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X-ray timing explorer mission

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Abstract. — The XTE will address a number of fundamental questions about the nature of the cosmos. The large effective area ($\sim 0.8 \mathrm{m}^2$ total) and broad band of sensitivity (2-200 keV) of its three instruments make it especially valuable for timing of intensity variations and for the determination of broad-band spectra from high-energy sources. For the first time, studies of variability ranging from about 1 microsecond to several years will be carried out. XTE's design and flexibility of operations will allow it to respond rapidly to changes in the X-ray sky (within hours) and will facilitate multifrequency observations. It is scheduled for launch on a Delta II vehicle prior to April 1996.

Key words: instruments: X-ray — observatory: X-ray — X-ray astronomy.

1. Introduction.

The X-ray Timing Explorer (XTE) will carry out its studies with the 3 instruments listed in Table 1. The two large area instruments (PCA and HEXTE) are a single powerful "telescope". The large areas and low backgrounds provide high sensitivity to weak sources. They can view a single source in their common 1 degree field of view. The third instrument is an All Sky Monitor (ASM) that scans most of the sky every 1.5 hours in order to monitor the intensities and spectra of the brightest ~ 75 sources in the sky. It will provide timely information on any large changes of intensity and spectral shape in a celestial object. This allows the powerful main instruments (PCA and HEXTE) to be pointed rapidly (within a few hours) at the object for studies with great sensitivity.

The power and uniqueness of XTE comes in large part from the natural synergism of the 3 instruments and the versatile spacecraft. These address a single well-defined objective: the timing and broad-band spectra of X-ray sources from 2 - 200 keV. The spacecraft permits rapid pointing to almost any point on the sky. The PCA/HEXTE measures short-term variability to microsecond levels while the ASM measures long-term (hours to months) light curves of bright sources. Long-term variability of faint sources may be monitored with repeated brief PCA/HEXTE observations. Multifrequency observations will be supported.

XTE will be placed in a low-earth orbit of altitude ~ 600 km and ~ 23° inclination by a Delta II vehicle; it should remain operational for 2–5 years. The launch is scheduled for no later than April 1996. Prior to 1992, XTE was to be carried aloft on the Space Shuttle and would have replaced EUVE on the Explorer Platform (Bradt *et al.* 1991). The new plan has a number of advantages: it provides XTE with its own dedicated spacecraft designed to support the scientific objectives and makes an extended mission more likely.

2. The instruments.

2.1. Proportional Counter Array (PCA).

The PCA consists of 5 large detectors with total net area of 6250 cm^2 (Fig. 1). Each detector is a version (50% larger) of a HEAO-1 A2 HED sealed detector (Rothschild *et al.* 1979). They are filled with xenon gas and achieve low background through efficient anti-coincidence schemes including side and rear chambers and a propane top layer. The xenon of the 3 signal detection layers is 3.6 cm thick at 1.0 atmosphere. Methane is used as a quench gas. The front window and a window separating the propane and the xenon/methane chambers are both aluminized mylar of thickness 25 μm. The propane layer may also be used as a signal layer in the energy range 1–3 keV.

The PCA is effective over the range 2-60 keV with 18% energy resolution at 6 keV and 255-channel pulse-height discrimination. The gain of the counter is monitored continuously with an americium radioactive source; detection

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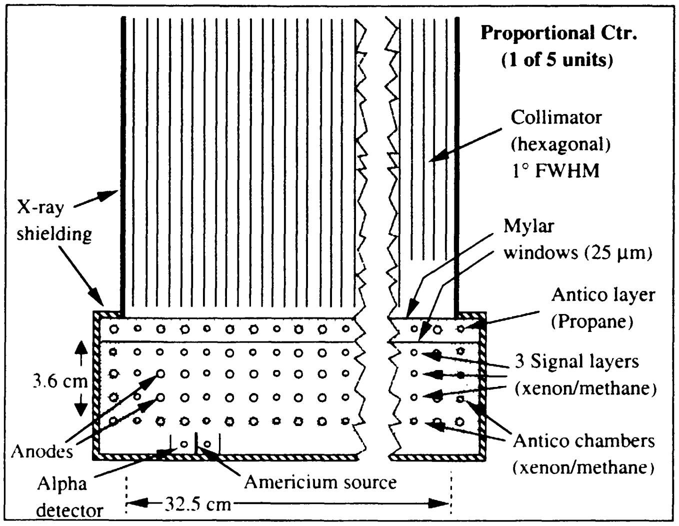

FIGURE 1. One of the 5 proportional counters. The overall footprint of the array of 5 counters is 1.4 m × 1.8 m.

of the alpha particle identifies the calibration X-rays. The 1° FOV (*FWHM*) of the tubular (hexagonal) collimators yields a source confusion limit at ~ 0.1 mCrab.

The Crab nebula will yield 8700 c s^{-1} (2–10 keV) and 1200 c s^{-1} (10–30 keV) in the PCA. The backgrounds in these 2 bands are respectively 20 and 24 c s^{-1}, corresponding to 2 and 20 mCrab respectively. With these backgrounds, an AGN source of intensity 1.3 mCrab (2–10 keV) and energy index 0.7 will be detected at $> 2\sigma$ in only 1 s at 2–10 keV and at 3σ in 10 s at 10–30 keV. (See Bradt *et al.* 1990 for additional rates.) Monitored anticoincidence rates will provide a measure of the background to at least 10% of its value.

The PCA electronics provide digital pulse-height data to the flight experiment data system (EDS) for binning and on board analyses (see below). The PCA is being provided by NASA's Goddard Space Flight Center.

2.2. EXPERIMENT DATA SYSTEM (EDS) FOR THE PCA AND ASM.

The EDS is a microprocessor-driven data system used for the on-board processing of the PCA and ASM data. The system will process count rates from the PCA up to $\gtrsim 500,000$ c s^{-1} (Sco X-1 yields $\sim 160,000$ c s^{-1}) and will be able to time photon arrivals to ~ 1 μs. The PCA data stream can be binned and telemetered in 6 different modes simultaneously by 6 independent Event Analyzers (EA) which operate in parallel, each analyzing the total PCA data stream. For example, a pulsar fold, a high-resolution spectrum, a low-resolution spectrum, and an autocorrelation function with 1 μs bins could all be carried out simultaneously.

Each EA includes a Digital Signal Processor (DSP) chip that will rapidly bin the individual events according to highly flexible criteria (e.g., non uniform pulse height bin widths and arbitrarily chosen timing bin widths) which may be specified for each observation. The DSP is used in conjunction with a table-lookup scheme to provide the required speed of classification for each event. (The tables hold the binning criteria for a given observation.) An additional microprocessor in each EA serves as the EA manager.

Each EA can also perform searches to capture X-ray bursts at high time resolution, pulsar folding, autocorrelation functions which yield Fourier power spectra to 5×10^5 Hz, cross correlation functions, and encoding of a single-bit high-speed mode for optimum transmission of the data stream with maximum possible time resolution. In addition, at low count rates, it will provide the familiar mode (Event Mode) wherein all bits describing each X-ray event are transmitted. The telemetry rate assigned to each EA may be changed from observation to observation to accommodate the scientific requirements.

Two of the 6 PCA EAs are intended to be reserved for two standard PCA modes with timing and spectral parameters that will remain unchanged throughout the mission to provide a uniform mission data bank. Currently, the two modes are a time series mode ($\Delta t = 0.1$ s, 6 energy channels) and a spectral mode ($\Delta t = 16$ s, 128 channels). Both would be compatible with the HEXTE standard data modes. If necessary, though, these modes can be reprogrammed in flight. Two other EAs will process the ASM data and control its rotation. The EAs will create data packets for transfer to the spacecraft memory from which they will be transmitted via the telemetry stream to the ground at a time average rate of 21 kb/s or at 256 kb/s for ~ 30 minutes a day. The EDS is being provided by the Massachusetts Institute of Technology.

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

The HEXTE experiment consists of two rocking clusters of NaI/CsI phoswich detectors that cover the energy range 20–200 keV (Fig. 2). The detectors are improved versions of the HEAO-1 A4 LED detectors (Matteson 1978) which attained the lowest in-orbit background for large-area scintillators to date. Each detector consists of a 3-mm thick NaI primary detector coupled to a 38-mm thick CsI anticoincidence crystal that also serves as a light guide to the photomultiplier tube. Each detector has 200 cm^2 net effective area. Each cluster contains 4 detectors; the total net area of the entire system is 1600 cm^2. The field of view is 1° *FWHM* and is coaligned with the PCA when on source.

Each cluster will be rotated ("rocked") on or off the source every ~ 15 s to provide alternate source and background measurements. Each cluster will sample background positions on two opposing sides of the source, and the two clusters will rock in mutually perpendicular di-

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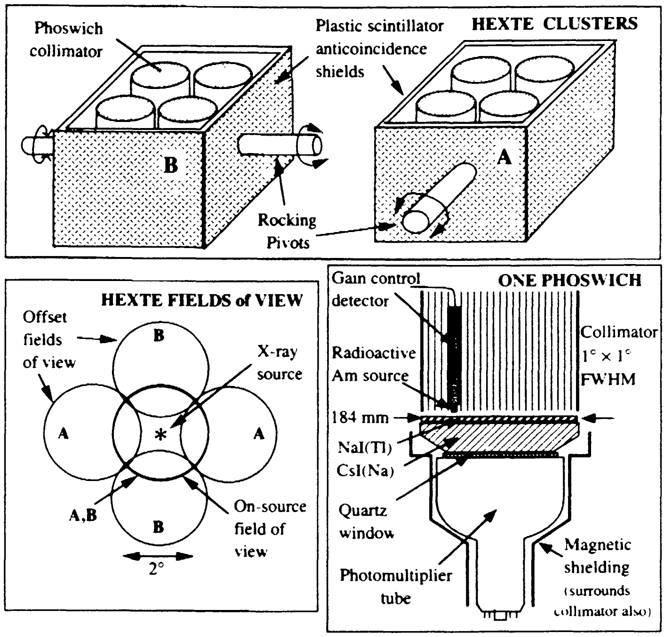

FIGURE 2. The HEXTE phoswich experiment. The two clusters rock in orthogonal directions.

rections by either 11.5° or 13.0°. Thus 4 background positions will be monitored. The rocking will be phased so that the source is continuously viewed by at least one of the clusters. A 5-sided plastic scintillator 'box', viewed with photomultiplier tubes, serves as an anticoincidence shield for background reduction. Automatic gain control on each detector reduces systematic uncertainties from gain variations.

The HEXTE flight data system will provide the following modes: binned, event encoded, burst trigger, and a standard output mode. The telemetry rate for HEXTE will be ~ 5 kb/s. The Crab nebula will yield 170 c s^{-1} (15–30 keV) and 130 c s^{-1} (> 30 keV) in 1 cluster (1/2 HEXTE). The background in these energy bands will be ~ 6 and ~ 29 c s^{-1} respectively. At 100 keV, the background is about 100 mCrab (1×10^{-4} cts cm^{-2} s^{-1} keV^{-1}). In the 90–110 keV band, the limiting sensitivity for detailed spectral analysis is expected to be about 1 mCrab (1×10^{-6} cts cm^{-2} s^{-1} keV^{-1}) or 1% of the instrument background. This sensitivity can be reached at 3σ in 10^5 s. The instrument is being provided by the University of California at San Diego.

2.4. ALL SKY MONITOR (ASM).

The ASM consists of 3 Scanning Shadow Cameras' (SSC) on one rotating boom with a total net effective area of 90 cm^2 (180 cm^2 without masks) (Fig. 3). Each SSC is a one-dimensional 'Dicke camera' consisting of a 1-dimensional mask and a 1-dimensional position-sensitive proportional counter (Doty 1988). The gross field of view of a single SSC is 6° × 90° *FWHM*, and the angular resolution in the narrow (imaging) direction is 0.2°. A $\sim 5\sigma$ detection provides a single line of position of 3′ × 90°. Two of the units view perpendicular to the rotation axis in nearly the same direction except that the two detectors are each rotated by ±12° about the view direction so that they serve as 'crossed slat collimators'. The crossed fields provide a positional error region of 0.2° × 1° for a weak source and 3′ × 15′ for a $\sim 5\sigma$ detection. A spacecraft maneuver could reduce this to 3′ × 3′. With high-statistics detections, precisions $\gtrsim 1'$ should be attainable. The third SSC unit views along the axis of rotation. It serves in part as a 'rotation modulation collimator' and surveys one of the 2 poles not scanned by the other two cameras.

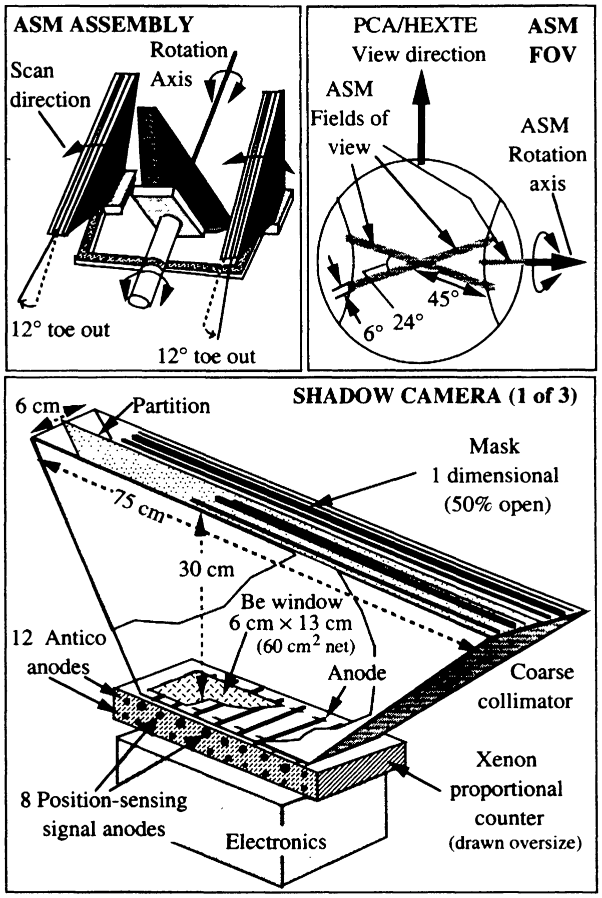

FIGURE 3. The All Sky Monitor experiment. The cameras rotate about the common axis with 6° steps.

Each SSC detector is a sealed proportional counter filled to 1.2 atm with xenon-CO_2, and has a sensitive depth of 13 mm. It has 8 position-sensitive anodes, a 50-μm beryllium window, a sensitive area of 60 cm^2 of which only 1/2 can view a given celestial position through the mask at a given time, anticoincidence chambers on the sides and rear, and sensitivity to 2–10 keV X-rays with three energy channels. The one-dimensional design of the SSC's greatly minimizes the required telemetry rate com-

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pared to two-dimensional systems. The data are telemetered in a spatial-image mode and in a time-series mode.

A motorized drive will rotate the three SSC's from field to field in 6° steps. At each resting position, a $\sim$ 100-s exposure of the X-ray sky will be made; a complete rotation is thus completed in $\sim$ 100 min. Since the 'crossed-field detectors' are stepped by only the 6° *FWHM* angle, each source is viewed twice. In this manner, each source gives rise to the entire mask pattern in the accumulated data, thus minimizing aliasing and side bands in the deconvolved results. During each rotation, $\sim$ 80% of the sky will be surveyed to a depth of $\sim$ 20 mCrab (about 50 sources). Frequent spacecraft maneuvers will make it likely that 100% of the sky is surveyed each day. In one day, the limiting sensitivity becomes $\gtrsim$ 10 mCrab ($\sim$ 75 sources). The drive can be commanded to stop for an extended observation of a given source, e.g. to obtain a precise position of a nova. The drive has a total rotation angle of $\sim$ 500°; it can be stepped or moved rapidly in either direction.

The intensities and other basic results derived from the data will immediately be made available in the XTE Science Operations Center and to the community in general via computer links. The results will make possible rapid acquisition by the PCA/HEXTE of sources when they undergo a change of state, e.g. when a transient appears or when a low-mass binary system moves to the horizontal branch of the color-color plot.

3. Spacecraft.

The XTE instruments and the service hardware (reaction wheels, star trackers, transmitters, etc.) are all integrated onto a common spacecraft structure (Fig. 4). The spacecraft components and their locations are chosen to optimize the scientific performance of XTE. The XTE is highly maneuverable (> 6°/min), and the PCA/HEXTE field of view can be pointed to any position on the sky on any day of the year provided the angle to the sun is > 30°. The pointing accuracy is < 0.1° with knowledge of aspect from star trackers and gyroscopes to $\lesssim 1'$. Rotatable solar panels make possible anti-sun pointing so that coordinated observations with optical telescopes can be carried on throughout the ground-based night.

The command and data links will be through the NASA TDRSS communication satellites. Both the multiple access and single access channels of TDRSS will be used to provide nearly continuous telemetry of data. At least one command link per orbit will be available. The time-averaged data rate will be about 32 kb/s of which 26 kb/s will be available for the scientific instruments. In addition, 256 kbs for about 30 min. a day will be available.

An operations scenario patterned after the *International Ultraviolet Explorer* (IUE) is being planned wherein the XTE Science Operations Center has the prime responsibility for scientific operations including pointing. Also, the scientific operations are being decoupled from engineering and servicing constraints. For example, since the two pointable antennas can transmit to any point on the sky, XTE can maintain communication with a TDRSS even if XTE is maneuvered to a previously unscheduled celestial target. No schedule changes need be negotiated with TDRSS, and on-board memory allocation is not subject to changing TDRSS schedules. These features should present an observer with the degree of flexibility and control similar to that experienced at a major ground-based observatory.

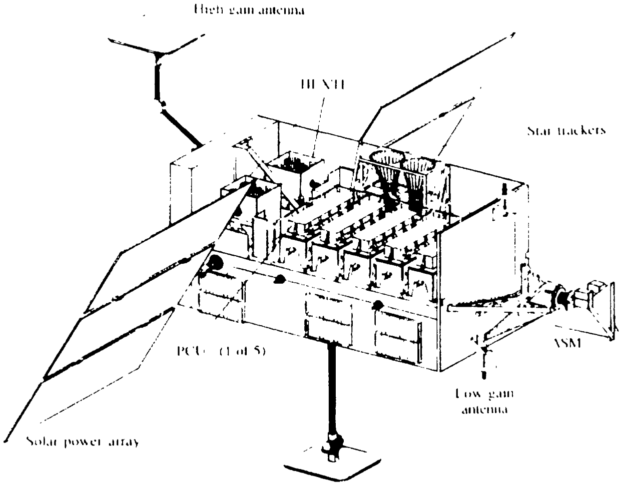

FIGURE 4. The XTE spacecraft.

4. User program.

The XTE observing program will be devoted 100% to Users from the International community, after a 30-d checkout period. The community will propose for observations with the PCA and HEXTE instruments. PI-institution observers will compete in this process to obtain observing time. The ASM observing plan is dictated for the most part by the requirements of the continuous monitoring. The basic ASM results (e.g., intensities, hardness ratios, routine FFT's) will be placed in the public domain in near real time by the PI team for the use of proposal writers, XTE observers, multifrequency observers, and paper writers.

A User committee will help set proposal guidelines. For example, it is anticipated that proposals will be accepted for contingency observations, e.g. for a transient with particular characteristics, that a proper balance will be maintained between individual-source studies and extended class studies, and that the handling of multifrequency proposals will consider the schedules of other observatories. Proposals to use ASM data for specialized analyses or limited observations should also be possible.

Real-time operations at the Science Operations Center will include examination of the data from the instruments

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and the sending of commands to adjust instrument parameters and possibly times for maneuvers to new targets, e.g., if a source is found to be "off". The ASM data will be examined for transients and changes of state of sources. This could dictate a change in the observing program. The management of the data system and the flexible maneuvering of XTE will help minimize the disruption to the preplanned schedule. Observers will be able to monitor their observations at the SOC, or at one of the Instrument-PI institutions, or from their home institution.

5. Multifrequency observations.

The importance of multi-frequency observations is recognized by the XTE team. The state of knowledge of accreting binary systems (cataclysmic variables and neutron-star binaries) is now sufficiently developed so that concurrent radio, IR, optical, ultraviolet, and X-ray observations may be required for detailed studies such as building geometric models. Similarly, the current attempts to construct unified models of AGN require concurrent observations from the radio to gamma rays.

The timing and spectral studies that will be made with XTE are thus often best served by complementary observations at other observatories. It is a specific goal of the XTE mission to facilitate multifrequency observing plans that are approved by the NASA proposal-review committee. Accordingly, the XTE spacecraft will be able to point the instruments anywhere beyond a 30° cone centered on the sun on any day of the year. Spacecraft systems are being designed to simplify operations which again will facilitate such observations.

6. Scientific objectives.

The timing and spectral data obtained by XTE probe numerous fundamental physical processes. Specific scientific objectives are described in (Bradt *et al* 1990). The galactic objects to be studied are mostly binary systems with an accreting neutron star, white dwarf, or possibly black-hole, i.e. systems near the end points of their evolution. The X-rays provide direct information about: (1) the conditions very close to the compact object, e.g. geometries, temperatures, magnetic fields, (2) the evolution of the binary systems (e.g. relation of low-mass systems to the millisecond radio pulsars), and (3) the nature of the compact object itself (e.g. neutron-star masses and internal structure of neutron stars).

The extragalactic objects include emission-line AGN (Seyferts and quasars) as well as BL-Lac type objects. Here again, the X-rays provide direct information about the regions close to the putative $\sim 10^8\ M_\odot$ black hole. The X-rays play a substantial role in the overall energetics and in the conditions of the optical and radio emitting regions. Measurements of the high-energy spectra of AGN to > 100 keV are critically needed to bound the power-law model and the AGNs' bolometric luminosities. Such data will also answer specific questions about the origin of the diffuse X-ray background.

The objects accessible to XTE are the thousand or more brightest X-ray sources in the sky. These are the closest or most luminous objects of the several classes, compared to the much fainter deep-sky objects detected with Einstein or AXAF. The relative brightness of these objects (e.g. QSO's at $V \sim 15$–16) makes them most desirable for detailed studies at other frequencies as well as in X-rays.

Many of these objects have only recently become available through identifications and classifications of HEAO-1 sky-survey sources. The identification of ROSAT sky survey and IPC slew survey sources are now providing many additional objects. XTE can stimulate detailed multifrequency studies of these objects as it brings to bear the unique capabilities of large aperture and high-energy response.

Acknowledgements.

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Table 1. *XTE instruments.*

Instrument		Detector	Net geom. area (cm^2)	Bandwidth (keV)	FOV (FWHM)	Time resolution	Telemetry rates (kb/s)	Sensitivity (mCrab)
PCA	Proportional Counter Array	5 Xe Prop. Counters	6250	2 - 60	1° × 1°	~1 µs	18 ; 256	0.1 (10 min)
HEXTE	High-Energy X-ray Timing Experiment	NaI/CsI (2 clusters)	1600	20 - 200	1° × 1° (Rocking)	10 µs	5	1 (10^5 s)
ASM	All-Sky Monitor (3 Shadow cameras)	1-dim PSPC + Mask	90	2-10	0.2° × 1° [a]	1.5 h	3	30 (1.5 h)[b]

[a] Effective beam of crossed fields; positions at $\gtrsim 5\sigma$ are obtained to $\lesssim 3' \times 15'$. Gross FOV of each SSC is $6^\circ \times 90^\circ$ FWHM.
[b] 10 mCrab in 1 day.