THE X-RAY TIMING EXPLORER*

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Abstract. The capabilities of the X-ray Timing Explorer (XTE) are described with particular attention paid to current scientific problems it will address from galactic neutron star systems to active galactic nuclei. It features a low-background continuous 2–200 keV response with large apertures (a 0.63-m^2 proportional counter array and a 0.16-m^2 dual rocking NaI/CsI scintillation array). Rapid response (in hours) to temporal phenomena, e.g. transients, is obtained by virtue of a scanning all-sky monitor and rapid maneuverability. XTE will carry out detailed energy-resolved studies of phenomena close to neutron stars (e.g. QPO's) because of its sub-millisecond timing (to 10 μs), its high telemetry rates (to 256 kb/s), and the high throughput of its data system (to $\gtrsim 2 \times 10^5$ c s^{-1}).

1. Introduction

The X-ray Timing Explorer will carry out timing studies of compact objects, galactic and extragalactic. Its instrument complement will consist of a large-area proportional counter array (PCA; 2–60 keV; 6250 cm^2), a high-energy crystal scintillation experiment (HEXTE; 15–200 keV; 1600 cm^2), and a continuously scanning all-sky monitor (ASM; 2–10 keV; 90 cm^2). The essential parameters of XTE are given in Table I. The fields of view of the instruments are shown in Fig. 1. The effective areas of XTE and of other missions are given in Fig. 2. Expected accumulated counts for several types of sources (for differing time intervals) are given in Table II. XTE will be carried on the NASA Explorer Platform for at least 2 years. It is scheduled for launch in early 1995.

The mission was described in 1984 (McClintock and Levine 1984); the instruments have since been reduced by about 30% to reduce costs and to make them compatible with a Delta vehicle should the shuttle become unavailable (Bradt, Swank and Rothschild 1990). The science that can be addressed by the XTE and

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TABLE I
Parameters and Features

POINTED INSTRUMENTS	
	6250 cm^2; Xe Proportional Counters; 2 - 60 keV; 'PCA'; GSFC HEAO-A2 type; low background. 1600 cm^2; NaI/CsI; 15 - 200 keV; 'HEXTE'; UCSD; rocks on-off source continuously; low background
PARAMETERS OF POINTED INSTRUMENTS	
Net Area	3000 cm^2 at 3 keV 6000 cm^2 at 10 keV 1200 cm^2 at 50 keV (NaI); 800 cm^2 at 50 keV (Xe) 1100 cm^2 at 100 keV 300 cm^2 at 200 keV
Field of View	1° FWHM circular; PCA and HEXTE coaligned
Energy Resolution	18% at 6 keV (Xe) 18% at 60 keV (NaI)
Sensitivity*	0.1 mCrab 2-10 keV (in minutes); limit of source confusion 1 mCrab 90 - 110 keV (3σ; 10^5 s)
Time Resolution	10 μs (system uncertainty)
Background	2 mCrab 2-10 keV 100 mCrab (1 $\times$ 10^{-4} cts cm^{-2} s^{-1} keV^{-1}) at 100 keV
Telemetry	18 kb/s (PCA) and 5 kb/s (HEXTE) continuous; 256 kbs ~30 min/day (PCA)
Flight Data System (MIT) (for PCA/ASM)	Flexible binning criteria (microprocessor-driven) Pulsar folding and high time resolution burst searches Simultaneous binning with different criteria Real-time sub-ms resolution FFT's High throughput, >2 $\times$ 10^5 ct s^{-1}
HEXTE Data Modes	Binned, event encoded, pulsar fold, burst trigger, optimum high-speed code
ALL-SKY MONITOR ('ASM'; MIT)	
Energy Range	2-10 keV; 3 energy channels
Net Area	90 cm^2 net
Positional Resolution	0.2° x 2° (Positions to 3' x 30')
Scan time	90 min; 80% of the sky per orbit
Sensitivity	30 mCrab in 1.5 h; 10 mCrab in 1 day
Telemetry	3 kb/s
Dissemination	Routine analyses carried out immediately to assess need for pointed studies, i.e. a S/C maneuver. Results placed in public domain (computer access) to aid community in proposal writing, optical observations, etc.
SPACECRAFT and OPERATIONS	
Maneuverability	25°/min; precise to < 0.1 deg.; aspect to 0.02 deg. 85% of sky accessible (includes anti-sun pointing for coordinated observations)
Response to Transients	Target acquisition a few hours after detection
USER (GUEST) PROGRAM	
PCA/HEXTE	100% of time competitively assigned (PI's also compete) Single object, class studies, or contingency (i.e. transients) proposals allowed Observing at SOC or at PI institutions (with less support) Remote observing from observer's home institution possible Multi-wavelength coordinated observations encouraged.
ASM	Proposals for specialized analyses possible

* 1 mCrab ≈ 1.06 μJy at 5.2 keV

TABLE 2: Expected Counts*

	2-10 keV	10-30 keV	>30 keV
Proportional Counter Array (PCA)**			
Background (1s)	20 cts	24 cts	16 cts
Crab Nebula (1s)	8700	1205	80
Her X-1 (1.24s) 1390	850	15	
X1728-34 (1s; burst)	10,625	3750	2
Sco X-1 (1s) 160,000	4600	4	
Cyg X-1 (1ms flare) (2.5 Crab)	23	9	1
SS Cyg (5 mCrab; 1s)	44	4	-
AGN (1.3 mCrab; 10 s)	113	42	4
1/2 High-Energy Experiment (HEXTE)***			
Background (1s)	-	6 cts	29 cts
Crab Nebula (1s)	-	170	130
Her X-1 (1.24s) -	40	2	
X1728-34 (1s; burst)	-	80	8
Sco X-1 (1s) -	1670	40	
Cyg X-1 (1ms flare) (2.5 Crab)	-	1	3
SS Cyg (5 mCrab; 1s)	-	–	–
AGN (1.3 mCrab at 5 keV; 10 s)	-	9	10
1/3 All Sky Monitor (ASM)****			
Diffuse background (1s):	40		
Crab Nebula (1s):	90		
Sco X-1 (1s) 1400			

* The assumed integration time for each source is given.
** "1 mCrab" nebula flux ≈ 1.06 μJy at 1.25×10^{18} Hz (5.2 keV).
*** Nominally, only 1/2 the HEXTE is on a source at a given time due to the 'rocking' collimators.
**** Counts are for one of the 3 shadow cameras with 30 cm^2 net effective area (60 cm^2 gross) for a given source. (The mask occults 1/2 of the total 60-cm^2 sensitive area.)

by the Japanese *Ginga* mission was the subject of a workshop in 1985 which was given a vivid presentation by the organizers (Epstein *et al.* 1986).

2. Unexplored measurement phase space

The power and uniqueness of the mission for timing and broad-band spectral studies derives from the synergism of its capabilities. The domains of largely unexplored phase space in 1995 will be:

Sub-millisecond timing (to 10 μs). This is made possible by high telemetry rates (32 kb/s continuous and 256 kb/s for ~ 30 min. per day), large apertures, and high-rate processing capability to $\gtrsim 2 \times 10^5$ c s^{-1} (e.g. Sco X-1). The sub-millisecond regime must be explored; the natural time scale for matter near a 10-km neutron star is ~ 0.1 ms (size ÷ free fall speed ≈ dynamical time scale).

Rapid response to temporal phenomena. The ASM and the rapid maneuvering capability (180° in 7 min) make possible early detection and rapid PCA/HEXTE

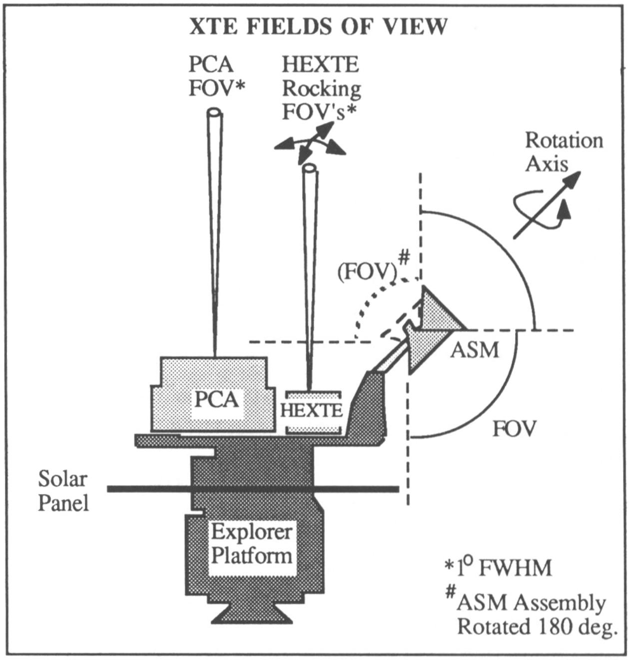

Fig. 1. Schematic view of XTE showing the fields of view of the Proportional Counter Array (PCA), the High-Energy X-ray Timing Experiment (HEXTE), the All-Sky Monitor (ASM), and elements of the Explorer Platform, i.e., the Multi-Mission Spacecraft (MMS) and the Payload Equipment Deck (PED).

acquisition of temporal phenomena (e.g. transients and state changes) within a few hours of an ASM detection.

Multi-wavelength observations. The PCA can be maneuvered rapidly (see above) and can be pointed to $\sim$85% of the sky any day of the year (i.e. the solar constraints are minimal). This makes possible all-night coordinated optical observations (anti-sun pointing by XTE) and source acquisition by XTE during exact times of coordinated observations.

Continuous sensitive spectra from 2 keV to 200 keV. The large effective apertures over the entire 2-200 keV band together with the low and well measured backgrounds of both the PCA and HEXTE should make XTE significantly more sensitive than other missions with comparable bandpasses.

Long-term and very-sensitive monitoring of fluxes and pulsar phases. The flexible maneuvering capability of XTE permits frequent repeated observations with the PCA. (The ASM will routinely perform such measurements for the brighter sources.)

3. The explorer platform (EP)

The Explorer Platform is essentially the same type of Multi-Mission Spacecraft (MMS) that carries the Solar Maximum mission. It is highly maneuverable (25°/min)

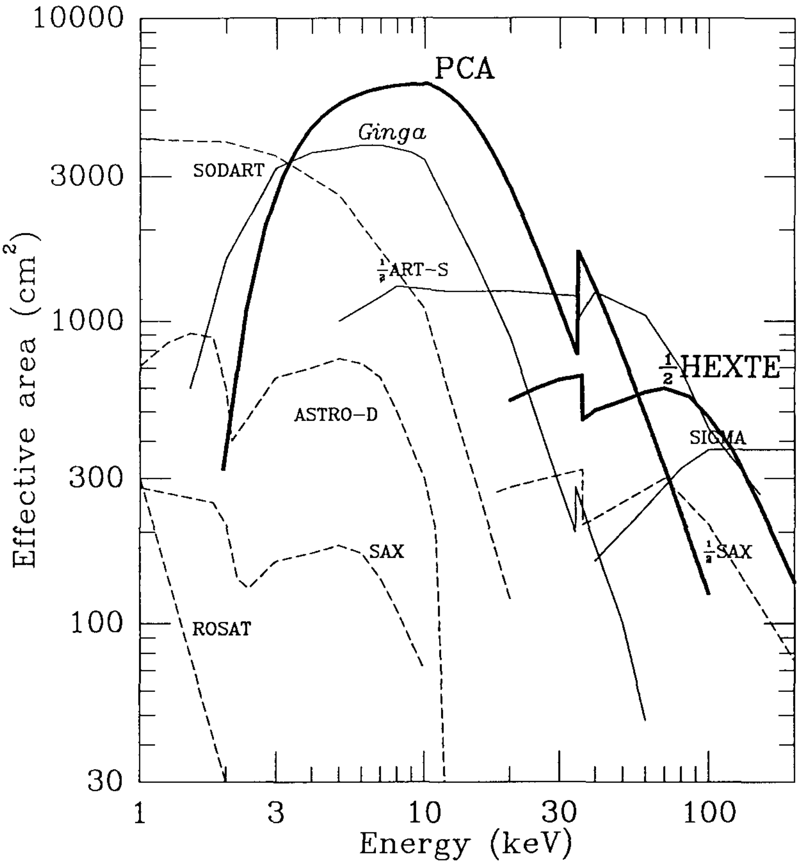

Fig. 2. Effective areas for XTE (dark lines) and other missions or instruments. The two HEXTE assemblies usually each rock on and off the source; thus nominally only 1/2 the area is on the target source at a given time. The *Granat* mission (launched 1989) carries ART-S (Sunyaev 1990) and SIGMA (Debouzy 1983). The *Spectrum* X mission (1993) will carry SODART (Schnopper 1990). The curves represent the estimated net area of the entire detection system, except for the SODART curve which shows the design goal for the geometrical area of the concentrator. *Ginga* and *Granat* are currently in orbit (Makino *et al.* 1987). The areas for *Astro-D* (1993) (Tanaka, private communication), SAX (1992) (Spada, private communication), and ROSAT (1990) (Aschenbach 1988) are also shown. The curves for future missions (dashed lines) represent our understanding of the instruments and missions; we caution that the designs for some of these instruments are still evolving. Finally, the XTE backgrounds may be somewhat less than that of other non-focusing missions. This would enhance the XTE faint-source sensitivity (in a given time) relative that of higher-background instruments.

and can point the PCA/HEXTE to any point on the sky on any day of the year provided the PCA-sun angle is $> 30°$. It will provide, via tape dumps through TDRSS, a continuous telemetry rate of 32 kb/s of which 26 kb/s will be available for the scientific instruments. In addition, 256 kb/s for about 30 min. a day will be available. Neither XTE nor the Platform carries expendables that would artificially limit the active lifetime in orbit. XTE will be preceded on the Platform by the Extreme Ultraviolet Explorer (EUVE). XTE will be carried into orbit on the shuttle, and the EP/EUVE will be captured and placed in the shuttle bay. XTE will be exchanged with EUVE in the bay, and then the EP/XTE will be deployed. The orbit will, of necessity, be a low-earth orbit at altitude $\sim$ 500 km at 28° inclination. The XTE mission would terminate when another experiment replaces it on the Platform.

4. The proportional counter array (PCA)

The proportional counter array will be 5 large detectors with net area of 6250 cm^2 (Fig. 3). Each detector is a large version of the HEAO-1 A2 HED detectors (Rothschild *et al.* 1979) that featured low-background through efficient anti-coincidence schemes including side and rear chambers and a propane top layer. The two window (the front one and the one separating the propane and xenon/methane chambers) are each 25-μm Mylar. The xenon of the 3 detection chambers is 3.6 cm thick at 1.0 atmosphere. The PCA is effective over the range 2-60 keV with 18% energy resolution at 6 keV and at least 128-channel pulse height discrimination. The 1° FOV (FWHM) yields a source confusion limit at $\sim$ 0.1 mCrab. The PCA is being provided by GSFC; principal investigator J. Swank.

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. Monitored anticoincidence rates will yield the background reliably to at least 10% of its value.

The microprocessor-driven flight data system for the PCA can handle high throughputs to $\gtrsim 2 \times 10^5$ c s^{-1} (Sco X-1 yields 160,000 c s^{-1}) and can time events to 10 μs. The data stream can be binned and telemetered in several modes simultaneously. Each such mode can be chosen arbitrarily for optimum tradeoffs of timing and spectral information. The binned data can be preprocessed prior to being telemetered. Features of the system in the current design are burst searches at high time resolution, pulse folding, and on-line FFT's with time resolutions to 10 μs. The data system, which will also be used for the ASM, is being provided by MIT.

5. The 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 15–200 keV (Fig. 4). The detectors are improved versions of the HEAO-1 A4 LED detectors (Matteson 1978) which attained the low-

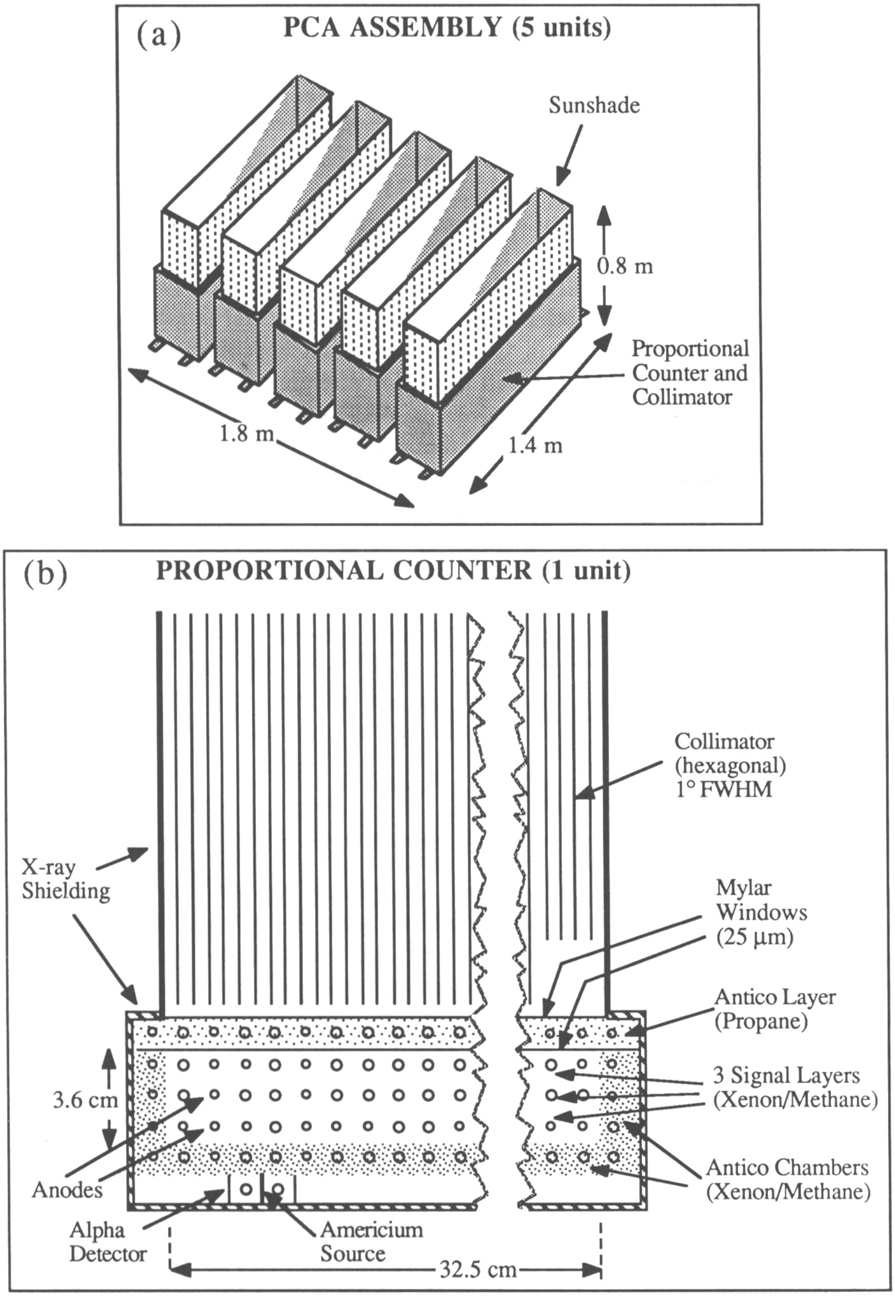

Fig. 3. Schematics of the Proportional Counter Array. (a) The 5 units of the PCA. (b) One unit of the PCA showing principal components but not engineering details (end view).

est 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 'rocking' field of view is 1° FWHM and is coaligned with the PCA when on source. The instrument will be provided by UCSD; principal investigator R. Rothschild.

The phoswich/collimators, under most circumstances, will be rotated ("rocked") on or off the source every $\sim$ 15 s to provide alternately 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 directions. Thus 4 background positions will be monitored. The rocking will be phased so that the source is continuously viewed by one of the clusters. A plastic scintillator 'box', viewed with photomultiplier tubes, serves as an anticoincidence shield for background reduction on the sides and underside of the cluster. Automatic gain control on each detector further refines the background knowledge.

The HEXTE flight data system will provide the following modes: binned, event encoded, pulsar fold, burst trigger, and an optimum high-speed code. The telemetry rate for HEXTE will be at least 3 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 $\sim$ 6 and $\sim$ 29 c s^{-1} respectively. At 100 keV, the background is about 100 mCrab (1×10^{-4} c 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 3 σ in 10^5 s.

6. The All-Sky Monitor (ASM)

The all-sky monitor (Fig. 5) 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). Each SSC is a one-dimensional 'Dicke camera' (Dicke 1968) consisting of a 1-dimensional mask and a 1-dimensional imaging proportional counter. 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 weak source provides a single line of position of 0.2° × 90°. Two of the units view perpendicular to the rotation axis in nearly the same direction except that the detectors are rotated slightly (5° each) about the view direction. Thus they serve as 'crossed slat collimators'. The crossed fields provide a positional error region of 0.2° × 2° for a weak source and 3′ × 30′ for a brighter, $\sim 5\sigma$, source. A spacecraft maneuver could reduce this to 3′ × 3′ . The third (similar) 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. The ASM will be provided by MIT; principal investigator H. Bradt.

Each SSC detector is a sealed proportional counter filled to 1 atm with xenon-CO_2 and with a sensitive depth of 15 mm, in the current design. It has 9 position-sensitive anodes, a 50 μm beryllium window, a sensitive area of about 60 cm^2 of which only 1/2 can view a given celestial position at a given time, anticoincidence

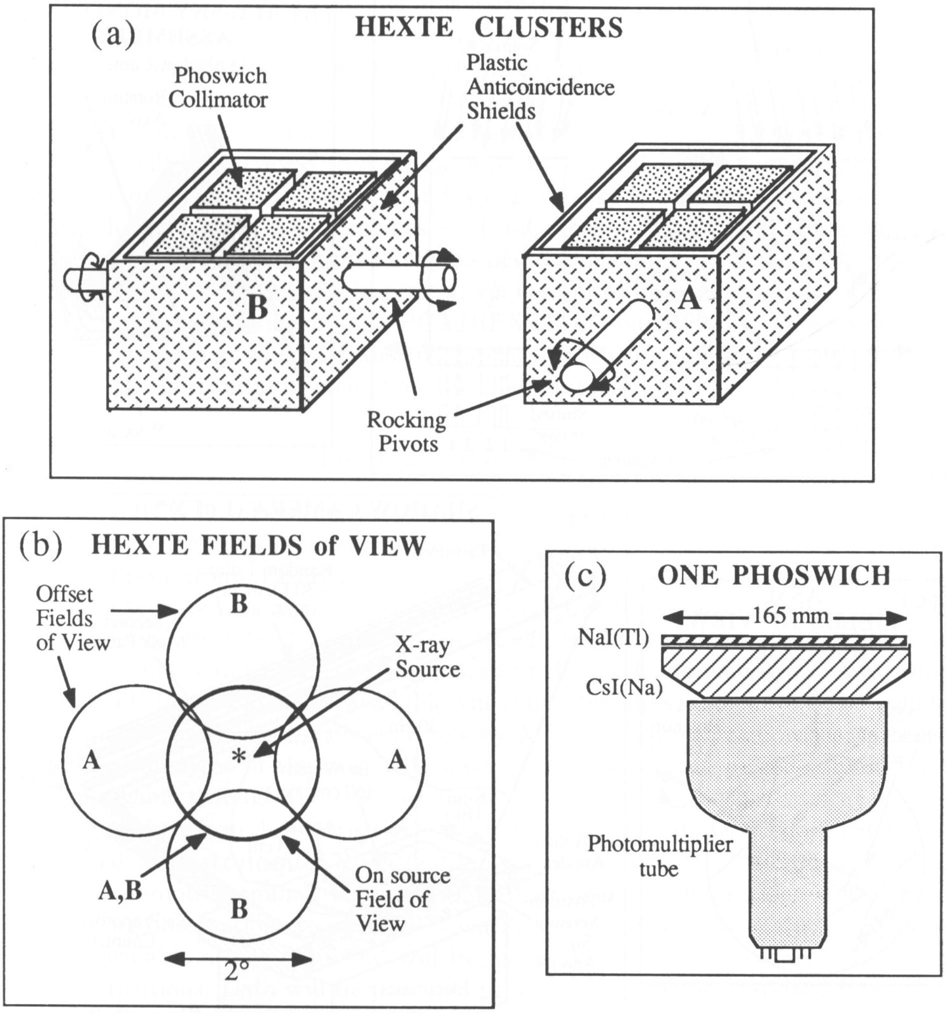

Fig. 4. Schematics of the HEXTE detector system: (a) The two rocking clusters, each with 4 phoswich detectors which lie inside a plastic scintillator anticoincidence shield ('box'). The collimators are not shown. (b) The fields of view sampled during the on-source and off-source orientations. (c) One of the 8 phoswich detectors shown without its collimator; the crystals are square when viewed from above.

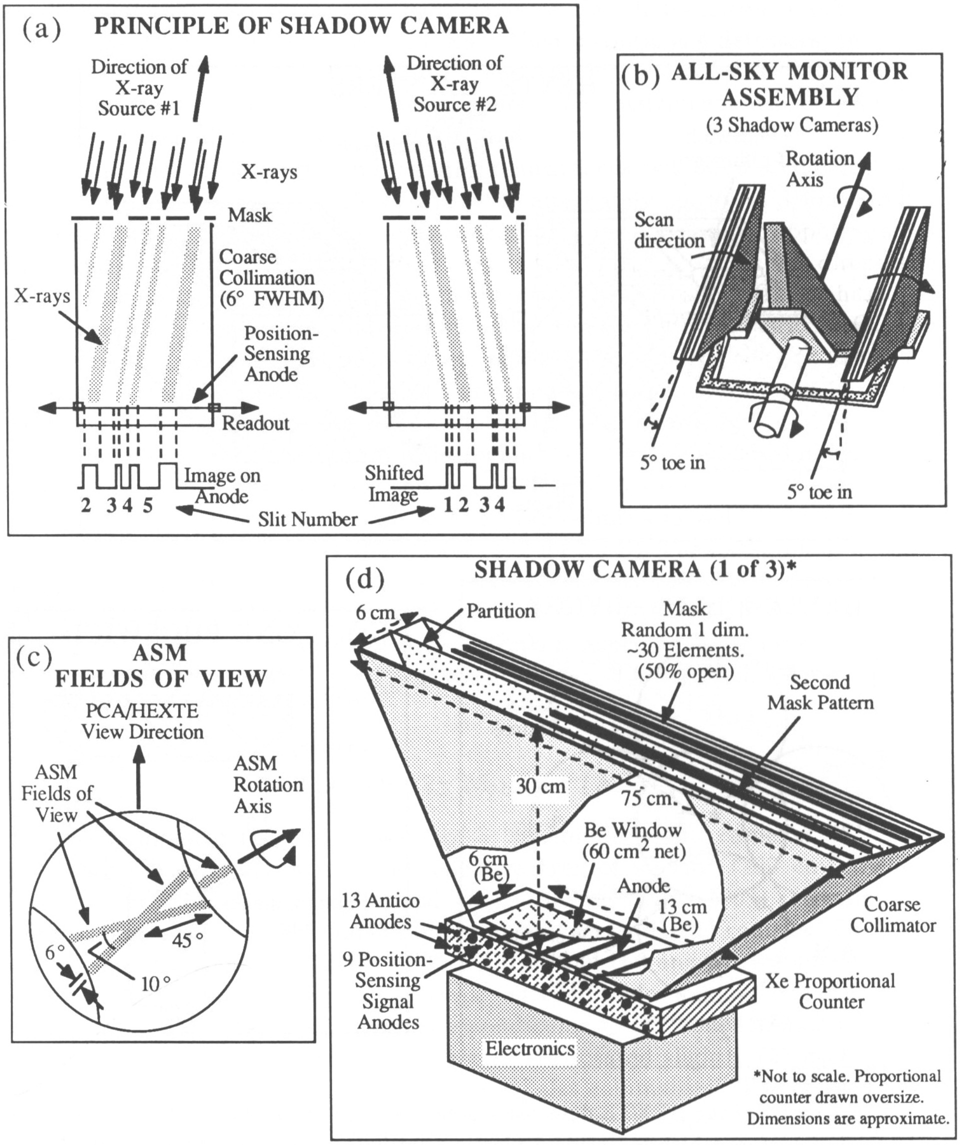

Fig. 5. Schematics of the All Sky Monitor system. (a) Principle of one-dimensional imaging showing shifted image for source #2. (b) Arrangement of the 3 shadow cameras. (c) Regions (grey) of the celestial sphere viewed by the 3 cameras at one angular position. (The rotation axis is shown oriented as in Fig. 1). (d) One of the 3 shadow cameras.

chambers on the sides and rear, and sensitivity to 2-10 keV x-rays with 3 energy channels. The one-dimensional nature of the SSC's minimizes the required telemetry rate. The scanning (or stepping) operation of the 'crossed-field detectors' ensures that each source gives rise to the entire mask pattern in the binned data, thus minimizing aliasing and side bands in the deconvolved results. The field of view in the scan direction is restricted to $\sim 6°$ to reduce source confusion and to reduce position smearing due to the finite depth of the detector. The relative merits of the SSC concept are described in some detail by Doty (1988).

The instruments will make a complete revolution once every 90 min, and $\sim$ 80% of the sky will be surveyed to a depth of 30 mCrab (about 40 sources). Frequent spacecraft maneuvers will insure that 100% of the sky is surveyed each day. In one day, the limiting sensitivity becomes $\sim$ 10 mCrab ($\sim$ 75 sources). The intensities derived from the data will immediately be made available in the 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 hardness-intensity plot.

7. The User (Guest) Program

The PCA/HEXTE observing program will be devoted 100% to guests ('Users') after a 30-d checkout period; proposal evaluation will be carried out by a NASA-appointed peer group. PI-institution observers will compete in this process. Proposals will be accepted for contingency observations, e.g. for a transient with particular characteristics. Results of an automated straightforward analysis of the ASM data (e.g., light curves and FFT's) will be placed in the public domain in near real time by the XTE team and made available via computer links. It is hoped the results will stimulate proposals for observations by XTE and optical/radio observatories. Specialized analyses of the raw ASM data or of preprocessed public-domain data will be possible through the User program.

Observations can be carried out at a Science Operations Center (SOC, at GSFC), at an instrumental-PI institution, or at the observer's home institution through a remote terminal. Adjustment of instrument configurations will be possible during observations to optimize scientific return. Standard analysis programs will be available at the SOC and will be made available to Users for use at their home institutions. Data will be provided promptly to Users in standard formats.

Real-time operations at the SOC will include examination of ASM data by the SOC staff and generation of commands for prompt observation of transients, etc. (Data rights will be determined by proposal; see above.) The flexible maneuvering of XTE should permit the transient observation and the previously scheduled observation to be multiplexed, thus minimizing disruption of the preplanned schedule.

The large community of U.S. observers, not limited to x-ray astronomers, is expected to be a major factor in making XTE a highly productive mission. International participation is also expected.

Multi-wavelength observations of necessity involve a wide community. The state of knowledge of the stellar systems (e.g. cataclysmic variables) is now sufficiently developed so that coordinated observations often are required for model building. Steps to facilitate such observations (e.g. by convenient scheduling) will be implemented.

8. The science objectives of XTE

XTE's capabilities allow it to address many astrophysical problems. In view of other missions expected to fly in coming years, XTE's observing program is likely to emphasize those objectives for which XTE is particularly well suited. We discuss here important XTE objectives and 1 or 2 specific observations pertaining to each.

8.1. NATURE OF THE X-RAY SOURCE IN ACTIVE GALACTIC NUCLEI

X-ray emission from quasars, Sy 1 galaxies, and BL Lac objects provides direct information about the regions close to the power source, presumably a massive black hole (10^6 to 10^8 $M_\odot$). At present, among the x-ray sources in the HEAO-1 LASS survey (Wood *et al.* 1984), 180 emission-line AGN (including ~ 50 quasars) and 31 BL Lac objects are now securely identified (Remillard 1990; Bradt *et al.* 1988). These sources are all brighter than 0.7 μJy at 5 keV, well above the source confusion limit (0.1 μJy at 5 keV) of XTE. Spectra to above 100 keV may be obtained in a few days. They are also bright at optical wavelengths ($V \sim 14$–16) and thus are highly amenable to optical/x-ray studies.

Spectral studies are of utmost importance for several reasons: (1) The most elementary quantity, the x-ray luminosity, is not yet known for most objects; the energy flux per decade, νF_ν, is still rising at ~ 30 keV and must cut off somewhere, possibly at 40 - 100 keV as suggested by a comparison to the diffuse x-ray background spectrum. (In a few cases, the spectrum is known to extend to $\gtrsim 40$ MeV, e.g. Swanenburg *et al.* [1978].) (2) Extrapolations of the AGN spectra do not readily explain the diffuse x-ray background (Rothschild 1983) although AGN are a likely source of background. (3) Phenomena such as e^-e^+ pairs in the plasma or reprocessing of a high-energy beam by a cool accretion disk will influence the 2-200 keV spectrum in a manner that is discernible only in broad-band measurements.

Variability from 10^2 s to months has been detected in a number of AGN (see review by Urry [1988]), and these yield indications of the masses of the central engines. The speed-of-light crossing time for regions close to an engine of $\sim 10^7$ $M_\odot$ is $10^2 - 10^4$ s. The large-area, low-background, and high-energy response of XTE makes possible time-resolved spectral studies on these time scales which, for instance, should show hard vs soft lags if thermal Compton scattering is important. In 100 s, an AGN of 1.0 μJy (at 5 keV) yields in the PCA a 19σ detection at 2-10 keV and 6.5σ at 10-30 keV, and in the HEXTE, a 1.4σ detection at > 30 keV. Power density spectra from EXOSAT have slopes close to -1 down to ~ 2000 s indicating *no characteristic time scale* (Lawrence *et al.* 1987; McHardy and Czerny 1987). XTE observations should be able to push this down to $\lesssim 200$ s and to explore the variability at *higher* photon energies. Very low-frequency variability can be effectively monitored with daily short observations of ~ 12 AGN.

BL Lac objects may be the most variable x-ray objects of all. The BL Lac object H0323+022 (Doxsey *et al.* 1983) is highly active in both HEAO-1, *Einstein* (to 60 s) and *Ginga* data (Doxsey *et al.* 1983; Feigelson *et al.* 1986; Ohashi 1988). PKS 2155-305 varies in hours (Snyder *et al.* 1980; Urry and Mushotzky 1982). The nature of variability is likely to be closely related to the relativistic jets that are believed to be operating in these objects. Spectra of the varying component above $\sim$ 10 keV should distinguish between a soft synchrotron spectrum and a hard inverse Compton spectrum. BL Lac objects are quite numerous in the HEAO-1 surveys (see above) but are deficient among the fainter *Einstein* serendipitous objects (Maccacaro 1984). The BL Lac phenomenon in the brighter HEAO-1 objects can be studied by XTE with the advantages of high statistics, a wide band pass, and a large sample of systems.

Observation: Spectra and rapid time variability. The 2-150 keV spectra of 20 bright ($\gtrsim$ 0.7 μJy at 5 keV) AGN can be measured with XTE during long observations ($\gtrsim 10^5$ s) simultaneously with the variability in the 2-10 keV band on time scales down to $\sim$ 10 s, and to $\sim$ 100 s in the 10-30 keV band. The analyzed data will bound the total x-ray luminosity, determine if AGN can provide the high-energy x-ray background, and permit a search for a characteristic time scale from the power density spectrum to $\lesssim$ 200 s.

Observation: Low-frequency variability. Low-frequency (days to years) variability of $\sim$ 10 bright AGN can be monitored with short daily PCA observations. This will yield the previously unexplored *very* low-frequency end of the PDS .

8.2. Structure of Accreting Neutron Stars

The masses of neutron stars have been deduced from determinations of x-ray and optical mass functions through measurements of the Doppler shifts of the x-ray pulsing. (See review by Joss and Rappaport [1984]) Neutron-star radii have been determined from measures of burst temperatures and luminosities, for assumed distances. Evidence that some burst luminosities are Eddington limited have made possible direct measures of distance (Ebisuzaki 1984). Better time-resolved spectra by XTE can yield markedly improved x-ray measures of the distance to the galactic center (Joss 1988).

Fluctuations in rotation rate of x-ray pulsars (accreting neutron stars) for the most part have their origin in the torques due to infalling accreting matter. The response of the neutron-star to the accretion torques depends upon its internal structure and can be detected through the timing of x-ray pulsations (Lamb 1978). If magnetized vortices embedded in the superfluid core provide coupling to the crust, the response provides a measure of the degree to which the vortices are pinned to the crust. Studies of both x-ray and radio pulsars have established that the interior of a neutron star is not well described by a simple model with only 2 components, a crust and a loosely coupled superfluid core (F. Lamb 1985). Measurements of the angular acceleration of Vela X-1 are consistent with the neutron star being a rigid body, but with weak limits ($\lesssim$ 80%) on the amount of loosely coupled moment of inertia (Boynton *et al.* 1984).

XTE observations will provide improved instantaneous statistics that should reduce the limit on uncoupled moment of inertia to $\sim$ 10% and will extend the spectrum to higher frequencies, from time scales of several days to several hours. Frequent intermittent observations (possible with XTE's maneuverability) will yield the low-frequency power. XTE can expect to carry out measurements on a large sample of pulsars. Models of the internal structure of neutron stars will be substantially constrained.

Observations : Her X-1. (1) Study angular-acceleration fluctuations to obtain an improved limit on the loosely coupled moment of inertia of the neutron star. (2) Obtain correlations of angular acceleration with flux and pulse shape to diagnose torque and pulse-beaming mechanisms and to obtain values of the magnetic moment. (3) Search for phase shifts indicative of torque-free precession of the pulsing neutron star suggested by 35-day modulation of pulse shapes. Confirmation would imply a stiff equation of state for the neutron star.

8.3. BEHAVIOR OF MATTER CLOSE TO STELLAR BLACK HOLES

Several binary x-ray sources are thought to contain stellar black holes because of their high optical mass functions. Several of these exhibit rapid aperiodic fluctuations on time scales down to a few milliseconds, e.g. Cyg X-1 (Meekins *et al.* 1984). Intense flares on this time scale have also been reported from Cyg X-1 (Rothschild *et al.* 1977). The origin of this variability is not known; the time scales indicate strongly that it arises from the innermost region of the accretion disk. The innermost stable orbits for black holes have periods that scale linearly with mass; for 5 $M_\odot$, they are 0.4 ms and 3.0 ms for maximally rotating and non-rotating black holes respectively.

The large area, high throughput, and sub-ms time resolution of XTE make possible definitive studies of the nature of this variability. The character of the power density spectrum (slopes and cutoffs) could show a strong quasi-periodicity due to strong Doppler beaming from the orbiting material (Sunyaev 1973). The frequency would be a function of the mass of the black hole and its degree of rotation. Temporal lags (of a few ms) in rapid variability as a function of photon energy are expected due to scattering delays for inverse Compton models of the formation of the spectrum. The timing characteristics of a number of sources could establish distinctions between black holes and neutron stars of low magnetic field which could also exhibit ms variability. At least one neutron-star system, Cir X-1, is known to exhibit $\sim$ 10-ms QPO variability (Tennant 1987).

Observation: Cyg X-1. A definitive study of millisecond variability in Cyg X-1 should be carried out. The sub-ms capability and high telemetry rates of XTE are required for this study. The character of the ms variability (aperiodic and quasi-periodic) will provide strong diagnostics of the innermost regions of accretion disks of black holes, including possible (quasi) periodicities by accreting relativistic matter in the innermost orbits. Use PCA and HEXTE burst trigger modes to study millisecond bursts in detail.

8.4. The Nature of Quasi-Periodic Oscillators in Accreting Systems

The discovery of quasi-periodic oscillations (QPO's) in the 5 - 50 Hz range by EXOSAT (van der Klis 1985) has added an important, and possibly epochal, new diagnostic tool for the processes occurring in accreting x-ray binary systems. The QPO phenomenon is a major breakthrough because it exhibits the fastest (quasi-)periodic variability yet detected in accreting systems and because it occurs largely in the low-mass binary systems that have been notably difficult to diagnose because of the usual absence of total eclipses and coherent pulsing. The QPO could be a direct consequence of an underlying millisecond pulsar.

The QPO phenomenon can be a highly reproducible phenomenon that depends uniquely upon the 'state' of the source (e.g. its instantaneous position on an intensity/hardness plot). In addition, the frequency varies systematically with luminosity, and the power in a 'Low Frequency Noise' component (LFN, e.g. ~ 5 Hz) can be correlated with the QPO strength. (See reviews by Lamb 1988; Lewin, van Paradijs, and van der Klis 1988.) *These systematic features suggest strongly to us that the phenomenon is ripe for detailed understanding, similar to that of coherent periodicities.* The QPO phenomenon is clearly much more promising than that of completely aperiodic variability which appears to be much farther from detailed understanding.

A very promising model is the 'beat-frequency' model (Alpar and Shaham 1985; Lamb *et al.* 1985) wherein the periodicity is due to the interaction of the magnetosphere of a very rapidly rotating neutron star (e.g. $P = 7$ ms) and blobs of material in Keplerian orbits with, e.g., $P = 6$ ms. The observed frequency would then be the beat frequency of 24 Hz. The expected compression of the magnetosphere as the accretion flow increases naturally yields the variation of QPO frequency with intensity, I ($\nu \propto I^2$) observed in GX 5-1. This model is not universally accepted because of some counter examples in certain sources, but it exhibits the clear possibility that the QPO is driven by an underlying millisecond rotator. This is of great importance because it is likely (but not proven) that such accretion-driven rapid pulsars in low-mass x-ray binary systems are the precursors of the millisecond radio pulsars (Helfand, Ruderman, and Shaham 1983).

XTE can probe deeply the QPO phenomenon by using its sub-ms time resolution, large aperture, and high-throughput capabilities (e.g. 160,000 events per second for Sco X-1). The high sensitivity of XTE should lead to the discovery of QPO in many fainter objects thus permitting studies under a wide range of conditions.

Observation: Search for underlying coherent millisecond pulsing. XTE can search for the underlying pulsing up to and beyond the expected ~ 1 ms minimum rotation period expected from instabilities involving gravitational radiation (Friedman 1983; Wagoner 1984). There are several reasons why the pulse amplitude might be small (e.g. low beaming because of low magnetic field). A sensitive search is nevertheless of crucial importance because the existence of a fast rotator would directly demonstrate a low magnetic field ($10^9 - 10^{10}$ G) for the neutron star in an (old) low-mass x-ray system. This is to be compared to pulsing high-mass (young) x-ray systems with $\sim 10^{12}$ G. This is then direct evidence for magnetic-field decay in neutron stars, a topic currently the subject of much discussion (Sang and Chanmugan 1987). Coherent millisecond pulsing would provide a direct connection to millisecond radio pulsars which also exhibit low magnetic fields. The large aperture of XTE is essential to minimize the effects of period smearing due to orbital motion of the neutron star. XTE's sub-ms timing is essential to this study.

Observation: QPO phase-lag studies as a function of x-ray energy. Phase lags of QPO pulsing in hard x-rays (> 5 keV) relative to soft x-rays (< 5 keV) of order 5 ms and as much as 70 ms are observed respectively in EXOSAT (Hasinger 1986) and *Ginga* (Mitsuda *et al.* 1988) data. (*Soft* lags are seen in one unusual source, the rapid burster.) Comptonization models can provide delays of a few ms because of the larger number of scatterings required for higher (or lower for down scattering) energies; however the 70-ms delay appears to be untenable. *Thus the phenomenon is a direct diagnostic of the processes (and geometries) of the formation of the x-ray spectrum.* Exploitation of this phenomenon requires time-resolved spectra on the ms time scale together with the high statistics and broad bandpass that XTE can provide.

8.5. X-RAY TRANSIENT STUDIES OF ACCRETION TORQUES, COMPACT-STAR MASSES, AND STELLAR WINDS

The sudden appearance of a very bright x-ray source where none existed previously is one of the more dramatic occurrences in the sky. These events, called 'x-ray transients' or 'x-ray novae', are known to be the result of a major episode of accretion onto a neutron star. They can brighten by factors up to $> 10^6$ and have decay times of 10^1 to 10^2 days and rise times (not well observed) ranging down to hours. The transients may be classified into 2 or 3 classes. Basically, some occur in low-mass systems (exhibiting soft spectra and no x-ray pulsing) while others are in high-mass systems (exhibiting hard spectra and x-ray pulsing). It is the onset and decline of accretion in these systems that provide unique diagnostic tools.

The *high-mass* systems ('hard' transients) are often widely spaced binaries consisting of a Be star and a neutron star in a wide elliptical orbit (van den Heuvel and Rappaport 1988). The onset of accretion presents an opportunity to diagnose episodic accretion, both optically and in x-rays. The orbiting x-ray source acts as a probe of the geometries, densities, and velocities of the material ejected from the Be star. X-ray pulse timing yields the size and eccentricity of the orbit and the position of the neutron star during the measurements. Discovery of a correlation between the pulse period and orbital period in these systems appears to indicate that the accreting gas in most systems arises primarily from the slowly expanding dense circumstellar disk around the Be star (and not a high-velocity low-density wind) (Corbet 1984, 1986). The properties of the accretion onto the neutron star and of the x-ray beaming from the neutron star can be studied best by following a *single* transient through a wide range of accretion rates. This was exemplified by the serendipitous EXOSAT discovery of a hard transient (EXO 2030+375) that showed the accretion rate (luminosity) to be strongly correlated with the neutron-star spin-rate change and with the pulse shape (Parmar *et al.* 1989a,b). This is a powerful diagnostic tool that XTE can use to probe other systems.

The *low-mass systems* ('soft' transients) have been more difficult to probe definitively because most do not pulse and because the optical light from the x-ray illuminated accretion disk masks the feeble optical light from the (K star) companion during outburst. The cause of the onset of accretion is not known though models exist that could possibly be distinguished through studies of the precursor and rising phases with XTE. Most important, these low-mass systems present the opportunity to study *optically* the binary systems after the x-rays have subsided. Excellent limits on the mass of the compact object (neutron star or black hole) can be obtained as exemplified by A0620-00, currently the strongest black-hole candidate (McClintock and Remillard 1986). A hard component, to ~ 100 keV, has been observed in these systems (Wilson and Rothschild 1983 and Sunyaev 1988). It probably originates in the inner accretion disk and could be an indicator of the putative black hole.

Transient events usually occur at unanticipated places on the sky; thus detection requires wide-field monitor detectors such as were carried on *Ariel*-5 (pin-hole camera) and SAS-3 (scanning slats). These satellites could only bring a low aperture (few $\times 10^2$ cm^2) to bear upon the discovered objects. More recent satellites with larger aperture lacked a monitor (EXOSAT) or had a rather modest one (*Ginga*). XTE, with its ASM and high maneuverability, is expected to detect *and* study (with high aperture) some dozen such events a year. Optical identifications of new transients will lead to fruitful optical studies. Some transients are recurrent and already identified.

Observation: Spin rate and pulse-shape changes in 'hard' transients. The spin-rate and pulse-shape changes in ~ 10 hard transients will be studied. The spin-rate change in EXO 2030+375 agreed remarkably well with the expected relation, $-dP/dt \propto\sim L^{6/7}$, except at low luminosities where the pulsar may have been spinning down. Confirmation of the spin-down phenomenon by XTE would provide a measure of neutron-star magnetic field strength from conventional accretion theory. The pulse-shape changes with luminosity permit direct modeling of beaming processes and geometries.

Observation: Masses of compact objects through detection of 'soft' transients. 'Soft' x-ray transients will be detected with the ASM, optically identified, and (later, in quiescence) studied optically to determine the optical mass functions. These yield directly strong lower limits on the mass of the compact partner. Pioneering studies of Cen X-4 and A0620-00 indicate that the former contains a neutron star and the latter a black hole. Optical identifications with the $3' \times 30'$ uncertainty region derived from the ASM data will be rapid and straightforward because the optical counterparts brighten by $\gtrsim 5$ mag.

8.6. The Magnetic Fields of Neutron Stars and White Dwarfs

Magnetic cataclysmic variable systems, i.e. the DQ Her or AM Her types with white-dwarf magnetic fields of $10^6 - 10^8$ G, exhibit an exceptionally hard x-ray component, typically $kT > 20$ keV. This most likely arises from shocks above (or at) the stellar surface caused by accreting material being channeled along the converging magnetic field lines. (See reviews by Patterson 1984, Liebert and Stockman 1985, D. Lamb 1985.) Studies of the hard emission as a function of the orbital phase provide direct information about the temperatures, geometries and magnetic fields. A continuing puzzle is the 'soft x-ray problem': the hard x-ray flux from AM Her objects appears to be insufficient to produce the observed intense very soft (~ 30 eV) flux through reprocessing in the stellar surface and accretion shock (Beuermann 1988, D. Lamb 1988, Osborne 1988). Observations with good sensitivity to hard x-rays would help resolve this issue by giving better definition to the hard x-ray emission region.

Most accretion-driven pulsing neutron stars appear to have fields of $\sim 10^{12}$ G, based upon their spin-up rates and luminosities. The discovery and confirmation of a spectral feature in Her X-1 at 35 keV (if absorption) or 58 keV (if emission) is widely believed to be cyclotron emission from a $\sim 10^{12}$ G field, i.e. it is a direct indicator of the magnetic field (Trumper *et al.* 1978; Gruber *et al.* 1980). Discovery of harmonics by XTE would firmly establish the cyclotron resonance phenomenon. The ratios of line strengths would provide an estimate of the 'transverse' plasma temperature. Variation of line widths as a function of temperature and spin angle (of the neutron star) can establish the 'parallel' plasma temperature and the magnetic field direction. Beam geometries can be forthcoming from these studies also.

Observation: AM Her type cataclysmic variables. Measure the hard x-ray flux (2-30 keV) of the 6 brightest AM Her objects to determine the white-dwarf mass and the extent and height of the accretion shock.

Observation: Cyclotron features from neutron stars. Measure the hard spectrum of several accretion-driven pulsing sources out to ~ 100 keV as a function of pulse phase to detect cyclotron features including harmonics. The transverse and parallel plasma temperatures and magnetic field directions would be forthcoming. XTE will be sensitive to cyclotron features an order of magnitude or more weaker than that in Her X-1.

8.7. NATURE OF X-RAY EMISSION FROM THE GALACTIC PLANE

Results from previous x-ray observatories, e.g. EXOSAT, indicate the existence of a galactic 'ridge' of unresolved x-ray emission (Warwick *et al.* 1985). Its nature is not understood; it may consist of discrete sources of known or unknown classes. Recent *Ginga* studies of the galactic plane show the existence of a class of 'weak' (2–10 μJy; actually quite bright for XTE) and hard-spectrum transients with durations of hours to a few days in the galactic plane (Koyama *et al.* 1989). One or more of these can be found on any given scan of the plane with a 1° field of view. The nature of the transients is not known; however, their hard spectra and transient nature indicate they may be Be-star pulsing binaries.

Observation: Repeated scans of the galactic ridge. Repeated (daily to monthly) scans, each of 6-hr duration, of 1000-deg^2 of the galactic plane with the PCA should be carried out (1) to map with high sensitivity the structure on the 1-deg^2 scale of the 'galactic ridge' and (2) to determine its temporal variability. Discovered transients would be observed in the pointed mode to diagnose their nature. This could greatly increase the sample of x-ray emitting Be-star systems which are excellent stellar-wind laboratories (see above).

8.8. SEARCH FOR, AND STUDY OF, NEUTRON STAR IN SN1987A

XTE will be in orbit during the period 7–9 years after the implosion that led to SN 1987A and will be able to complement observations by other observatories, including balloons and rockets. Although highly uncertain, it is not unlikely that the ejecta will become optically thin to $>$ 20-keV x-rays at age $\sim$ 10 years and that lower-energy photons will still be absorbed or scattered (Xu *et al.* 1988). High-energy response with large aperture is thus important for the study of SN 1987A.

Successful discovery of pulsing x-rays would demonstrate unequivocally that a neutron star rather than a black hole was formed. Subsequent pulse-timing measurements would reveal binary membership and would yield measures of the braking index and response to 'glitches'. Such results address the fundamental underlying physics of SN 1987A, specifically the evolution of the progenitor, the magnetic dipole moment of the pulsar, and the structure of the neutron star.

Observation: SN1987A. A 9000-s observation with the PCA ($>$ 20 keV) will make possible a search for pulsations in 1000 frequency bins (1–1000 Hz) with $\sim$ 99.9% confidence, for a source with the luminosity of the Crab pulsar in the LMC. If pulsing were discovered, each subsequent observation of 6×10^4 s would yield a 10-bin summed light curve with 5σ confidence in each bin.

8.9. STUDIES OF NEW PROTOTYPE OBJECTS

Specific compelling objectives for XTE also follow from the ongoing discovery of new bright ($>$ 0.7 μJy at 5 keV) objects through optical identifications (Bradt *et al.* 1988) of cataloged x-ray sources (e.g. the HEAO-1 LASS catalog of 842 sources [Wood *et al.* 1984]). These identifications are yielding objects that extend substantially the canonical parameters of known classes. Recent examples include: (1) a QSO with unusually steep x-ray spectrum and with very strong optical FeII emission (highly pertinent to the formation of broad-line clouds and to massive accretion disks) (Remillard *et al.* 1986a, 1988), (2) a possible slightly asynchronous AM Her type object, H0538+608 (Remillard *et al.* 1986b), and (3) a BL Lac object, H1720+117, with the highest known optical polarization (17%) among x-ray selected objects (Brissenden *et al.* 1990). Such objects demand detailed studies at all wavelengths; they are likely to become prototypes of new subclasses.

The numbers of known, bright, optically identified (or x-ray classified) objects with hard ($>$ 2 keV) emission in each of the classes (e.g. low-mass neutron-star binary, QSO's, Sy 1, AM Her type, etc.) is currently not high, from a few to $\sim$ 100. Thus each newly identified or classified object may well have important unique properties, e.g. the aforementioned examples, and hence be worthy of detailed study. *We stress that the population characteristics of the* $\sim 10^3$ *brightest x-ray sources in the sky are not yet fully known.*

Identifications and optical/x-ray classifications of HEAO-1 and EXOSAT sources are rapidly increasing the pool of unstudied 'bright' objects. The ROSAT survey ($<$ 2 keV) will yield many more objects. Thus we anticipate a continual infusion of new discoveries and questions into XTE's observing program.

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