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Surveying the Hard X-ray Sky: Imaging in Space and Time

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One of the few remaining astronomical bands (factor of ∼10 in energy range) still without an all-sky imaging survey is the hard x-ray band (10-600 keV). This is in spite of sensitive imaging all- sky surveys already conducted at soft x-ray (0.2-2 keV; ROSAT) and soft/hard γ-ray (∼750 keV - 10 GeV; COMPTEL/EGRET) energies and imminent for medium x-ray energies (2-10 keV; ABRIXAS). A hard x-ray imaging survey conducted with wide-field coded aperture telescopes allows both hight sensitivity (and spatial/spectral resolution) and broad temporal coverage. We derive a generalized survey sensitivity/temporal parameter, Q, and compare previous and planned hard x-ray surveys with the proposed EXIST mission. Key scientific objectives that could be addressed with the enhanced capability of EXIST are outlined.

Key words: x-ray surveys; x-ray binaries; black holes; neutron stars; AGN

AAA subject classification:

1. Introduction

All sky surveys in the soft-medium x-ray band, defined here as 0.2 - 10 keV, are most effectively carried out with focussing x-ray telescopes executing scanning missions. The premier examples are of course ROSAT (0.2-2 keV; Trumper 1983) and the planned (1999 launch) ABRIXAS mission (2-10 keV; Staubert, these proceedings). At hard x-ray energies, defined here as being 10-600 keV to overlap with the focussing soft-medium surveys and to both study the non-thermal universe and to extend above the natural astrophysical break point of 511 keV positron emission, the techniques and capabilities of an all sky survey change dramatically. Instead of being a narrow field (instantaneous) survey limited in temporal coverage, a hard x-ray survey can be executed as a wide field scanning survey sensitive to a broad range of timescales. The wide field (∼30°) but pointed soft/hard γ-ray surveys carried out with COMPTEL/EGRET (∼750 keV-10 GeV) on CGRO are limited by the pointing, rather than survey, duration.

We consider a simple general parameterization for x-ray surveys (soft-hard) which can (and should) survey both spatial and temporal images, ideally all sky. We compare the parameters of the principal missions already carried out or now in final planning stages and extend this to the proposed EXIST mission concept (Grindlay et al 1995, 1997). We then summarize briefly the key scientific objectives of EXIST and then outline the wide-field coded aperture imaging telescope and detector system which would allow such a mission to be conducted.

2. Generalized Surveys

Surveys are essential for moving beyond the study of a few objects pre-selected for their likely emission or properties based on other bands, and they allow the discovery of entirely new classes of objects and astrophysical phenomena. Population and evolution studies require the complete samples of surveys.

Generally surveys are either spatial (e.g. deep images, mosaiced to cover a particular field or the whole sky) or are temporal (e.g. monitoring of time variability of a source or collection of sources). For maximum sensitivity, in either flux or temporal resolution, imaging is essential. Source confusion is the familiar limit for a given beam size, or imaging resolution element, r, but is usually not the limiting factor for non-imaging (e.g. collimated, or scanning) x-ray or gamma-ray surveys. Rather, these are instead usually limited in flux by either short exposure, high backgrounds, or both. Thus a spatial survey of total coverage or solid angle (fov), F (vs. instantaneous telescope fov, G), has $M = F/r^2$ pixels for which a sensitivity limit of minimum detectable source flux, f, is achieved per pixel and per survey total exposure time. Similar considerations apply to temporal surveys, where the image resolution element (time resolution, t) and image fov (time duration, T), define the number, $N = T/t$, of temporal pixels in the temporal image that can be formed with flux sensitivity, g, per pixel. For each spatial image pixel, the temporal flux sensitivity limit, g, is usually significantly greater than the spatial flux limit, f, since

$$g \sim f \cdot \sqrt{\mathrm{N}} \qquad (1)$$

for all but periodic source behaviour. In the case of a survey for known periodic sources (e.g. monitoring of x-ray pulsars), the above sensitivity estimate would apply with N replaced by p, the number of phase bins containing the pulsed signal.

An ideal survey would maximize M and N, which are the effective survey size/sensitivity parameters m = M/f and n = N/g. Surveys can then be compared by their tracks in a normalized m,n plane. We may also define an overall survey quality factor, Q, which combines the spatial and temporal parameters by their harmonic mean:

$$Q = \sqrt{\mathrm{m} \cdot \mathrm{n}} = \mathrm{M}^{1/2} \cdot \mathrm{N}^{1/4}/\mathrm{f} \qquad (2)$$

where we have used Equation 1 for the relative sensitivities f and g appropriate to the more general case of a survey sensitive to bursts and transients of unknown timescale.

3. Previous Hard X-ray Surveys

It is remarkable that the hard x-ray band (10-600 keV) has been neglected for the two decades since the only survey conducted by the HEAO-A4 experiment. This pioneering first survey was limited in sensitivity (reaching ~50 mCrab at 13-180 keV) and both angular resolution (~3° ; set by the non-imaging detector with 1.5° × 20° collimator or effective G ~6°) and temporal coverage and resolution (each source observed, typically, for only ~1 week each 6 months, for three such observations). Some 70 sources were detected, all known from previous soft-medium x-ray surveys (e.g. UHURU and HEAO-A1), and of these only 14 were detected in the 80-180 keV band (Levine et al 1984). These objects were (understandably) the brightest in their respective classes, including Crab, Cyg X-1, Cen A, NGC 4151 and 3C273, and no new classes of object were discovered.

Only one other all-sky survey at hard x-ray energies (20-100 keV) has now effectively been carried out (although not yet processed) using the BATSE experiment: A galactic plane survey (b = ±20°) is in progress and preliminary results have been reported (Grindlay et al 1996) using the automated occulation-image scanning analysis system CBIS (CfA BATSE Image Scan) developed at CfA. Extension to a full sky survey could be done for similar total sensitivity (~50 mCrab), angular resolution (~1°) and temporal resolution (~1 orbit = 1.5h).

Table 1: Chronological Summary of Hard X-ray Surveys

Mission	ΔE (keV)	Det./Tel. Sys.	F, G (°)	r (°)	T (d)	t (h)	f (mCrab)	Q
HEAO-A4	13-180	NaI; scan collim.	AS, 6	3	1e+3	0.5	50	20
BATSE	20-100	NaI; occultation	AS, AS/2	1	2e+3	1.5	50	54
ABRIXAS	2-10	CCD; focussing	AS, 0.7	0.03	1e+3	1.5	0.2	3.7e+5
INTEGRAL	15-200	CdTe; coded mask	GP, 20	0.2	1.e+3	2e-4	3	1.5e+4
EXIST	10-600	CdZnTe; coded mask	AS, 40	0.2	270	2e-4	0.3	2.5e+5

Notes: AS = all sky: F = 40,000 deg^2; GP = gal. plane: F ~ 7200 deg^2. See text for definitions of G, r, T, t, f and Q.

Otherwise there are at present only two planned surveys which partially overlap with a full all-sky hard x-ray imaging survey: the ABRIXAS survey (2-10 keV; Staubert, these proceedings) and the galactic plane survey to be conducted with INTEGRAL (15 keV-10 MeV; Ubertini et al 1996). These missions are planned for launches in 1999 and 2001, respectively. In Table 1 we summarize these various missions by their key parameters as well as the survey quality parameter Q defined above (Eq. 2). EXIST complements ABRIXAS and greatly extends the energy range and temporal coverage at comparable total sensitivity.

4. EXIST Concept and Capability

The Energetic X-ray Imaging Survey Telescope (EXIST) was selected (April 1995) as one of the 27 New Mission Concept (NMC) studies for a future NASA astrophysics mission. It would conduct the first hard x-ray imaging all sky survey with a sensitivity some 100× greater than the HEAO-A4 experiment in 1977-79 (Levine et al 1984). The need, and priority, for such an all sky imaging hard x-ray survey mission has been pointed out in the recent report

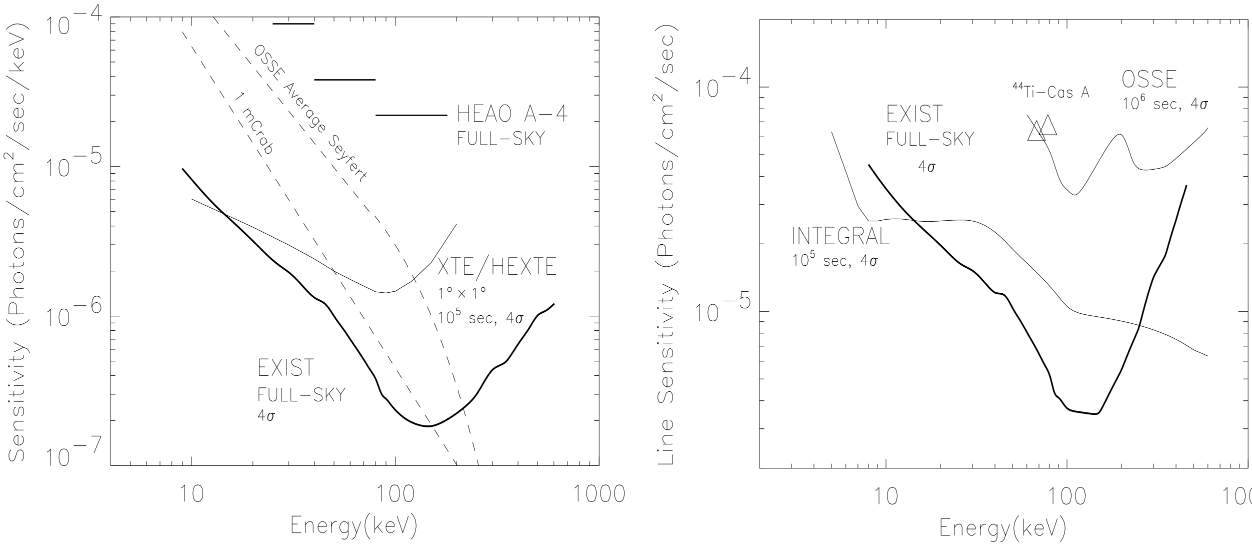

Figure 1: Sensitivity of EXIST (MIDEX) for continuum (left) and narrow line (right) spectra vs. other missions.

of the NASA Gamma-Ray Program Working Group. An overall description of the initial and proposed EXIST concepts is given by Grindlay et al (1995, 1997) (and see *http://hea-www.harvard.edu/EXIST/EXIST.html*).

EXIST would incorporate two coded aperture telescopes, each with fov = 40° × 40° (above ∼40 keV; at 10-30 keV a low energy collimator would restrict the FOV to 3.5° in one dimension), with a combined fov = 40° × 80° yielding 60% sky coverage each orbit and full sky each 50d orbital precession period. A Cd-Zn-Te (CZT) pixellated detector array of total area of 2500 cm^2 is at the focal plane of each telescope.

Because of its very large fov and large area detectors with high intrinsic resolution (both spatial and spectral), EXIST could reach the unprecedented all-sky sensitivity shown in Figure 1. The sensitivity plots are for EXIST for its proposed 9-month all-sky survey which would allow total integration times of $\sim 10^6$ sec for any source. The mission could then be operated as a pointed (observatory) for additional exposure and higher sensitivity on selected high priority targets (e.g. M31 GRB/SGR and BHC surveys; galactic bulge survey). EXIST could be proposed for MIDEX or as a Space Station attached payload.

5. Scientific Objectives: All Sky Survey and Monitoring

5.1. Surveys

Hard x-ray spectra and luminosity function of AGNs: Active galactic nuclei (AGN) are now measured by OSSE to have hard spectra with breaks typically in the 50-100 keV range for Seyferts (cf. Zdjiarski et al 1995) and with multi-component or non-thermal spectra extending to higher energies likely for the blazars. EXIST will have an all-sky sensitivity some 10× better than that needed to detect the "typical" Seyferts seen with OSSE. More than 1000 AGN should be detected in the all sky survey and EXIST has the required sensitivity in the poorly explored 30-200 keV band to measure accurate spectra for all known AGN detected with Ginga or with the Einstein slew survey.

A major objective for AGN studies and surveys is the detection and inventory of heavily obscured or self-absorbed AGN. Such objects, primarily Seyfert 2's but also including (some) star-formation galaxies, are now being discovered in pointed observations with SAX and will also likely be discovered with the focussing ABRIXAS all sky survey. However, the most heavily obscured objects, with absorbing column densities $\gtrsim 10^{24-25}$cm^{-2} yielding low energy cutoffs in the 5-10 keV range, will be more readily detected with EXIST. This will yield the first measure of the luminosity function of obsured AGN, which are likely significant for the x-ray background.

Survey for black hole and neutron star compact binaries. Studies of compact objects over a wide range of timescales and luminosity are possible throughout the Galaxy. A deep galactic survey for x-ray binaries containing black holes vs. neutron stars and pulsars will allow the relative populations of black holes in the Galaxy to be constrained. All previous galactic hard x-ray surveys have been constrained to the brightest decade in source flux (and luminosity); EXIST would extend this 1-2 decades deeper, allowing spectral studies. Whereas the INTEGRAL galactic plane survey(s) will also make great strides, the EXIST (all sky) survey would be more sensitive and not be limited to the central $\sim \pm 10°$ of galactic latitude covered by the smaller fov of INTEGRAL.

Emission line surveys: hidden supernovae via ^{44}Ti emission and 511 keV sources: The array of CZT imaging detectors proposed for EXIST achieves high spectral resolution (e.g. $\lesssim 5\%$ at 60 keV) enabling emission line surveys. The decay of ^{44}Ti (lines at 68 and 78 keV) with long (68 y) halflife allows a search for the long-sought population of obscured supernovae in the galactic plane at sensitivities significantly better than the possible detection of Cas-A (cf. Figure 1). Similarly, 511 keV emission from black hole binaries (or AGN) can be searched for (e.g. in transient outbursts) and imaged with better sensitivity than OSSE (cf. Figure 1).

Study of the diffuse hard x-ray background: The spectra of a significant sample of AGN will test the AGN origin of the diffuse background for the poorly explored hard x-ray band. Because the background measured by the EXIST detectors below 100 keV is dominated by the cosmic diffuse spectrum, its isotropy and fluctuation spectrum can be studied with much higher sensitivity than before.

5.2. Monitoring

EXIST would survey 60% of the sky each orbit anc accumulate $\sim$10 orbits/day (allowing for SAA, etc.) $\times \gtrsim 10$ min exposure/orbit or $\gtrsim 6000$ sec/day for each source observed. This yields a daily flux sensitivity (30-100 keV) of $\sim$1-2 mCrab, sufficient for the brightest AGN and essentially all known accretion-powered binaries in the Galaxy. Pulsar timing allows even fainter flux limits, as demonstrated with the extensive BATSE monitoring project. Over one sky survey epoch ($\sim$50d), each source is observed for $\gtrsim$ 25d, giving $\sim$0.3mCrab limits for $\sim$month timescales.

Faint hard x-ray transients: black hole population in Galaxy: The sensitivity to $\sim$1-10d transients is $\gtrsim 30 \times$ better than BATSE, so that the low resolution occultation-imaging survey for faint transients being conducted with BATSE (cf. Grindlay et al 1996) can be extended to correspondingly lower outburst luminosities or greater source distances. With a 1-10d sensitivity of $\sim$1 mCrab, BH transients can be detected with their characteristic peak luminosities of $\sim 10^{37-38}$erg/s (10-100 keV) out to 100 kpc, enabling the first BH-transient survey of the LMC/SMC.

Monitoring and Study of X-ray Pulsars: The measurement and monitoring of spin periods, pulse shapes and luminosity/spectra of a large sample of accretion-powered pulsars would extend the BATSE sample of Bildsten et al (1997) to the entire sample ($\gtrsim 30$) of known accretion-powered pulsars. The high spectral resolution of the CZT detectors on EXIST would allow high sensitivity studies of cyclotron features in pulsar spectra, greatly extending current RXTE/HEXTE studies of relatively few objects to a much larger sample.

Studies of Gamma-ray Bursts: EXIST would have a GRB sensitivity approximately 20$\times$ that of BATSE so should detect GRBs overall at about 1/2 the rate, or $\sim$0.5/day, as BATSE with its much larger fov but reduced sensitivity. GRBs would be located to $\lesssim 1$-$5'$ positions, thereby providing definitive tests of repeaters. Burst positions and spectra would be brought down in real time for rapid followup studies of GRB afterglows and identifications.

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