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X-ray timing beyond the Rossi X-ray Timing Explorer

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Abstract

With its ability to look at bright galactic X-ray sources with sub-millisecond time resolution, the Rossi X-ray Timing Explorer (RXTE) discovered that the X-ray emission from accreting compact stars shows quasi-periodic oscillations on the dynamical timescales of the strong field region. RXTE showed also that waveform fitting of the oscillations resulting from hot spots at the surface of rapidly rotating neutron stars constrain their masses and radii. These two breakthroughs suddenly opened up a new window on fundamental physics, by providing new insights on strong gravity and dense matter. Building upon the RXTE legacy, in the Cosmic Vision exercise, testing General Relativity in the strong field limit and constraining the equation of state of dense matter were recognized recently as key goals to be pursued in the ESA science program for the years 2015–2025. This in turn identified the need for a large (10 m^2 class) aperture X-ray observatory. In recognition of this need, the XEUS mission concept which has evolved into a single launch L2 formation flying mission will have a fast timing instrument in the focal plane. In this paper, I will outline the unique science that will be addressed with fast X-ray timing on XEUS.

Keywords: Stars: neutron; Stars: black holes; General relativity; Accretion; Accretion disk; X-rays: stars

1. Fast time variability and strong gravity

The X-ray emission from accreting compact stars (neutron stars and black holes) has been shown to vary on (sub)-millisecond timescales, i.e., on timescales comparable to the dynamical timescales of the innermost regions of the accretion disk. This variability was discovered with RXTE (Bradt et al., 1993) just 10 years ago in the form of kilo-Hz quasi-periodic oscillations (QPOs) in Fourier power density spectra (see the review by van der Klis (2006) and Fig. 1). There is a wide consensus that these QPOs probe the motion of matter under strong gravity with the signal originating from within a few Schwarzschild radii of the compact star. This is a region where the spacetime curvature is extreme, orders of magnitude larger than that sampled in weak field tests (e.g., Gravity-Probe B). This is a regime where the most dramatic effects of GR are expected, and where fundamental predictions of GR, such as the existence of an innermost stable circular orbit (ISCO) have yet be tested. With RXTE, X-ray timing has thus become a complementary tool to X-ray spectroscopy, polarimetry and gravitational wave measurements to probe strong field GR. It has even been claimed that studying black hole variability might be used to test alternative theories of gravity (Psaltis, 2004).

1.1. Overall QPO properties

It is beyond the scope of this paper to review the properties of kHz QPOs, and the reader is referred to van der Klis (2006) for a recent review and *X-ray Timing 2003 – Rossi and Beyond* by Kaaret, Lamb and Swank (2004, AIP Conference Proceedings, vol. 714, Melville, NY: American Institute of Physics) on which the present paper draws heavily on. Here I will focus on their general properties, relevant to some of the points discussed below. So far, kHz QPOs have been detected from about 20 neutron star low-mass X-ray binaries (about 10% of known systems) (Swank, 2004), and from a

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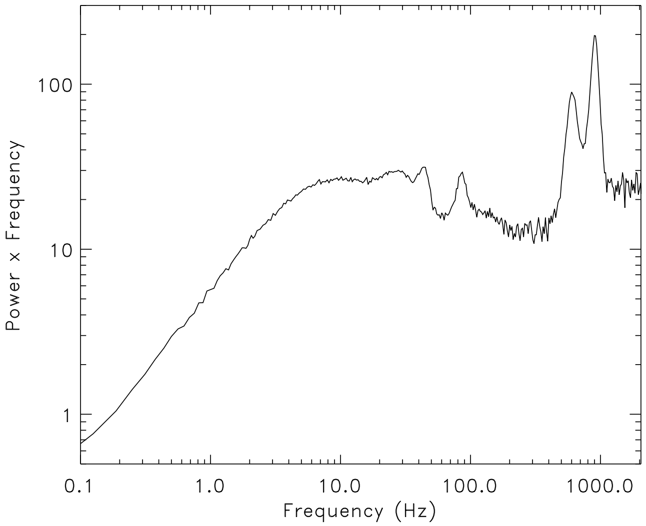

Fig. 1. Power density spectrum of Sco X-1 in a $\nu F\nu$-like representation, showing two kHz quasi-periodic oscillations (data courtesy of Michiel van der Klis).

handful of binaries containing a black hole candidate. In general 2 kHz QPOs are observed. The properties of the QPO (frequency, amplitude and width) vary in a complicated way with parameters such as the source luminosity. For neutron stars, the QPO frequencies can vary by at least two orders of magnitude with the amplitude decreasing with increasing frequency. There is a trend for the QPO fractional amplitude to increase with energy, reaching in some cases 20% at ~20 keV. In black holes, QPOs are detected closer to the sensitivity limit of RXTE with typical amplitudes of 1%: they are transient, show stable frequencies and are detected in the hardest X-ray bands (typically above 10 keV) (Remillard, 2004).

1.2. *QPO interpretation*

The true nature of the underlying signal is unknown and there is a wide range of possible models to be considered, mostly focussing on predicting QPO frequencies. Because the disk is a natural source of periodicities, from orbital to epicyclic motions and disk oscillations, it is generally agreed that QPOs originate in the cool (~1–2 keV) accretion disk. This implicitly assumes that the oscillator must survive the strong damping forces thought to be present in the disk and that an amplification mechanism operates to account for the fact that QPOs show larger amplitude at higher energies (~10–20 keV). For neutron star QPOs, the main constraint for the models so far comes the observation that the frequency separation between the twin QPOs is close to the spin frequency or half the spin frequency of the neutron star (where that is known). This strongly suggests that the spin is involved in the generation of the QPOs. For black holes, the main constraint for the models comes from the observations that QPOs, when observed in pairs, have commensurate frequencies, with ratios close to small integer ratios (e.g., 3:2) (Remillard, 2004), lending support to the idea that a resonance mechanism is involved in the make up of the QPOs.

Some models (not all of them consistent with the constraints above) relate QPO frequencies directly characteristic frequencies of test particles moving in the strongly curved spacetime (General Relativistic orbital and epicyclic frequencies (Abramowicz and Kluźniak, 2004)), others link the QPO frequencies to the frequency of orbiting clumps interacting with radiation from the neutron star (Miller et al., 1998). Some models involve global disk oscillations, relativistic (Kato, 2001), or not (Titarchuk and Wood, 2004). Yet others associate QPOs with strong field GR effects, e.g., relativistic dragging of inertial frames (Stella and Vietri, 1999), see (van der Klis, 2006) for a more complete list of references.

There is, however, a trend in the models to associate QPOs with resonance phenomena, involving General Relativistic frequencies. As an example, in the accreting millisecond pulsar, SAXJ1808-3658, it has been proposed that the two QPOs (whose frequency difference is just equal to half the neutron star spin frequency) are generated at a radius in the disk where the difference between the general relativistic orbital frequency and radial epicyclic frequency is equal to half the spin frequency (Wijnands et al., 2003). Similarly, to account for the 3:2 frequency ratios observed in black hole systems, a parametric resonance concept has been put forward, in which the QPOs are produced at a radius in the disk where two of the three general relativistic frequencies (orbital, vertical and radial epicyclic) have commensurate values, matching the observed QPO frequencies (Abramowicz and Kluźniak, 2004). Although this is still very much under discussion, it is interesting to note that the latter two models link QPOs directly to general relativistic frequencies.

1.3. *The innermost stable circular orbit*

The ISCO is one of the key predictions of strong gravity GR stating that there exists a region around sufficiently compact stars within which no stable circular orbital motion is possible. In a Schwarzschild geometry, the radius of the ISCO is 6 GM/c^2, which is larger than the radii of neutron stars, deduced from models constructed with most modern high-density equations of state (Akmal et al., 1998). Interestingly enough, claims have already been made that the QPO properties have revealed signatures of the ISCO. Prior to the launch of RXTE, it was suggested that the ISCO might induce a frequency cutoff in the power density spectrum (Kluzniak et al., 1990). After the discovery of kHz QPOs, it was proposed that signatures of the ISCO could include a frequency saturation of kHz QPOs with increasing mass accretion rate, or a drop in the quality factor and amplitude of kHz QPOs as they approach a limiting frequency (Miller et al., 1998). A saturation of the QPO frequency with count rate (Zhang et al., 1998) or inferred mass accretion rate (Bloser et al., 2000), as well as a sudden