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New Astronomy Reviews 48 (2004) 237–241
New Astronomy Reviews
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# Tracing cosmic star formation with EXIST

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**Abstract**

We describe the energetic X-ray imaging survey telescope EXIST, designed to carry out a sensitive all-sky survey in the 10–600 keV band. The primary goal of EXIST is to find black holes in the local and distant universe. EXIST also traces cosmic star formation via gamma-ray bursts and gamma-ray lines from radioactivity ejected by supernovae and novae.
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*PACS:* 95.55.Ka; 97.60.Bw; 97.30.Qt; 97.80.Gm; 98.62.Nx; 97.60.Lf; 97.10.Bt

*Keywords:* Gamma-ray telescopes; Supernovae; Novae; Bursts; Black holes; Stars-formation

## 1. EXIST

EXIST is proposed as the black hole finder probe in NASA's *Beyond Einstein Program*, and would operate in zenith pointing scanning mode ($F_oV$ of $180° \times 75°$), to provide all-sky coverage every orbit. Variable sources on the sky would be monitored daily. Each source would be in the $F_oV$ for at least 20 min every 95 min orbit, and sampled with millisecond resolution. EXIST will monitor known variable sources, detect outbursts of known and new sources, and detect gamma-ray bursts (GRBs) with a coverage probability of $P = F_oV/4\pi \sim 0.5$. Technical details are presented in Grindlay et al. (2003a) and also <http://exist.gsfc.nasa.gov/>. The "reference design" (Fig. 1(a)) will be refined in a proposed mission concept study. EXIST surveys the sky from a low-inclination (22°), low-altitude (~500 km) orbit. With a mission life of 5–10 years, EXIST could

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doi:10.1016/j.newar.2003.11.055

Fig. 1. The “reference design” of EXIST, with three Tungsten coded-mask imaging telescopes (2.7 $m^2$ of CZT per telescope).

explore the hard X-ray universe in 2010–2020, a century after Albert Einstein developed special and general relativity.

EXIST employs $\sim$2.7-$m^2$ CZT for each of its three telescopes, and images the sky in the 10–600 keV range with Tungsten coded masks with angular resolution of a few arcmin, and 10–50 arcsec source localization. In the 10–200 keV band EXIST will have a continuum sensitivity of $\sim$2 mCrab (each orbit), and $\sim$0.05 mCrab for a 1-year survey. Above 200 keV the per-orbit sensitivity would be $\sim$20 mCrab, and $\sim$0.5 mCrab for a 1-year survey. Fig. 2 shows continuum and line sensitivities as a function of energy. This sensitivity level would partly fill the “MeV-gap” discussed at length at this conference. A MEGA-like mission would provide a similar advance at the high-energy side of the gap, and represent a significant step towards a future advanced Compton telescope (ACT). EXIST (Fig. 1) would also complement observations with GLAST, which will study sources in the 20 MeV – 300 GeV (Gehrels and Michelson, 1999), and ground-based VHE/UHE instrumentation, such as HESS, MAGIC, and VERITAS. The development of new detector technology is launching gamma-ray astronomy (Schönfelder, 2001) into an exciting new era of breakthroughs in the MeV to TeV regime.

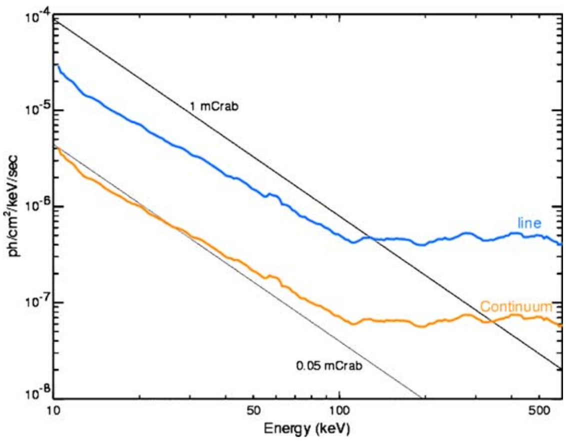


Fig. 2. Sensitivity estimate (5$\sigma$, 1-year survey) based on an exposure time of $10^7$ s, allowing for 20% source duty cycle. Estimates of the continuum sensitivity assume $\Delta E/E = 1$, and for lines $\Delta E/E = 0.01$. The actual FWHM energy resolution below 150 keV will be less than 1 keV. Above 150 keV, Compton events will reduce the resolution.

## 2. Scientific objectives

EXIST will perform a sensitive all-sky hard X-ray search for black holes, including massive black holes found in active galactic nuclei and stellar mass black holes in the Milky Way. The hard X-ray survey probes the accretion history of black holes, clarifies the growth mechanism, and investigates their role in galaxy evolution (Grindlay et al., 2003b). We focus on objectives relevant to this conference, and the capabilities for gamma-ray burst (GRB) studies.

### *2.1. Gamma-ray bursts*

GRBs are associated with host galaxies at large redshifts (van Paradijs et al., 2002; Meszaros, 2002). The red shift record is $z = 4.5$ for GRB000131 (Andersen et al., 2000). In at least two cases evidence exists for supernova associations: GRB 980425 and SN1998bw (Galama et al., 1998) at $z = 0.008$ and GRB030329-SN2003dh (Hjorth et al., 2003) at $z = 0.169$. The spectra of these two supernovae are very similar and characteristic of Type Ic hypernovae, such as SN1997ef (Woosley et al., 1999; Branch, 2001; Nomoto et al., 2001; Kawabata et al., 2003). The emerging paradigm is a link of massive stars with (long) GRBs, consistent with the predictions of the collapsar model (Woosley, 1993). In this scenario the collapse of a rotating, massive star to a black hole ultimately drives relativistic outflows through a collapsing envelope (e.g., MacFadyen and Woosley, 1999) producing a GRB-jet after the breakout, and a subsequent supernova. Under some circumstances the formation of a stellar mass black hole is thus heralded by a burst of $\gamma$-rays, followed by a decaying afterglow from X-rays to radio (van Paradijs et al., 2002). GRBs thus provide a unique opportunity to trace the process of star formation to large, cosmological distances (Lamb and Reichart, 2000). Theoretical studies (Abel et al., 2002; Bromm and Loeb, 2002; Loeb, 2003) indicate that the first generation of stars may have formed at $z > 10$, re-ionizing the universe, perhaps with a bias towards more massive stars due to the low metallicity in the early universe. Observational support for the emergence of the first stars in the red shift range $z \sim 10$–30 ($\sim$100–400 millionyears after the bigbang) comes from the polarization of the CMB (Kogut, 2003). Black holes from these population III stars may have played a significant role in seeding AGN cores. Even at such large distances it is easy to detect a red-shifted GRB. A sensitivity of 1 mCrab in the hard X-ray band is sufficient to detect GRBs like GRB 990123 at essentially all realistic distances. Based on the assumption that the GRB rate traces the cosmic star formation rate, we estimate that $\sim$7% of all GRBs detected by EXIST originate at $z > 10$ (Fig. 3). To enable ground-based and space-based (e.g., NGST) studies of these bursts, EXIST provides 10″–50″ locations in near real time. The total burst rate will be a few per day. EXIST would serve as the primary GRB observatory in the post-Swift era (Grindlay et al., 2001), during a time when sensitive neutrino detectors (IceCube) and gravity wave detectors (LISA, LIGO-II) may be able to detect the high-energy (>PeV) neutrino and gravity wave signature of GRBs (Meszaros et al., 2003).

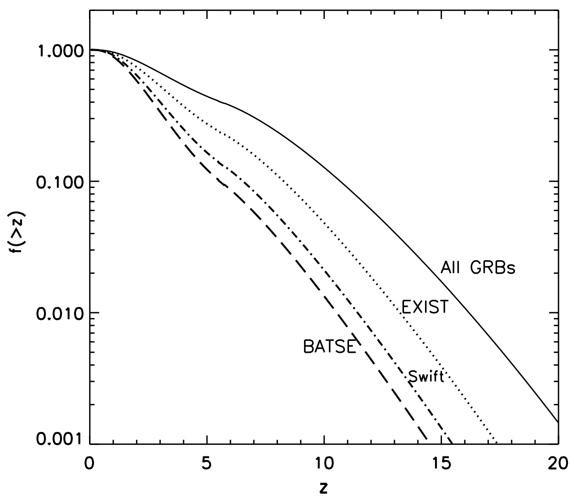


Fig. 3. Predicted fraction of GRBs with red shift greater than $z$.

Detection of the first generation of stars may require GRBs as a tracer, as galaxies beginning to form stars are faint. Spectroscopy of host galaxies will require observations with large aperture telescopes (Loeb, 2003), and are likely to revolutionize our ability to trace and probe structure formation and galaxy evolution to the earliest times. GRBs provide signposts along "the road to galaxy formation" (Keel, 2002), and shed light on the crucial question of halo formation via a more or less smooth collapse or successive mergers of independently evolving proto-galactic fragments. The star formation rate during halo collapse is sensitive to stellar feedback (e.g., Hartmann et al., 2003; Marri and White, 2002). Thus high-$z$ GRBs could improve our understanding of a key ingredient in galaxy formation and evolution.

The star formation rate and burst rate may be related, but not 1-to-1. As metallicity decreases, the IMF changes due to changes in the cooling function of the gas. After formation, mass loss from stellar winds is a sensitive function of the metal content in the stellar envelope, affecting subsequent evolution and probabilities for creating the right conditions for GRBs (Heger et al., 2003). GRBs provide a new tool for studies of early galaxy evolution, and may lead to the elusive Population III stars and their feedback on protogalaxies (Barkana and Loeb, 2001).

EXIST will also detect many X-ray rich GRBs (the so called X-ray Flashes, Heise, 2001, 2003). This new burst phenomenon is in many ways similar to classical long duration GRBs, but, as the name indicates, characterized by a lower energy of the bulk of the emission. While the peak in the $\nu F_\nu$ spectrum of GRBs is clustered around 200 keV (Preece et al., 2000), the currently small sample of XRFs suggests a peak value of $\sim$50 keV. The nature of XRFs is not yet clear. XRFs could be highly red-shifted GRBs, but observations of the host galaxies of XRF 011030 and XRF 020427 (Bloom et al., 2003) argue against that interpretation. Perhaps they are simply the off-axis emissions of GRBs (e.g., Zhang et al., 2003; Yamazaki et al., 2003).

### 2.2. Supernovae

Supernova rates determine the multi-phase structure of the ISM and the chemical history of galaxies (e.g., Pagel, 1997; Clayton, 2003). Various tracers ($H_\alpha$, $L_{IR}$, etc.) are available to estimate the star formation rate (SFR), but even for the Milky Way this key quantity is rather uncertain. In combination with assumptions about the IMF one can use tracers, such as the historic supernova rate or the 1.809 MeV map from $^{26}$Al. If most of the 1.809 MeV line flux is due to $^{26}$Al from massive stars, Timmes et al. (1997) showed that calculated yields imply a SFR of $5 \pm 4 M_o$, or equivalently a supernova rate of $3.4 \pm 2.8$ per century (Type II/Ib events). This rate implies $\sim$30 supernovae within the past millennium. Only a half dozen of these events are contained in the historic record (Stephenson and Green, 2002), due to the large bias introduced by extinction in the ISM.

The hard X-ray band provides an opportunity to find hidden Galactic supernovae through $\gamma$-ray line emission from $^{44}$Ti (e.g., Hartmann et al., 1993). Abundant production of $^{44}$Ti (yield $\sim 10^{-4} M_o$: Timmes et al., 1996; Rauscher et al., 2002) and a mean lifetime of $\tau_{44} \sim 87 \pm 2$ years (e.g. Görres et al., 1998) suggests that $\gamma$-ray surveys should find a significant number of 1.156 MeV sources, which is not the case. To date only the $\sim$330-year-old SNR Cas A has been clearly detected by this method (Iyudin et al., 1994). Is Cas A not a typical $^{44}$Ti-producing supernova? The et al. (2003) study the lack of $^{44}$Ti sources and associated issues of the rate and spatial distribution of Galactic supernovae and conclude that either core collapses have been improbably rare in the Galaxy during past centuries or $^{44}$Ti-producing supernovae are not typical. The EXIST survey would detect all $^{44}$Ti sources similar to Cas A to a distance of $\sim$6 kpc and age >300 years, and potentially settle the issue of the "missing $^{44}$Ti sources".

The late time bolometric light curve of SN 1987A may in large part result from energy deposition due to the decay of $^{44}$Ti (Woosley et al., 1989; Fransson and Kozma, 2002), but contributions from $^{44}$Ti can only be ascertained by measurement. INTEGRAL observations could reveal $^{44}$Ti in SN 1987A, unless severe ionization of the ejecta reduce the flux significantly. EXIST would detect $^{44}$Ti in SN 1987A (lines at 68 and 78 keV) even with ionization corrections (Mochizuki et al., 2003).

### 2.3. Novae

Novae may contribute significantly to galactic chemical evolution for isotopes such as $^{7}$Li, $^{13}$C, $^{15}$N, and $^{17}$O (Woosley et al., 1997; Jose and Hernanz, 1998; Mateucci, 2001; Romano and Matteucci, 2003). Their contribution to $^{26}$Al in the ISM may not dominate the diffuse 1.809 MeV emission (see Prantzos and Diehl, 1996; Knödlseder, 1999), but could still represent a significant fraction of this signal. To reliably determine the nova contribution, one needs to know accurately the product of yield and event rate. Unfortunately, the galactic nova rate is still rather uncertain, with values ranging from 100 to 20 year$^{-1}$ (Mateucci, 2001). The large uncertainty is due to the fact that observations of novae in extragalactic systems and extrapolations from the detections of Galactic novae yield very different results. Population synthesis models for nova rates in other galaxies depend on the calibration in the Milky Way (Matteucci et al., 2003), and favor smaller rates (Shafter, 1997). A reliable estimate of the nova rate can be established with EXIST, which will detect a large fraction of Galactic novae in X-rays. EXIST will advance our understanding of the physics of the outburst in these accreting white dwarfs through early detection. Discovery of novae in the optical band is delayed relative to the X/$\gamma$-ray signal of these events (Hernanz et al., 2001, 2002). EXIST would detect 511 keV emission that emerges within hours of the nova, and provide an alert system to distances of $\sim$6 kpc. X-ray observations will improve our theoretical understanding of nova physics, and establish their rate and spatial distribution.

## Acknowledgements

We thank the staff of the Kloster Seeon for outstanding hospitality and all participants for many valuable discussions.

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