where the optical condensations are ≈ 1 arc sec in size (36); their masses are about 10^{-5} $M_{\odot}$ or less per clump, and their number may total 3500. In all probability, their mass loss is very low, thus allowing a lifetime exceeding that of the PN stage. At present, it is not known what the fate of these clumps is, if they survive. If they are gravitationally bound, they will eventually collapse into solid bodies, leaving behind a cooling white dwarf surrounded by thousands of planets; otherwise, they will expand and dissipate once the PN stage has transpired.

REFERENCES AND NOTES

1. C. Messier, list of nebulous objects, originally published in *Connaiss. Temps* (1784); republished by H. Shapley and H. Davis, *Observatory* **41**, 318 (1918).
2. Wide binaries are noninteracting double stars, that is, there is or was no mass exchange or mass overflow from one component to the other, in contrast to close binaries, for which, in the case of mass loss by one component, a "common envelope" may form.
3. V. Weidemann, *Annu. Rev. Astron. Astrophys.* **28**, 103 (1990).
4. S. Kwok, *Publ. Astron. Soc. Pac.* **106**, 344 (1994).
5. R. L. Kingsburgh and M. J. Barlow, *Mon. Not. R. Astron. Soc.* **271**, 257 (1994).
6. Expressions like [O III] indicate emission lines. For example, O III indicates doubly ionized oxygen (a I implies neutral gas). Brackets indicate a "forbidden" transition, which are hardly or not at all observable under normal laboratory conditions because of the extremely low plasma densities from which they originate.
7. G. Jacoby, L. Ciardullo, H. Ford, *Astrophys. J.* **356**, 332 (1990).
8. The asymptotic giant branch (AGB) is so called because the calculated evolutionary tracks approach the giant branch more or less asymptotically. I. Iben Jr., *Phys. Rep.* **250**, 1 (1995).
9. H. D. Curtis, *Publ. Lick Obs.* **13**, 55 (1918).
10. F. A. Rasio and M. Livio, *Astrophys. J.* **471**, 366 (1996).
11. E. A. Dorfi and S. Höfner, *Astron. Astrophys.* **313**, 605 (1996).
12. G. Mellema and A. Frank, *Mon. Not. R. Astron. Soc.* **273**, 401 (1995); B. Balick, *Am. Sci.* **84**, 342 (1996).
13. A short description of the ROSAT satellite and its capabilities is given in *Sky Telesc.* **90**, 35 (August 1995).
14. According to recent results obtained by D. Pequignot (in *Proc. Int. Astron. Union Symp. 180*, in press), 30 elements can be traced in PNe.
15. J. H. Lutz, in (37), pp. 19–22.
16. L. H. Aller, *Physics of Thermal Gaseous Nebulae* (Astrophys. and Space Library 112, Reidel, Dordrecht, Netherlands, 1984), pp. 98 and 120.
17. K. M. Xilouris, J. Papamastorakis, E. Paleologou, Y. Terzian, *Astron. Astrophys.* **310**, 603 (1996); K. J. Borkowski, C. L. Sarazin, N. Soker, *Astrophys. J.* **360**, 173 (1990).
18. R. W. Tweedy and R. Napiwotzki, *Astron. J.* **108**, 978 (1994).
19. H. E. Bond, R. Ciardullo, L. K. Fullton, K. Schaefer, in *Proc. Int. Astron. Union Symp. 180*, in press.
20. J. B. Kaler, *Annu. Rev. Astron. Astrophys.* **23**, 89 (1985).
21. R. H. Mendez, R. P. Kudritzki, A. Herrero, D. Husfeld, H. G. Groth, *Astron. Astrophys.* **190**, 113 (1988).
22. A P Cygni profile is an emission line with a blueshifted absorption component.
23. M. Perinotto, in (37), pp. 57–64.
24. K. Werner and U. Heber, *Astron. Astrophys.* **247**, 476 (1991); T. Rauch, J. Köppen, K. Werner, *ibid.* **286**, 543 (1994); R. Napiwotzki, thesis, Christian-Albrechts-Universität zu Kiel (1993).
25. K. Werner and T. Rauch, *Astron. Astrophys.* **284**, L5 (1994).
26. I. Iben Jr., J. B. Kaler, J. W. Truran, A. Renzini, *Astrophys. J.* **264**, 605 (1983).
27. Y. Sakurai, *Int. Astron. Union Circ. 6325* (1996); *Int. Astron. Union Circ. 6328* (1996).
28. H. W. Duerbeck and S. Benetti, *Astrophys. J.* **468**, L111 (1996); F. Kerber *et al.*, in *Proc. Int. Astron. Union Symp. 180*, in press; F. Kerber, H. Gratl, M. Roth, *Int. Astron. Union Circ. 6601* (1997).
29. H. E. Bond, J. W. Liebert, A. Renzini, M. G. Meakes, in *ST-EFC/StScI Workshop: Science with the HST*, P. Benvenuti and E. Schreier, Eds. (European Southern Observatory, Garching, Germany 1992), pp. 139–141.
30. A. M. van Genderen and A. Gautschy, *Astron. Astrophys.* **294**, 453 (1995).
31. I. Iben, in (37), pp. 587–596.
32. G. Jacoby and R. Ciardullo, in (37), pp. 503–513.
33. J. J. Feldmeier, R. Ciardullo, G. H. Jacoby, *Astrophys. J.* **461**, L25 (1996).
34. M. Arnaboldi, S. Beaulieu, M. Capaccioli, K. C. Freeman, P. J. Quinn, *ESO Workshop on Science with the VLT*, J. R. Walsh and I. J. Danziger, Eds. (Springer, Berlin, 1995), pp. 232–235.
35. P. J. Huggins, in (37), pp. 147–154.
36. C. R. O'Dell and K. D. Handron, *Astron. J.* **111**, 1630 (1996).
37. R. Weinberger and A. Acker, Eds., *Proc. Int. Astron. Union Symp. 155* (1993).
38. The PNe images are courtesy of B. Balick and J. Alexander (University of Washington), A. Hajian (U.S. Naval Observatory), M. Perinotto (University of Florence), P. Patriarchi (Arcetri Observatory, Florence), Y. Terzian (Cornell University and NASA), and R. Sahai and J. Trauger (JPL–California Institute of Technology), in collaboration with the Wide Field–Planetary Camera 2 IDT and NASA.

Using Neutron Stars and Black Holes in X-ray Binaries to Probe Strong Gravitational Fields

Philip Kaaret and Eric C. Ford

Neutron stars and black holes can be studied by observation of the radiation produced as matter falls into their gravitational fields. X-ray binaries, which are systems consisting of a neutron star or black hole and a companion gaseous star, produce radiation in this manner. Recently, oscillations at frequencies near 1000 cycles per second have been detected from x-ray binaries. These oscillations are likely produced in regions of very strong gravitational fields within a few tens of kilometers of the compact star. The oscillations have been interpreted as evidence for the existence of an innermost stable orbit near a compact star, a key prediction of general relativity theory. The study of x-ray binaries has also advanced the search for definitive evidence of black holes. Recent developments in our understanding of accretion flows in x-ray binaries have provided evidence for the existence of event horizons in x-ray binaries thought to contain black holes.

Neutron stars and stellar-mass black holes are born in the deaths of gaseous stars, when exhaustion of the nuclear energy of a star causes it to collapse under the pull of gravity. Here we consider x-ray binaries, which are stellar binary systems composed of a black hole or neutron star in orbit with a companion gaseous star, in which the compact star is made visible by matter taken from the companion and drawn toward the compact star (1). Matter falling in the gravitational field of the compact star gains kinetic energy that can be released as radiation. In certain x-ray binaries, x-ray emission can arise from a region only a few tens of kilometers across near the compact star. These x-rays are a direct probe of the region of strong gravitational fields near the compact star.

Perhaps the strongest motivation for the study of x-ray binaries is to investigate strong gravitational fields. Because the radius of a stellar-mass neutron star is only about 10 km, the gravitational field at the surface of a neutron star is 10^5 times stronger than at the surface of the sun. In gravitational fields of such strength, qualitatively distinct predictions arise when general relativity is compared to Newtonian theories of gravity. One such prediction of general relativity is that matter orbiting sufficiently close to a compact star will be unable to maintain a stable orbit and will fall into the star (2). A possible signature of the boundary between stable and unstable orbits has been identified in oscillations detected from neutron star x-ray binaries during the past year (3).

Observations of x-ray binaries may also provide evidence of objects that have suffered complete gravitational collapse: black holes (4). The most striking difference between a black hole and a neutron star is that neutron stars have surfaces whereas black holes do not. The boundary of a black

The authors are at the Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA. E-mail for P. Kaaret: kaaret@astro.columbia.edu

hole—the event horizon—has no distinguishing features that would mark the location of a "surface" to a local observer. Matter falling through the event horizon does not stop and release observable radiation, it simply falls in. The radiation observed from black hole x-ray binaries is emitted from matter before the matter falls into the black hole. In contrast, matter striking the surface of a neutron star produces copious radiation. Proving that an object is a black hole is tantamount to demonstrating that a compact star has no surface. Appropriately, the proposed evidence is an absence of radiation (*5*).

Neutron Star X-ray Binaries

Firm evidence that a compact star is not a black hole can come from the detection of radiation from a surface. X-ray bursts, which are intense flashes of x-rays typically lasting a few seconds, were discovered from a number of x-ray binaries in the 1970s (*6*). The spectrum of radiation of x-ray bursts is a blackbody spectrum with a temperature of a few 10^7 K (*7*). Extensive observation and theoretical analysis of x-ray bursts has confirmed that they are thermonuclear flashes, ignited when sufficiently thick layers (1 m) of hydrogen and helium build up on the surface of a compact stellar object (*1*). Detection of an x-ray burst establishes that a compact star has a surface and is thus a neutron star rather than a black hole.

In the neutron star binaries of interest here, matter drawn from the companion star forms an accretion disk around the neutron star (Fig. 1). Interactions within the accretion disk cause dissipation of energy and transport of angular momentum (*8*). Transport of angular momentum outward through the disk allows matter in the disk to gradually spiral inward toward the neutron star. Dissipation of energy heats the matter in the disk and leads to the emission of radiation. Infrared (IR) and optical light come from the outer and cooler parts of the disk, whereas x-rays come from the inner and hotter parts of the disk. If energy is radiated efficiently (*9*), matter in the disk will follow circular orbits. In this case, the orbital frequency ν_K of an element of the disk is uniquely related to its distance, r, from the neutron star according to Kepler's third law, $\nu_K^2 = GM/4\pi^2r^3$, where M is the neutron star mass and G is the gravitational constant. The Keplerian orbital frequency increases closer to the star, with the highest orbital frequencies being at the inner boundary of the accretion disk near the neutron star. For a typical inner radius of 10 to 20 km, the orbital frequency is near 1000 Hz.

Recently, oscillations near 1000 Hz were detected (*10–13*) from several neutron star x-ray binaries in x-ray observations made with NASA's Rossi X-Ray Timing Explorer satellite (RXTE) (*14*). A typical timing power spectrum (Fig. 2) (*11*) shows narrow peaks at high frequencies. The peaks indicate oscillations that are not completely periodic but still have a well-defined average frequency, so they are considered quasi-periodic oscillations (QPOs).

Most of the high-frequency QPOs arise from a class of neutron-star x-ray binaries referred to as atoll sources (*15*). Atoll sources are thought to have weak magnetic fields ($<10^8$ G), and low luminosities ($L < L_E$ where L_E is the Eddington luminosity) (*16*). The atoll sources often show two distinct QPOs that appear simultaneously (Fig. 2). The QPO frequencies vary and are strongly correlated with source flux. However, the frequency difference between the two simultaneous QPOs is independent of source flux. In the atoll source 4U 0614+091, the frequency difference between the two QPOs is consistent with a constant value of 323 ± 4 Hz in observations covering a time span of 3 months (Fig. 3) (*17*). This indicates the presence of a clock in the system that is stable over time scales of at least 3 months.

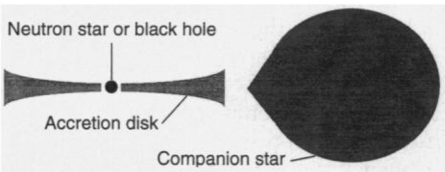


Fig. 1. An x-ray binary system containing a compact star, the accretion disk surrounding the compact star, and a companion star.

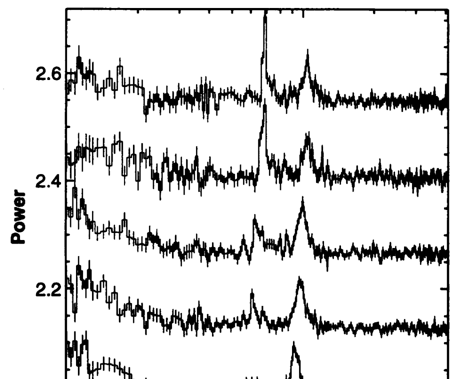


Fig. 2. Timing power spectrum of x-ray emission from the neutron star x-ray binary 4U 1728–34 (*11*). Narrow peaks are present in each power spectrum at frequencies near 1000 Hz. The peaks are significantly broader than would be expected for a coherent periodic oscillation and are referred to as QPOs.

A simple interpretation of the QPO frequencies from atoll sources involves the differential rotation of the inner part of the accretion disk and the neutron star (*18*). In this model, there are three relevant frequencies in the system: the frequency of Keplerian orbits at the inner edge of the accretion disk ν_K, the spin frequency of the neutron star ν_S, and the difference between these frequencies: the "beat" frequency $\nu_B = \nu_K - \nu_S$ (Fig. 4). The higher frequency QPO is identified as ν_K and the lower frequency QPO is identified as ν_B. As the rate

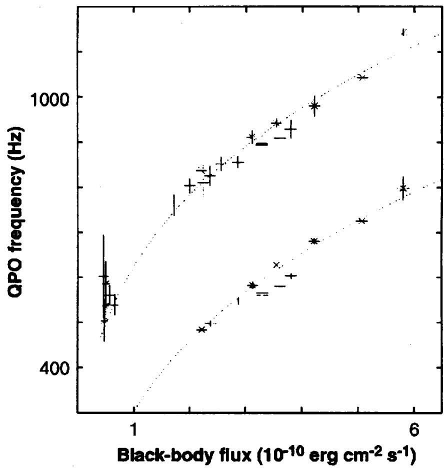


Fig. 3. Behavior of the high-frequency QPOs from the atoll source 4U 0614+091 as a function of the flux of a black-body component in the x-ray spectrum of the source, adapted from (*19*). In most observations, two QPOs are present simultaneously. Plus signs indicate observations taken in April 1996; asterisks indicate observations taken in August 1996. The errors indicated are 1σ for both frequency and flux. The frequency difference between the simultaneously detected QPOs is consistent with 323 ± 4 Hz in all cases.

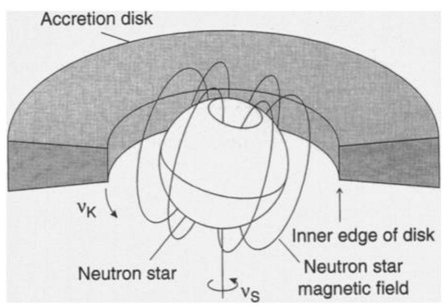


Fig. 4. Schematic representation of the inner accretion disk near the neutron star. Only half of the inner part of the disk is shown for clarity. In the beat frequency model there are three relevant frequencies. Matter at the inner edge of the disk orbits at a Keplerian orbital frequency ν_K. The neutron star spins at a frequency ν_S. Differential rotation of the accretion disk and the neutron star generates the beat frequency $\nu_B = \nu_K - \nu_S$.

of the neutron star's spin changes very slowly, the frequency difference between ν_K and ν_B should remain constant, as is observed from 4U 0614+091.

A striking confirmation of the beat frequency model comes from observations of the atoll source 4U 1728-34. Strohmayer *et al.* (*11*) detected two simultaneous high-frequency QPOs (Fig. 2) with a constant frequency difference of 360 ± 6 Hz . They also detected single QPOs during x-ray bursts. The QPO frequency reaches a constant value of 363 Hz and becomes essentially coherent toward the end of the burst. As x-ray bursts are known to originate at the surface of the neutron star, the QPO frequency during the bursts is a direct detection of ν_S. The spin frequency is equal to the difference of the two QPOs detected simultaneously in the persistent emission (*11*), as expected in the beat frequency model.

In 4U 0614+091 and 4U 1728-34, the QPO frequencies increase as the x-ray count rate increases (*11, 17*). The higher frequency QPO in 4U 0614+091 is well correlated with the flux of a blackbody component of the x-ray spectrum (Fig. 3) (*19*). If the blackbody flux is taken as an indicator of the mass accretion rate, this implies that the inner edge of the accretion disk moves inward as the mass accretion rate increases. This can be explained if the position of the inner edge of the accretion disk is determined by either magnetic or radiation forces.

For neutron stars with sufficiently strong magnetic fields, the inner boundary of the disk is located at the magnetospheric radius, the point where the kinetic energy in the accretion flow equals the magnetic field energy (*20*). At the magnetospheric radius, matter in the disk is channeled along the magnetic field lines of the neutron star and the accretion disk is disrupted. Inward of this point, matter will rotate synchronously with the neutron star. The magnetospheric radius shrinks, and therefore ν_K increases, as the mass accretion rate increases. The relation between ν_K and flux observed for 4U 0614+091 (Fig. 3) is consistent with that expected from a simple magnetospheric model (*18*) and observed in x-ray pulsars (*21*).

For neutron stars with sufficiently weak magnetic fields, the position of the inner edge of the accretion disk may be determined by radiation produced at the surface of the star rather than by the magnetic field of the star (*22*). Photons from the neutron star scattering in the accretion disk can remove angular momentum from the disk and cause matter in the disk to spiral in toward the star. The inner boundary of the disk occurs at the sonic radius, where the radial speed of the infalling matter exceeds the local sound speed in the disk. Matter inward of the sonic radius spirals rapidly into the neutron star and creates a pattern frequency at the neutron star surface equal to ν_K at the sonic radius. The sonic radius and ν_K depend on the mass accretion rate in the disk and the luminosity from the surface of the neutron star (*23*). QPOs may be generated at the sonic radius even if radiation forces are not important in determining the location of the sonic radius (*22*).

In contrast to the atoll sources, the source Sco X-1 exhibits two simultaneous QPOs with a varying frequency difference (*10*). The frequency difference is near 310 Hz at low frequencies and decreases sharply to 230 Hz as the QPO frequency reaches the maximum observed value of 1085 Hz. Sco X-1 is classified as a "Z" source and has a much higher luminosity ($L \approx L_E$) and a higher magnetic field ($B \approx 10^8 - 10^9$ G) than the atoll sources (*15*). Theoretical models other than the beat frequency picture have been suggested to explain the high-frequency QPOs in Z sources, most notably the photon bubble oscillation model (*24*). However, recent observations show none of the additional QPOs predicted by this model (*25*).

The QPOs observed in Z and atoll sources are similar: two simultaneous QPOs with varying frequency, maximum QPO frequencies near 1100 to 1200 Hz, and a frequency difference of several 100 Hz. The data from atoll sources are consistent with a simple beat frequency model (*26*), but the varying frequency difference in Sco X-1 rules out the simplest beat frequency model for Z sources. As the properties of Z sources differ from those of atoll sources, it is not unreasonable to suppose that the high-frequency QPOs in the two classes of sources have different origins. However, the similarity of the QPOs in Sco X-1 to those in the atoll sources suggests that it should be possible to describe both classes of sources with a single model. The change in the frequency difference in Sco X-1 is relatively small (80 Hz, or 7% of the maximum frequency of 1085 Hz). Such a model will likely include effects of both magnetic and radiation forces.

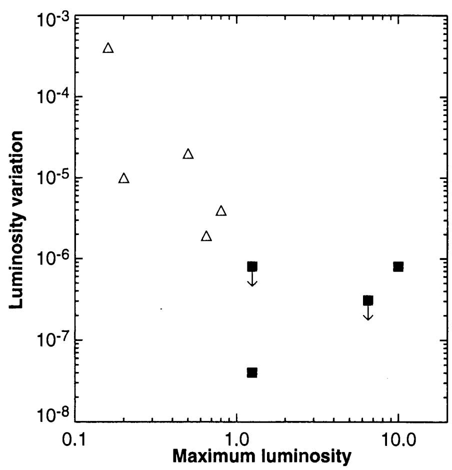


Fig. 5. Luminosity variation versus maximum observed luminosity for neutron star and black hole x-ray transients, adapted from (5). The triangles are neutron star systems and the squares are black hole candidate systems. The maximum luminosity is given in units of the L_E (*16*) for a 1.4 $M_\odot$ star. The luminosity variation is the ratio of the minimum observed luminosity to the maximum observed luminosity. For two of the black hole candidate systems (squares with arrows), only upper bounds on the minimum luminosity are available. Transient systems are identified as containing a neutron star if x-ray bursts have been observed or as black hole candidates if the compact star mass is in excess of 3 $M_\odot$.

Neutron Star Masses and the Marginally Stable Orbit

If the frequency of a QPO is identified with a Keplerian orbital frequency, then the QPO frequency can be used to estimate the mass of the neutron star. This is because there is a maximum ν_K for a star of a given mass. In Einstein's theory of general relativity, stable orbits exist only outside a certain radius from a massive object. Particles orbiting inside the radius of the marginally stable orbit (MSO) invariably spiral into the central object. For a nonrotating neutron star, the radius of the MSO is $r_{ms} = 6GM/c^2$, which gives a maximum $\nu_K = (GM/4\pi^2 r_{ms}^3)^{1/2} = (2198 \text{ Hz}) (M_\odot/M)$ (*22*) ($M_\odot$ is the mass of the sun).

The MSO has been incorporated in accretion disk models since the original papers on the theory of thin accretion disks around compact stars (*27*). The MSO is taken as the inner boundary of disks surrounding black holes or neutron stars with sufficiently small radii and low magnetic fields. Above, we discussed models in which the inner boundary of the disk varies with mass accretion rate because of the effect of magnetic or radiation forces. If the disk's inner boundary moves inward to the MSO, then magnetic and radiation forces will no longer determine its position; the boundary will remain near the MSO. This places an upper bound on the orbital frequencies that can be observed from an accretion disk around a neutron star of a given mass.

Conversely, observation of a particular orbital frequency places an upper bound on the mass and radius of the compact star (*22*). The maximum QPO frequencies observed from neutron star x-ray binaries all lie in a relatively narrow range of 1000 to 1200 Hz (*28*). If this maximum frequency is interpreted as the Keplerian frequency at the MSO, then the inferred neutron star masses are near 1.8 to 2.0 $M_\odot$ (*17*, *28*). If this interpretation is correct, the neutron star radii must be smaller than the 17-km radius of the MSO (*17*, *22*).

If the inner disk is terminated at the MSO, then QPOs may be generated at the sonic radius (*29*). Muchotrzeb-Czerny found that the sonic radius lies close to, but outside, the MSO and moves only slightly (less than 10%) with varying mass accretion rate (*30*). The behavior of the QPOs in certain sources has been interpreted as evidence that the accretion disk actually reaches the MSO (*3*). The atoll source 4U 1608-52 exhibits QPOs with nearly constant frequency; the QPO frequency varies by less than 10% as the total x-ray flux changes by a factor of 2 (*12*). In contrast, the QPO frequencies in 4U 0614+091 (Fig. 3) and in 4U 1728-34 (*11*) change by a factor of 2 as the total x-ray flux changes by a factor of 2. These two qualitatively distinct QPO behaviors can be explained by a single mechanism if the position of the inner edge of the accretion disk varies relative to the position of the MSO (*3*). In 4U 0614+091 and 4U 1728-34, the position of the inner edge of the accretion disk shifts as the mass accretion rate changes. This leads to a QPO frequency that is correlated with x-ray flux. As the mass accretion rate increases, the inner edge of the accretion disk moves inward. At sufficiently high accretion rates, the inner edge of the disk will move near the MSO. At this point, magnetic and radiation forces no longer play an important role in determining the position of the inner edge of the accretion disk. Instead, the accretion disk is terminated near the MSO. This leads to a QPO frequency that is independent of x-ray flux (*3*).

The interpretation of the QPOs in 4U 1608-52 as evidence for the existence of the MSO requires that the QPO frequency be related to ν_K or ν_B and that the radius determining the QPO frequency wander over a narrow range near the MSO. Motivation for relating the QPO frequency to ν_K comes from the success of the beat frequency model in describing the data from atoll sources. The inadequacy of this model for the Z sources raises a caveat. It is also possible that the nearly constant frequency QPO in 4U 1608-52 is generated by a process unrelated to ν_K or ν_B (*31*). However, the atoll source 4U 1636-536 exhibits a pair of simultaneous QPOs with frequencies that correlate with inferred mass accretion rate and have constant frequency difference in some observations, and a single QPO with a frequency that is approximately constant and not correlated with mass accretion rate in other observations (*32*). The frequency of the single QPO lies near the maximum ν_B observed during the mass accretion rate–dependent phase. The near equality of the frequencies (*33*) and the fact that the two QPO behaviors are not seen simultaneously bolster interpretation of the mass accretion rate–independent QPO as related to ν_B at the MSO.

The question of where the QPO is generated relative to the MSO should be further investigated theoretically. Calculations of the sonic radius should be extended to a fully relativistic treatment and carried out for a variety of accretion disk models and viscosity prescriptions. Independent measurement of the neutron star mass would allow determination of the MSO radius. Although optical mass measurements are notoriously difficult for neutron star x-ray binaries, recent results on transient x-ray binaries (*34*) and IR photometry of neutron star x-ray binaries (*35*) are encouraging, and such measurements should be given high priority on large telescopes. Confirmation of the relation between the MSO and QPOs would provide the first confirmation of this key prediction of general relativity theory.

Identification of an observed QPO frequency from 4U 1636-536 with ν_B at the MSO provides a measurement of the neutron star mass, rather than merely an upper limit. The dragging of inertial frames around a rotating neutron star slightly modifies the position of the MSO. The neutron star mass is then $M = 2.198\ M_\odot(\nu_K/1000\ \mathrm{Hz})^{-1}\ (1 - 0.748j)^{-1}$, to first order in dimensionless angular momentum of the neutron star $j = 2\pi cI\nu_S/GM^2$, where I is the moment of inertia of the neutron star and c is the speed of light (*3*, *36*, *37*). The QPO and neutron star spin frequencies measured for 4U 1636-536 imply a mass of $1.98 \pm 0.12\ M_\odot$. The largest uncertainty in the mass determination comes from theoretical uncertainty in the relative locations of the MSO and the orbit that gives rise to the observed QPOs (*38*). This mass is greater than the masses of neutron stars found in the relativistic binary radio pulsars, which are all near 1.4 $M_\odot$ (*39*) and are thought to represent the neutron star mass at formation. The total mass transfer required to increase the mass to 2 $M_\odot$ is compatible with estimates of the total accretion over the lifetime of an x-ray binary (*28*) and also with the inferred mass of the companion star (0.4 $M_\odot$) in the 4U 1636-536 system (*40*). The existence of a neutron star of 2 $M_\odot$ would have significant implications for the equation of state of nuclear matter (*41*, *42*).

Black Hole X-ray Transients

Certain x-ray binary systems produce x-rays only intermittently. During outbursts, soft x-ray transients (*43*), also known as x-ray novae, have reached peak luminosities in excess of 10^5 times the luminosity of the sun, and some have produced collimated jets moving at speeds up to 0.92*c* (*44*). The compact stars in the brightest x-ray transients are thought to be black holes. Curiously, the best evidence that the compact stars are black holes and also the best direct evidence for the existence of event horizons comes from observations made when these transient sources are in their quiescent states and produce relatively few x-rays.

The traditional method to prove that a compact star is a black hole is simply to demonstrate that its mass is in excess of 3.2 $M_\odot$. An upper bound of 3.2 $M_\odot$ can be placed on the mass of a nonrotating neutron star given the assumptions that general relativity theory is correct, the speed of sound in nuclear matter does not exceed the speed of light, and the equation of state of nuclear matter is known at densities less than 4.6×10^{14} g cm^{-3} (*45*). If these assumptions are accepted and the possibility of exotic compact stars is disallowed, then measurement of a compact star mass in excess of 3.2 $M_\odot$ implies the presence of a black hole.

The mass of the compact star in an x-ray binary can be determined from spectroscopy and photometry of optical light from the companion star in the binary system (*46*). As optical emission from the accretion disk and x-ray heating of the companion can lead to light curves that are complex and difficult to interpret, such measurements are best made when the x-ray flux from the system is low. The best mass determinations have been made for transient x-ray binaries in quiescence. This approach was pioneered by McClintock and Remillard (*47*), who derived a mass lower bound of 3.2 $M_\odot$, and thus a black hole identification, for the x-ray transient A0620-00. Subsequent mass determinations have led to several more identifications of black holes (*46*).

Evidence for the Event Horizon

Although lower bounds in excess of 3 $M_\odot$ on the masses of compact stars are generally considered evidence for the existence of black holes, this line of reasoning is unsatisfying because it uses none of the intrinsic properties of black holes. The most direct proof of the existence of a black hole would be evidence of an event horizon, confirmation of the absence of a surface in a compact star.

In standard thin accretion disk models, as discussed above for neutron star binaries, the release of gravitational potential energy heats the gas in the disk and the gas cools rapidly by radiating photons (*8*). It is assumed that the heat input, via viscous dissipation of released gravitational potential energy, and the heat output, by radiation, are balanced at each point in the disk. Such accretion disks radiate efficiently; typically nearly 10% of the rest mass energy of the accreted matter is radiated (*27*). Because the disk is so luminous, the release of energy at the surface of a neutron star increases the total luminosity by only a factor of 2 to 3 relative to a black hole system where luminosity comes only from the disk.

Accretion disks are expected to form in x-ray binaries where the accreting matter has non-zero net angular momentum. If the accreting matter has zero net angular momentum, it can fall toward a compact star without dissipation of angular momentum or energy, and the accretion flow is approximately spherical (*48*). The radiative efficiency—the fraction of rest mass energy of accreting matter released as radiation—of a spherical flow is very low (*49*).

The key new element in the search for the event horizon is the recognition that a spherical accretion flow can form in an x-ray binary if the accreting matter does not radiate efficiently (*50*). If the thermal energy of the accreting gas is not radiated, then it will be carried along with the infalling gas or advected. Advection is important when the time scale for radiation is longer than the time scale on which gas falls into the black hole. Radiation occurs mainly from interactions of electrons, whereas most of the energy released in viscous dissipation goes into ions. If the transfer of energy from ions to electrons is inefficient and the accreting matter is transparent to radiation, then the ions can become much hotter than the electrons and store thermal energy (*51*). Such conditions can arise if the mass accretion rate is low (*52*). Advection makes the differences between neutron star and black hole x-ray binary systems definitive. With advection in neutron star systems, the luminosity is dominated by energy released at the surface of the neutron star and the radiative efficiency is always about 10%. In black hole systems, there is no surface at which to release energy and luminosity arises only from the accretion flow; the radiative efficiency can drop below 0.1% (*53*).

Broad-band spectra from black hole candidate x-ray transients in quiescence have been interpreted as evidence for advection-dominated accretion flow (ADAF) (*53, 54*). The mass accretion rates required in the outer disk to produce the optical emission observed would produce an x-ray luminosity far higher than that observed if the inner disk is radiatively efficient. In the ADAF models, the efficiency of the inner disk is greatly reduced and the optical, ultraviolet (UV), and x-ray data can be fit simultaneously (*53*) However, this is not unambiguous evidence for an event horizon, as neutron star x-ray binaries have x-ray–to–optical luminosity ratios similar to those of black hole systems (*43*). Because the x-ray efficiency of neutron star systems cannot be low, the low x-ray luminosities indicate that the mass accretion rate onto the neutron star is lower than the accretion rate in the outer disk. This may indicate storage of material in the outer disk (*55*). If so, the same mechanism could operate in black hole systems. The low x-ray lumosities may instead be caused by repulsion of matter by the magnetosphere of the neutron star (*56*). This effect does not occur with black holes; however, accreted matter may be expelled as a jet or outflow rather than lost over the event horizon. An interesting test of ADAF models would be to attempt to fit the spectra of quiescent neutron star x-ray binaries with the use of ADAF models of black hole systems.

Luminosity variations in x-ray transients have been interpreted as evidence for the presence of black holes. Comparison of the ratio of minimum to maximum luminosity of neutron star and black hole systems (Fig. 5) shows that the black hole candidates all have a wider range of luminosity variation (*5, 57*). ADAF models predict that black hole binaries at low accretion rates will have very low radiative efficiency, as only a small fraction of the gravitational potential energy of the infalling matter is radiated before the matter passes over the event horizon. In neutron star systems, low radiative efficiencies are not obtained, even at very low accretion rates, because the accreted matter will radiate after striking the neutron star surface. At high accretion rates, both neutron star and black hole systems have high radiative efficiencies. Therefore, black hole systems should have larger luminosity variations than neutron star systems. In the context of the ADAF model, the difference in luminosity variations (Fig. 5) is directly related to the absence or presence of a surface and thus is evidence for the existence of event horizons in the black hole candidates (*5*).

However, the division between neutron star and black hole candidate systems (Fig. 5) is quite narrow, especially considering that the division should represent a qualitative change from compact stars with surfaces to compact stars without surfaces. The luminosity variation for the black hole candidate V404 Cyg differs from that of the neutron star system Cen X-4 only by a factor 2.5. As the radiative efficiency of V404 Cyg determined by fits of ADAF models to the quiescent emission spectrum is near 10^{-3} (*53*), and the efficiency for neutron star systems should be near 10^{-1}, the luminosity ratios should differ by a factor of 100. Part of this discrepancy may be due to magnetospheric repulsion of matter, which is possible only in neutron star systems (*56*).

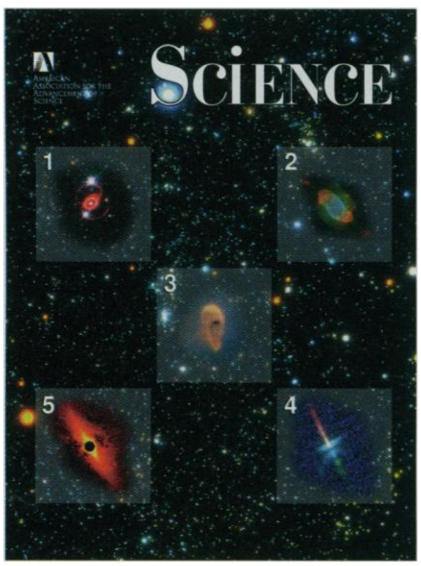
The true distinction between black hole and neutron star systems should be their differing radiative efficiencies: the ratio of luminosity to mass accretion rate. Substitution of a comparison of luminosity variations makes the implicit assumption that the range of variation in mass accretion rate is similar for neutron star and black hole systems. The smaller luminosity variations of the neutron star systems may simply reflect smaller variations in accretion rates (*58*). Optical and IR observations should allow an estimate of the accretion rate independent of the properties of the inner regions of the accretion flow and the properties of the compact star (*59*). The x-ray luminosity could then be used to estimate the radiative efficiency. We note that the accretion rates inferred from ADAF models for V404 Cyg, near $10^{-9}\ M_{\odot}\ \mathrm{year}^{-1}$, are an order of magnitude higher than those inferred for A0620-00, which are near $10^{-10}\ M_{\odot}\ \mathrm{year}^{-1}$ (*53*). As the luminosity ratio for the black hole candidate A0620-00 is more than an order of magnitude below that of the lowest neutron star system, the high quiescent luminosity of V404 Cyg may simply be due to an unusually high quiescent mass accretion rate.

The presence of an event horizon in black hole candidate x-ray binaries does provide a natural interpretation of the data on luminosity ratios of x-ray binaries and also of the broad-band spectra from x-ray transients in quiescence. Additional work may soon lead to definitive proof of the absence of surfaces in black hole candidate x-ray binary systems. It is remarkable that speculation about the existence of black holes has been superseded by sharply focused questions that can be answered directly by an observational search for the event horizon.

REFERENCES AND NOTES

1. For a recent extensive review of x-ray binaries, see W. H. G. Lewin, J. van Paradijs, E. P. J. van den Heuvel, Eds., *X-Ray Binaries* (Cambridge Univ. Press, Cambridge, 1995).
2. C. W. Misner, K. S. Thorne, J. A. Wheeler, *Gravitation* (Freeman, San Francisco, CA, 1970).
3. P. Kaaret, E. Ford, K. Chen, *Astrophys. J.* **480**, L27 (1997).
4. Throughout this article, we use the term black hole to refer only to stellar-mass black holes formed from gaseous stars. We do not consider supermassive black holes thought to exist in the cores of active galactic nuclei or primordial black holes.
5. R. Narayan, M. R. Garcia, J. E. McClintock, *Astrophys. J.* **478**, L79 (1997).
6. J. E. Grindlay *et al.*, *ibid.* **205**, L127 (1976); R. D. Belian, J. P. Conner, W. D. Evans, *ibid.*, p. L135.
7. J. H. Swank *et al.*, *ibid.* **212**, L73 (1977).
8. For a readable review of accretion disks, see J. E. Pringle [*Annu. Rev. Astron. Astrophys.* **19**, 137

(1981)] or J. Frank, A. King, and D. Raine [*Accretion Power in Astrophysics* (Cambridge Univ. Press, Cambridge, 1995)].
9. The time scale for gas to lose energy through radiation must be significantly shorter than the time scale on which angular momentum is transported in the disk. In addition, gravity must be the dominant force determining the structure of the disk.
10. M. van der Klis *et al.*, *Astrophys. J.* **469**, L1 (1996).
11. T. Strohmayer *et al.*, *ibid.*, p. L9.
12. M. Berger *et al.*, *ibid.*, p. L13.
13. W. Zhang *et al.*, *ibid.*, p. L17.
14. H.V. Bradt, R. E. Rothschild, J. H. Swank, *Astron. Astrophys. Suppl.* **97**, 355 (1993).
15. G. Hasinger and M. van der Klis, *Astron. Astrophys.* **255**, 79 (1989); F. K. Lamb, in *Neutron Stars: Theory and Observation*, J. Ventura and D. Pines, Eds. (Kluwer, Dordrecht, Netherlands, 1991) pp. 445–481.
16. The Eddington luminosity L_E is the maximum luminosity for an accreting source of a given mass and is equal to the luminosity at which radiation pressure from the outgoing radiation balances the gravitational force on the accreting matter.
17. E. Ford *et al.*, *Astrophys. J.* **475**, L123 (1997).
18. M. A. Alpar and J. Shaham, *Nature* **316**, 239 (1985).
19. E. Ford *et al.*, *Astrophys. J.*, in press.
20. P. Ghosh and F. K. Lamb *ibid.* **234**, 296 (1979); F. K. Lamb *et al.*, *Nature* **317**, 681 (1985).
21. L. Angelini, L. Stella, A. N. Parmar, *Astrophys. J.* **346**, 906 (1989).
22. M. C. Miller, F. K. Lamb, D. Psaltis, *ibid.*, in press.
23. One might expect the inner disk radius to move outward at high luminosities, thereby leading to an inverse correlation of frequency with count rate. However, the increased opacity of the accretion flow at high mass accretion rates may dominate over the effect of the luminosity and produce the observed correlation.
24. R. I. Klein *et al.*, *Astrophys. J.* **469**, L119 (1996).
25. M. van der Klis *et al.*, *ibid.* **481**, L97 (1997).
26. In the atoll source KS 1731-260, the frequency difference of persistent emission QPOs is equal to half the x-ray burst QPO frequency [R. A. D. Wijnands and M. van der Klis, *ibid.* **482**, L119 (1997)]. The x-ray burst QPO frequency is interpreted as twice the rotation frequency. In the atoll source 4U 1636-536, the frequency difference of QPOs detected in persistent emission differs by 1.9σ from half the x-ray burst QPO frequency [W. Zhang *et al.*, *IAU Circular 6541* (1997)]. However, the deviation is not statistically significant.
27. N. I. Shakura and R. A. Sunyaev, *Astron. Astrophys.* **24**, 337 (1973).
28. W. Zhang, T. E. Strohmayer, J. H. Swank, *Astrophys. J.* **482**, L67 (1997).
29. B. Paczyński, *Nature* **327**, 303 (1987).
30. B. Muchotrzeb-Czerny, *Acta Astronom.* **36**, 1 (1986).
31. One obvious interpretation, that the QPO frequency is the neutron star spin frequency, is excluded by the extent of the frequency variations.
32. R. A. D. Wijnands *et al.*, *Astrophys. J.* **479**, L141 (1997).
33. The QPO frequency observed at the higher mass accretion rate is slightly lower (3 to 7%) than at lower mass accretion rates. This can be understood if the sonic point moves outward at high accretion rates as suggested in (*30*).
34. J. Orosz and C. Bailyn [*Astrophys. J.* **477**, 876 (1997)] have measured the mass of the compact star in the transient black hole candidate x-ray binary GRO J1655-40 to an accuracy of 4% from observations made while the system was in quiescence.
35. T. Shahbaz, T. Naylor, P. A. Charles, *Mon. Not. R. Astron. Soc.* **265**, 655 (1993).
36. J. M. Bardeen, W. H. Press, S. A. Teukolsky, *Astrophys. J.* **178**, 347 (1972).
37. W. Kluźniak *et al.*, *ibid.* **358**, 538 (1990).
38. The mass uncertainty allows for a factor of 3 uncertainty in the moment of inertia.
39. J. H. Taylor and J. M. Weisberg, *Astrophys. J.* **345**, 434 (1989); A. Wolszczan, *Nature* **350**, 688 (1991).
40. The companion mass can be inferred from the 0.16-day orbital period of 4U 1636-536 [J. van Paradijs *et al.*, *Astron. Astrophys* **234**, 181 (1990)]. The binary radio pulsar PSR 1855+09 has a mass of $1.27^{+0.23}_{-0.15}$ $M_\odot$ and a companion of 0.23 $M_\odot$ and is thought to be the progeny of a low-mass x-ray binary [M. F. Ryba and J. H. Taylor *Astrophys. J.* **371**, 739 (1991)]. The lower neutron star mass may be related to the longer (12.3-day) orbital period. However, both neutron star masses are consistent with 1.73 $M_\odot$ at the 2σ level.
41. The existence of a neutron star with a mass of >1.74 $M_\odot$ (2σ confidence) would rule out a number of soft equations of state.
42. G. B. Cook, S. L. Shapiro, S. A. Teukolsky, *Astrophys. J.* **424**, 823 (1994).
43. Y. Tanaka and N. Shibazaki, *Annu. Rev. Astron. Astrophys.* **34**, 607 (1996).
44. I. F. Mirabel and L. F. Rodriguez, *Nature* **371**, 46 (1994); S. J. Tingay *et al.*, *ibid.* **374**, 141 (1995); R. M. Hjellming and M. P. Rupen, *ibid.* **375**, 464 (1995).
45. C. E. Rhoades Jr. and R. Ruffini, *Phys. Rev. Lett.* **32**, 324 (1974).
46. The inclination of the orbital plane and the ratio of the masses of the companion and the compact star can be determined from ellipsoidal variations, which are asymmetries in the photometric light curve caused by tidal distortion of the companion star. Combined with the mass function, calculated from the radial velocity curve derived from spectroscopy of emission lines from the companion, the mass of the compact star can be determined. For a recent review, see J. van Paradijs and J. E. McClintock, in *X-Ray Binaries*, W. H. G. Lewin, J. van Paradijs, E. P. J. van den Heuvel, Eds. (Cambridge Univ. Press, Cambridge, 1995), pp. 58–125.
47. J. E. McClintock and R. A. Remillard *Astrophys. J.* **308**, 110 (1986).
48. H. Bondi *Mon. Not. R. Astron. Soc.* **112**, 195 (1952).
49. S. L. Shapiro, *Astrophys. J.* **180**, 531 (1973).
50. The accretion flow forms a thin disk at very large radii and is quasi-spherical close to the compact star.
51. S. L. Shapiro, A. P. Lightman, D. M. Eardley, *Astrophys. J.* **204**, 187 (1976).
52. R. Narayan and I. Yi, *ibid.* **428**, L13 (1994); M. A. Abramowicz *et al.*, *ibid.* **438**, L37 (1995); X. Chen *et al.*, *ibid.* **443**, L61 (1995); R. Narayan and I. Yi, **452**, 710 (1995).
53. R. Narayan *et al.*, *ibid.*, in press.
54. R. Narayan *et al.*, *ibid.* **457**, 821 (1996).
55. It has been suggested that storage of material in the disk is required to produce bright x-ray transients. For a recent review, see (*43*).
56. Centrifugal force may reduce accretion onto neutron stars when the mass accretion rate is low and the magnetospheric radius is large; this is the "propeller effect" [A. F. Illarionov and R. A. Sunyaev, *Sov. Astron. Lett.* **1**, 73 (1975)]. The importance of the propeller effect is uncertain, in part due to our lack of knowledge of the spin rates of neutron stars in x-ray binaries. These spin rates are currently being determined through QPO observations as described in the previous sections.
57. J. E. McClintock and R. A. Remillard, *ibid.* **350**, 386 (1990).
58. The maximum luminosities of the black hole systems are certainly larger, because the L_E is higher for more massive stars. The quiescent mass accretion rates may differ because of the differing mass ratios of neutron stars versus black hole systems or because of irradiation of the companion in neutron star systems [see M. Ruderman *et al.*, *Astrophys. J.* **343**, 292 (1989) and J. M. Hameury *et al.*, *Astron. Astrophys.* **277**, 81 (1993)].
59. The accretion rates estimated in (*53*) use the x-ray luminosity and assume the validity of the ADAF model. These estimates are not suitable for a model-independent evaluation of the radiative efficiency.
60. We thank T. Strohmayer for supplying Fig. 2, M. C. Miller and R. Narayan for communicating results before publication, and K. Chen for useful discussions.



About the Cover: The cover is a collage of images that show some aspects of stellar birth and life (lower three panels) to death (upper two panels). Here is a brief synopsis of these images keyed to the cover (Left). (1) Supernova 1987A imaged within the Large Magellanic Cloud [Hubble Space Telescope (HST) image courtesy of R. Kirshner, P. Challis, and the Space Telescope Science Institute]. The central bright spot is radioactive debris from the explosion, and the rings are the remnants of the stellar winds from the progenitor star (Chevalier, p. 1374). (2) Planetary nebula NGC 7009 taken with HST [courtesy of B. Ballick] shows the central star, the small pink spot, in a gaseous envelope of dissipating stellar mass (Weinberger and Kerber, p. 1382). (3) The young star Ori 182-413, within the Orion Nebula (middle star in the sword of the constellation Orion), is enshrouded in a circumstellar cloud [HST image courtesy of J. Bally], a typical situation for very young stars (O'Dell and Beckwith, p. 1355). (4) The young star HH 30 [HST image courtesy of R. Mundt] has jets of gas bursting from its disk (O'Dell and Beckwith). (5) The dusty disk around Beta Pictoris, a main sequence star slightly hotter than our sun, located in the southern constellation Pictor. The disk was imaged by masking out the star on the University of Hawaii 2.2-meter telescope. An asymmetry in the disk may be from gravitational perturbation of an orbiting planet [courtesy of P. Kalas and D. Jewitt]. The background is a synthesized color image of the soft x-ray sky around the constellation Orion (5228 objects, including Ori 182–413, in an area of ~50° by 75°) derived from Röntgen X-ray Satellite images [courtesy of K. Dennerl, W. Voges, R. Neuhäuser].