Future X-ray timing missions

Didier Barret
Centre d’Etude Spatiale des Rayonnements, France

Michiel van der Klis
University of Amsterdam, Netherlands

Gerry K. Skinner
University of Birmingham, England

Rudiger Staubert
University of Tübingen, Germany

Luigi Stella
Astronomical Observatory of Roma, Italy

November 2nd, 2000

Abstract. Thanks to the Rossi X-ray Timing Explorer (RXTE), it is now widely recognized that fast X-ray timing can be used to probe strong gravity fields around collapsed objects and constrain the equation of state of dense matter in neutron stars. We first discuss some of the outstanding issues which could be solved with an X-ray timing mission building on the great successes of RXTE and providing an order of magnitude better sensitivity. Then we briefly describe the “Experiment for X-ray timing and Relativistic Astrophysics” (EXTRA) recently proposed to the European Space Agency as a follow-up to RXTE and the related US mission “Relativistic Astrophysics Explorer” (RAE).

Keywords: General relativity, X-ray timing, solid-state detectors

1. Introduction

In the last few years the predicted sub-millisecond plasma orbital periods and millisecond spin periods of accreting low-magnetic-field neutron stars (NS) have finally been detected by RXTE. The same satellite also found 0.1 kHz Quasi-Periodic Oscillations (QPOs) in black hole candidates (BH) and, the first (and so far only) accreting millisecond pulsar (see van der Klis 2000 for a review). RXTE has opened up a completely new field of investigation and it is now widely recognized that fast timing provides one of the most powerful tools for such objectives (a) to test General Relativity (GR) in strong gravity fields, (b) to constrain the fundamental properties of collapsed stars (EOS of NS, mass and spin of BH).

The RXTE discoveries were made possible by its large X-ray detector area (0.67 m², sub-µs time resolution and high data rates. The
RXTE All Sky Monitor (ASM) and the flexibility of operation and rapid response also played a major role in the success of the mission (Bradt et al. 1993).

For X-ray timing, the signal to noise ratio at which non-coherent variability such as a QPO is detected scales as the source count rate (i.e. the detector area) in the strong source limit (for a photon counting experiment). Based on this, here we describe how an instrument with ten times the detector area of RXTE could help to solve some of the outstanding issues in the astrophysics of collapsed stars.

2. The science of a future X-ray timing mission

High-frequency QPOs have been seen in both BHs and NSs. In BHs, the QPO models proposed invoke GR effects in the inner accretion disk and depend strongly on the BH spin, making these QPOs effective probes of spacetime near the event horizon (see e.g. McClintock 1998). In NSs, three types of QPOs are commonly observed (see Fig. 1, $\nu_{LF}$, 15–60 Hz, $\nu_1$, 200–800 Hz and $\nu_2$). Evidence is building that there exists a close relationship between the QPO properties of NS and BH X-ray binaries. In particular a remarkable correlation between the centroid frequency of QPOs (or peaked noise components) has been found which extends over nearly 3 decades in frequency and encompasses both NS and BH systems (Psaltis, Belloni & van der Klis 1999). In the relativistic precession model (Stella & Vietri 1998), $\nu_{LF}$, $\nu_1$, $\nu_2$ observed across a wide range of objects are identified with three fundamental frequencies characterizing the motion of matter in the strong field of a point mass as predicted by General Relativity (GR). The low-frequency QPO at $\nu_{LF}$ is thought to be due to nodal precession, dominated by the inertial-frame dragging predicted by GR in the vicinity of a fast rotating collapsed object. The lower frequency kHz QPO at $\nu_1$ is identified with relativistic periastron precession, an early crucial test of GR. Unlike the cases of Mercury and the relativistic binary pulsar PSR1913+16, for which weak field expansions apply, the periastron precession close to a collapsed star is dictated by strong field effects, requiring a full general relativistic treatment. Finally $\nu_2$ is the orbital (“Keplerian”) frequency; its value alone restricting the allowed range of mass and radius of the NS (Miller et al. 1998). Other models rely on a beat-frequency interpretation for both $\nu_1$ and $\nu_{LF}$ (Alpar and Shaham, 1985, Miller et al. 1998).

With an order of magnitude better sensitivity, QPOs from a few Hz to 1600 Hz should be detected from many objects with a high enough significance to use the data for crucial tests. Regardless of the physical origin of the QPOs at $\nu_{LF}$ and $\nu_1$, the increased sensitivity
Future X-ray timing missions

Figure 1. Power spectrum of Sco X-1 obtained with RXTE showing the kHz QPOs at \( \nu_1 \) and \( \nu_2 \) and the LF QPO (plus its harmonic). With EXTRA, about twenty kHz QPO sources will be measured at signal-to-noise similar to this (the fainter sources have stronger kHz QPOs). For Sco X-1 the signal-to-noise will improve tenfold.

and range will have dramatic benefits. At higher frequencies, either strong signatures of the innermost stable circular orbit (ISCO), which sets an upper bound on \( \nu_2 \), will be discovered from several sources (evidence has been found for one source so far: 4U1820-30, Zhang et al. 1998), or the frequencies themselves will allow the elimination of several candidate equations of state of dense matter (Miller et al. 1998). In the relativistic precession interpretation, there are several predictions that could be tested. First, the epicyclic frequency \( \Delta \nu = \nu_2 - \nu_1 \) steeply falls to zero as \( \nu_2 \) increases and the orbital radius approaches the ISCO. The behaviour of the epicyclic frequency in the vicinity of BH and NS is dominated by strong-field effects and drastically different from any Newtonian or post-Newtonian approximation. Hence it provides a powerful test of the strong field properties of the metric (see Stella & Vietri 1999). According to the model \( \Delta \nu \) should also decrease for low values of \( \nu_2 \). Second, \( \nu_{LF} \) should scale as \( \nu_2^2 \) over a wide range of frequencies (until “classical” terms due to stellar oblateness become important). Observing such scaling would provide an unprecedented test of the \( 1/r^3 \) radial dependence of \( \nu_{LF} \) predicted in the Lense-Thirring interpretation (Stella & Vietri 1999). We note that in the hydrodynamical model of the disk inner boundary developed by Psaltis & Norman (2000), the test particle frequencies (the same as in the relativistic precession model plus a few other additional frequencies, see also Psaltis 2000) are selected by the response of the inner disk, when this is subject to a wide-band input noise.

In the above models, the QPO frequencies depend sensitively on the mass (M) and angular momentum (J) of the compact star, as well as on the radius at which the QPOs are produced. M and J could
Simulated cycle waveforms for burst oscillations on a $1.8 \, M_\odot$ neutron star with a spin frequency of 364 Hz of radius $R = 4GM/c^2$ (solid line) and radius of $R = 5GM/c^2$ (dashed line). The more compact star (with smaller $R/M$) has a broader waveform, because it has stronger gravitational light deflection. The less compact star has larger waveform asymmetry because its surface rotation velocity is higher. Therefore, mass and radius can be determined independently by fitting the waveform. Constraints on mass and radius from waveform fitting. The contours show the 1 $\sigma$ confidence regions from RXTE (dotted) and from an instrument 10 times bigger than RXTE (drawn). The mass-radius relations labeled as in Miller et al. (1998) are also shown. (Courtesy of Cole Miller).

be independently estimated from waveform measurements at $\nu_2$, thus overdetermining the problem so that the underlying theories can be tested in critical ways. The increased sensitivity will enable QPOs to be detected within their coherence times. The cycle waveform, which it will be possible to reconstruct, depends on the Doppler shifts associated with the local velocity of the radiating matter in the emitting blob or spot, as well as on curved-spacetime light propagation effects. If the frequency $\nu_2$ of the orbit is known, QPO waveform fitting yields the mass $M$ (and Kerr spin parameter) of the compact object.

Nearly coherent oscillations at $\sim 300$ Hz or $\sim 600$ Hz have been observed during type I X-ray bursts from about 10 NS so far (see Strohmayer et al. 1998 for a review). These oscillations are probably caused by rotational modulation of a hot spot on the stellar surface. The emission of the hot spot is affected by gravitational light deflection and Doppler shifts (e.g. Miller & Lamb 1998). With the next generation timing mission, the oscillation will be detected within one cycle.

The composition and properties of the NS cores have been the subject of considerable speculation, and remain a major issue in modern physics: at the highest densities, matter could be composed of pion or kaon condensates, hyperons, quark matter, or strange matter (see, e.g., Heiselberg & Hjorth-Jensen 2000). By fitting the waveform, it will be possible to constrain simultaneously the mass and radius of the star.
(see fig. 2), and hence determine the equation of state of its high density core.

Beside the few examples described above, with its increased sensitivity, a future timing mission will also address a broad range of other astronomical issues (accreting millisecond pulsars, micro-quasars, X-ray pulsars, CVs, Novae, Soft gamma-ray repeaters, Anomalous X-ray pulsars, . . .). For instance, there is only one accreting millisecond pulsar known so far: SAXJ1808-3658 (Wijnands & Van der Klis 1998, Chakrabarti & Morgan 1998). Its properties suggest that all NS systems should show pulsations at some level. In most models, pulse amplitudes cannot be suppressed below ~0.1% (rms) without conflicting with spectroscopic or QPO evidence. With an instrument 10 times larger than RXTE, the sensitivity to persistant millisecond pulsations will be well below this level (pulsations at the level of 0.01% rms would be detected in 10000 seconds in Sco X-1). Detection of such pulsations in objects also showing kHz QPOs and burst oscillations would immediately confirm or reject several models for these phenomena involving the NS spin (e.g. Miller et al. 1998). In addition, it has been suggested that such objects could be among the brightest gravitational radiation sources in the sky, emitting a periodic gravitational wave signal at the star’s spin frequency (Bildsten 1998). Measuring the spin period very accurately would be therefore of great importance for periodicity searches with gravitational wave antennas (e.g. Brady et al. 1997).

Similarly for micro-quasars, the link between the very fast disk transitions observed in X-rays and the acceleration process could be studied on very short time scales, allowing the non steady state disk properties and their link to the formation of relativistic jets to be explored (Belloni et al. 1997, Fender et al. 1999). This would be of direct relevance to understanding the properties of AGNs, where presumably similar jet formation mechanisms operate on a much larger scale.

3. Proposed advanced timing missions: EXTRA and RAE

The “Experiment for X-ray Timing and Relativistic Astrophysics” (EXTRA) was proposed to ESA in January 2000 as a F2/F3 flexi-mission. This mission was not at that stage selected, but studies continue. In addition the “Relativistic Astrophysics Explorer” (RAE), a closely related concept, is being discussed in the US (Kaaret et al. 2000). The objectives and requirements of the two missions are essentially identical and the two will be discussed together here.
Both EXTRA and RAE have a main instrument consisting of a very large X-ray detector array, together with an all-sky monitor to provide source monitoring and alerts to transients.

The main detector array has a geometric area of about 10 m$^2$, giving about $\sim 6$ m$^2$ effective area at 6–10 keV. An area of this size can be accommodated within the fairings available with a low-cost launchers (Starsem Soyuz-ST or Delta II) without the need for deployable mechanisms (see fig. 3). The arrays are highly modular and in each case Si PIN diodes are being considered for the main detector. Si PIN diodes can now be manufactured with high yield at acceptable cost and provide a superior alternative to the proportional counters used on XTE. The absence of absorption edges in the critical 4–6 keV range is important for spectral studies. Furthermore, they are rugged and require neither high voltages nor special handling conditions. Similar Si PIN diodes have been proposed for the first layer of the ASTRO-E Hard X-ray Detector (Sugizaki et al. 1997).

By operating the detectors at reduced temperature, needing only passive cooling through the front face of the detector array, the leakage current can be reduced to a low level even for an area of $\sim 1$ cm$^2$ per element. The associated capacitance is reduced by using a thick detector (1–2 mm), also needed for good high energy response. In this way good energy resolution can be obtained with an off-chip pre-amplifier, allowing the silicon and processing to be optimised for X-ray detection. Resolution of 600 eV or better can be expected—a factor of two better than the RXTE PCA.

For both missions Silicon Drift Detectors (SDDs) are being considered as a possible alternative to PIN diodes, potentially offering even better energy resolution and perhaps larger area for a single detector, so reducing the total number of electronic channels. SDDs are, however, at a less advanced stage of development.

The number of electronic channels will be large ($\sim 52416$ for EXTRA) and the resulting electronic complexity requires careful optimisation and effective use of a modular construction concept. Similar numbers of channels are, however, being dealt with for the IBIS instrument on INTEGRAL and on AGILE.

The detector background is reduced because charged particles passing through the relatively dense detectors will normally deposit an energy larger than the upper limit of the operating range. Simulations show that particle interactions in the collimator and surrounding material often produce showers of secondaries, so the background can be further reduced by operating nearby pixels in anti-coincidence with each other. Nevertheless, because of the unprecedented area the total background rate may approach 2500 Counts s$^{-1}$ between 1 and 50
keV. The missions are intended to study bright sources and the data rates will often be high, requiring careful optimisation of the on board electronics and data systems. With the proposed detector area, the Crab will produce about 400000 cts/s. A low, near equatorial, orbit is to be preferred in order that the background be low and stable and also because of considerations of data recovery. The objective is to telemeter information about the time and energy of every event, leading to considerable volumes of data. Nevertheless this turns out to be feasible with only minimal constraints. For example, the EXTRA studies led to the proposal to use the Matra-Marconi Space LEOSTAR bus, which provides 160 Gbit solid state memory. By reorienting to direct a X-band antenna toward the ground station during passes, the full memory can be dumped during a single pass, using a 240 Mbits s$^{-1}$ link. Observations of the brightest sources ($\sim 10$ Crab) would thus be restricted to orbits followed by ground station passes.

4. Conclusions

The need for a follow-up to RXTE has been clearly identified; fast timing studies are now widely recognized as a powerful tool to study the spacetime around collapsed stars, and to derive constraints on the fundamental properties of neutron stars and black holes. The studies carried out for EXTRA have demonstrated that a mission using
solid-state detector technologies providing an order of magnitude improvement over RXTE can be done within the limits of a modest size mission. It has also shown that there are existing platforms with resources matching the specific needs of such a mission. More importantly, the large number of active astronomers that gathered around the proposals demonstrates that there is a very large community supportive of such a mission.

It is a real pleasure to thank all the people who have contributed to the EXTRA proposal (J.L. Atteia, T. Belloni, E. Bravo, A. Brunton, S. Campana, D. Chakrabarti, F. Cotin, D. Dal Fiume, C. Done, E.C. Ford, R.P. Fender, C. Hellier, W. Hermsen, G.L. Israel, P. Jean, P. Kaaret, E. Kuulkers, C. Labanti, S. Larsson, N. Lund, J.E. McClintock, S. Mereghetti, C.M. Miller, C. Motch, J.F. Olive, M. Orlandini, S. Paltani, A. Santangelo, R.A. Sunyaev, A. Zdziarski, P. Zykci), and those of you who have given their scientific or engineering support to EXTRA (A. Bazzano, L. Burderi, M. Böer, H. Bradt, S. Brandt, C. Castelli, A. Castro-Tirado, M. Cochi, T. Courvoisier, M. Cropper, A.M. Cruise, D. De Martino, C. Eyles, M. Gilfanov, J.M. Hameury, G. Henry, E. Kendziorra, W. Kluzniak, L. Kuiper, J.P. Lasota, F.K. Lamb, G. La Rosa, J. Poutanen, R. Rothschild, R. Svensson, M. Tavani, G. Vedrenne, N.E. White, R. Wijnands, J. Wilms, W. Zhang).

References

Alpar, A. & Shaham, J., 1985, *Nature*, 316, 239
Belloni, T., et al., 1997, *ApJ*, 479, L145
Bildsten, L., 1998, *ApJ*, 501, L89
Bradt, H., Rothschild, R. & Swank, J.H., 1993, *A&A*, 97, 355
Brady, P.R., et al., 1997, *Physics Review*, D57, 2101
Chakrabarti, D. & Morgan, E. H., 1998, *Nature*, 394, 346
Fender, R. et al., 1999, *MNRAS*, 304, 865
Heiselberg, H. & Horth-Jensen, M., 2000, Physics Report, in press
Kaaret, P. et al., 2000, *Astrophysics Letters & Communications*, in press
Van der Klis, M., 2000, *ARA&A*, in press.
McCintock, J.E., 1998, *AIP conference proceeding*, 431, 290
Miller, M.C., Lamb, F.K. & Psaltis, D., 1998, *ApJ*, 508, 791
Miller, M.C. & Lamb, F.K. &., 1998, *ApJ*, 499, L39
Psaltis, D., Belloni, T., & van der Klis, M. 1999, *ApJ*, 520, 262
Psaltis, D. & Norman, C. 2000, ApJ, in press (astro-ph/0001391)
Psaltis, D., 2000, *ApJL*, submitted (astro-ph/0010316)
Stella, L. & Vietri, M., 1998, *ApJ*, 492, L59
Stella, L. & Vietri, M., 1999, *Physical Review Letters*, 82, 17
Strohmayer, T., 1998, *The Active X-ray Sky*, 69, 129
Sugizaki, M. et al., 1997 , *Proc. SPIE* 3115, 244
Wijnands, R. & Van der Klis, M., 1998, *Nature*, 394, 344
Zhang, W. et al., 1998, *ApJ*, 500, L71