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# ACCRETION POWERED COMPACT OBJECTS: THEORY AND OBSERVATIONS

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## ABSTRACT

Black holes, neutron stars, and white dwarfs present extremes of physics beyond the range of experiments on Earth. By accreting material from companion stars, these systems become visible across Galactic distances in X-rays. We identify key questions about them, addressed by Canadian scientists: What are black holes? What are neutron stars made of? What drives the transfer of material through accretion disks? How are jets formed? Do we see intermediate-mass black holes? How are neutron stars spun up to produce millisecond pulsars? How do white dwarfs produce supernovae? To promote Canadian leadership in these science areas, we recommend that Canada seek involvement (1) in the International X-ray Observatory (IXO); (2) in X-ray missions such as Astro-H to lay the groundwork for IXO; and (3) in first-class ground-based optical and radio telescopes.

*Subject headings:*

## 1. BLACK HOLES

The identification of some X-ray sources as stellar-mass black holes (BHs) accreting from companion stars has been a triumph of general relativity. Measurements of the radial velocity curves of companion stars for 18 X-ray binaries (Fig. 1; most of which undergo transient X-ray brightenings, and periods of X-ray quiescence >1000 times fainter) give clear evidence that the massive compact objects have masses well above 3 $M_\odot$ (Remillard & McClintock 2006), the maximum believable mass for neutron stars, and seem not to have surfaces (e.g. **Rutledge** et al. 2000; Narayan & **Heyl** 2002). (Canadian authors in bold type.) High-angular-resolution infrared observations have constrained the density of the compact mass at the center of our galaxy, ruling out virtually all alternative explanations to a supermassive ($3 \times 10^6$ $M_\odot$) BH (Schodel et al. 2002); see the white papers by **Ferrarese** et al. and **McNamara** et al. (on their manifestations as active galactic nuclei). Now submillimeter observations (involving the Atacama Large Millimeter Array, ALMA, under construction) are close to showing us direct evidence of the event horizon of the central BH, and the motion of material in highly curved spacetime (**Broderick** & Loeb 2006). Compelling evidence that these objects are indeed the BHs predicted by general relativity is likely from expected detections of gravitational waves generated by the inspiral and coalescence of pairs of BHs by detectors such as LIGO (Abramovici et al. 1992), which will encode information on the structure of the merging objects (see **Poisson** et al. white paper).

## 2. GENERAL ACCRETION PROBLEMS

Compact objects, such as BHs, in binary systems accrete matter through an accretion disk, which has a low accretion rate when cold and neutral. If the accretion disk becomes hot enough to be ionized, its viscosity and accretion rate increases dramatically, leading to X-ray "outbursts", as well as outflows of matter. The viscosity mechanism is thought to involve a magnetorotational instability, but is not fully understood (Balbus & Hawley 1998; **Vishniac** 2009). X-ray observations are now reaching the spectral resolution necessary to probe the characteristics (density, temperature, velocity) of the accretion disk and associated outflows (e.g. Miller et al. 2006, Fig. 2), suggesting that a real understanding of the angular momentum transfer process may be reached through higher sensitivity observations at high spectral resolution. The proposed International X-ray Observatory (IXO) is designed to meet this need (see **Gallo** et al. white paper).

The transient X-ray brightenings of X-ray binaries display varied spectral and timing features, interpreted as dramatic changes in the mode and geometry of accretion, between standard thin accretion disks and two-temperature, geometrically thicker flows which advect more of the energy down to the compact object (Remillard & McClintock 2006). Some of these states, and changes between states, are associated with the production of energetic jets (e.g. Fender et al. 2004; Fig. 3). Such jets, on the larger scale of active galactic nuclei, are critical in shaping the evolution of galaxies and clusters of galaxies (**McNamara** & Nulsen 2007). Their production and evolution can be most efficiently studied in X-ray binaries in our galaxy, due to the shorter timescales and simpler geometries present, making studies of X-ray binary states key to understanding jets and their effects. To continue these remarkable discoveries requires advances on several fronts; X-ray spectroscopy (particularly IXO), X-ray timing (requiring high effective area and sub-millisecond timing resolution, from the current RXTE and ASTROSAT to the proposed AXTAR or

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EXIST), and multiwavelength studies (from $\gamma$-ray missions such as Fermi, through optical/infrared telescopes, to radio facilities such as ALMA (under construction), and the proposed Square Kilometer Array (SKA)). A key Canadian opportunity would be involvement in a small X-ray polarimetry satellite (such as GEMS), which can directly explore the geometry of X-ray emission (see **Kaspi** et al. 2009).

## 3. ULTRALUMINOUS X-RAY SOURCES

Ultraluminous X-ray sources are X-ray binaries in other galaxies (not in their nuclei) which show very high X-ray luminosities ($\gtrsim 3\times10^{39}$ ergs/s), higher than the Eddington luminosity limit for a $\sim 20\ M_\odot$ stellar-mass BH. These X-ray binaries may contain BHs of "intermediate mass", between the masses of products of normal supernovae and the supermassive BHs at the centers of galaxies, formed perhaps in stellar clusters (e.g. Portegies-Zwart et al. 2004). Alternatively, they are somehow exceeding the Eddington limit, e.g. by beaming–emitting radiation into less than $4\pi$ steradians (King et al. 2001)–or accreting through a "leaky" disk, allowing super-Eddington accretion (Begelman 2001). Either possibility has implications for understanding active galactic nuclei; identifying intermediate-mass BHs is critical for understanding how supermassive BHs are formed, while jets produced by active galactic nuclei accreting at high rates truncate star formation in galaxies and clusters of galaxies. Extending X-ray studies to higher energies with a focusing hard X-ray telescope (e.g. Astro-H) will allow interpretation of the X-ray spectrum, directly comparing standard vs. super-Eddington accretion models (**Gladstone** et al. 2009; Fig. 4). Direct BH mass measurements should be possible through radial velocity measurements of the faint companion stars, with existing telescopes (e.g. Gemini), or very large planned telescopes such as the Thirty-Meter Telescope (TMT).

## 4. NEUTRON STAR ACCRETION

Neutron stars (NSs) contain matter with mean densities over 3 times the density of atomic nuclei, a state of matter that cannot be directly probed on Earth (see the white paper by **Stairs & Thompson**). Their accretion processes are similar to those of BHs, with two additional factors; the existence of (sometimes strong) magnetic fields that direct the infalling matter, and a stellar surface that is affected by the accretion. Accreting NSs are spun up to shorter periods, and their magnetic field strengths decreases, with time, terminating (for some low-mass companions) in the NSbeing "reborn" as a millisecond radio pulsar (Bhattacharya & van den Heuvel 1991; Fig. 5). The details of how material flows onto the NSs, and thus how the NS is spun up, are unclear (Campana et al. 1998), as are the details of how the magnetic field strength is reduced (e.g. **Cumming** et al. 2001). Nuclear burning on the NS surface, visible as bright thermonuclear flashes or a quasi-periodic component in the persistent emission, can be used to test how the accreted material spreads across the surface of the star (Heger, **Cumming** & Woosley 2007). Recent progress has been driven by the identification of some 12 accreting X-ray binaries showing millisecond pulsations (Wijnands & van der Klis 1998), where the magnetic field can be measured, and the process of spinup and orbital evolution can be directly observed over time and compared with theoretical models (e.g. **Nelson** & Rappaport 2003, **Ivanova** et al. 2008). X-ray and optical observations of millisecond radio pulsars and millisecond X-ray pulsars suggest deep similarities (**Bogdanov** et al. 2005; Deloye et al. 2008). A recent key discovery is a radio pulsar turning on after observations showing an accretion disk (**Archibald** et al. 2009). Progress will require X-ray detectors with sub-millisecond timing resolution and higher sensitivity (ASTROSAT, then AXTAR or EXIST), all-sky X-ray monitoring to catch new objects, and radio pulsar discoveries from the SKA.

## 5. NEUTRON STAR INTERIORS

The composition of NS cores is uncertain–possibilities range from mostly neutrons with <10% protons and electrons, to condensations of pions or hyperons, to deconfined quark matter (Lattimer & Prakash 2004, **Ouyed** & Sannino 2002). These alternatives give different predictions for the maximum masses achievable by NSs, the radii of NSs, and the emission of neutrinos from the core, each of which is testable in X-ray binaries. Thus X-ray binary studies offer the hope of constraining the behavior of matter at extreme densities.

Radio pulsars in double NS systems permit accurate mass measurements, consistent with $1.35\pm0.1$ $M_\odot$(**Stairs** et al. 2004). However, these double NSs require specific evolutionary histories, and may not be representative of all NSs (**van Kerkwijk** 2004). The masses of pulsating X-ray binaries, however, can be measured through optical radial velocity studies (which with X-ray timing of the NS, gives the mass ratio) plus fitting of X-ray eclipse profiles or optical lightcurves (to measure the inclination), e.g. van der Meer et al. (2007). Arguably the highest current mass measurement is the high-mass X-ray binary Vela X-1, with NS mass >1.6 $M_\odot$(Barziv et al. 2001), and accreting millisecond X-ray pulsars are promising targets. Measuring the masses of a variety of NSs requires $R \gtrsim 10000$ spectrographs at a range of telescopes, culminating with the proposed TMT for the faintest NS systems.

Radius constraints are more difficult, but are possible through high-sensitivity X-ray spectroscopy and/or timing (none measure radius directly, but the gravitational redshift or the radiation radius, $R_\infty = R/[1 - 2GM/(Rc^2)]^{1/2}$–therefore measurements of radius *and* mass for the same star would be invaluable). Much effort has been expended searching for absorption lines during thermonuclear burning flashes, which if from the NS surface would allow calculation of the gravitational redshift, a function of the NS mass and radius. An early report of the detection of narrow, redshifted iron and oxygen lines during such a flash (Cottam et al. 2002), which inspired deeper observations of many similar sources, is no longer seen as highly credible (**Chang** et al. 2006; Rauch et al. 2008; Galloway et al. 2009). (Note that broad absorption lines *are* clearly observed from some young NSs, but their interpretation is not yet settled; see the white paper of **Stairs & Thompson**.) An alternative constraint on the compactness of NSs comes from modeling the lightcurves of X-ray pulsars, as the gravitational bending of light smooths the pulse profile from the surface (e.g. **Leahy** et al. 2008; Fig. 6). (Similar work is being done for radio millisecond pulsars, e.g. **Bogdanov** et al. 2007.) Progress here will require high sensitivity, sub-millisecond timing X-ray missions such as AXTAR or EXIST to produce high signal-to-noise lightcurves for multiple sources in multiple outbursts.

Spectroscopy of NSs in deep quiescence, between accretion episodes, can constrain the redshifted NS radius. NSs reradiate the heat which they absorbed during accretion episodes during quiescence, producing a blackbody-like spectral component, modified by passage through a hydrogen atmosphere (Zavlin et al. 1996). Such a component is clearly seen in many NS X-ray binaries in quiescence (**Rutledge** et al. 1999, Fig. 7; a second, harder component is present in many cases, but its nature is not understood). Measuring the NS temperature and luminosity gives $R_\infty/d$; if $d$ is otherwise constrained (e.g. the binary is in a globular cluster, or its distance otherwise determined), the radius can be constrained (**Rutledge** et al. 2002a); the smallest uncertainties are now 12% (90% conf., **Heinke** et al. 2006, Fig. 8). Astro-H will permit better constraints on the harder quiescent spectral component (of unknown origin), and thus help refine results from current soft X-ray telescopes (Chandra and XMM-Newton). IXO promises major progress, as its higher sensitivity will reduce the uncertainties to a few percent, and break the mass/radius degeneracy to give precise masses *and* radii for several NSs, strongly constraining their makeup.

Accretion episodes inject heat into the cores of NSs, which leaks out over long timescales ($10^5$ years). Comparing the quiescent X-ray luminosity of NSs to predictions from their time-averaged mass-transfer history allows us to infer the rate of neutrino emission from the stellar cores (Brown, Bildsten & **Rutledge** 1998). Some NSs show much higher rates of neutrino emission than others, suggesting differences in their central compositions; higher mass NSs likely engage more effective neutrino emission processes (**Heinke** et al. 2007). Immediately after long accretion episodes, the heat deposited in the crust during the most recent episode dominates the quiescent X-ray luminosity, allowing the crust cooling timescale to be measured (e.g. **Rutledge** et al. 2002b). The thermal flux results indicate the location of a transition between a classical and quantum crystal, and the existence of a neutron superfluid throughout the inner crust (Brown & **Cumming** 2009; Fig. 9). An additional probe of the crust temperature comes from long duration thermonuclear flashes, particularly in ultracompact X-ray binaries (**Cumming** et al. 2006). Progress here requires all-sky X-ray monitoring and soft X-ray followup, for which ASTROSAT is well suited.

## 6. ACCRETING WHITE DWARFS

White dwarfs accreting mass are of interest both for detailed studies of their accretion and evolution, and for understanding the Type 1a supernovae produced by thermonuclear explosions of white dwarfs when their masses exceed the limit sustainable by electron degeneracy pressure (see **Carlberg** et al. white paper). White dwarfs provide simpler, closer laboratories to study accretion mediated by strong magnetic fields, and the production of jets. Some Type 1a supernovae may be produced by white dwarfs which accrete at high enough rates to maintain thermonuclear burning continuously on their surface ("supersoft sources"; which prevents the removal of mass by transient thermonuclear explosions), while others are thought to be produced by the merger of pairs of white dwarfs. Radial velocity observations of supersoft sources to determine their component masses are thus critical (Cowley et al. 1998). The evolution of X-ray binaries containing white dwarfs is easier to study than that for other compact objects, due to their greater numbers, allowing modeling of their long-term evolution and Type 1a supernova possibilities (Howell, **Nelson** & Rappaport 2001; **Ivanova** & Taam 2004). Progress in this science requires ground-based optical spectroscopy, such as $R\gtrsim 10000$ spectrographs on $\gtrsim$8-m class telescopes, and innovative surveys such as the Large Synoptic Survey Telescope to identify many more accreting white dwarfs, and all-sky soft X-ray monitoring (e.g. LOBSTER).

## 7. SUGGESTED DIRECTIONS

Canada can play a leading role in these directions, as a partner in major telescopes and by developing small exploratory missions, as outlined in the white paper by **Gallo** et al. and the HEA-DWG report (**Kaspi** et al. 2009). Canadian partnership in missions such as ASTROSAT and telescopes like ALMA is crucial in providing us access to data, as well as for shaping future high-energy directions and training Canadian scientists.

Our major long-term recommendation is that Canada seek involvement in the planning and production of IXO, the key X-ray observatory of the next 20 years (planned launch in 2021; see **Gallo** et al. paper). IXO will provide the high-resolution X-ray spectroscopy and large effective area needed to delve into the physics of accreting matter, and to measure the sizes of neutron stars. Current plans also call for instruments providing hard X-ray imaging, high time resolution, and polarimetry, making IXO ideal for most of the X-ray projects outlined here.

However, X-ray observations, and Canadian involvement, have a long path to IXO. Many of IXO's key technologies (quantum calorimeters, polarimetry, hard X-ray imaging) have not been tested on satellites. Pathfinder missions, such as Astro-H and GEMS, are needed to test these technologies. They also provide opportunities for Canadian industry to become involved, particularly in the area of metrology, critical for hard X-ray imaging. CSA and industry involvement in metrology provides a natural path through Astro-H (anticipated launch 2014) to IXO. Other possibilities include involvement with polarimetry (GEMS, launch 2014), an extremely sensitive all-sky monitor (e.g. LOBSTER) and with a medium-size mission focused on timing such as AXTAR (mid-decade?) or EXIST (∼2017?). Canada should be ready to take advantage of opportunities for Canadian industry and science to work together on any of these missions (see **Gallo** et al., **Kaspi** et al.).

Finally, X-ray observations require multiwavelength input for full understanding. Medium-resolution optical spectroscopy is most critical to Canadian astronomers; in the short-term on current instruments, and on the 2020 timescale for the TMT. Radio observations are crucial for understanding jet formation, in the next few years by the eVLA and ALMA, and by ∼2020 with the SKA. We recommend Canadian involvement across a range of wavelengths, which will maximize Canadian science, sponsor cooperation with Canadian industry, and raise the international profile of Canadian science.

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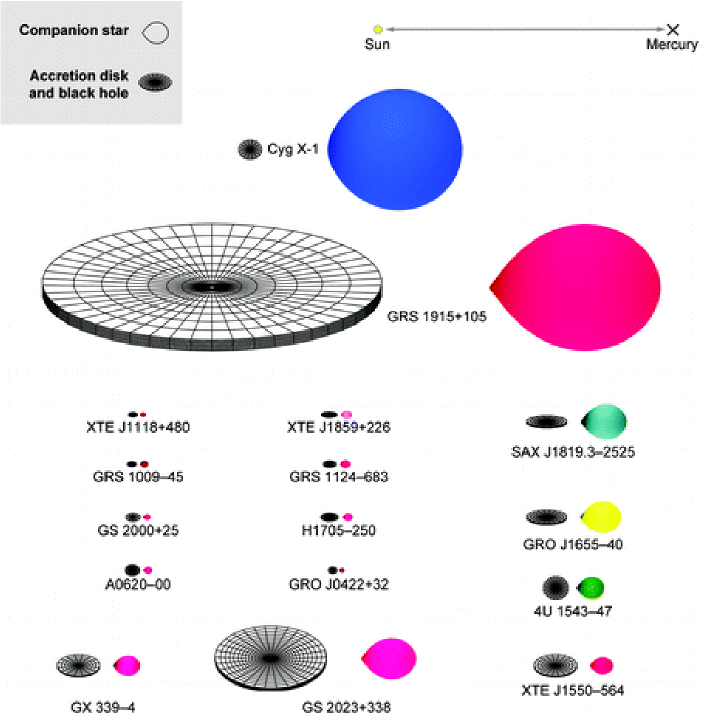

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FIG. 1.— Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz), with the Sun-Mercury distance shown at top. The color of the companion star roughly indicates its surface temperature; the size and inclination of the disks indicate those of the accretion disks. Remillard & McClintock 2006.

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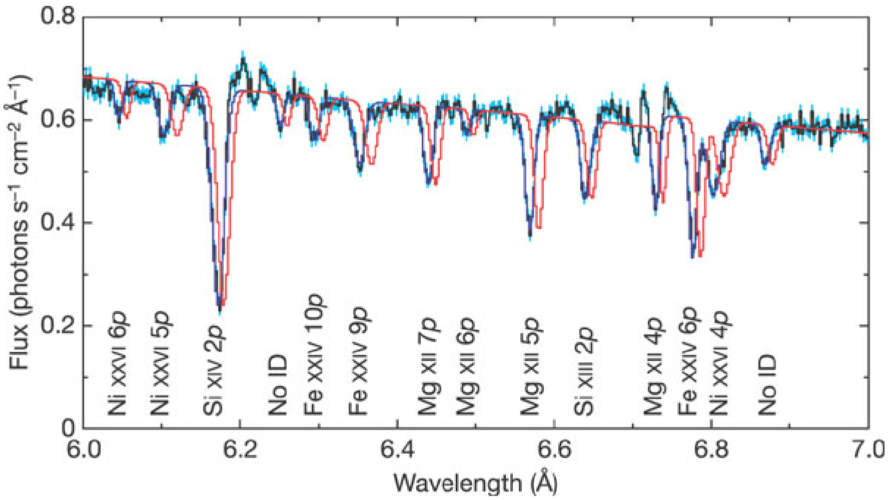

Fig. 2.— Black points are (part of) the disk wind spectrum from GRO J1655-40 obtained with *Chandra* grating spectroscopy, Miller et al. 2006. Best-fit model in blue (red line plots the natural wavelengths, illustrating the blueshift). Identifications of absorption lines are indicated. The outflow velocity and ionization state of this wind have been used to argue that only magnetic-rotational instabilities in the disk can drive this wind.

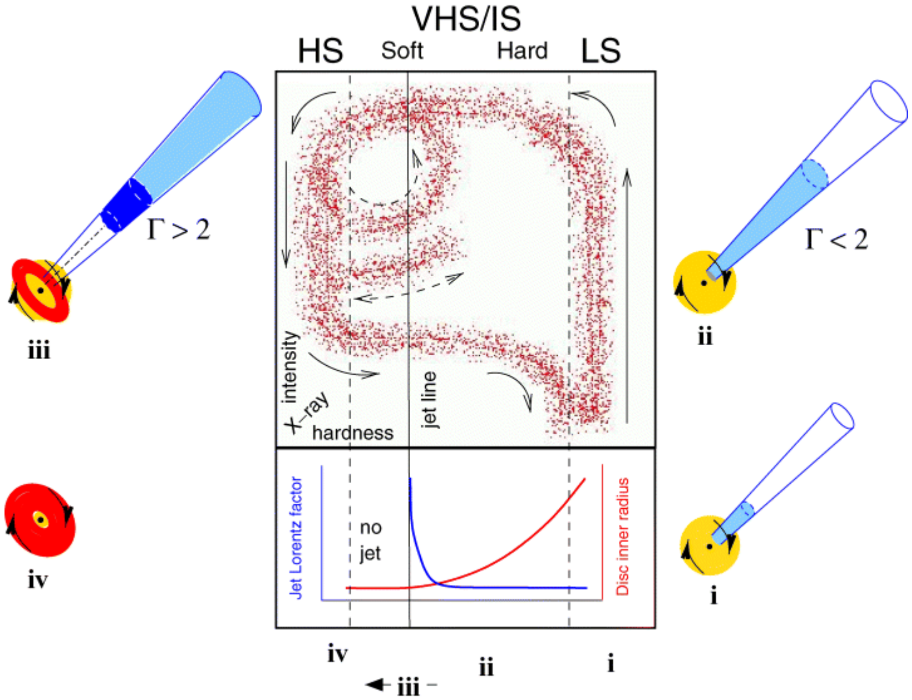

Fig. 3.— Schematic representation of the model for disk-jet coupling in black hole binaries, from Fender et al. 2004. The center box plots X-ray hardness (to right) vs. X-ray luminosity (to top) during a black hole outburst. The lower box suggests qualitatively the variation in the inner radius of the thin disk (material interior to the thin disk is thought to be in a geometrically thick, 2-temperature state) and of the Lorentz factor of the jet. Illustrations show the turning on of a jet as the outburst begins, the production of a jet shock as the disk transitions to the soft (disk-dominated) state, and the termination of the jet.

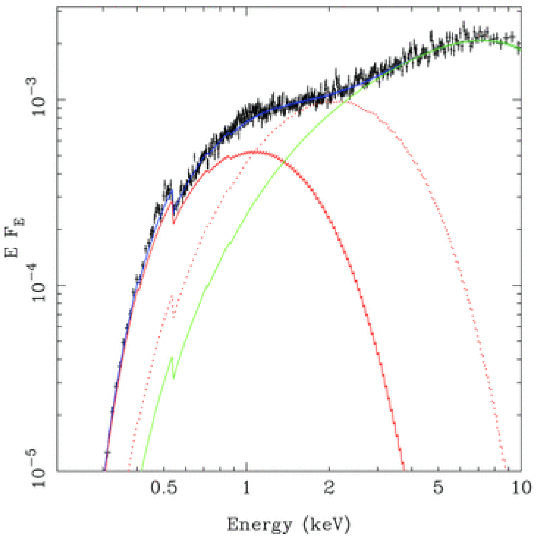

FIG. 4.— XMM-Newton spectrum from the ultraluminous X-ray source Holmberg IX X-1, fit with an X-ray spectral model for super-Eddington accretion onto a stellar-mass black hole (**Gladstone** et al. 2009). The full model is in blue, while the disk components are in red; solid line for the outer disk region, dotted line for the inner disk (energetically coupled to, and masked by, the corona), and green for the optically thick Compton-scattering corona. Observations at higher energies (possible with Astro-H and IXO) can distinguish this model from standard disk models, appropriate for sub-Eddington emission from intermediate-mass black holes.

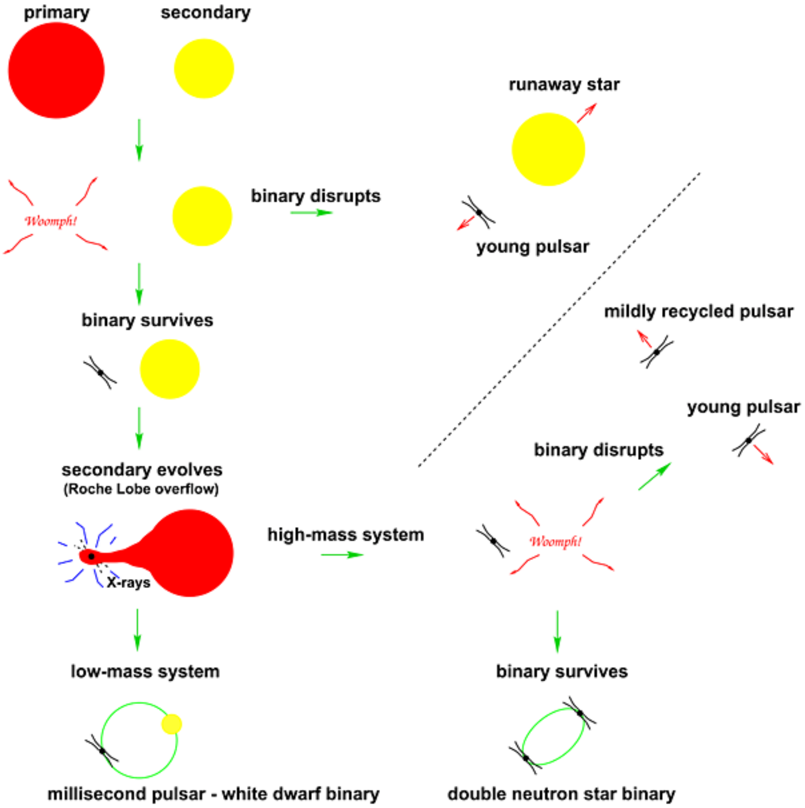

FIG. 5.— Cartoon showing the major known pathways of the evolution of binary star systems containing neutron stars (Lorimer 2008, Living Reviews in Relativity, 11, 8). Supernovae are indicated (Woomph!), as are episodes of accretion and spinup of the neutron star (leading to highly spun-up neutron stars if the secondary is low-mass and thus long-lived).

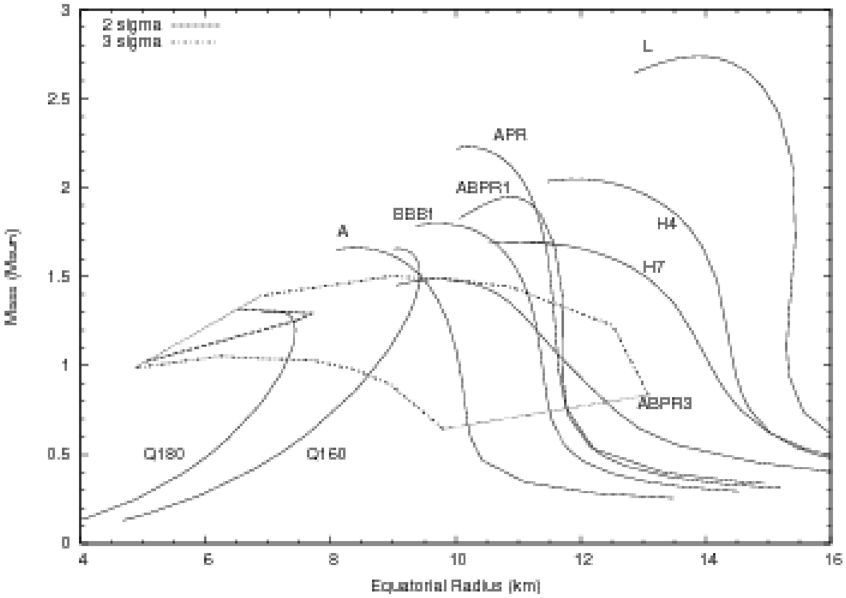

FIG. 6.— Confidence contours in neutron star mass and radius from modeling the lightcurve of SAX J1808.4-3658 (**Morsink & Leahy** 2009, submitted). Plots of the radius for a neutron star over their range of masses (solid curves), are shown for a variety of possible neutron star interior structures, including quark stars (Q180 and Q160). Confidence contours are shown for 2 sigma (dashed) and 3 sigma (dotted).

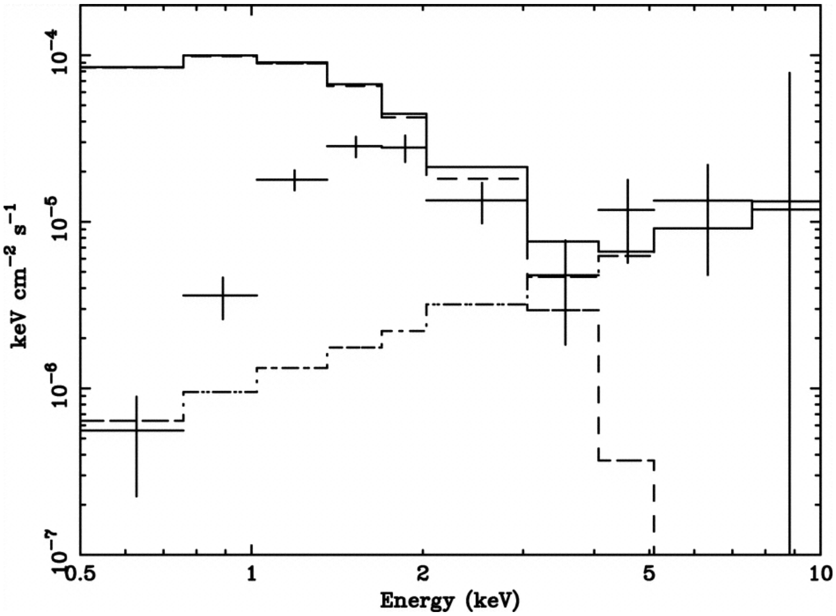

FIG. 7.— *Chandra* X-ray spectrum (data as crosses) of the X-ray binary KS 1731-260 during quiescence, showing two components; a spectrally "hard" component dominant at high energies, described with a power-law, and a "soft" component at low energies due to blackbody-like radiation from the neutron star surface. The intrinsic fluxes from the two components are plotted here, taking into consideration the absorption of low-energy X-rays by interstellar gas and dust.

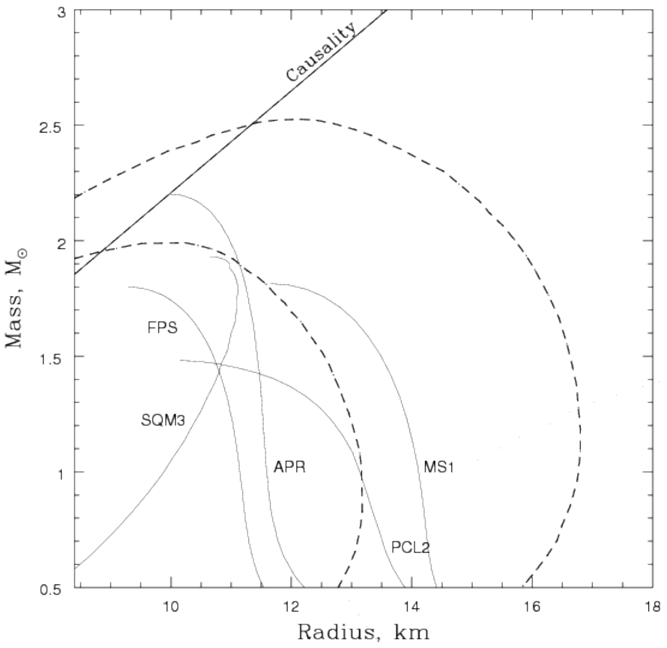

FIG. 8.— 90% confidence contours for the neutron star mass and radius from fitting the spectrum of the quiescent X-ray binary X7 in the globular cluster 47 Tuc with a hydrogen-atmosphere model (**Heinke** et al. 2006). Mass-radius curves for several possible neutron star interiors are shown, as in Fig. 6. The portion of the graph above the line marked Causality cannot contain realistic neutron stars.

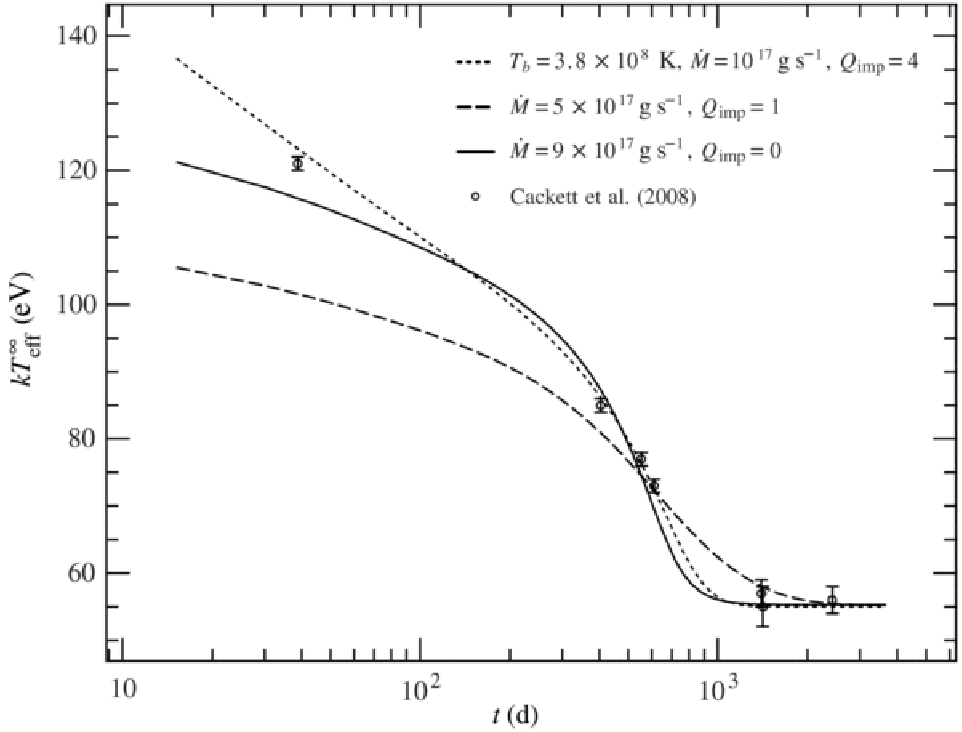

FIG. 9.— Comparison between the observed temperature decrease of an X-ray binary after the termination of accretion (at t=0), and several numerical calculations with different choices of impurity in the crust, mass transfer rate during accretion, and temperature at the base of the crust $T_B$ (Brown & **Cumming** 2008).