EXIST: A High Sensitivity Hard X-ray Imaging Sky Survey Mission for ISS

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Abstract. A deep all-sky imaging hard x-ray survey and wide-field monitor is needed to extend soft (ROSAT) and medium (ABRIXAS) x-ray surveys into the 10-100 keV band (and beyond) at comparable sensitivity (\(\sim\)0.05 mCrab). This would enable discovery and study of \(\gtrsim\)3000 obscured AGN, which probably dominate the hard x-ray background; detailed study of spectra and variability of accreting black holes and a census of BHs in the Galaxy; Gamma-ray bursts and associated massive star formation (PopIII) at very high redshift and Soft Gamma-ray Repeaters throughout the Local Group; and a full galactic survey for obscured supernova remnants. The Energetic X-ray Imaging Survey Telescope (EXIST) is a proposed array of 8 \(\times\) 1\(m^2\) coded aperture telescopes fixed on the International Space Station (ISS) with 160\(^\circ\) \times\) 40\(^\circ\) field of view which images the full sky each 90 min orbit. EXIST has been included in the most recent NASA Strategic Plan as a candidate mission for the next decade. An overview of the science goals and mission concept is presented.

I INTRODUCTION

The full sky has not been surveyed in space (imaging) and time (variability) at hard x-ray energies. Yet the hard x-ray (HX) band, defined here as 10-600 keV, is key to some of the most fundamental phenomena and objects in astrophysics: the nature and ubiquity of active galactic nuclei (AGN), most of which are likely to be heavily obscured; the nature and number of black holes; the central engines in gamma-ray bursts (GRBs) and the study of GRBs as probes of massive star formation in the early universe; and the temporal measurement of extremes: from kHz QPOs to SGRs for neutron stars, and microquasars to Blazars for black holes.

A concept study was conducted for the Energetic X-ray Imaging Survey Telescope (EXIST) as one of the New Mission Concepts selected in 1994 (Grindlay et al 1995). However the rapid pace of discovery in the HX domain in the past \(\sim\)2 years,
coupled with the promise of a likely 2-10 keV imaging sky survey ABRIXAS2 (see http://www.aip.de/cgi-bin/w3-msql/groups/xray/abrixas/index.html) in c.2002-2004 and the recent selection of Swift (see http://swift.gsfc.nasa.gov/) which will include a ∼10-100 keV partial sky survey (to ∼1 mCrab) in c.2003-2006, have prompted a much more ambitious plan. A dedicated HX survey mission is needed with full sky coverage each orbit and ∼0.05 mCrab all-sky sensitivity in the 10-100 keV band (comparable to ABRIXAS2) and extending into the 100-600 keV band with ∼0.5 mCrab sensitivity. Such a mission would require very large total detector area and large telescope field of view. These needs could be met very effectively by a very large coded aperture telescope array fixed (zenith pointing) on the International Space Station (ISS), and so EXIST-ISS was recommended by the NASA Gamma-Ray Program Working Group (GRAPWG) as a high priority mission for the coming decade. This mission concept has now been included in the NASA Strategic Plan formulated in Galveston as a post-2007 candidate mission. In this paper we summarize the Science Goals and briefly present the Mission Concept of EXIST-ISS. Details will be presented in forthcoming papers, and are partially available on the EXIST website (http://hea-www.harvard.edu/EXIST/EXIST.html).

II SCIENCE GOALS AND OBJECTIVES

EXIST would pursue two key scientific goals: a very deep HX imaging and spectral survey, and a very sensitive HX all-sky variability survey and GRB spectroscopy mission. These Survey (S) and Variability (V) goals can be achieved by carrying out several primary objectives:

S1: Sky survey for obscured AGN & accretion history of universe
It is becoming increasingly clear that most of the accretion luminosity of the universe is due to obscured AGN, and that these objects are very likely the dominant sources for the cosmic x-ray (and HX) diffuse background (e.g. Fabian 1999). No sky survey has yet been carried out to measure the distribution of these objects in luminosity, redshift, and broad-band spectra in the HX band where, as is becoming increasingly clear from BeppoSAX (e.g. Vignati et al 1999), they are brightest. EXIST would detect at least 3000 Seyfert 2s and conduct a sensitive search for Type 2 QSOs. Spectra and variability would be measured, and detailed followup could then be carried out with the narrow-field focusing HX telescope, HXT, on Constellation-X (Harrison et al 1999) as well as IR studies.

S2: Black hole accretion on all scales
The study of black holes, from x-ray binaries to AGN, in the HX band allows their ubiquitous Comptonizing coronae to be measured. The relative contributions of non-thermal jets at high \( \dot{m} \) requires broad band coverage to \( \gtrsim 511 \) keV, as does the transition to ADAFs at lower \( \dot{m} \) values. HX spectral variations vs. broad-band flux can test the underlying similarities in accretion onto BHs in binaries vs. AGN.
**S3: Stellar black hole content of Galaxy**

X-ray novae (XN) appear to be predominantly BH systems, so their unbiased detection and sub-arcmin locations, which allow optical/IR identifications, can provide a direct measure of the BH binary content (and XN recurrence time) of the Galaxy. XN containing neutron stars can be isolated by their usual bursting activity (thermonuclear flashes), and since they may solve the birth rate problem for millisecond pulsars (Yi and Grindlay 1998), their statistics must be established. A deep HX survey of the galactic plane can also measure the population of galactic BHs not in binaries, since they could be detected as highly cutoff hard sources projected onto giant molecular clouds. Compared to ISM accretion onto isolated NSs, for which a few candidates have been found, BHs should be much more readily detectable due to their intrinsically harder spectra and (much) lower expected space velocities, \( V \), and larger mass \( M \) (Bondi accretion depending on \( M^2/V^3 \)).

**S4: Galactic survey for obscured SNR: SN rate in Galaxy**

Type II SNe are expected to disperse \( \sim 10^{-4} M_\odot \) of \(^{44}\text{Ti} \), with the total a sensitive probe of the mass cut and NS formation. With a \( \sim 87\text{y} \) mean-life for decay into \(^{44}\text{Sc} \) which produces narrow lines at 68 and 78 keV, obscured SNe can be detected throughout the entire Galaxy for \( \gtrsim 300\text{y} \) given the \( \sim 10^{-6} \) photons \( \text{cm}^{-2} \text{s}^{-1} \) line sensitivity and \( \lesssim 2 \) keV energy resolution (at 70 keV) possible for EXIST. Thus the likely detection of Cas A (Iyudin et al 1994) can be extended to more distant but similarly (or greater) obscured SN to constrain the SN rate in the Galaxy. The all-sky imaging of EXIST would extend the central-radian galactic survey planned for INTEGRAL to the entire galaxy.

**V1: Gamma-ray bursts at the limit: SFR at \( z \gtrsim 10 \)**

Since at least the “long” GRBs located with BeppoSAX are at cosmological redshifts, and have apparent luminosities spanning at least a factor of 100, it is clear that even the apparently lower luminosity GRBs currently detected by BeppoSAX could be detected with BATSE out to \( z \sim 4 \) and that the factor \( \sim 5 \) increase in sensitivity with Swift will push this back to \( z \sim 5-15 \) (Lamb and Reichart 1999). The additional factor of \( \sim 4 \) increase in sensitivity for EXIST would allow GRB detection and sub-arcmin locations for \( z \gtrsim 15-20 \) and thus allow the likely epoch of Pop III star formation to be probed if indeed GRBs are associated with collapsars (e.g. Woosley 1993) produced by the collapse of massive stars. The high throughput and spectral resolution for EXIST would enable high time resolution spectra which can test internal shock models for GRBs.

**V2: Soft Gamma-ray Repeaters: population in Galaxy and Local Group**

Only 3 SGR sources are known in the Galaxy and 1 in the LMC. Since a typical \( \sim 0.1\text{sec} \) SGR burst spike can be imaged (5\( \sigma \)) by EXIST for a peak flux of \( \sim 200 \text{mCrab} \) in the 10-30 keV band, the typical bursts from the newly discovered SGR1627-41 (Woods et al 1999) with peak flux \( \sim 2 \times 10^{-6} \text{erg cm}^{-2} \text{s}^{-1} \) would be
detected out to \( \sim 200 \) kpc. Hence the brightest “normal” SGR bursts are detectable out to \( \sim 3 \) Mpc and the rare giant outbursts (e.g. March 5, 1979 event) out to \( \sim 40 \) Mpc. Thus the population and physics of SGRs, and thus their association with magnetars and young SNR, can be studied throughout the Local Group and the rare super-outbursts beyond Virgo.

**V3: HX blazar alert and spectra: measuring diffuse IR background**
The cosmic IR background (CIRB) over \( \sim 1-100 \mu \) is poorly measured (if at all) and yet can constrain galaxy formation and the luminosity evolution of the universe (complementing S1 above). As reviewed by Catanese and Weekes (1999), observing spectral breaks (from \( \gamma - \gamma \) absorption) for blazars in the band \( \sim 0.01-100 \) TeV can measure the CIRB out to \( z \sim 1 \) if the intrinsic spectrum is known. Since the \( \gamma \)-ray spectra of the detected (low \( z \)) blazars are well described by synchrotron-self Compton (SSC) models, for which the hard x-ray (~100keV) synchrotron peak is scattered to the TeV range, the HX spectra can provide both the required underlying spectra and time-dependent light curves for all objects (variable!) to be observed with GLAST and high-sensitivity ground-based TeV telescopes (e.g. VERITAS).

**V4: Accretion torques and X-ray pulsars**
The success of BATSE as a HX monitor of bright accreting pulsars in the Galaxy (cf. Bildsten et al 1997), in which spin histories and accretion torques were derived for a significant sample, can be greatly extended with EXIST: the very much larger reservoir of Be systems can be explored, and wind vs. disk-fed accretion studied in detail. The wide-field HX imaging and monitoring capability will also allow a new survey for pulsars and AXPs in highly obscured regions of the disk, complementing S4 above.

**V5: QPOs and accretion disk coronae**
The rms variability generally and QPO phenomena appear more pronounced above \( \sim 10 \) keV for x-ray binaries containing both BH and NS accretors, suggesting the Comptonizing corona is directly involved. Thus QPOs and HX spectral variations can allow study of the poorly-understood accretion disk coronae, with extension to the AGN case. Although the wide-field increases backgrounds, and thus effective modulation, the very large area (\( \gtrsim 1 \text{m}^2 \)) of HX imaging area on any given source means that multiple \( \sim 100 \) mCrab LMXBs could be simultaneously measured for QPOs with 10% rms amplitude in the poorly explored 10-30 keV band.

### III EXIST-ISS MISSION CONCEPT

To achieve the desired \( \sim 0.05 \) mCrab sensitivity full sky up to 100 keV (and beyond) requires a very large area array of wide-field coded aperture (or other modulation) telescopes. The very small field of view (\( \sim 10' \)) of true focussing (e.g. multi-layer) HX telescopes precludes their use for all sky imaging and monitoring.
EXIST-ISS would take the coded aperture concept to a practical limit, with 8 telescopes each with 1m² in effective detector area and 40° x 40° in field of view (FOV). The individual FOVs are offset by 20° for a combined FOV of 160° x 40°, or ~2sr. By orienting the 160° axis perpendicular to the orbit vector, the full sky can be imaged each orbit if the telescope array is fixed-pointed at the local zenith. This gravity-gradient type orientation, and the large spatial area of the telescope array, are ideally matched for the ISS, which provides a long mounting structure (main truss) conveniently oriented perpendicular to the motion, as depicted on the EXIST website.

The sensitivity would yield ~10⁴ AGNs full sky, thus setting a confusion limit resolution requirement (~1/40 “beam”) of ~5′. With this coded mask pixel size, high energy occulting masks (5mm, W) can be constructed with 2.5mm pixel size for minimal collimation. The mask shadow is then recorded by tiled arrays of CdZnTe (CZT) detectors with effective pixel sizes of ~1.3mm, yielding a compact (1.3m) mask-detector spacing. The CZT detectors would likely be 20mm square x 5mm thick (for ≥ 20% efficiency at 500 keV) and read out by flip-chip bonded ASICs (e.g. Bloser et al 1999, Harrison et al 1999).

The 8-telescope array is continuously scanning (sources on the orbital plane drift across the 40° FOV in 10min; correspondingly longer exposures/orbit near the poles), with each photon time-tagged and aspect corrected (~10") so that ISS pointing errors or flexure are inconsequential over the large FOV. Source positions are centroided to ≤ 1′ for ≥ 5σ detections. The resulting sky coverage is remarkably uniform with ≤ 25% variation in exposure full sky over the ~2mo precession period of the ISS orbit. More details of the current mission concept are given in Grindlay et al (2000), and will be further developed in the implementation study being conducted by the EXIST Science Working Group (EXSWG).

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