RELATIVISTIC ASTROPHYSICS EXPLORER

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ABSTRACT

The great success of the Rossi X-Ray Timing Explorer (RXTE) has shown that X-ray timing is an excellent tool for the study of strong gravitational fields and the measurement of fundamental physical properties of black holes and neutron stars. Here, we describe a next-generation X-ray timing mission, the Relativistic Astrophysics Explorer (RAE), designed to fit within the envelope of a medium-sized mission. The instruments will be a narrow-field X-ray detector array with an area of 6 m$^2$ equal to ten times that of RXTE and a wide-field X-ray monitor. We describe the science made possible with this mission, the design of the instruments, and results on prototype large-area X-ray detectors.

INTRODUCTION

Timing is a key tool of X-ray astronomy. The first definitive source identifications made using X-ray data alone were of X-ray pulsars – identified via periodic signals with sinusoidal period modulation due to orbital motion (Tananbaum et al. 1972). Recently, X-ray timing has made substantial and unique contributions to our understanding of accreting compact objects including the behavior of matter in strong gravitational fields, the formation of relativistic jets, the physical geometry and emission mechanisms of active galactic nuclei, the evolution of neutron stars in binaries, and X-ray emission regions in cataclysmic variables by exploiting the large effective area of the Rossi X-Ray Timing Explorer (RXTE) (for a review see Bradt 1999).

These successes are a strong indication that further advances in X-ray timing instrumentation will engender further scientific advances. To take an ‘order of magnitude’ step, a next generation X-ray timing mission will need an X-ray detector with an area ten times that of RXTE, on the order of 6 m$^2$ (Kaaret et al. 2001). With an order of magnitude increase in photon counting rate, it will be possible to go beyond the initial steps made with RXTE and exploit high frequency X-ray timing to test models of the behavior of matter in strong gravitational fields and to measure the fundamental physical properties of black holes and neutron stars. In addition, the increased sensitivity will make possible new discoveries of unanticipated phenomena. Here, we describe two examples highlighting application of X-ray timing to the study of strong-field gravity and ultradense matter.

Fast quasiperiodic oscillations from black hole candidates

Quasiperiodic oscillations (QPOs) have been discovered in the X-ray emission from several accreting black hole candidate (BHC) systems with frequencies up to 450 Hz. In two sources the fast QPO frequencies appear constant regardless of the source state, while in a third the QPO frequency varies by 10% (Remillard et al. 1999). The fast QPO frequencies appear to be harmonically related, occurring at integer multiples of a (usually absent) fundamental frequency. A number of models of the QPOs have been proposed, most of which involve strong-field general relativistic effects. One very intriguing model explains the harmonic structure as due to resonances between orbital and epicyclic motion around a rotating black hole (Abramowicz and Kluzniak 2001). These fast QPOs from BHCs are weak (amplitudes near 1%), often detected only at hard X-ray energies (above 12 keV), and difficult to study in detail with RXTE. Distinguishing amongst the
various models will be difficult with the current data or any data likely to be obtained in the remaining lifetime of RXTE. The increase in the photon statistics with a 6 m² X-ray detector would enable reliable detection of the fast QPOs with relatively short integrations, allowing accurate measurement of the QPO parameters and their variations with time or correlations with spectral or other timing parameters. Such detailed measurements should lead to unique identification of the physical process generating the QPOs. With a unique model, it should be possible to exploit these QPOs to probe strong-field gravity and measure the spin, and possibly mass, of the black holes.

### Millisecond oscillations in X-ray bursts

Millisecond oscillations have been discovered in X-ray bursts from several accreting neutron stars. The detection of oscillations with very high coherence in a long-duration X-ray burst (Strohmayer and Markwardt 2002) and the detection of burst oscillations at the known spin frequency of the millisecond pulsar SAX 1808.4-3658 (D. Chakrabarty 2002) show that the oscillations are related to the neutron star spin and are likely due to inhomogeneous nuclear burning on a rotating neutron star. The burst oscillations probe conditions at the neutron star surface and detailed measurements of their properties should lead to constraints on the mass-radius relation of neutron stars and therefore on the equation of state of ultradense matter. Because the strength of relativistic light bending due to the gravity of the neutron star depends on the neutron-star mass-radius relation, the observed maximum modulation in the burst oscillations places direct constraints on the mass-radius relation (Strohmayer et al. 1998). In addition, the spectrum of the emitted radiation should be modified by Doppler shifts as the line-of-sight velocity of the nuclear burning hot spot changes as the neutron star rotates (Ford 1999). This provides a direct measure of the surface velocity and, hence, the neutron star radius since the spin period is known. A 6 m² X-ray detector would detect roughly 1000 counts in each oscillation cycle near the peak of a bright X-ray burst. This would permit detailed examination of individual oscillation cycles and allow accurate measurement of the modulation amplitude and Doppler shifts for individual oscillation cycles.
Fig. 2. Perspective view of the Relativistic Astrophysics Explorer – a satellite for X-ray timing with a modular, large-area X-ray detector.

INSTRUMENT REQUIREMENTS

The key characteristic of RXTE is its large effective area. To achieve an order of magnitude increase in X-ray timing capabilities, a “next generation” X-ray timing mission will need a large area X-ray detector with an effective area equal to ten times that of RXTE, on the order of 6 m$^2$ (Kaaaret et al. 2001; Barret et al. 2001). Good sensitivity extending up to energies of 20 to 30 keV is required because the modulation of timing signals detected from Galactic accreting objects is, in general, much higher at high energies. Figure 1 shows the rms modulation versus energy for several typical high frequency signals detected with RXTE. The strong increase at high energies is clear. Because the time required for detection of a signal at fixed source counting rate scales inversely with the fourth power of the rms modulation and the detection significance for a fixed integration time scales as the square of the rms modulation, there are great advantages to be gained from a timing instrument with significant collecting area at high energies. Furthermore, there are some signals, such as the higher frequency QPOs from accreting black holes candidates discussed in the previous section that are detected only at high energies. For GRO J1655-40, the second QPO at higher frequency was detected only at energies above 13 keV (Strohmayer 2001).

Focusing of X-rays in the hard band is difficult because of the extremely small graze angles required for efficient broad-band reflection and it is unlikely that focusing telescopes will achieve the required areas, of order 6 m$^2$, in the near future. The Hard X-ray Telescope (HXT) on the Constellation-X mission is expected to have a total area of less than 0.6 m$^2$ at 10 keV, and even the extended XEUS mission may achieve only 1.7 m$^2$ at 10 keV with the area decreasing rapidly at higher energies (Aschenbach et al. 2001). Integrated over the band where the second QPO from GRO J1655-40 was detected, the effective area of XEUS is less than that of the RXTE PCA. While some advance in X-ray timing will be possible with the currently planned major observatories, a significant increase in X-ray timing capabilities will likely require a dedicated mission. Only moderate energy resolution ($\sim$ 1 keV at 6 keV) and no position resolution are required. The detector may be non-imaging with a field of view limited by a collimator. Better energy resolution is desirable, but is not essential for X-ray timing.

Non-focusing instruments do not suffer from the difficulties of reflecting hard X-ray photons and large effective area in the 10–30 keV band is relatively easily achieved. The high energy response is typically limited by absorption depth in the detector. High efficiency up to 20 or 30 keV can be achieved by gaseous or solid state detectors as described in the next section. The primary disadvantage of a non-focusing instrument is the relatively high background counting rate. For this reason, great care must be taken to actively veto background events. Large non-focusing instruments can easily be constructed in a modular fashion. In addition to reducing costs and facilitating construction, dividing the full effective area of the instrument into multiple independent units decreases the count rate for each unit. This is particularly advantageous for a timing mission because the effect of instrumental dead time decreases, making it possible to achieve...
very high total count rates with minimal dead time effects.

A large detector area with sensitivity over a broad band extending up to high energies (2-30 keV) is the critical requirement for achieving the very high source counting rate essential for the success of a future X-ray timing mission. To effectively exploit such high rates, a high telemetry bandwidth is also required. To fully telemeter the event rate of $2 \times 10^5$ c/s from a bright source, comparable in intensity to the Crab nebula, will require a telemetry rate of the order of 10 Mbps. Multiple ground stations may be needed to achieve the required average telemetry rate. To buffer events while out of ground contact and for very bright sources, a large on-board memory (of order 100 Gbit) will be required.

Most of the sources of interest for high frequency X-ray timing are variable or transient. To maximize the scientific return of a timing mission, or timing observations in general, it is critical to have an all-sky monitor sufficiently sensitive to discover and localize new transients and determine the state of known persistent sources. In addition, flexible observation scheduling and rapid response to targets of opportunity are needed in order to perform observations while the sources are in interesting states. This is something that may be very difficult to achieve with a multi-purpose large observatory and is a strong advantage for a dedicated mission. An X-ray timing mission should be designed so that a large fraction of the sky is accessible at any instant and so that frequent repointing can be performed in order to contemporaneously monitor multiple targets.

**DETECTOR TECHNOLOGIES**

The primary technology driver for a new X-ray timing mission will be the large area X-ray instrument. We have considered both gas proportional counters and solid-state silicon detectors for the detection technology. Gas proportional counters have a long history in space. However, proportional counters require delicate construction, need high-voltage, and are notoriously tricky to build and finicky to operate, particularly after the first one or two years of operation. Each proportional counter unit (PCU) in the PCA on RXTE currently requires attention to its history of operation with each PCU being cycled on and off to prevent sparking and detector damage. More advanced proportional counter technologies have been developed recently, including gas electron multipliers and microwell arrays, but these are lacking in flight heritage.

Silicon is, perhaps, the most widely used radiation detection medium today. Silicon has a long heritage in radiation detection applications, including specifically satellite-borne X-ray detectors which have been operated successfully in high radiation environments (e.g. Aukerman, Vernon, & Song 1984). Silicon detectors are operated without high-voltage or internal amplification, and are robust and have stable operation over long periods. Furthermore, the technology for processing silicon is well understood and widely available. Hence, detectors, even those requiring large amounts of material, can be fabricated by industry with existing facilities and at reasonable cost.
The simplest silicon detector is the p-i-n photodiode, and we have studied the suitability of p-i-n photodiode detectors for a large-area X-ray detector. The energy resolution of a large area p-i-n photodiode detector is limited by electronic noise originating in the device. Good energy resolution, better than $\Delta E = 1$ keV at 6 keV, can be achieved for devices with areas of 1 cm$^2$. Assuming an area for each individual detector pixel of 0.6 cm$^2$, a total of $10^5$ pixels would be required for a 6 m$^2$ detector. One electronics channel, with preamplifier, shaping amplifier, and sample/hold, would then be required for each pixel, leading to a total electronics channel count of $10^5$. With an expected power per channel near 2 mW, the total power required is near 200 W. Our preliminary studies and also those done for the European Experiment for X-ray Timing and Relativistic Astrophysics (EXTRA) proposal (Barret 2001) show that p-i-n photodiode detectors can meet the scientific requirements of an X-ray timing mission.

Until now, silicon detectors have been limited primarily to the soft or standard X-ray band (below 10 keV) due to the limited absorbing power of the relatively thin (typically 300µm or less) wafers commonly used by the microelectronics industry. To extend the reach of silicon-based detectors to higher energies, thick devices must be used to obtain sufficient stopping power. The key problem with thick silicon detectors is that a high bias voltage must be applied to fully deplete the silicon and allow efficient collection of the charge produced by incident X-rays. Many previous attempts to fabricate thick silicon detectors have failed because either the detectors break down when the bias voltage is applied or the bias required causes large dark currents, leading to poor performance. Recently, some success has been obtained by Ota et al. (1999) who developed thick p-i-n diodes for the hard X-ray instrument on Astro-E (now Astro-E2) and by Phillips et al. (2001) who demonstrated the X-ray detection capabilities of a thick diode developed for heavy-ion detection.

Multi-guard ring structures allow high bias voltages to be applied without causing excessive dark currents or premature detector breakdown (Evensen et al. 1993; Avset & Evensen 1996; Da Rold et al. 1997). Figure 3 shows schematics of such devices. Working with Photon Imaging, Inc., we have designed new multi-guard ring structures and fabricated devices from thick silicon wafers with good efficiency up to 30 keV. The devices were fabricated by Photon Imaging from high resistivity silicon to lower the depletion voltage. The starting material was carefully selected and the pixel p/n junction diffusion structures were optimized to further increase the breakdown voltage (Sze & Gibbons 1966; Waver 1972; Beck et al. 1996). These advanced designs produced very low dark currents, leading to 1.5 mm thick detectors with good X-ray performance.

Figure 4 shows the spectral response of 1.5 mm thick diodes to X-rays emitted by the radioactive isotopes $^{55}$Fe and $^{109}$Cd. The X-ray response was measured with the diodes fully depleted at 500 V. A three-stage thermoelectric cooler was used for cooling to $-30^\circ$ C. A standard low noise NIM-based amplifier and a PC-based multi-channel analyzer were used for data collection. The preamplifier was not optimized for the leakage currents and capacitances of such large diodes. For the 1.5 mm thick diodes with an area 25 mm$^2$ cooled to $-30^\circ$ C, the measured energy resolution is 775 eV FWHM at 5.9 keV and 800 eV at 22 keV. This energy resolution meets the scientific requirements for a new X-ray timing mission.
CONCLUSION

There have been only two US-lead major X-ray astrophysics observatories in the past decade: RXTE and Chandra. Although Chandra was very recently launched, next-generation capabilities in X-ray imaging and spectroscopy are already under serious development. RXTE has addressed scientific issues, including relativistic gravity and the physics of extreme phenomena, which are central to NASA’s scientific goals. Further advances in X-ray timing, which are unlikely to come from any currently planned mission but are possible with a dedicated mission, will likely lead to further significant advances in our understanding of compact objects and accretion in strong gravitational fields.

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