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THE X-RAY TIMING EXPLORER: PROGRESS AND SCIENCE PROSPECTS

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Abstract. The X-Ray Timing Explorer is on schedule to be launched in the fall of 1995 on a new spacecraft designed to give excellent capability with modest resources. XTE's emphasis is on timing over a broad energy range. The goals of XTE are complementary to those of higher resolution spectroscopic missions and imaging missions. The high time resolution capability extends to microseconds. The experiment area will be large enough from 2 – 200 keV to support sub-millisecond studies for bright galactic sources and the spacecraft will provide the necessary telemetry capacity. Longer term variability studies will be supported by commitment to the multiple observations needed to examine phenomena of both binaries and active galactic nuclei. Transients will be detected within hours of outburst and can be observed with the pointed instruments before reaching maximum. By exploring the X-ray characteristics of galactic black holes, neutron stars and white dwarfs, XTE should make significant contributions to the physics of matter under extreme conditions of density, magnetic field and gravity. The experiments will be sensitive to sources as weak as a few tenths of a mCrab. Spectra of many Seyfert galaxies will be extended to 150 keV in exposures of about a day, while at the same time variations at lower energies are studied. Thus both galactic and extragalactic sources will be important targets for XTE observations. The observing program will be proposal selected.

Key words: instruments: X-ray, observatory: X-ray, X-ray astronomy

1. Introduction

Since the discovery of X-ray emission from Sco X-1, fascination with compact objects has inspired rocket, balloon, and satellite experiments. Because of the variety of systems in which they occur and the variety of the signatures, compact objects have been targets in some form of probably all of the non-solar X-ray missions. Many missions have built up our current knowledge about variable sources. They provided successive discoveries of new phenomena, including eclipses, pulsations, Doppler shifts of the pulse times, spin-ups, bursts, atomic emission lines and absorption, dips in intensity, occultations, flares, and quasiperiodic oscillations. Models for

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these phenomena have led to predictions of manifestations not yet observable and designs of new experiments to expand the phase space of measurements.

The X-rays from compact objects are likely to vary at least as fast as the dynamic time scales of the objects, $\propto (G\rho)^{-1/2}$, $100\mu\text{s}$ for a neutron star. Studies of sub-millisecond variability for bright accreting stellar-mass black holes require large experiment area. A large effective area is also required to accurately measure the high energy spectra of weak sources. Two pointed instruments on XTE, the Proportional Counter Array (PCA) and the scintillator High Energy X-ray Timing Experiment (HEXTE), together provide 0.8 m^2 , the largest area yet to be fielded for simultaneous study of X-ray sources over the energy range $2 - 200\text{ keV}$. Accreting compact objects also vary on long time scales, sometimes periodically, but often unpredictably. The variations take the luminosity through factors > 100 and are sometimes accompanied by radical changes in spectrum and variability characteristics. In order to exploit these occurrences fully, XTE carries an All Sky Monitor (ASM) with a sample time of hours. Further, the spacecraft has been designed to support the observation by the pointed instruments of the targets of opportunity that the ASM will discover.

A set of scientific goals that the XTE instrument capability could address was described in Bradt *et al.* (1990), based on a study by the XTE instrument groups at GSFC, the Massachusetts Institute of Technology (MIT) and the University of California San Diego (UCSD). These remain good experiments to do with XTE; results obtained since then by Ginga, GRANAT, CGRO, and ASCA will help refine the questions and the choice of targets. Here we first review in general the scientific goals of studies of compact objects and then relate the XTE instrument capabilities to those required for these goals. Second, we describe the mission and the instruments, as the instruments near completion. The design of the spacecraft now being built was begun in 1991 (Bradt *et al.* 1993). There have been some changes in design details since then, but not major changes. In conclusion we discuss some of the new science that can be done with XTE.

2. Scientific Objectives of Compact Object Studies

In black holes and neutron stars, states of matter that are theoretical abstractions relative to the states found in earth's laboratories, are macroscopic realities. Astrophysical compact objects are our only laboratories of strong gravity ($GM/Rc^2 = 0.1 - 1$), the highest density equations of state, and the highest magnetic fields. But usually it is not simple to measure their properties. They come embedded in the complex surroundings of companion stars and accreting gas. During the three decades of X-ray astronomy, accreting compact objects have been identified, and distinguished as probably black holes, neutron stars or white dwarfs. Many mechanisms involved in producing the observed spectral and temporal phenomena have been identified. At this juncture, what are the things that are not known about black holes, neutron stars, and white dwarfs? The following are some of the aspects of these objects and their interaction with surrounding material that are important and not understood.

— Black holes. Since X-rays are a major signature of black holes from stellar to galactic in size, we hope that the X-rays can be used to confirm the relations of the

“size” of the black hole to the central mass and its spin. This has not yet been done. Is there indeed an innermost stable orbit at a certain radius and does any radiation escape from inside of it? How are the disks and radio jets related?

— Neutron stars. Early in their lifetime neutron stars may all be radio pulsars (at least after the debris from the supernova becomes optically thin). Those that are the product of a single, rather than a double star, cool to temperatures of 10^6 K and lower. Those with a companion star become accreting neutron stars. They are observed spinning up and down, reflecting the torques on them in the accretion process. In principle the rotation rates hold unique dynamic clues to the interiors of the stars, clues that have only begun to be explored. Whether the X-ray beam from an accreting neutron star comes out roughly along the magnetic field or roughly perpendicular to it, has been a model dependent inference. Now it is clear that cyclotron features exist and can provide a new perspective. The magnetic fields of the neutron stars in all but three low-mass X-ray binaries have not been identified at all.

— Plasma interactions of binaries. The X-ray binary sources are subject to many kinds of changes of state, apparent changes in accretion rate, and oscillations in the luminosity. Instabilities in mass flow near the compact object, in the accretion flow through a disk or in the interaction between the radiation and the accreting material could explain the observations, but explicit correlations have not been identified.

— Evolution of stars and galaxies. Do accreting white dwarfs grow in mass to collapse to neutron stars? Do low-mass X-ray binaries spin up neutron stars to leave them as millisecond pulsars? What systems produce low mass binary black holes and what do they in turn become? We need to identify manifestations of other phases of the systems to fill out the picture of how they evolve. Some fraction at least of galaxies have active nuclei during some part of their evolution. The active galactic nuclei are of many types, Seyfert 1 and 2, radio loud and radio quiet quasars, BL Lac objects. In a unified model, they may be all of the same type viewed from a different perspective. How do they evolve? What are the active galactic nuclei that explain the diffuse X-ray background spectrum?

3. Experiment Capabilities Required for Compact Object Studies

What kinds of experiments are needed to answer these questions and to verify theories? Some objects are only detected in one or a few bands of the electromagnetic spectrum, e.g., radio or X-rays. Others are important targets for experiments at all wavelengths. For accreting compact objects, X-rays are special in carrying a large fraction of the radiated energy and XTE is designed for definitive studies of these. XTE cannot accomplish all the observational objectives of such studies. We briefly touch on the instrument choices that were made.

Timing down to tenths of milliseconds is necessary to be sensitive to the fastest rotation periods possible for neutron stars and for the inner-most stable orbits of stellar black holes. Irregularities of accretion flow associated with the size of the polar caps of neutron stars could occur in 1–10 microseconds (Orlandini and Morfill 1992). The Crab Nebula produces $1.6 \text{ counts cm}^{-2} \text{ s}^{-1}$ in the 2–10 keV range in an XTE-like proportional counter and 0.625 m^2 of area is needed to obtain 10 counts

in 1 millisecond. Of course, sensitivity is greater for both periodic and quasiperiodic phenomena and non-periodic phenomena must be studied on a statistical basis. In addition to large area, high time resolution experiments require fast electronics, on board data storage, and telemetry resources sufficient to download large volumes of data.

Observing some compact objects (high redshift quasars, cooling neutron stars) requires an imaging experiment with arc minute to arc second spatial resolution. But, of the 300 brightest, accreting sources in the Galaxy, only about 20 are closer together than 1° . Simple mechanical collimation with a 1° field of view can then avoid source confusion, with a few exceptions, and it is used by XTE to gain area and sensitivity at high energies. Maps of complex regions like the Galactic Center obtained by imaging and coded mask experiments can be used in many cases to guide pointing offsets to avoid neighboring sources. Scans of confused regions will be possible with XTE to verify the expected source distribution.

Because of this mechanical collimation, XTE is background limited for weak sources, as were HEAO 1 A-2 and Ginga. For the PCA the internal background will be larger than sky background, but there are significant variations of the latter with sky position. On statistical grounds a 3 sigma detection in the PCA (2 – 10 keV) would be on the order of $0.1 \text{ mCrab}/\sqrt{t/300}$, (with t in seconds), but at 0.1 mCrab ($2 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$), the variance of the diffuse background due to discrete source contributions limits the determination of source flux, unless the field is known from the images of another experiment. There are, conservatively, more than 700 extragalactic sources above this sensitivity limit.

A wide energy range is required for several objectives:

- Cyclotron lines. Cyclotron lines have been tentatively identified in the range 10 – 60 keV. So far only a fundamental and a 2nd harmonic have been reported, with the latter only deduced on the basis of the reduction of flux at energies above the fundamental (e.g., Clark *et al.* 1990). The features that have now been seen by many experiments for Her X-1, and for many pulsars by Ginga (See summary by Makishima and Mihara 1991) are consistent with widths of 5 – 15 keV. The PCA resolution at 20 keV should be $\approx 2 \text{ keV}$. The HEXTE energy resolution should be $\approx 10 \text{ keV}$ at 60 keV.

- Active galactic nuclei X-ray spectral cut-offs. AGN X-ray spectra are very hard, by most X-ray source spectrum standards. The EGRET experiment on CGRO has established a component of emission in blazars, but not in Seyferts, in the γ -ray region 30 MeV to 10 GeV (Fichtel *et al.* 1993), far higher than XTE's X-ray range. This is a separate component. The lower energy component rolls over, at least in some cases, in the region of 100 – 200 keV (Bassani *et al.* 1993; Maisack *et al.* 1993; Johnson *et al.* 1994). To understand the component seen in the X-ray regime, it is important to cover these energies with sufficient sensitivity to study time variability on time scales of a day and less.

- Stellar black hole candidates and LMXB. Ginga (Tanaka 1989) and GRANAT (Gilfanov 1994) results have implied that the very variable hard power law component is typical of the black hole candidates. From two of the sources a feature close to 511 keV was detected by GRANAT's SIGMA experiment. The detector used for HEXTE is not efficient at energies above 250 keV. A 511 keV photon backscattered

off a low temperature electron could appear at 100 – 200 keV (Goldwurm *et al.* 1993). Evidence of such a feature might be seen, but the annihilation line itself will be the province of other missions covering higher energies than HEXTE.

Extension of the energy range to lower energies (below 2 keV) would be valuable for the soft components of black hole candidates, although not useful for sources with high column densities. Most extragalactic targets of course do not have high column densities due to the Galaxy and the low as well as the high energies are of great interest. However, the low energies are well covered by ASCA, and, in the future, Spectrum X-Gamma, and XMM.

Spectra of galactic and extragalactic compact objects are known to include line features. Fe contributes, around 6 keV, features well isolated from those of other elements. The PCA will be sensitive to the total Fe K line emission and absorption edge in the spectra of many of the targets. Similar detectors discovered these features. Other missions, such as ASCA, are carrying on the studies of features that require higher energy resolution, especially those features due to various metals that are in the range 0.5 – 2 keV and the structures of the Fe features. ASCA, Spectrum X-Gamma, and XMM have energy resolution $E/\Delta E = 10 - 50$. Some of these missions will be active at the same time as XTE, so that simultaneous coverage may be possible. The higher resolution measurements of the structure of the Fe features will be important in providing insight into the flows of disk, wind, and magnetospheric material. It should be possible to relate the detailed line structure to features seen with proportional counters. Then it will be possible to track the time dependence with the XTE PCA.

Emissions from compact object systems at different wavelengths may be due to spatially distinct regions or to different processes in the same region. A definitive accounting needs to consider several wavelength regimes. For galactic compact objects, the observations at different wavelengths must be nearly simultaneous. There is variability at any time scale, practically. Some spacecraft have not allowed the instruments to point anti-sun, as preferred for optical observations. In addition, there is unpredictable variability that requires flexibility of operations in order to change the observing plan. Such changes have been achieved occasionally with previous missions and the scientific return has been rewarding.

4. The XTE Mission

Observations will be carried out by the PCA and HEXTE of sources brighter than about 0.1–0.2 mCrab. The durations of the points to a given position can be as short as about 10 minutes or as long as days. Sequences of short slews can accomplish a map of a small region ($< 10^\circ$) of the sky. During times when the spacecraft attitude is held fixed for an orbit or longer, the All Sky Monitor (ASM) rotating on its boom will scan over 70% of the sky, sampling a given point on the sky on the time scale of 1.5 hour and accumulating long term light curves of all sources brighter than about 10 mCrab. The appearance of a new source or certain changes in the state of a known source will alert monitoring scientists to the onset of an X-ray transient, which would be a possible target of opportunity for observations with the PCA and HEXTE.

In 1991 a plan to launch the XTE instruments on the shuttle and to replace the EUVE instruments on the Explorer Platform spacecraft (Bradt *et al.* 1991) was abandoned. The engineering division at GSFC designed a dedicated spacecraft for the XTE mission and NASA has scheduled a Delta launch in August 1995. Launched from the Kennedy Space Center in Florida, the Delta would be able to put XTE into a 600 km orbit at an inclination of as low as 23° . NASA is committed to a 2 year mission, although the possibility of a 4 – 5 year mission is not excluded by the design. At the price of some increase in detector background, the orbit should be high enough that the atmospheric drag associated with the approach of the next Solar Maximum in year 2002 does not jeopardize its lifetime.

In a low earth orbit, many sources will be occulted by the earth for a third of the satellite orbit. The satellite will also pass through the South Atlantic Anomaly during about a third of the satellite orbits per day and the detectors will be disabled to protect them from the high particle fluxes. In practise then, 50 – 70% of real time is good observing time. Data will be stored on a solid state recorder on the spacecraft. It will be transmitted via the U.S. Tracking Data Relay Satellite System (TDRSS), using two satellites which will be in view of XTE 90% of the time. The total instrument telemetry rate averaged over a day is expected to be about 32 kbps.

The Guest Observer program will begin with a NASA Research Announcement in late 1994. The observation program will begin about a month after launch, after an in-orbit check-out of the instrument and spacecraft systems. Non-U.S. observers will be able to propose for time, but not for funding by NASA. The selected observations will be scheduled by a Science Operations Center (SOC) at GSFC, which will also schedule calibration observations as needed. The SOC expects to be able to accommodate a reasonable number of observations for which the schedules need to be adjusted to support observations with ground observatories or other space missions operating then (e.g., ASCA, CGRO, HST, SAX, Spectrum X-Gamma). Observers may be present during observations and make a limited number of near real-time adjustments. When the possibility has been preplanned, it may be possible to switch from the planned target, if it is not in an expected or required state, to an alternative target.

The SOC will process data into FITS files which will be read by software tools similar to those being used currently for other X-ray missions. The FITS files, software to read them, and instruction in their use will be provided to the observers by the SOC. The ASM results will be made available on-line to the community, so that the behavior of bright sources can be monitored by any observer or interested scientist.

5. The XTE Instruments

5.1. PROPORTIONAL COUNTER ARRAY (PCA)

The PCA is being built at GSFC. It comprises 5 gas proportional counters sensitive in the range 2 – 60 keV. The counter design is based on that of two of the detectors, HED1 and HED3, of the HEAO 1 A-2 experiment (Rothschild *et al.* 1979), but scaled up by about 50% (Glasser *et al.* 1994; Zhang *et al.* 1993). The A-2 counter performance during the 18 month HEAO 1 mission provides the standard of low

background and stability that the PCA counters should achieve. On this basis the expected total background originating from particles or photons was estimated to be equivalent to a 2 mCrab source in the 2 – 10 keV band.

The 5 counters are to be coaligned to 0.1° of the target position. The collimators are hexagonal tubes with a response that goes to zero at $1.0^\circ - 1.2^\circ$ from the bore-sight, depending on the azimuth. Measurements of the angular response indicate that flattening of the response at small angles, due to dispersion in tube directions, for example, will be a few arc minutes. Optical and X-ray measurements indicate good alignment of the modules making up the collimators for the individual counters. The effective open area per counter (taking into account the average reduction due to offset) will be about 1250 cm^2 , for a total effective instrument area of 6250 cm^2 .

Each proportional counter has a propane gas layer in front of a volume of 90%-10% mixture of xenon and methane containing 4 layers of anodes. The first 3 xenon layers provide a depth of 3.6 cm of xenon at 1 atmosphere. The quantum efficiency peaks near 100% at 7 – 10 keV and falls to 15% at 60 keV. The entrance window and the window separating the propane and xenon are $25 \mu\text{m}$ of mylar with $700 \text{ \AA}$ of aluminum on both sides, leaving a first layer xenon efficiency of 10% at 2.4 keV. The propane layer quantum efficiency is about 10% at 2 keV. With the anticipated effective open area, the expected total xenon count rate for a Crab-like spectrum would be 10 counts s^{-1} per mCrab. (See Table I.)

The propane layer, Vp, primarily acts to detect particles entering through the front window, counting them and allowing signals in the xenon layer to be vetoed. This signal also can be used for sources bright in the 1 – 3 keV range. Each anode is surrounded by cathode wires or a conducting surface to make a cell. All the cells in the xenon volume that are contiguous with the counter's aluminum body form a 3-sided guard, the xenon veto chain, Vx. Vx and Vp form a 4 sided box used to veto through-going particles. There is only a small solid angle for particles to enter at the ends without triggering more than 1 anode. The central 3 layers have anodes divided into 6 sets, or anode chains, such that ideally no more than one should fire for absorption of an X-ray. The internal background includes some weak spectral lines due to radioactive materials and fluorescence induced by charged particles (Zhang *et al.* 1993).

Each detector has 9 amplifier chains, a logic network, a single 8 bit analog to digital converter (ADC) and a 2 bit converter for Vx. One of the chains reports an alpha particle from an internal Am^{241} source, so that the coincident X- rays can be identified as calibration lines. Fig. 1 shows a calibration spectrum in a flight detector.

An X-ray interaction leads to a pulse within $1/4 \mu\text{s}$. The ADC, which is common to all the anode chains (except Vx) is busy for $8.5 \mu\text{s}$. The amplifier chain that detects an event recovers after an energy dependent time, a maximum of $22 \mu\text{s}$ for 60 keV. Therefore an event in a detector is followed by $8.5 \mu\text{s}$ of no events, and 1 out of 6 good event chains (the one that activated the last event) does not recover till $1-13 \mu\text{s}$ later than the others. Fig. 2 shows measurements of the dead time for 6 and 22 keV. We have chosen to accept a small, but measurable energy dependence of the dead time rather than a fixed dead time of twice the average of about $10 \mu\text{s}$.

Fig. 1. Calibration spectrum (Am^{241}) in Layer 1 of a PCA flight detector. These are the nuclear and atomic lines from the Np^{237} product and a K escape line.

Fig. 2. Histograms of the time to the next event for 6 keV (dashed line) and 22 keV (solid line) photons. (a) Next event on same anode chain, showing the dead time of a single anode chain. (b) Next event on any anode chain, showing that other chains are on-line after an energy-independent time.

For a source as bright as the Crab the dead time due to source and background may be about 4%. For a source as bright as Sco X-1, it would be 40%. The saturated count rate for one counter is 10^5 s^{-1} , or 50 times the Crab.

Flight detectors are being calibrated with an X-ray beam at GSFC using a variety

of target materials. During calibration data runs each event is recorded. These data are being used to measure all contributions to the effective dead time. Plans are in progress for using a tunable monochromatic source to accurately measure the response across the xenon L and K edges.

A complete description of an event tells which of the anode chains had a signal during the approximately $10\ \mu\text{s}$ that the electronics logic was busy. All the events seen within the detector produce 19 bits of information, which includes the energy, defined to 0.24 keV, of the triggering anode. This package of bits is passed to the EDS system, where all veto and selection operations are performed.

5.2. EXPERIMENT DATA SYSTEM

The Experiment Data System (EDS), designed and built at the Massachusetts Institute of Technology (MIT) (Bradt *et al.* 1991; 1993) will process data for both the PCA and the ASM. The EDS contains 6 identical Event Analyzers (EAs) to which each PCA event is presented. There are another 2 EAs to which ASM data is presented. Each EA contains specialized hardware, a digital signal processor, and a microprocessor that can process events fast enough to keep up with rates as high as can be generated by the detector systems.

Each proportional counter may send one event to the EDS as often as once per $7\ \mu\text{s}$, i.e. a rate of $1.4 \times 10^5\ \text{Hz}$. Each EA first adds additional bits to the 19 incoming bits describing an event, 3 bits to define which detector it came from, and 15 bits of time relative to a 31.25 ms clock tick. Thus the event's time has a resolution of $0.953\ \mu\text{s}$. The EA clocks are independent, but synchronized. An event can wait behind others a few microseconds, before being processed further in an EA, but its time is assigned on arrival. Further, while there is a lag between the initiating X-ray interaction in the PCA and an event's arrival in the EDS, it is an almost constant lag. There is less than a $1/4\ \mu\text{s}$ jitter between the X-ray event and the detected pulse, according to the position of the X-ray interaction in a cell. After the event is analyzed, it waits for the next pulse of a 4 MHz clock before being transferred to the EDS. Measurements with a test pulse signal found that for 2 flight detectors the lag between the pulse and the assigned time was $18.2\ \mu\text{s}$.

In each PCA EA, each event is rejected or selected for processing and is transformed into a 16 bit word according to a table-lookup scheme. This process is matched to scientific goals via the reprogrammable content of the lookup table. For example, the EA can build a 10 ms binned rate of events in layer 1 of detector 1 by rejecting all other events and counting the layer 1 events that come in 10 ms intervals. If it is desired that only good events be sent to the ground, all events with multiple flags indicating a charged particle would be rejected. Thus the EA does the anticoincidence work that is usually desired. For diagnostic purposes full details of every event can be transmitted. The EA accumulates the series of 16 bit words in packets which are transferred from the EDS to the spacecraft data system (SDS). The SDS stores and buffers the data, which is then transmitted to the ground.

Within certain rules the EA's can be flexibly programmed. It is necessary to limit the telemetry loading to a manageable amount. On examination of the possibilities, optimal programming of the EDS appears complex. However, about 400 different data processing programs will be stored in ROM on-board, so that they can be

called by number. The average telemetry rate that was contracted for the PCA under normal operating conditions is 18 kbps, or 1.6 Gbits per day. Since this spacecraft has a solid state recorder, there is flexibility about the permitted rates, and use of high rates can be balanced with use of low rates. There is no need to record data when the detectors are off during passage of the particle belts of the South Atlantic Anomaly. While 18 kbps is relatively large for an average telemetry rate, it is not much for millisecond work over extended observations. For example, 8 bit spectra for 32 channels from 5 detectors per 8 ms requires 160 kbps of telemetry. Such rates are permitted for short intervals per day: the equivalent bits to 256 kbps for 30 minutes, i.e. 0.46 Gbits can be acquired. Thus observations of 5 – 10 minutes at up to 512 kbps will be possible. This even allows telemetering 2 bits of pulse height (4 channels) per event with 1 μ s time resolution. Event modes assign various bits of information to each event and produce an amount of data that depends on the source brightness. Since the data is being recorded on a finite storage medium and read out at intervals, care must be exercised not to overwrite or to lose data. The Science Operations Center duty scientists will be concerned with this planning.

The EDS provides additional flexibility to increase the possible information yield within a limited telemetry rate. The PCA analog electronics produces 256 channels of fixed width in energy, while the detector energy resolution elements increase in width as the square root of the energy. (The 64 channels of the HEAO 1 A-2 detectors were quasi-logarithmically binned.) The EDS can produce up to 256 output channels from the input channels according to any desired prescription. The recommended usages of this capability are being codified for loading on board as set prescriptions, although they could be custom built if necessary.

Each EA can process data according to one of 6 mode types. We have given examples of Binned modes and Event modes above. Usually a binned mode can produce a whole array of things binned on a given time scale. In some modes, 2 EAs or even 3 EAs can work in parallel to output different information about each event detected. The other modes are FFT, Single Bit, Pulsar Fold, and Burst mode. Two of the EAs are reserved for data in standard modes that will apply to all observations. This is to make the data of different observations easily comparable, and provide needed information about calibration, particle contamination, and dead time in the same standard way throughout the mission. The two standard modes basically give light curves of the detectors at 1/8 s resolution, calibration spectra for all the anode chains at 128 s resolution, good event spectra with 129 energy channels and 16 s resolution, and “housekeeping” rates such as the rates of anticoincidences and of counts in the veto layers, with which to calculate particle contamination and dead time.

5.3. HIGH ENERGY X-RAY TIMING EXPERIMENT (HEXTE)

Like the PCA, HEXTE also has heritage in HEAO 1, in the A-4 experiment, although a number of changes were made to reduce background and improve spectral resolution (Rothschild *et al.* 1989; Rothschild *et al.* 1991; Pelling *et al.* 1991). HEXTE has 2 sets, or clusters, of 4 NaI(Tl)-CsI(Na) phoswich scintillator detectors, each detector coupled to a photomultiplier tube. The NaI on the collimator side of the detector is sensitive to absorption by the iodine of X-rays above about

10 keV that traverse the 1 mm thick Be window. By 250 keV the HEXTE NaI crystal absorbs $< 10\%$ of the flux. The crystal is kept thin to limit the background from activation by charged particles, in order to maximize sensitivity to the flux at below 200 keV. The detector is also surrounded on 4 sides with plastic scintillator sheets coupled to phototubes which form an active anticoincidence guard (Hink *et al.* 1991). Even so, the background is estimated to be the equivalent of 100 mCrab at 100 keV. Of AGN, only Cen A and NGC 4151 are brighter than the 3 mCrab intensity of 3C273. To be able to measure some 10 AGN at an energy as high as 100 keV, HEXTE must be sensitive to sources as weak as a mCrab. In the strongly background limited situation, HEXTE observations will have to sum on the order of a day of data. The HEXTE background has orbital variations and longer term variations. To correct for these, the 2 clusters of detectors rock on and off source with a 16 s dwell time on source, out of phase, so that the source is always covered with half of the total HEXTE area of 1600 cm². The off-source positions can be 1.5° or 3° from the target. It is possible for bright sources to use both clusters on source, without rocking.

In the on-source position HEXTE's field of view is the same as that of the PCA, $\approx 1^\circ$ FWHM. Like the PCA EDS, the HEXTE data system can output data consisting of an event list, histogram bins for a selected number of channels, and scalar rates in 8 energy ranges on a time scale between 0.5 ms and 1 s. HEXTE's data system can use 1 mode at a time in addition to a standard mode of data. The Crab will generate about 300 counts s⁻¹. Full characterization of an event takes 7 bytes. The event list can include specified bytes of this set and the relatively low count rate makes it possible to get event list data from rather bright sources without going above the nominal telemetry allocation of 5 kbps.

5.4. SUMMARY OF THE PCA AND HEXTE

Targets are observed simultaneously with the two pointed instruments. The energy range of overlap 15 – 60 keV will allow cross calibration of detector area and efficiency. Spectra will extend from 2 keV to a maximum of 250 keV, when exposure time and source spectrum warrant. Table I summarizes the estimated information about rates that have appeared elsewhere. More detailed estimates are given in Bradt *et al.* (1990). Preliminary laboratory performance confirms these estimates, approximately, and expectations based on the laboratory calibrations are being prepared. Fig. 3 shows a simulated Crab spectrum as expected from both instruments.

TABLE I
Estimated Pointed Instrument Rates

Instru.	Energy (keV)	Crab	Background	(Counts s ⁻¹)		Telemetry Av. kbps
		Counts s ⁻¹	2 – 10 keV	> 10 keV		
PCA	2 – 60	10,000	20	40		16
HEXTE	20 – 250	300	...	35		5

Simulation of PCA and HEXTE Observation
of the Crab Nebula for 100 s

Fig. 3. Simulated spectrum of the Crab as seen in PCA and HEXTE.

6. The All Sky Monitor (ASM)

The ASM uses 3 Scanning Shadow Cameras (SSCs), 1-dimensional position sensitive proportional counters with coded masks (Doty 1988), which can be rotated about a single axis by a drive assembly to scan the sky and measure the intensities of bright X-ray sources. The main elements of the configuration and sensitivity were described in Bradt *et al.* (1990; 1993). The sealed detectors are filled with a 95%-5% mixture of xenon and carbon dioxide, respectively, at a total pressure of 1.2 atm. They are sensitive to 2–10 keV X-rays. Three channels of energy information are included in the telemetry. Detailed simulations have been made to optimize the sensitivity of the cameras as a function of types of mask, size of collimator, and relative orientation. Fig. 4 shows the flight configuration of the detectors and masks. Position sensitivity in the long (90°) direction of a collimator, i.e., anode to anode, has been added by dividing the mask into 6 sections with different mask patterns. Thus a single camera can provide 2-dimensional information. With 3 kbps of telemetry assigned to it, the ASM sends down the histograms of counts, in the 3 energy channels, along the length of each of the anodes. The 3 detectors step in 6° increments around the boom axis and pause for measurements for ≈ 100 s, completing a scan of the sky in a satellite orbit of ≈ 90 minutes. The rates and accuracy of position determinations for bright and moderate source strengths are given in Table II.

In general a source will be in view for two of the 100 s dwells during a 90 minute scan. The single scan 3σ sensitivity is 20 mCrab for a Crab-like source seen in two of the cameras. Averaging over a day, 10 mCrab sources, outside the galactic bulge region, should be detected at the 3σ level. This is more than a factor of 10 better than the sensitivity of the Ariel 5 All Sky Monitor or the Vela 5B results. The source intensities will be put on-line as a publicly available data base in order to provide, to any observers and to proposers, knowledge of current intensity history

Fig. 4. The ASM Scanning Shadow Cameras, showing the segmented coded mask.

of the sources. But the most important and unique role of the ASM for XTE is to catch X-ray transients on the rise. An X-ray nova may be undetectable before outburst and rise to be brighter than the Crab within half a day to a week. A linear rise in half a day to the intensity of the Crab would correspond to a change of intensity of 125 mCrab per ASM scan. If the source is in the half of the sky covered by the two cameras with crossed fields of view, the position obtained may be as good as $1' \times 5'$. If it is in the $1/4$ of the sky covered by the single camera, the error box is smaller than $1' \times 2^\circ$. These accuracies are sufficient to allow the PCA and HEXTE fields of view to be maneuvered to see the target and to permit optical identification. Small motions of the spacecraft or additional ASM data could further refine the position. The ASM does get timing data for the detector as a whole and will be able to identify a bright source as very variable or pulsing. The energy information will indicate whether the spectrum is hard or soft. Such information will be helpful in making a decision as to whether the planned observing program should be interrupted to observe the transient with the PCA and HEXTE. While

TABLE II
Summary of Nominal ASM Characteristics

Parameter	Value	No. cameras	Comment
Threshold (3σ)	30 mCrab	1	in 100 s
Position accuracy ¹	$3' \times 15'$	2 crossed fields	5σ detection
	$1' \times 5'$	"	$> 15\sigma$
	$1' \times 2^\circ$	1	"
Area	30 cm^2	1	source at peak
Rates	90 counts s^{-1}	1	Crab
	40 counts s^{-1}	1	diffuse background

X-ray novae are the most obvious transients, a sudden change of state of Cyg X-1, for example, from a low to a high state, would be a candidate for identification as a target of opportunity.

7. The Spacecraft

The spacecraft is expected to be able to point anywhere outside of 30° to the sun. It can slew between targets at up to 9° a minute, so it can cross the sky in 20 minutes, but it is not designed to support routine repointing to avoid earth occultations of a target. The pointing schedule should not be restricted by communication needs, because the spacecraft has an antenna on both sides, one of which will have satisfactory contact, except for about 10 minutes per orbit, with one of the satellites of the U. S. Tracking and Data Relay Satellite system. Generally, observing constraints will be accepted. The observing program will be constructed to satisfy the constraints according to priorities and to be as efficient as possible.

The solid state recorder will be a circular buffer of about 1 Gbit. Data is sent to it as it is acquired by the instruments. When the spacecraft is transmitting, data are being read from the buffer. Commands can be sent to redump the data before it is overwritten. There is a range of possible transmission rates, 32 kbps to 1 Mbps. If the higher rates work well, the recorder should never be filled. If the rates are close to the recording rate, the buffer would have to be managed carefully. The allowed amount of high rate data fills half the recorder, so that the margin is not high, if for some reason it were not possible to transmit the data for several orbits.

The attitude control system uses reaction wheels and magnetic torquing coils as actuators. The primary sensors are four gyros and two CCD star trackers. One tracker is coaligned with the average PCA boresight and one is offset by 9.5° . The star catalog, which contains over 2500 stars, is carried on board. More than one guide star brighter than 6.5 magnitude should usually be available. The spacecraft attitude is determined on board and inserted into telemetry. Gyro and star tracker data are sent to the ground for diagnostic and calibration purposes only. Since there are many separately mounted detector modules making up the PCA and HEXTE, each with its own boresight, accurate knowledge of the projected area each detector presents to a source depends on in-orbit calibration of the offsets and on stability of the spacecraft to thermal distortion and to the motions of parts of the spacecraft and payload. The spacecraft is subject to many internal torques as the HEXTE clusters rock in orthogonal directions, the ASM assembly steps around the boom, the solar panels adjust for maximum power, the high gain antennas slew to lock onto the relay satellite, and the reaction wheels are driven by the gyros to keep the stars still in the tracker fields. We hope that at all times the attitude of each detector will be known to better than $3'$, which translates to an error of $< 5\%$ on the relative area. Simulations have shown that under certain conditions the PCA boresights could jitter at some high frequencies (above 1 Hz) with an amplitude of $10 - 30''$. We believe the jitter can be avoided for observations which might be sensitive to it (QPO sources).

XTE will carry oven clocks, stable to better than $1/10^9$ per day. Corrections to UTC will be determined using tracking data. The accuracy of correlation between

the spacecraft clock time and UTC is required to be better than 1 ms (and may be as good as 100 μ s) with the spacecraft position known to 3 km. The rotation of Her X-1 is a clock good to $1/10^8$ over a day. The clock stability requirements for measurements of accreting pulsars are very mild compared to the $1/10^{14}$ over a year measurable with some radio pulsars (e.g. Taylor 1989).

8. SCIENCE PROSPECTS

The accreting galactic binaries are the prime targets of XTE. In conclusion, we discuss some examples of observations that could be done, chosen to emphasize new data that will be possible to obtain with XTE and which has either been impossible to obtain with other missions, or has been obtained so rarely that the subject has only been touched on and not explored.

- Millisecond variability

— Millisecond bursts. Consider bursts like those that Rothschild *et al.* (1974) reported from Cyg X-1, 1 ms in duration, with a powerlaw energy spectrum with a number index of 1.6. An individual burst of 2.5 Crab intensity would give about 33 counts in the PCA. For repeated events this is enough to investigate structure on a statistical basis, although not enough, clearly, for behavior to be manifest in a single event. It will be possible to resolve bursts to 0.1 ms for 40 kbps per energy bin. A burst in either the PCA or HEXTE can be programmed to trigger telemetry of high rate data for both instruments for a period surrounding the event.

— QPO. Consider the QPO observed at about 50 Hz in some LMXB on the horizontal branch. Telemetry of 4 bits per channel per millisecond for 16 channels would provide spectra of the QPO signal for 64 kbps. Use of this mode for a day would fill the data recorder, but there are modes being implemented that provide the equivalent information at a lower average telemetry rate. From Ginga results it is already known that the different kinds of QPO in the different spectral branches of LMXB —horizontal, normal, and flaring— have different lags or leads of the hard versus the soft photons, although the behavior is not well characterized. (See the review by van der Klis 1994, and references therein.) XTE data should allow extraction of the spectra of the pulse at several pulse phases.

— Pulsar periods. Consider searches for coherent pulsations in LMXB or in SN 1987A. Data modes can be chosen for which the Nyquist frequency is 10^4 Hz to cover sensitivity to the shortest possible periods for a neutron star.

- Ultra-rapid variability

The phase space of time scales between 1 μ s and 1 ms is accessible to XTE for some types of phenomena. While the area is not large enough for significant detections of individual bursts of these durations, burst trains as well as periodicity can be detected. Orlandini and Boldt (1993) have shown that granularity that the Rayleigh-Taylor instability causes in the accretion flow onto the neutron star in wind-fed pulsars could cause bursts of flux. Accretion onto black holes and neutron stars may be expected to be distinguished by their behavior at the highest frequencies. Accreting neutron stars may show a correlation signature of the surface of the neutron star. While each proportional counter unit (PCU) has a dead time of at least 8.5 μ s, the other counters are not dead and the number of coincidences

Fig. 5. Number of pairs of events per time interval between events in 2 different detectors adjacent to each other in the lab.

between detectors is a sensitive measure of whether the flux is bunched in short intervals at relatively higher intensity, on time scales below the time scales which can be observed directly.

Fig. 5 shows the histograms of times between events in two detectors along side each other in the laboratory. The coincident events in this case are believed to be due to electron-positron pairs created by γ -rays interacting in the ceiling above the detectors. These events show that the PCA/EDS system can observe microsecond coincidences.

- Pulse Variability

The spinups of accreting pulsars at first appeared to simply bear witness to the expected capture of angular momentum by the neutron star from the matter coming through the inner Lagrangian point via the accretion disk (Rappaport and Joss 1977). Then, the accumulating record of pulse periods of the wind-fed pulsars exhibited large fluctuations which appeared consistent with random walk of the period under random white noise torques (Boynton *et al.* 1984; Deeter *et al.* 1989). No evidence has been found in the power spectra of the accelerations for degrees of freedom inside neutron stars, but the constraints are very weak. Now CGRO's BATSE experiment has been monitoring pulsars regularly for 2 years and an unexpected phenomenon of long term spin down of disk accretors has emerged. Averages over 1-10 days have generally been necessary to obtain period measurements of sufficient statistical accuracy. Sufficiently accurate period measurements have generally averaged over a day or more. In the case of BATSE, only the high energy behavior (> 20 keV) of the source is known. XTE will obtain accurate periods averaged over time intervals of hours, along with measurements of the total luminosity and the pulse

shapes as functions of energy.

- Longer time scale studies

The flexible observing constraints mean that sources farther than 30° from the ecliptic can be observed any time. Many pulsars could be observed at any time, as could sources in the Cygnus region. Sources near the galactic center are not available for up to 2 months. SS433 would be unavailable for 26 days, but the 164 day precession period can be covered. XTE will be able to observe at the same time as optical observations are possible. Time constrained observations will be supported, in particular, to obtain particular phases of binary periods, to support multiwavelength observation commitments, and to obtain repeated observations at specified intervals. Monitor programs involving short observations of a set of sources, e.g., AGN or Be binaries, are possible with 10 – 20 targets a day and observations as short as 10 – 20 minutes.

- X-ray novae and other transients

Transients can be observed with PCA and HEXTE within 7 hr of ASM detection or of notification of an event detected by another observatory. The data rights for targets of opportunity will be assigned according to rules to be specified when observing proposals are invited. Proposals for transients will be possible. Alternate targets can be allowed to a limited extent to allow a trial observation to determine if a source is in the state suitable for the proposed observations or to hold a place for something like a dwarf nova outburst. Exercise of this option may be restricted according to the load on the operations resources.

The ability to begin PCA and HEXTE observations about 1/3 day after observation by the ASM will make it possible to study a substantial part of the rise of most X-ray novae over the 2 – 250 keV energy range, rather than the limited energy and temporal bandwidths of the monitor. The triggering mechanism has not been identified in the soft transients and measurements of the time dependence and spectrum during the rise will have a chance at seeing effects originating from near the compact object. For example, a hard precursor has been reported in the evolution of the very soft transients (See summary in White *et al.* 1984). Its relation to the hard spectral component seen after the peak is not known.

The fundamental problems that are unique to accreting compact objects and of broadest interest are far from being solved, although more is being learned all the time and the general ideas of some physical models are firm. XTE's capabilities are different in several respects from those of previous missions and will support exploration of a larger phase space. Observations should be proposed that are needed to fill in the missing pieces of puzzles, so that our understanding of the objects can advance as much as possible.

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