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The high energy X-ray timing experiment on XTE

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Abstract. The High Energy X-ray Timing Experiment (HEXTE) is one of three science instruments of NASA's X-ray Timing Explorer (XTE) mission, which was launched into low earth orbit in late 1995. Its energy range of 15–250 keV overlaps with the OSSE and BATSE detectors of the Compton Gamma Ray Observatory (CGRO). The HEXTE consists of eight NaI scintillation detectors grouped into two independent clusters, each with its own data processing electronics. State-of-the art detector resolution is achieved with the help of an automatic gain control system. Like OSSE, the HEXTE permits on-the-fly correction of internal background by beam-switching to blank fields adjacent to the source on the sky. We present here a description of the HEXTE, and demonstrate some aspects of its performance by a spectral simulation of a bright Galactic source with cyclotron absorption. While the HEXTE's large collecting area yields the high event rates essential for temporal studies, the sensitivity to faint sources (such as active galaxies) is limited by systematic effects in the residual background, which we discuss in some detail.

Key words: space vehicles — instrumentation: detectors — instrumentation: miscellaneous

1. Introduction

The X-Ray Timing Explorer (Bradt et al. 1993) provides a platform for three science instruments: the 2–10 keV All Sky Monitor (ASM), the 2–60 keV Proportional Counter Array (PCA), and the 15–250 keV High Energy X-ray Timing Experiment (HEXTE), which provides the overlap in energy range with OSSE and BATSE on board CGRO.

The HEXTE, a descendent of the A4 experiment on HEAO-1 (Matteson 1978), consists of 2 independent clusters of 4 NaI/CsI "phoswich" scintillation detectors optically coupled to photomultiplier tubes. Discrimination against charged particles is provided by 4 plastic anticoincidence scintillators in the form of a box around each cluster, and by the CsI crystal, which also shields against ambient photons and acts as a light guide between the NaI and the photomultiplier tube. The HEXTE cluster assemblies are shown in Fig. 1.

Detector background is measured as the clusters "rock" independently along orthogonal axes, to sample fields 1.5 or 3.0 degrees from the spacecraft's pointing axis with dwells of 16, 32, 64 or 128 s. For most (background-limited) observations, the rocking of the clusters is synchronized such that one cluster is always on-source while the other is sampling the background.

The 1 degree FWHM field of view of each detector is defined by collimators consisting of a lead honeycomb. The net open area of each detector is 200 cm^2. Automatic gain control is made possible by a ^{241}Am calibration source mounted in the collimator assembly. The resulting spectrum contains line features which are used in a feedback cycle every 0.5 s to keep gain variations below 0.1%, and is telemetered every 10 min to provide a reference for long-term monitoring of detector stability.

2. Performance of the HEXTE

The HEXTE has undergone an extensive series of calibration observations during XTE's 30-day in-orbit checkout period immediately after launch. A large amount of calibration data has also been accumulated during instrument and spacecraft tests on the ground.

2.1. *Timing properties*

For sources fainter than 1 Crab, the HEXTE is able to provide event data tagged to 7.8 μs, and ground calibrations have shown the HEXTE time stamps to be accurate to 1 μs. For sources which are too bright for event mode data (which would saturate the telemetry), the HEXTE's on-board processing provides a number of telemetry data formats which give observers a trade-off between temporal and spectral sampling. Even for these cases, each cluster has a Burst List data buffer which can record 25000 successive events when a source rises quickly above a predefined "trigger" threshold.

Dead time in the HEXTE detectors, typically $\simeq 0.3\%$, is due to the finite speed of the pulse-height analysis of incoming events, and is measured as an average over 1 to 16 s, depending on the selected telemetry format.

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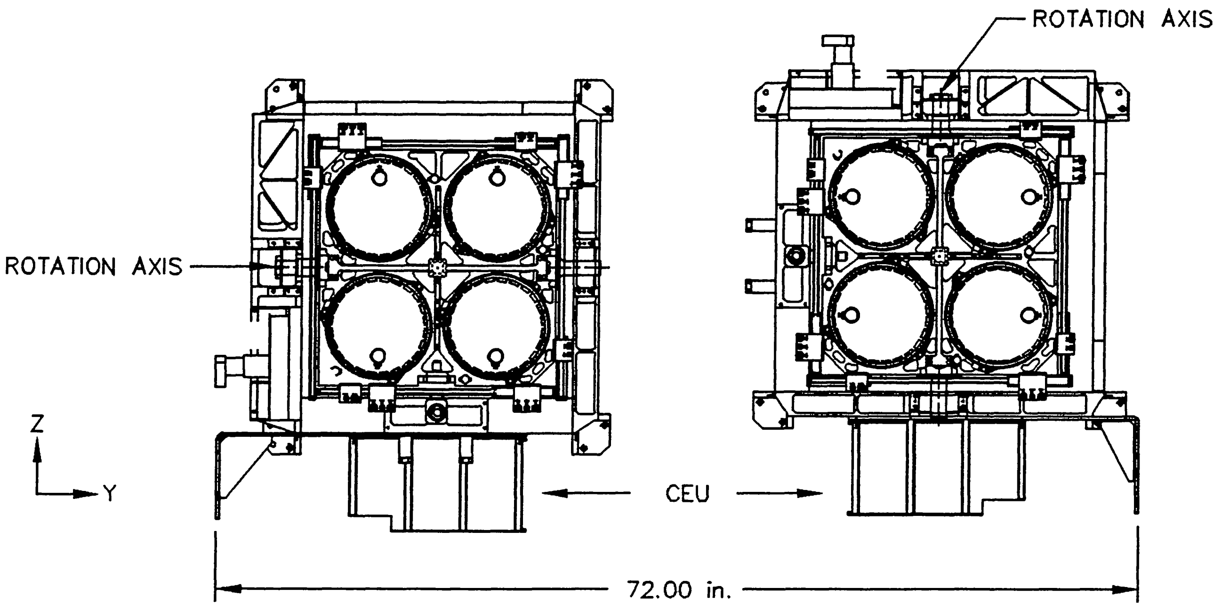

Fig. 1. A view of the two HEXTE clusters looking down the XTE spacecraft's pointing axis. Visible are the 4 cylindrical collimators of the phoswich detector assemblies, each with their own gain calibration sources mounted off-center. Each cluster can rock independently around its rotation axis, and has its own Cluster Electronics Unit (CEU) which performs all the event selection and telemetry formatting

2.2. Energy range and spectral resolution

Scintillation pulses are analyzed by the event selection logic and assigned a pulse-height channel number from 0 to 255, which is closely proportional to the incident X-ray photon energy. The HEXTE has been designed to detect X-rays with energies as low as 5 keV, but the PCA is much more sensitive at these energies. Therefore, in normal operation the HEXTE's lower level discriminators are set to 15 keV to reduce the total background event rate. Overall detection efficiency decreases slowly at higher energies; the upper end of the HEXTE energy range is set at 250 keV.

Incoming X-rays of a given energy will produce a spread in detected pulse height, due to the Poisson statistics of the photoelectrons produced by their scintillations in the phoswich. For this reason, the FWHM spectral resolution is roughly proportional to $\sqrt{\text{energy}}$. With the addition of a small offset in energy due to gain variations across the face of each detector, the HEXTE detectors have been measured to follow this relation, with a FWHM resolution of 9 keV at 60 keV.

2.3. An example: Spectral simulation of a pulsar

To facilitate comparison with OSSE on CGRO, we have performed a spectral simulation of a 3600 s HEXTE observation of a moderate-outburst Be star/X-ray binary with cyclotron absorption. The model is based loosely on the HEXE (Kendziorra et al. 1994) and OSSE (Grove et al. 1995) observations of A0535+26 in outburst (Fig. 2). The input spectrum is a power law of photon index 1.2 with $10^{23}\,\text{cm}^{-2}$ of photoelectric absorption and a high energy cut-off at 20 keV (with e-folding energy 25 keV). Cyclotron absorption lines at 50 and 100 keV are superposed on this continuum, with optical depths of 0.2 and 2.0 and half-widths of 14 and 28 keV, respectively. The normalization is 100 mCrab in the 2−10 keV band.

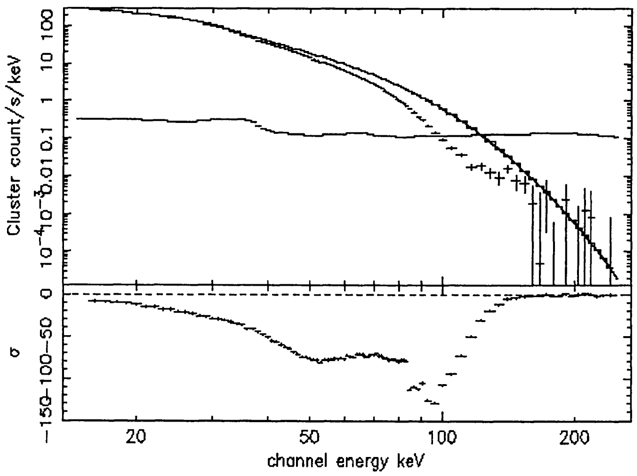

Fig. 2. Simulated 3600 s HEXTE observation of a 100 mCrab Be binary in outburst, with cyclotron absorption at 50 and 100 keV. The upper solid line shows the best-fit continuum only; the residuals (in units of 1σ uncertainties) demonstrate the detection of the cyclotron absorption components, which are also resolved by the HEXTE. The lower solid line shows the HEXTE residual background spectrum

Both cyclotron harmonics are clearly visible in the residuals to the continuum, and both line profiles are resolved. It is apparent that the broad energy range of the HEXTE is well suited to investigations of such sources.

3. Background-limited observations

While the large collecting area of the HEXTE yields the high count rates necessary for fast temporal studies of bright sources, the limiting detection sensitivity (see Fig. 3) for faint sources is also determined by the residual (non-vetoed) background, which averages 50 count/s in each cluster (for reference, the Crab produces 300 count/s). This background is almost entirely due to ambient particle fluxes; it is much less than for BATSE and OSSE because of the greatly reduced detector mass per unit area and the narrow collimation.

The dominant statistical and systematic errors are from the detector internal background and its variation in orbit. Here we discuss the origin of the internal background and list possible sources of systematic error. We then discuss the effects of systematics on the results of spectral and temporal analyses.

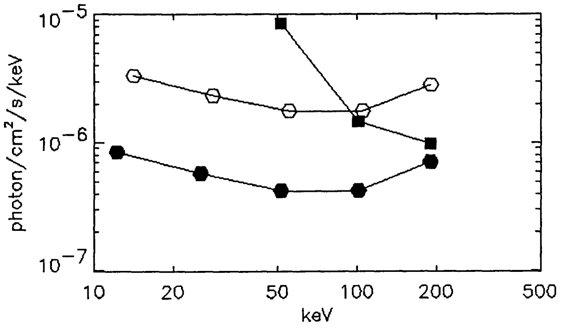

Fig. 3. Comparison of 3-σ sensitivities for OSSE (squares) and the HEXTE (hexagons). Filled symbols correspond to a total exposure of 1 week; the open symbols show the HEXTE sensitivity achieved in a 1 day (10^5 s) exposure

3.1. Origin of the HEXTE detector background

Most of the detector background in the HEXTE is internal radioactivity stimulated by cosmic rays. Its spectrum is dominated by fairly flat and featureless beta continua (see Fig. 2) plus some visible lines. Lines come from: (i) K X-rays at 80 keV from the lead collimator, (ii) K X-rays at 25–30 keV from spallation daughters, mainly tellurium, in the detector, (iii) a 58 keV inelastic scattering gamma in iodine, and (iv) combined X- and gamma-ray photons at 67 and 190 keV from K-capture de-excitations of certain spallation daughters. For the expected internal background rate of 40 count/s, the 32-s Poisson error is 3%. Strong time variability is seen as the spacecraft moves in the geomagnetic environment, the dominant effects being the change of cosmic ray cutoff and the region of trapped particles in the South Atlantic Anomaly.

3.2. Systematics of background subtraction

The rocking of each HEXTE cluster allows the simplest background correction to be performed to first order for a given source dwell by accumulating counts during the adjacent half of each background dwell and subtracting them. Most detections will come from longer observations, but in principle rely on the accumulation of this basic subtraction. The reliability of this method is considered here.

3.2.1. Second-order residuals from rocking

The rocking measures the internal background and allows its subtraction to first order in time over 1 cycle. To estimate the size of the second-order residuals, we analyzed archival data from the HEAO-1 A4 experiment. The quadratic residual for 41-s subtractions of the $\geq$ 10 MeV counting rate, almost entirely cosmic ray primaries, was measured to have a daily RMS of 0.3%. This cosmic ray orbital variation is an upper limit to energy band variation. For observations longer than half an orbit the quadratic residual can be treated as a random variable, thus the error decreases as the square root of the number of dwells. At 0.3% it is already negligible in comparison with the Poisson error.

3.2.2. Orientation dependence of detector background

In low earth orbit the cosmic-ray East–West effect is strong with an anisotropy of about a factor of 3. Orientation in this flux will be modulated by the rocking and by the orbital motion. Changes in activation will nevertheless be very small because cosmic rays are so penetrating. The cross section for activation is of the order of 10 mbarn, and for a typical path length the maximum optical depth is then roughly 0.004. Multiplying this by the rocking displacement in radians gives an upper limit to the change of activation of 0.01%. Even this tiny value will be eliminated to first order by the double-sided rocking. The cross sections to ambient neutrons can be quite a bit larger, but the neutron fluxes are considerably more isotropic than the cosmic rays.

3.2.3. Gain jitter

The automatic gain control introduces a gain RMS measured at 0.25% on 16-second averages. Gain error can propagate into flux level error with a regression less than or of order unity. For long accumulations it is also a random variable.

3.2.4. Sky background fluctuations

For long accumulations the dominant error in background subtraction comes from weak unidentified sources in the background fields. For the extragalactic sky this error level can be estimated by extrapolation from the HEAO-1 A2 measurements of the fluctuation level of the diffuse background (Shafer 1983). Scaling to the XTE beam size of 1 degree FWHM we determine a beam-to-beam fluctuation level of 8.1% for the diffuse flux. However, the aperture flux from the diffuse background (Marshall et al. 1980;

Gruber 1992) contributes only 1% or less of the total counting rate, so the net error is negligible for short observations. For long observations, of the order of one day, a steady unknown source at the Shafer level will come to dominate Poisson errors. Given the predicted internal background rate, we calculate that with a 10^5 s observation the RMS sky fluctuation noise will dominate Poisson noise by a factor of 5 in the 15−31 keV band and 3.5 for 31−62 keV, is equal at 62−125 keV, and smaller by a factor of 7 at 125−250 keV. Sizeable variability on time scales less than a day in the sources which dominate the diffuse flux could reduce this systematic error.

4. Systematic effects in HEXTE data

The propagation of Poisson counting errors and the accounting for the effects of detector dead time will be straightforward for the HEXTE, in comparison with earlier experiments. Systematic errors, on the other hand, are quite important because the XTE is expected to explore finer temporal and spectral structure than previous high energy missions. The systematic errors in background determination discussed above will manifest themselves in both spectral and timing studies, as outlined below.

4.1. Source flux and spectral determinations

The observation of faint sources is compromised by granularity of the diffuse background in the source and background fields. A program for special analysis of the background fields of all long extragalactic observations, supported by short PCA observations of these fields, will be maintained during the first observing cycle. Observers will be alerted to the presence of possible near-threshold confusing sources.

Systematic errors in the HEXTE detector response matrices will be minimized by ground calibrations. In addition, simultaneous observations of the Crab with CGRO, and of 3C 273 with ASCA and SAX are planned. Remaining systematics will be much less than the Poisson errors for the majority of fainter sources which the HEXTE will observe.

4.2. Power spectral analysis

The systematics discussed above should behave as white noise processes up to a maximum frequency. This maximum corresponds to the rocking period (32 or 64 s in most cases), but for gain jitter it is 2 Hz. The effect will be to raise the variance per frequency element to slightly above 2.0; this increase will be a function of energy. To measure and characterize these subtle systematics, a sizeable portion of in-orbit checkout has been devoted to observations of background fields, the Crab pulsar and SMC X-1.

5. Conclusions

Since the end of the HEAO mission there has been a dearth of high energy, large area space observatories covering the 10−250 keV range. As the only NASA missions available in the interim, OSSE and BATSE on CGRO have extended their energy ranges downwards to cover this spectral region. In concert with XTE's other instruments, the HEXTE is now providing us with significant advances in our knowledge of Galactic and extragalactic sources. HEXTE observations will also benefit those made by CGRO by defining continuum shapes at the low energy end of the OSSE range — an important input constraint in spectral fits to OSSE data. The HEXTE will provide the highest quality database of pointed observations in this spectral region for some time in the future.

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References

Bradt H., Rothschild R.E., Swank J.H., 1993, A&AS 97, 355
Grove J.E., et al., 1995, ApJ 438, L25
Gruber D.E., 1992, in: The X-Ray Background, X. Barcons, A.C. Fabian (eds.). Cambridge University Press, p. 44
Kendziorra E., et al., 1994, A&A 291, L31
Marshall F.E., et al., 1980, ApJ 235, 4
Matteson J.L., 1978, AIAA 16th Aerospace Sciences Meeting, p. 78
Shafer R.A., 1983, PhD. Dissertation, University of Maryland