesting point for which there is the strongest observational evidence is that neutron stars have space velocities considerably higher than those of the massive stars thought to form them. The proper motions of many pulsars have been measured, and the best-fitting velocity distributions indicate that many pulsars are likely to have escaped the Galaxy (see, e.g., Hobbs et al. 2005). The scale height of low-mass X-ray binaries is about 1 kpc, larger than for any "normal" stellar component. Some black holes show evidence for large space velocities, as well, and the black holes also show a large-scale height (Jonker and Nelemans 2004).

7.2 Extragalactic X-Ray Binaries, Intermediate Mass Black Holes, and Other Unusual Objects

In recent years with the launch of the Chandra and XMM-Newton observatories, it has been possible to make detailed studies of the X-ray point source populations of a large number of nearby galaxies. Two major motivations exist for this work. One is to understand X-ray source populations in order to gather new data to test binary stellar evolution models, and, in the case of globular cluster X-ray sources, new data to test dynamical formation mechanisms for close binaries. The other motivation is to look for sources whose parameters fall outside the range seen in the Milky Way.

There are several problems which plague studies of X-ray source populations within the Galaxy. The most important is the difficulty in measuring source distances in the Galaxy (see above). Without reliable distance estimates, both the luminosity distributions of sources and the scale heights of source classes are difficult to determine. Another key problem is that the Galactic foreground absorption means that samples of X-ray binaries are incomplete in the Galaxy in ways that are difficult to quantify. A third problem is simply the small size of the Galactic X-ray binary population. On the other hand, for faint sources, only the Milky Way galaxy, and, to some extent the nearby dwarf spheroidal galaxies, can be studied in the X-rays with current instrumentation.

Globular cluster X-ray sources are, in particular, something which can be studied in a much different manner in nearby galaxies than in the Milky Way (see ➋ *Fig. 12-5* for an X-ray image of a nearby elliptical galaxy). Only 12 of the Milky Way's 150 or so globular clusters has been found to contain a bright ($L_X > 10^{35}$ ergs/s) X-ray source, although two of them have now been shown to contain at least two such sources at various times. One key result of extragalactic globular cluster X-ray source studies include the discovery that metal rich clusters are several times more likely to contain X-ray sources than metal poor clusters (Kundu et al. 2002), something which

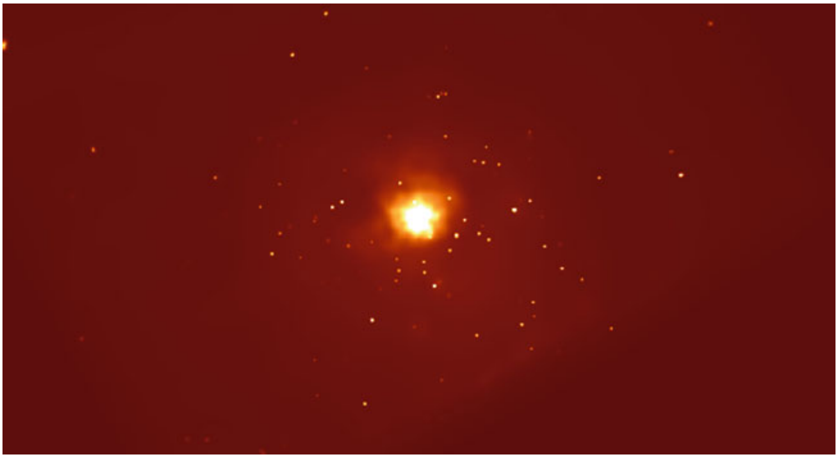


Fig. 12-5

An X-ray image from the Chandra X-ray observatory of the galaxy NGC 4472, the optically brightest galaxy in the Virgo Cluster. This image contains about 140 X-ray point sources. About 40% of the X-ray sources in regions with good optical coverage from the Hubble Space Telescope are associated with globular clusters. The diffuse emission in the center of the galaxy is truly diffuse hot gas emission, rather than a superposition of X-ray point sources

had been suggested in the Milky Way (e.g., Silk and Arons 1975) but could be proven with the small number of Milky Way cluster sources, and the correlations between metallicity and other parameters for Milky Way clusters. Extragalactic clusters have also shown the first clear evidence for a stellar-mass black hole in a globular cluster (Maccarone et al. 2007) and the best evidence to date for an intermediate mass black hole (i.e., a black hole of more than about 1,000 $M_{\odot}$) in a globular cluster (Gebhardt et al. 2005; Ulvestad et al. 2007).

Additionally, searches of nearby galaxies have turned up the class of ultraluminous X-ray sources. The standard definition of ultraluminous is having measured luminosity greater than 10^{39} ergs/s, with the measurements of nearby galaxies nearly all being made in the 0.5–10 keV energy range where imaging instruments are effective. Many of the Galactic black hole X-ray binaries have, at least briefly, reached this luminosity threshold, but only GRS 1915+105 has maintained a luminosity at or near this level for an extended period of time. Many of the ultraluminous X-ray sources have remained steadily above 10^{39} ergs/s over time scales of years or longer, and some have steadily emitted at luminosities over 10^{40} ergs/s.

These ultraluminous X-ray sources are of great interest because either they are manifesting a mode of accretion not observed in the Milky Way or they harbor intermediate mass black holes as their accretors. A few of the brightest ultraluminous X-ray sources show X-ray spectra which are best fitted with disk components of lower temperature than those seen from high luminosity black hole X-ray binaries in the Galaxy, and where the normalizations of the disk spectral components imply a large inner radius for the accretion disk. If one assumes that the disk black-body model is the physically correct description of the data, rather than merely a model which is statistically consistent with the data, and that the disk extends in to the innermost stable circular orbit around the black hole, then the implied black hole masses of this subclass of ultraluminous X-ray sources are typically $\sim 1,000\ M_{\odot}$ – much larger than what can be produced through normal stellar evolutionary channels, but much smaller than the black holes seen in galactic nuclei.

Several caveats apply here, and several alternative models exist. First, the X-ray spectra of the ultraluminous X-ray sources with cool disks look qualitatively different from the X-ray spectra of stellar-mass black holes in all the sub-Eddington spectral states – they typically have X-ray spectra with bright cool disks but dominant power-law components (Soria et al. 2007). There exist mechanisms to explain their high luminosities by relativistic beaming (Körding et al. 2006), or by some combination of geometric beaming and the capability of nonspherical flows actually to exceed the Eddington limit (e.g., King 2002).

Other evidence, apart from ultraluminous X-ray sources has been suggested for the existence of intermediate-mass black holes. In globular clusters, one can attempt to measure the distribution of stellar velocities around the cluster centers. If a sufficiently massive black hole is present, it should dominate the gravitational potential for a large enough number of stars that their motions should indicate its presence. To date, there are some suggestive hints for intermediate-mass black holes from these observations, but the dynamical data taken alone have always been consistent with alternative explanations, such as anisotropic velocity distributions for the stars in the cluster (see, e.g., Noyola et al. 2008). In one case, the extragalactic globular cluster G1 in M 31, there exists both dynamical evidence (Gebhardt et al. 2005) and accretion evidence, in the form of both radio and X-ray emission (Trudolyubov and Priedhorsky 2004; Ulvestad et al. 2007), for the existence of an intermediate mass black hole.

8 Formation of Compact Objects and Compact Object Binaries

The formation of black holes and neutron stars, and the understanding of how these systems end up in binaries is an important process to understand in astrophysics. The supernova explosions that produce neutron stars and black holes also contribute substantial fractions of many of the heavy elements in the Universe. They represent one of the few known classes of events capable of producing detectable neutrino emission. They may be responsible for a substantial fraction of the kinetic energy input into the Galaxy and other galaxies.

Additionally, the formation of X-ray binaries represents an opportunity to test theories of the evolution of close binary stars. Understanding binary evolution is a key certainly to understanding how gravitational wave emitting binaries form and how Type Ia supernovae occur. It may also be important for understanding cosmic γ-ray bursts, and the formation and evolution of exotic classes of optically emitting stars, such as blue stragglers, extreme horizontal branch stars, and subdwarf B stars. At the same time, X-ray binaries are one of the very few classes of individual stars that can be seen out to distances of 20 Mpc, in which is enclosed a wide range of types of galaxies, so that the effects of stellar population on source class production can be examined.

8.1 Black Hole and Neutron Star Formation in Supernovae and Related Events

Black holes and neutron stars form in core collapse supernovae. When the core of the star has exhausted its nuclear fuel by fusing all its material into iron-peak elements, its only available source of energy is gravitational collapse. At the low end of the range of stellar masses sufficient to undergo core collapse, nucleonic degeneracy pressure will be sufficient to support the core after this happens, leaving a neutron star. At the upper end of this mass range, a full collapse will take place, turning nearly the entire star into a black hole (see, e.g., Fryer and Kalogera 2001 for a discussion).

In the case where the core of the massive star turns into a neutron star, there remain two possibilities. In some cases, the gravitational binding energy released by the collapse will be sufficient to blow away the entire remaining mass in the star in the ensuing supernova. For somewhat more massive stars, the supernova explosion unbinds only a fraction of the material from the outer star, and a fallback of the remainining material onto the young neutron star takes place, leading to the formation of a black hole through the accretion of this material, rather than through the prompt collapse scenario. As a result, these "fallback" black holes might be expected to have natal kicks. The small amount of observational data that exists to test this idea supports it – GRO J1655-40 is a relatively low mass ($\sim 6\, M_\odot$) black hole, and has a space velocity of about 100 km/s relative to its local standard of rest, a value which is difficult to accommodate with just a Blaauw kick (e.g., Nelemans et al. 1999). Additionally, a recent reexamination of the distances to low mass X-ray binaries has indicated that the scale height of the black hole LMXB population is about 1 kpc, similar to that of the neutron star LMXB population, and much larger than the scale height of the donor star population (Jonker and Nelemans 2004).

It is important to note that the mass estimates for black holes and neutron stars come predominantly from compact objects in close binary systems. Because of this, the measured mass functions of black holes, especially may be severely biased. Theoretical work indicates that the binary evolutionary processes that lead to black hole X-ray binary formation can have significant effects on the masses of the black holes that are produced.

The formation channels for compact objects in binary systems are necessarily rather complicated in most cases. Simply evoking independent evolution of two stars in a binary system would yield the result, for example, that it is impossible to form most neutron star X-ray binaries. The mass loss of the supernova explosion will take away more than half the mass of the binary system in most such cases. The most prominent solution to this problem is to invoke common envelope evolution early in the lifetime of the binary system. What this means is that when the heavier of the two stars in a binary system evolves off the main sequence, it expands to the point where it envelopes the other star. During this process, a considerable amount of mass can be ejected, making possible the formation of low-mass X-ray binaries with neutron stars. See, e.g., Taam and Sandquist (2000) for a review of common envelope evolution.

It is also possible, but still somewhat controversial, that some neutron stars through accretion induced collapse events in systems with accreting whife dwarfs (or for two white dwarfs to merge). In particular, it has been suggested that a large fraction of the neutron stars in globular clusters should form in this manner (e.g., Ivanova et al. 2008) in order to solve the problem that very few neutron stars would be retained in globular clusters given a velocity distribution similar to that seen for isolated pulsars.

The formation scenarioes for intermediate-mass black holes are more numerous and more controversial. Stars formed from the metal free gas in the early universe should have masses of a ~ 100–$1,000\, M_\odot$. Most evolutionary calculations indicate that these stars should have very little mass loss during their lifetimes, and that in some mass ranges, they should undergo prompt collapses, in which most or all of the stellar mass ends up in a black hole (e.g., Heger and Woosley 2002). In other mass ranges, they are thought to undergo pair instability supernovae, and to be destroyed entirely. Lower redshift star formation may lead to the formation of intermediate-mass black holes as well, especially in dense star clusters, where runaway mergers of massive stars may lead to the creation of a super-massive star (Portegies Zwart and

McMillan 2002). This supermassive star would have stronger stellar winds than a Population III star of the same mass but might be able to reach an equilibrium at a few hundred solar masses.

8.2 Natal Kicks

The large space velocities of pulsars and the large-scale heights of low-mass X-ray binaries containing neutron stars indicate that it is likely neutron stars are born with a velocity kick. In order to establish clearly that an actual velocity kick is imparted to the neutron star at birth, it is necessary to demonstrate that other mechanisms of increasing the neutron star's velocity cannot be responsible for the observed space velocities and spatial distributions.

Rather large space velocities for supernova products can be achieved without a velocity impulse being applied during (or shortly after) the supernova, if the supernova takes place in a binary system (Blaauw 1961). Rapid mass loss from a star, taking place over a timescale much shorter than the orbital period of the binary, should lead to a recoil velocity being applied to the binary system such to make up for the momentum lost to the ejected material. Even a spherically symmetric explosion will carry away linear momentum, given that the spherically symmetric explosion will come from a star which has a motion about the center of mass of the binary.

Several mechanisms exist for explaining the natal kicks. One possibility is that the supernova explosion itself may be asymmetric. Another is that the proto-neutron star may be emitting radiation or neutrinos asymmetrically.

9 Conclusions

A wealth of knowledge has been collected about neutron stars and black holes in the roughly five decades in which astronomers have been studying them. These objects have already placed important limits on fundamental physics, and three Nobel Prizes have been awarded for work on them. At the same time, many of the key questions remain open, or, at least, have answers which have not yet reached consensus level. The coming years should yield more clear answers on issues such as the mass distribution and formation mechanisms for black holes and neutron stars, the neutron star equation of state, the spin distributions of black holes, the mechanisms by which jets are launched, the reasons for variability in accretion disks in general, and quasi-periodic oscillations in particular and the mechanisms by which pulsars emit, among other questions.

References

Abramowicz, M. A., & Kluzniak, W. 2001, A&A, 374, L16

Abramowicz, M. A., Kluzniak, W., & Lasota, J.-P. 2002, A&A, 396, L31

Alpar, M. A., Cheng, A. F., Ruderman, M. A., & Shaham, J. 1982, Nature, 300, 728

Archibald, A. M., et al. 2009, Science, 324, 1411

Armitage, P. J., & Natarajan, P. 1999, ApJ, 523, L7

Baade, W., & Zwicky, F. 1934, PNAS, 20, 254

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., & Goss, W. M. 1982, Nature, 200, 615

Balbus, S. A., & Hawley J. F. 1991, ApJ, 376, 214

Bardeen, J. M., & Petterson, J. A. 1975, ApJ, 195, L65

Basko, M. M., Sunayev, R. A. & Titarchuk, L. G. 1974, A&A, 31, 249

Becker, W., & Trümper, J. 1997, A&A, 326, 682

Bennett, D. P., et al. 2002, ApJ, 579, 639

Bhattacharya, D., & Datta, B. 1996, MNRAS, 282, 1059

Blaauw, A. 1961, BAN, 15, 265

Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433

Blandford, R. D., & Konigl, A. 1979, ApJ, 232, 34

Bradshaw, C. F., Fomalont, E. B., & Geldzahler, B. J. 1999, ApJ, 512, L121

Brocksopp, C., Bandyopadhyay, R. M., & Fender, R. P. 2004, NewA, 9, 249

Camilo, F., et al. 2009, ApJ, 705, 1

Casella, P., Altamirano, D., Patruno, A., Wijnands, R., & van der Klis, M. 2008, ApJ, 674, L41

Chatterjee, S., et al. 2009, ApJ, 698, 250

Chen, K., & Ruderman, M. 1993, 402, 264

Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ, 491, 312

Coppi, P. S. 1999, ASPC, 161, 375

Corbel, S., Fender, R. P., Tomsick, J. A., Tzioumis, A. K., & Tingay, S. 2004, ApJ, 617, 1272

Cordes, J. M., & Lazio, T. J. W. 2003, astro-ph/031598

Cottam, J. Paerels, F., & Mendez, M. 2002, Nature, 420, 51

Cumming, A., Zweibel, E., & Bildsten, L. 2001, ApJ, 557, 958

Curtis, H. D. 1918, PLicO, 13, 55

Davis, S. W., Done, C., & Blaes, O. M. 2006, ApJ, 647, 525

Dhawan, V., Mioduszewski, A., & Rupen, M. 2006, VI Microquasar Workshop: Microquasars and Beyond. Proceedings of Science, MQW6, 52

Done, C., Gierlinski, M., & Kubota, A. 2007, A&ARv, 15, 1

Dubus, G. 2006, A&A, 456, 801

Dubus, G., Lasota, J.-P., Hameury, J.-M., & Charles, P. 1999, MNRAS, 303, 139

Eggleton, P. P. 1983, ApJ, 268, 368

Fender, R. P. 2003, MNRAS, 340, 1353

Fender, R. P. 2006, in Compact Stellar X-ray Sources, ed. W. Lewin, & M. van der Klis (Cambridge: Cambridge University Press)

Fender, R. P., Gallo, E., & Russell, D. M. 2010, MNRAS, 406, 1425

Fender, R., Wu, K., Johnston, H., Tzioumis, T., Jonker, P., Spencer, R., & van der Klis, M. 2004, Nature, 427, 222

Fragile, P. C., Mathews, G., & Wilson, J. 2001 ApJ, 553, 955

Frank, J., King, A., & Raine, D. 1995, Accretion Power in Astrophysics (Cambridge: Cambridge University Press)

Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548

Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60

Galloway, D., Lin, J., Chakrabarty, D., & Hartman, J. M. 2009, astro-ph/0910.5546

Garcia, M. R., McClintock, J. E., Narayan, R., Callanan, P., Barret, D., & Murray, S. S. 2001, ApJ, 553, L47

Gebhardt, K., Rich, R. M., & Ho, L. C. 2005, ApJ, 634, 1093

Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869

Grindlay, J., Gursky, H., Schnopper, H., Parsignault, D. R., Heise, J., Brinkman, A. C., & Schrijver, J. 1976, ApJ, 205, L127

Hankins, T. H., Kern J. S., Weatherall J. C., Eilek. J. A., 2003, Nature, 422, 141

Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532

Hjellming, R. M., & Johnston, K. J. 1988, ApJ, 328, 600

Ho, W. C. G. 2007, MNRAS, 380, L71

Hobbs, G., Lorimer, D. R., Lyne, A. G., & Kramer, M. 2005, MNRAS, 360, 974

Homan, J., van der Klis, M., Wijnands, R., Belloni, T., Fender, R., Klein-Wolt, M., Casella, P., Mendez, M., Gallo, E., Lewin, W. H. G., & Gehrels, N. 2007, ApJ, 656, 420

Hoyle, F., Fowler, W. A., Burbidge, G. R., & Burbidge, E. M. 1964, ApJ, 139, 909

Hynes, R. I. 2002, in “The Physics of Cataclysmic Variables and Related Objects,” Astronomical Society of the Pacific Conference Proceedings, Vol. 261, ed. B. T. Gänsicke, K. Beuermann, K. Reisch (San Francisco: Astronomical Society of the Pacific), 676

Hynes, R. I., Steeghs, D., Casares, J., Charles, P. A., & O’Brien, K. 2004, ApJ, 609, 317

Ichimaru, S. 1977, ApJ, 214, 840

Ivanova, N., Heinke, C. O., Rasio, F. A., Belczynski, K., & Fregeau, J. M. 2008, MNRAS, 386, 553

Jonker, P. G., & Nelemans, G. 2004, MNRAS, 354, 355

Jonker, P. G., Steeghs, D., Chakrabarty, D., & Juett, A. M. 2007, ApJ, 665, L147

Körding, E., Fender, R. P., & Migliari, S. 2006, MNRAS, 369, 1451

Kaplan, D. L. 2008, AIPC, 983, 331

Kaplan, D., van Kerkwijk, M. H., & Anderson, J. 2002, ApJ, 571, 447

Kaspi, V., Roberts, M. S. E., & Harding, A. K. 2006, in Compact Stellar X-ray Sources, ed. W. Lewin, & M. van der Klis (Cambridge: Cambridge University Press)

Kerr, R. P. 1963, PhRvL, 11, 237

King, A. R. 2002, MNRAS, 335, L13

Koerding, E., Falcke, H., & Markoff, S. 2002, A&A, 382, L13

Kotani, T., Kawai, N., Aoki, T., Doty, J., Matsuoka, M., Mitsuda, K., Nagase, F., Ricker, G., & White, N. E. 1994, PASJ, 46, L147

Kundu, A., Maccarone, T. J., & Zepf, S. E. 2002, ApJ, 574, L5

Kuulkers, E. 2004, NuPhS, 132, 466

Kuulkers, E., den Hartog, P. R., in't Zand, J. J. M., Verbunt, F. W. M., Harris, W. E., & Cocchi, M. 2003, A&A, 399, 663

Lorimer, D. R. 2008, LRR, 11, 8

Lyne, A. G., & Graham-Smith, F. 2006, Pulsar Astronomy (Cambridge: Cambridge University Press)

Maccarone, T. J. 2003, A&A, 409, 697

Maccarone, T. J. 2005, MNRAS, 360, L30

Maccarone, T. J. 2008, ASPC, 401, 191

Maccarone, T. J., & Coppi, P. S. 2003, MNRAS, 338, 189

Maccarone, T. J., Coppi, P. S., & Poutanen, J. 2000, ApJ, 537, L107

Maccarone, T. J., Kundu, A., Zepf, S. E., & Rhode K. L. 2007, Nature, 445, 183

Magdziarz, P., Zdziarski, A. A. 1995, MNRAS, 273, 837

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993

Margon, B., Grandi, S., Stone, R. P .S., & Ford, H. C. 1979, ApJ, 233, L63

Massi, M., & Kaufman Bernado, M. 2009, ApJ, 702, 1179

McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-ray Sources, ed. W. Lewin, & M. van der Klis (Cambridge: Cambridge University Press)

McLaughlin, M., et al. 2006, Nature, 439, 817

Merloni, A., Fabian, A. C., & Ross, R. R. 2000, MNRAS, 313, 193

Migliari, S., & Fender, R. P. 2006, MNRAS, 366, 79

Migliari, S., Fender, R. P., Rupen, M., Wachter, S., Jonker, P. G., Homan, J., & van der Klis, M. 2004, MNRAS, 351, 186

Migliari, S., Tomsick, J. A., Maccarone, T. J., Gallo, E., Fender, R. P., Nelemans, G. P., & Russell, D. M. 2006, ApJ, 643, L41

Miller, J. M., Reynolds, C. S., Fabian, A. C., Minniutti, G., & Gallo, L. C. 2009, ApJ, 697, 900

Miller-Jones, J. C. A., Jonker, P. G., Dhawan, V., Brisken, W., Rupen, M. P., Nelemans, G., & Gallo, E. 2009, astro-ph/0910.5253

Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46

Narayan, R., & Yi, I. 1994, ApJ, 428, L13

Nelemans, G., Tauris, T. M., & van den Heuvel, E. P. J. 1999, A&A, 352, L87

Nowak, M. A. 1995, PASP, 107, 1207

Nowak, M. A., Wilms, J., Heindl, W. A., Pottschmidt, K., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 316

Noyola, E., Gebhardt, K., & Bergmann, M. 2008, ApJ, 676, 1008

Orosz, J. A., et al. 2007, Nature, 449, 872

Özel, F., Gülver, T., & Psaltis, D. 2009, ApJ, 693, 1775

Pacini, F. 1967, Nature, 216, 567

Pacini, F. 1968, Nature, 219, 145

Paczynski, B. 1971, ARA&A, 9, 183

Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899

Possenti, A., Cerutti, R., Colpi, M., & Mereghetti, S. 2002, A&A, 387, 993

Remillard, R. A., Lin, D., Cooper, R. L., & Narayan, R. 2006, ApJ, 646, 407

Rezzolla, L., Yoshida, S.'i., Maccarone, T. J., & Zanotti, O. 2003, MNRAS, 344, L37

Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G., Zavlin, V. E., & Ushomirsky, G. 2002, ApJ, 580, 413

Salpeter, E. E. 1964, ApJ, 140, 796

Schwarzschild, K. 1916, AbhKP, 189

Seyfert, C. 1943, ApJ, 97, 28

Shafee, R., McClintock, J. E., Narayan, R., Davis, S. W., Li, L.-X., & Remillard, R. A. 2006, ApJ, 636, L113

Shakura, N. I., & Sunyaev, R.A. 1973, A&A, 24, 337

Shapiro, S. L., & Teukolsky, S. A. (1983), in Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects (New York: Wiley-Interscience)

Silk, J., Arons, J. 1975, ApJ, 200, L131

Smak, J. 1984, AcA, 34, 161

Soria, R., Goncalves, A. C., & Kuncic, Z. 2007, AIPC, 924, 919

Strohmayer, T. E. 2001, ApJ, 552, L49

Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., Day, C., & Lee, U. 1996, ApJ, 469, L9

Swank, J. H., Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., & Serlemitsos, P. J. 1977, ApJ, 212, L73

Taam, R. E., & Sandquist, E. L. 2000, ARA&A, 38, 113

Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R., & Jones, C. 1972, ApJ, 177, L5

Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255

Thorne, K. S., & Price, R. H. 1975, ApJ, 195, L101

Trudolyubov, S. P., & Priedhorsky, W. C. 2004, ApJ, 616, 821

Tudose, V., Fender, R. P., Linares, M., Maitra, D., & van der Klis, M., 2009, MNRAS, 400, 2111

Ulvestad, J. S., Greene, J. E., & Ho, L. C. 2007, ApJ, 661, L151

van der Klis, M. 2006, in Compact Stellar X-ray Sources, ed. W. Lewin, & M. van der Klis (Cambridge: Cambridge University Press)

van Kerkwijk, M. 1993, A&A, 276, L9

van Paradijs, J., & McClintock, J. E. 1994, A&A, 290, 133

Weltevrede, P., Stappers, B. W., Rankin, J. M., & Wright, G. A. E. 2006, ApJ, 645, L149

Wijnands, R. 2004, NuPhS, 132, 496

Wijnands, R., et al. 2006, A&A, 449, 1117
Wijnands, R., Homan, J., Miller, J. M., & Lewin, W. H. G. 2004, ApJ, 606, L61
Wilms, J., Schönherr, G., Schmid, J., Dauser, T., & Kreykenbohm, I. 2009, AIPC, 1126, 295
Woosley, S. E., & Taam R. E. 1976, Nature, 263, 101