Scientific Challenges for a New X-ray Timing Mission

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Abstract. The *Rossi X-ray Timing Explorer* (*RXTE*) is an immensely successful mission of exploration and discovery. It has discovered a wealth of rapid X-ray variability phenomena that can be used to address fundamental questions concerning the properties of dense matter and strong gravitational fields as well as important astrophysical questions. It has answered many questions and is likely to answer many more, but to follow up fully on the major discoveries *RXTE* has made will require a new X-ray timing mission with greater capabilities. This introduction to the present volume describes briefly the advantages of X-ray timing measurements for determining the properties of dense matter and strong gravitational fields, indicates some of the key scientific questions that can be addressed using X-ray timing, and summarizes selected achievements of the *RXTE* mission. It concludes by citing some of the scientific capabilities a proposed follow-on mission will need in order to be successful.

INTRODUCTION

The "X-ray Timing 2003" meeting was convened to review the important scientific advances that have been achieved during the past two years with *RXTE* and to ask what important questions can now be addressed by the *RXTE* mission, what questions could be answered by a new, more capable X-ray timing mission, and what instruments and performance a new timing mission would need to answer them.

The properties of ultradense matter and strongly curved spacetime are among the most fundamental current problems in physics and astronomy. Neutron stars and black holes provide cosmic laboratories that allow us to test our understanding of physics at ultrahigh densities and in strong gravitational fields, regimes that are not accessible in terrestrial laboratories.

In this introductory paper I indicate the advantages of X-ray timing measurements for studying the fundamental physical and astrophysical questions posed by neutron stars and black holes, summarize some of the most important scientific results that have been achieved using *RXTE*, and note some of the scientific and technical issues that need to be considered for a new X-ray timing mission. I do not attempt to be comprehensive or to provide complete (or even adequate) references in this introduction. The papers that follow address more thoroughly the questions and results introduced here and provide many references to the literature that describes them.

Important advances made early in the *RXTE* mission included the discovery of $\sim$300–600 Hz oscillations in the emission of weak-field accreting neutron stars during thermonuclear X-ray bursts, of kilohertz quasi-periodic oscillations (QPOs) in the accretion-powered X-ray emission of such stars, and of $\sim$50–300 Hz oscillations in the accretion-powered X-ray emission of black holes of stellar mass.

During the past year, the *RXTE* mission has achieved major breakthroughs in the core *RXTE* science of neutron stars, black holes, and strong gravity. These advances are arguably the most important since those made during the first year of the mission. Discoveries made during the past year have demonstrated conclusively that the X-ray burst oscillations are produced by the spin of the star and that the star's spin plays a central role in generating the kilohertz QPOs. These advances support the basic idea that interaction of the star's spin with the orbital motion of gas around the star is important, while forcing revision of our ideas about the specific mechanism involved.

Many of these advances are the result of detailed studies of accretion-powered millisecond X-ray pulsars. Long predicted, these pulsars were finally discovered using *RXTE*. Five such pulsars have been found so far—four within the past two years—and all are transient sources that remain bright for only a few weeks. They have been discovered in part by systematic searches that made use of what we learned from the first accretion-powered millisecond pulsar discovered. Other discoveries made during this period have sharpened basic questions concerning the mechanisms responsible for generating the high-frequency X-ray oscillations of black holes and appear to exclude many previous ideas about how these QPOs are produced.

Importantly, the relationships revealed by these discoveries are relatively simple and indicate that high-frequency oscillations can indeed be used as tools to study quantitatively the strong gravity and fundamental physics of neutron stars and black holes, as well as important astrophysical questions. There is every reason to believe that similar advances are possible during the next 2 to 4 years. RXTE is uniquely able to study accretion-powered millisecond pulsars and the high-frequency X-ray oscillations and variability of stellar-mass black holes.

THE PROMISE OF X-RAY TIMING

Neutron stars and black holes provide cosmic laboratories for studying important astrophysical questions and questions of fundamental physics—including the properties of ultradense matter and strong gravitational fields—that cannot be addressed in terrestrial laboratories. X-ray timing measurements have important advantages for studying these objects:

- Much of the power from accreting neutron stars and black holes is at X-ray energies.
- X-radiation is by its nature relatively penetrating.
- Timing of the rapid X-ray variability of these objects reveals their characteristic frequencies.
- Interpretation of X-ray timing measurements is relatively simple for rotating motions.
- In many cases, high-precision measurements are possible.

Questions of fundamental physics that can be addressed by high-resolution X-ray timing measurements include:

- What are the properties of ultradense matter?
- What are the properties of strong gravitational fields?
- What are the effects of quantum electrodynamics in superstrong magnetic fields?

Important astrophysical questions that can been explored by X-ray timing measurements include:

- What are the masses, spin rates, and magnetic fields of neutron stars and how do they evolve with time?
- What nuclear processes occur in accreting neutron stars?
- Do accreting neutron stars produce significant gravitational radiation?
- What are the masses and spin rates of stellar-mass black holes? Of supermassive black holes?
- What are the structures of accretion disks?
- How do iron lines form in active galactic nuclei?
- Do active galactic nuclei produce quasi-periodic brightness oscillations similar to those of galactic black-hole candidates?

The *RXTE* mission has revealed not only that the X-ray emission of neutron stars and black holes varies on the natural dynamical times scales of these objects, which was expected, but also that much of this variation is *systematic* and relatively (sometimes even highly) *coherent*, allowing precise measurements to be made. Examples of X-ray variations that can be measured with high precision include:

- Neutron star spin frequencies, which are extremely stable and of fundamental importance for understanding the properties of neutron stars and gravitational radiation and the evolution of accreting neutron-star systems.
- X-ray burst oscillation frequencies, which are relatively stable and highly stable in the tails of some bursts and can therefore be measured with high precision.
- QPO frequencies, some of which are relatively stable (Q values $\nu/\delta\nu$ up to ~ 200) and can therefore be measured with relatively high-precision.

Major recent advances in understanding these X-ray variations are described below. Measurements of these systematic, rapid, and relatively coherent X-ray variations can in principle be used to determine with precision the properties of dense matter and strong gravitational fields.

SELECTED SCIENTIFIC ACHIEVEMENTS OF *RXTE*

The discovery using *RXTE* of oscillations in the X-ray emission of accreting neutron stars and black holes that have frequencies comparable to dynamical frequencies near these objects has provided important new tools for studying the properties of dense matter and strong gravitational fields.

RXTE observations of neutron stars in low-mass X-ray binary systems (LMXBs) have proved to be particularly valuable for investigating the innermost parts of accretion disks, gas dynamics and radiation transport in strong radiation and gravitational fields, and the properties of dense matter, because the magnetic fields of many of these stars are relatively weak ($\sim 10^7$–10^{10} G) but not negligible. Magnetic fields of this size are weak enough to allow at least a fraction of the accreting gas to remain in orbit as it moves into the strong gravitational and radiation fields of these stars, but strong enough to produce anisotropic accretion flows and X-ray emission, allowing the spin rates of these stars to be determined. The "clockwork" of these systems is remarkably regular and systematic.

Among the most important results obtained by *RXTE* that bear on the fundamental physics of accreting neutron stars are:

- Discovery of the long-sought accretion-powered millisecond X-ray pulsars. Five have now been discovered (see below), with spin frequencies ranging from 185 Hz to 435 Hz. Study of these systems has had an enormous impact on our understanding of the high-frequency variability of accreting neutron stars, the formation of millisecond rotation-powered pulsars, and the evolution of ultracompact binary systems.
- Discovery of twin kilohertz QPOs (see Fig. 1). They have now been detected in 25 weak-field neutron stars and have frequencies ranging from $\sim$100 Hz up to $\sim$1300 Hz. The separation of the twin peaks remains constant to within a few tens of Hz while their frequencies vary by factors of at least $\sim$2–3. Some kilohertz QPOs have rms amplitudes $\sim$15% and values of $Q \equiv \nu/\delta\nu \sim 200$. They are so common that they are almost as good an indicator of neutron stars as are thermonuclear X-ray bursts.
- Discovery of millisecond oscillations during thermonuclear X-ray bursts (see Fig. 2). These have now been detected in 13 accreting neutron stars, with frequencies ranging from 270 Hz to 619 Hz.

As discussed below, the study of these oscillations is providing a wealth of diagnostic information about the gravitational fields, magnetic fields, spin rates, masses, and radii of these neutron stars.

RXTE observations of black holes in low-mass binary systems have provided a wealth of information about the innermost parts of accretion disks around black holes, gas dynamics and radiation transport in strong gravitational fields, and the properties of stellar-mass black holes. Among the most important results obtained by *RXTE* that bear on the properties of black holes in binary systems are:

- Discovery of multiple high-frequency QPOs (see Fig. 3). They have now been detected in 7 black holes in binary systems and have frequencies ranging from $\sim$40 Hz up to 450 Hz.
- Discovery of a strong correlation between the X-ray spectra and X-ray variability of accreting black holes of stellar mass.
- Discovery that the launch of jet material is correlated with changes in the inner part of the accretion disk ("disk-jet connection").

The study of this X-ray variability is providing tantalizing clues about the masses and spin rates of these black holes and the strongly curved spacetime near them.

The discovery with *RXTE* of X-ray variability on the natural dynamical time scales of black holes and neutron stars has revolutionized the study of accretion and X-ray emission by these objects. The highest-frequency oscillations are thought to come from regions where the grav-

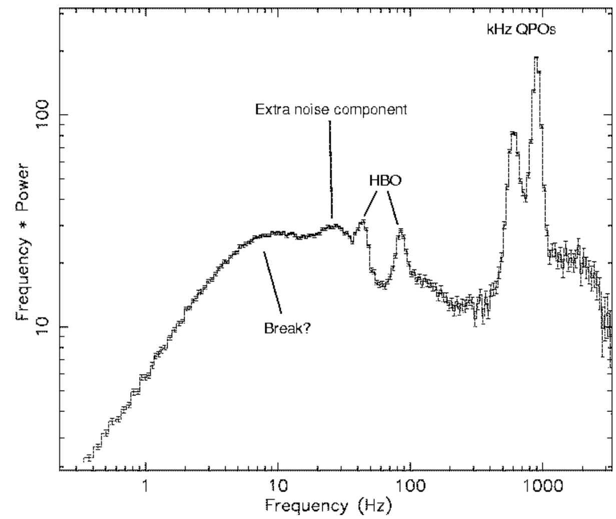

FIGURE 1. Twin kilohertz QPOs and other variability of the X-ray flux of Sco X-1. The total variation (power density times frequency) is dominated by the kilohertz QPOs, which in this observation are at $\sim$600 Hz and $\sim$900 Hz. The horizontal-branch oscillation (HBO) at $\sim$50 Hz and its second harmonic at $\sim$100 Hz are also visible, as are several broad-band noise components. After [10].

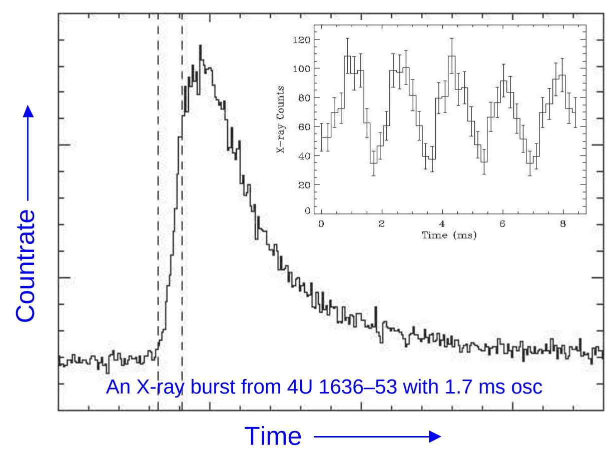

FIGURE 2. X-ray burst and millisecond burst oscillations seen in 4U 1636$-$53. *Main panel*: X-ray countrate vs. time in 2-second units, showing the rapid rise and approximately exponential decay of the burst. *Inset panel*: X-ray light curve during the time interval bounded by the vertical dashed lines in the main panel, showing the strong $\sim$580 Hz brightness oscillations during this phase of the burst. T. Strohmayer, personal communication; see also [8].

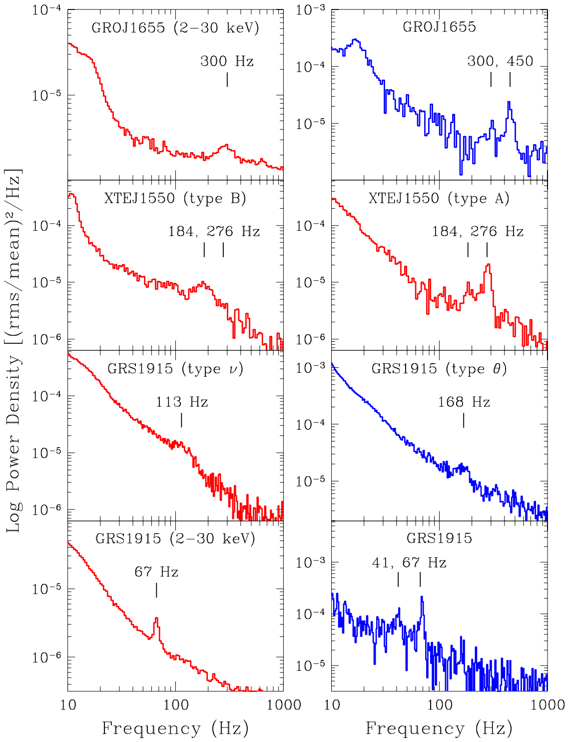

FIGURE 3. Power density spectra of the X-ray brightness variations observed in three galactic black-hole candidates. Dark curves are power spectra based on counts in the 13–30 keV band whereas the lighter curves are based on counts in the 6–30 keV band or, when noted in the figure, the 2–30 keV band. Note the QPO peaks at 300 Hz and 450 Hz in the power spectra of GRO J1655−40, at 184 Hz and 276 Hz in the power spectrum of XTE J1550−564, and at 41 Hz, 67 Hz, 113 Hz, and 168 Hz in the power spectra of GRS 1915+105. After [5, 6, 7].

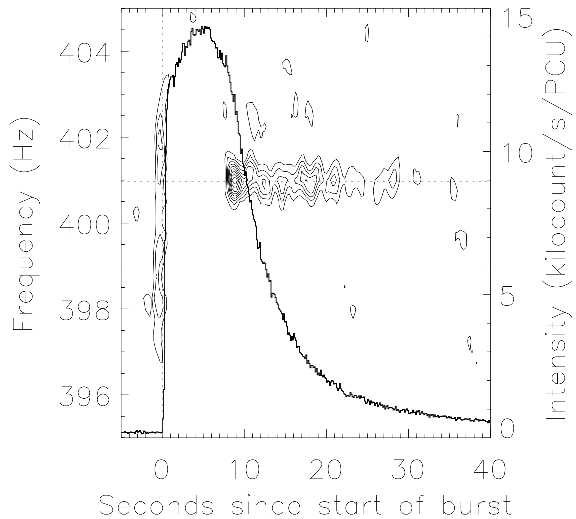

FIGURE 4. An X-ray burst with millisecond X-ray brightness oscillations observed in SAX J1808.4−3658 on 18 October 2002. *Dark curve and scale at right*: X-ray countrate as a function of time during the burst. *Contours and scale at left*: Dynamic power spectrum of the X-ray brightness, showing the rapid increase in the frequency of the burst oscillations from 397 Hz to 403 Hz during the rise of the burst, the disappearance of the oscillations at the peak of the burst, and their reappearance about 10 s after the start of the burst. The horizontal dashed line shows the frequency of the neutron star's spin inferred from its accretion-powered brightness oscillations. From [1].

itational field of the compact object is very strong. Study of these oscillations may provide the best near-term opportunity to observe and measure general relativistic effects that have no analogs in Newtonian gravity and to determine the properties of the ultradense matter in neutron stars. Before the launch of *RXTE*, Newtonian models were often used; since the launch of *RXTE*, strong-field general relativistic calculations have become the norm and are often required for quantitative comparisons of models with *RXTE* data.

An example of a strong-field effect is the absence of stable circular orbits close enough to sufficiently compact relativistic objects. Gravitomagnetic (Lense-Thirring) precession is an example of an effect that is typically weak in astrophysical systems but has no Newtonian analog. (The term "gravitomagnetic" refers to the close analogy between the motion of a test particle in the spacetime near a circulating mass current and the motion of a charged particle in the magnetic field near a circulating electrical current. No magnetic field is involved.) *RXTE* continues to provide a wealth of new information on conditions close to the surfaces of neutron stars and the event horizons of black holes and to stimulate imaginative new thinking about the physical processes that operate in these extreme conditions.

RXTE is continuing to make important progress in addressing its core science goals. Major breakthroughs made within the past two years include:

- Discovery of 4 more accretion-powered millisecond X-ray pulsars, establishing beyond any doubt that many accreting neutron stars in LMXBs have dynamically important magnetic fields.
- Detection of persistent periodic oscillations at the stellar spin frequency ("pulsations") *and* oscillations during thermonuclear X-ray bursts ("burst oscillations") *in the same star*. Both types of oscillations are observed in the accretion-powered millisecond X-ray pulsars SAX J1808.4−3658 [1] and XTE J1814−338 [9].
- Demonstration that the frequency of the burst oscillations in these two pulsars is equal to the spin frequency of the star (see Fig. 4), establishing beyond any doubt that burst oscillations are produced by

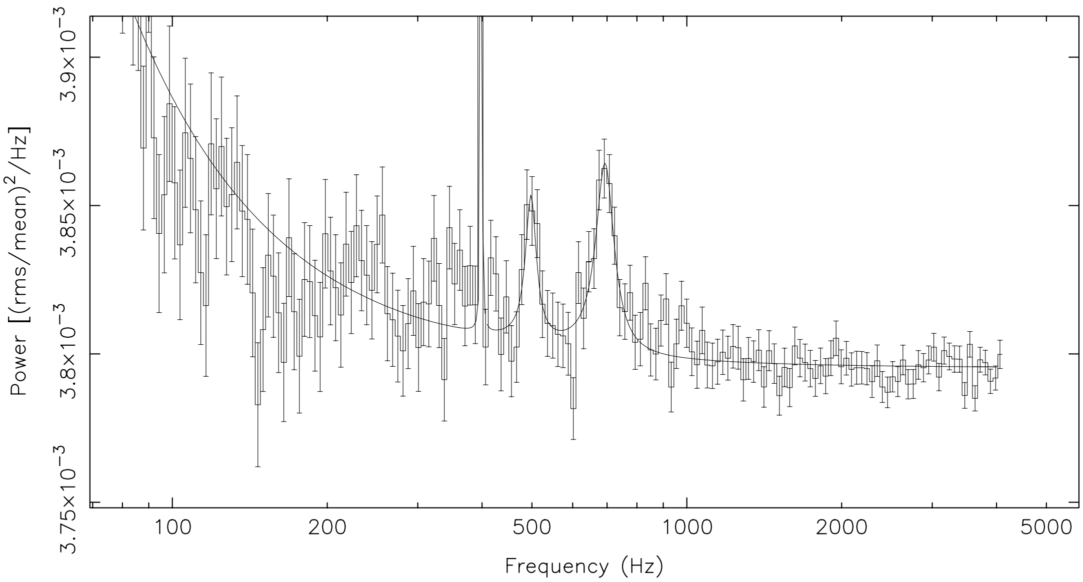

FIGURE 5. Power density spectrum of the X-ray brightness variations of the accretion-powered millisecond X-ray pulsar SAX J1808.4−3658 observed on 18 October 2002, showing the 401 Hz periodic oscillations ("pulsations") at the star's spin frequency, the lower kilohertz QPO at 499±4 Hz and the upper kilohertz QPO at 694±4 Hz [11]. The separation between the kilohertz QPO pair is consistent with *half the spin frequency*, showing that the spin of the star plays a central role in the generation of the kilohertz QPOs. Twin kilohertz QPOs have also been discovered in a second accreting millisecond X-ray pulsar, XTE J1807.4−294, which has a spin frequency of 191 Hz [3]. In this pulsar, the separation between the kilohertz QPO pair is consistent with *the spin frequency*, confirming the central role of the stellar spin in the generation of the kilohertz QPOs.

spin modulation of the burst flux from the neutron star surface and reveal directly the spin frequency of the star. This discovery is making possible more detailed observational and theoretical studies of nuclear burning in the surface layers of spinning neutron stars.

- The fact that the frequency of burst oscillations is equal to the spin frequency of the neutron star means that measurements of burst oscillation frequencies can be used to determine the distribution of neutron star spins, to study the spin evolution of neutron stars in LMXBs, and to explore directly, for the first time, the connection between millisecond accretion-powered pulsars and millisecond rotation-powered pulsars.
- The discovery that the burst oscillations in SAX J1808.4−3658 and XTE J1814−338 are closely phase-locked to their persistent periodic oscillations. This confirms that these two neutron stars have dynamically important magnetic fields and opens for direct study the effects of stellar magnetic fields on the development of X-ray bursts.
- The discovery of twin kilohertz QPOs in the pulsars SAX J1808.4−3658 [11] (see Fig. 5) and XTE J1807−294 [3]. These discoveries establish beyond any doubt that some neutron stars that produce kilohertz QPOs have dynamically important magnetic fields.
- The discovery that the separation of the twin kilohertz QPOs in XTE J1807−294 is equal to the spin frequency [3] whereas the frequency separation in SAX J1808.4−3658 is *half* the spin frequency [11].
- These new results provide further support for models in which the frequency of the upper kilohertz QPO is the frequency of gas orbiting the neutron star at a special radius. Assuming this is the case, the frequency of the upper kilohertz QPO can be used to derive strong constraints on the masses and radii of the neutron stars that produce kilohertz QPOs and the equation of state of neutron-star matter (see Fig. 6).
- These discoveries falsify models in which the frequencies of the kilohertz QPOs are various relativistic precession frequencies or are generated by interactions between these frequencies, because these models cannot explain the commensurability of the kilohertz QPO frequency separation and the spin and require spin frequencies much higher than those observed.
- These discoveries confirm the prediction of the original sonic-point beat-frequency model [4] that the

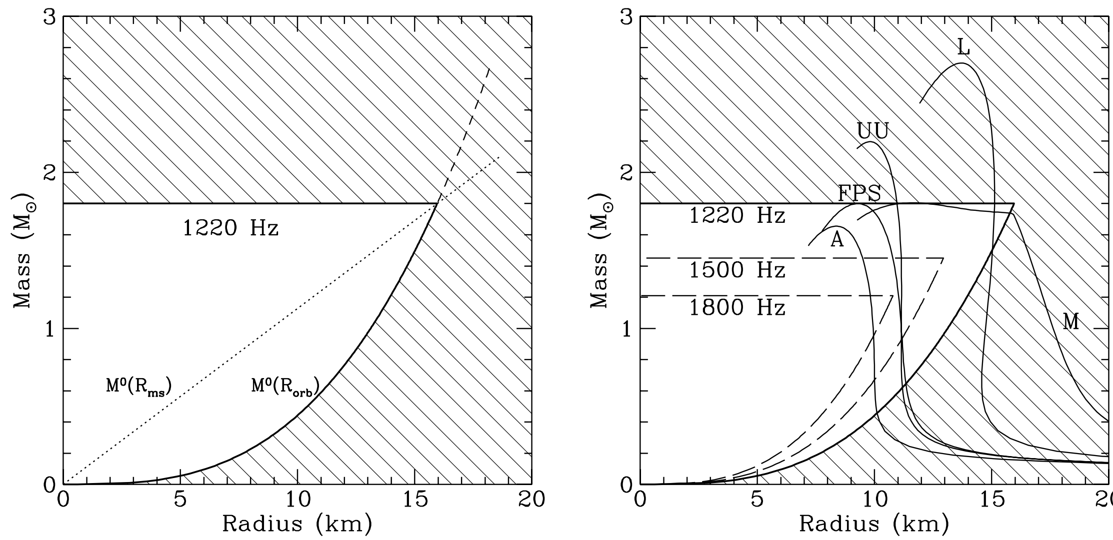

FIGURE 6. Radius-mass plane showing the constraints on neutron star masses and radii and the equation of state of neutron-star matter that can be derived from the frequency of the upper kilohertz QPO, here 1220 Hz, which is thought to be the orbital frequency of gas accreting onto the star. *Left panel*: The dashed curved line shows the relation between the mass of the star and the radius $R_{\rm orb}$ of the orbit for a nonrotating star, which is an upper bound on the radius of a nonrotating star. The diagonal dotted line shows the relation between the mass of the star and the radius $R_{\rm ms}$ of the marginally stable orbit, which must be larger than $R_{\rm orb}$ in order for the gas to make the hundreds of orbits around the star indicated by the coherence of the kilohertz QPO waveform. Consequently the mass and radius of the star must correspond to a point inside the unshaded "slice of pie". If the QPO frequency is shown to be that of the marginally stable orbit, then $R_{\rm orb} = R_{\rm ms}$ and the mass of the star is determined precisely. *Right panel*: Curves of mass-radius relations for nonrotating stars constructed using several proposed neutron-star matter equations of state (EOS), showing that a 1220 Hz QPO is barely consistent with EOS M. The higher the observed QPO frequency, the tighter the constraints. After [4].

separation of the kilohertz QPOs is commensurable with the spin of the neutron star and that the stellar spin plays a central role in the generation of the kilohertz QPOs. But they also show that the original model is incorrect or at least incomplete, because it cannot explain a frequency separation equal to *half* the spin frequency.

- These new results appear to restrict possible mechanisms for generating kilohertz QPOs separated by half the spin frequency to mechanisms in which the stellar spin forces commensurate motions in the accretion flow, perhaps by resonant excitation. One possibility is resonant excitation of vertical motion of the gas in the disk at the radius where the vertical epicyclic frequency resonates with the stellar spin. The lowest-order linear resonance of this type can excite vertical motion at a frequency equal to half the stellar spin frequency [2].

Other examples of important recent advances using *RXTE* include the demonstration that soft γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are isolated neutron stars with similar properties, including superstrong magnetic fields; observations showing that X-ray and TeV flares of Blazars are correlated; measurements of the variability of broad iron K lines in active galactic nuclei which show that the formation of these lines may be more complex than originally thought. These and many other important new results are discussed in the papers that follow.

A NEW X-RAY TIMING MISSION

What performance should the next-generation X-ray timing mission have? Obviously, such a mission would require a highly capable main instrument with an effective area substantially larger than *RXTE* and covering at least the ~ 5 keV to ~ 15 keV energy band in which the rms relative amplitudes of the high-frequency X-ray oscillations of neutron stars and black holes tend to be high. An effective area ~ 10 m^2 would enable study of the waveforms of the various types of high-frequency oscillations with modest averaging. An energy resolution $E/dE \sim 20$ or better would be highly desirable.

The community's experience using *RXTE* shows that a highly capable all-sky monitor is also essential, because so many cosmic X-ray sources of fundamental importance are transient. These include all the known accretion-powered millisecond pulsars and most of the black holes discovered to date. These sources rise in brightness within a few days and remain bright enough for study at the highest time resolutions for only a few days or weeks. The *RXTE* mission has shown that being able to point the main instrument anywhere in a large sector of the sky and to re-point it on relatively short notice is important for making full use of an all-sky monitor and maximizing the science return.

To be successful in gaining scientific support and funding, a new X-ray timing mission must meet at least four requirements:

- A compelling case must be made that a follow-on mission will answer definitively at least one or two fundamental questions. The results obtained using *RXTE* indicate that this case can be made for a larger-area X-ray timing mission.
- The satellite and instruments must have the capacity to make unexpected discoveries. Again, the community's experience using *RXTE* indicates that a larger-area X-ray timing mission with an all-sky monitor would have this capability.
- A follow-on mission must be able to support other prospective missions, such as *Advanced LIGO*, *LISA*, and *Constellation-X*. A new X-ray timing mission is the only way to achieve independent timing of several different types of gravitational wave sources that *Advanced LIGO* and *LISA* are expected to observe.
- The mission concept must attract the interest of a broad section of the astrophysics and physics communities, including more theorists. Given the capabilities and expected achievements outlined here, this should be possible.

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REFERENCES

1. Chakrabarty, D., Morgan, E.H., Muno, M.P., Galloway, D.K., Wijnands, R., van der Klis, M., and Markwardt, C.B., Nature, 424, 42 (2003).
2. Lamb, F.K., and Miller, M.C., submitted, astro-ph/0308179.
3. Markwardt, C.B., et al., in preparation (2004).
4. Miller, M.C., Lamb, F.K., and Psaltis, D., ApJ, 508, 791 (1998).
5. Remillard, R.A., Muno, M.P., McClintock, J.E., and Orosz, J.A., ApJ, 580, 1030 (2002).
6. Remillard, R.A., Muno, M.P., McClintock, J.E. and Orosz, J.A., in Proc. 4th Microquasar Workshop, eds. Durouchoux, Fuchs, and Rodriguez (Center for Physics: Kolkata), 57.
7. Remillard, R.A., Muno, M.P., McClintock, J.E., and Orosz, J.A., BAAS, 35, 648 (2003).
8. Strohmayer, T.E. et al., ApJ, 498, L135 (1998).
9. Strohmayer, T.E., Markwardt, C.M., Swank, J.H., and in't Zand, J.J.M., ApJ, 596, L67 (2003).
10. Wijnands, R., and van der Klis, M., ApJ, 482, L65 (1997).
11. Wijnands, R., van der Klis, M., Homan, J., Chakrabarty, D., Markwardt, C.B., and Morgan, E.H., Nature, 424, 44 (2003).