Draft White Paper for *EXIST*

1. *EXIST* Mission Overview

EXIST (Energetic X-ray Imaging Survey Telescope) will be the first telescope to image the entire sky every 90 minutes. Covering the 10-600 keV, hard X-ray band, *EXIST* will monitor all sources on timescales ranging from microseconds to years, with ~100 times the angular resolution and ~1000 times the sensitivity of previous telescopes in this band.

EXIST observations will contribute to meeting all four of the SEU science objectives. (i)As the natural successor to Swift, it will be the premier instrument for the detection and study of Gamma Ray Bursts (GRB) and Active Galactic Nuclei (AGN) and will use these observations to monitor the formation of stars and the growth of galaxies and their nuclei from the earliest times. (ii) By measuring the emission lines produced by the prompt decay of several isotopes, *EXIST* will determine the nova and supernova rate (and neutron star formation) and quantify the cycling of mass, heavy elements and energy between the various constituents of the Galaxy over its history. (iii)Through its penetrating measurements of hard X-rays from the gas orbiting close to the event horizons of black holes, it will probe strong-field gravity. (iv)Finally, by observing these environments and, especially, the surfaces of magnetized neutron stars, *EXIST* will allow us to observe fundamental physical processes at work under conditions that can never be reproduced in a terrestrial laboratory. However, as *EXIST* is an astronomy survey mission, opening up an enormous volume of sensitivy - angular resolution - temporal resolution space, we anticipate that its greatest contributions will come from unexpected discoveries.

EXIST has a strong scientific heritage. It has been studied since 1994, when it was selected as a New Mission Concept (along with GLAST and Con-X). In 1999, the Gamma-ray Astronomy Program Working Group recommended *EXIST* as a priority mission, and in 2000 the Astronomy and Astrophysics Survey Committee designated *EXIST* as its third priority, SEU moderate mission (after GLAST and LISA). *EXIST* can also contribute to some of the physics goals listed by the NRC committees on Gravitational Physics, the Physics of the Universe and the Physics Survey Committee. Although originally conceived as an International Space Station attached payload, *EXIST* is now designed as a free-flyer which has enhanced its capabilities. It could be ready for launch in 2007 after the end of the Swift mission although we present it here with a timeline leading to a 2010 launch. In order to achieve these launch goals, *EXIST* will require modest mission and detector development support (currently supported only by individual investigator SR&T programs) and a balloon-borne, flight hardware test program.

EXIST naturally complements planned and proposed telescopes, in space and on the ground. It will provide hard X-ray spectra and precise source locations for many of the new sources (including GRBs) that will be found by *GLAST* if launched before 2010. *EXIST* also provides a natural complement to the proposed Large Synoptic Survey Telescope (LSST), which will survey a large fraction of the optical sky at a similar rate to

EXIST as well as the gravitational radiation detectors *LIGO* and *LISA*. It will find Hard X-ray sources that can be followed up by spectroscopically by Constellation-X and, through its ability to penetrate star forming regions at large redshift will attack similar science to NGST from a different perspective.

Although conceived as a US-led mission, the *EXIST* team is currently negotiating with prospective European collaborators who can contribute vital technology and coordinated observing in other parts of the electromagnetic spectrum. The technological development of hard X-ray imaging and spectroscopic capability is of importance for airport scanners, the detection of radioactive material and medical imaging and *EXIST* plans to contribute to the development of these capabilities both directly and through the training of students.

In the following sections we describe *EXIST*'s principal science goals and new areas of discovery space, mission requirements, mission development status and partnerships, and *EXIST's* strategic role.

2. EXIST Science Goals

The hard X-ray band (~10-600 keV) observed with *EXIST* covers the transition from the thermal X-ray universe of million-degree gas to the extremes of pair plasmas and the relativistically accelerated non-thermal universe. This band is prime discovery space: it has never been surveyed with a high-sensitivity, imaging detector. Hard X-rays can penetrate thousands of times more material than their softer counterparts, thus allowing a unique probe of the most compact and extreme phenomena.

Ten years ago, the entire soft X-ray sky was imaged with high sensitivity by ROSAT (~1' resolution, between 0.5 - 2keV). More than a hundred thousand sources were discovered, many of them normal stars. However, the soft X-ray sky offers a very different view than the hard X-ray sky, dominated by accretion-power and highly variable compact objects. With a sensitivity and resolution comparable to ROSAT and factors of 1000 and 100 times greater than the only previous (1979; HEAO-A4) broadband hard X-ray survey, *EXIST* will reveal the universe of the obscured, from supermassive black holes in galactic nuclei to stellar holes in molecular clouds and obscured supernova remnants. The all-sky coverage each orbit and wide-field hard X-ray imaging sensitivity and resolution makes *EXIST* an optimum Observatory for the study and use of Gamma Ray Bursts. *EXIST* makes major contributions to SEU science in a broad range. Several key examples follow.

2.1 Obscured AGN and Accretion Luminosity of Universe.

The most numerous objects in the *EXIST* survey are expected to be active galaxies; *EXIST* should locate at least 30,000 of these objects, scaling from optical/X-ray Active Galactic Nuclei (AGN) distributions. Furthermore, ~75% of the AGN that *EXIST* will detect should be obscured, i.e., AGN in which the active nucleus is not detected in the optical or radio (and is not prominent in the IR against what is often a star-forming background). The *EXIST* survey will therefore yield the first unbiased census of hidden AGN, strongly constraining the total accretion luminosity (per unit mass) of the universe. Understanding the frequency of obscured AGN will elucidate the correlation of black hole mass to galaxy bulge mass and also constrain the effect of massive black holes on galaxy formation. *EXIST* will measure the spectral and temporal properties of this entire distribution of AGN, constraining not only the nature and workings of the maelstrom at their cores, but also quantifying, finally, their contributions to the cosmic X-ray background. Furthermore, recent TeV detections of several blazars have shown that they can be used to measure the poorly known diffuse cosmic IR background. By measuring the blazars' TeV spectral breaks due to absorption by cosmic IR photons, and knowing their intrinsic spectra, predicted from Compton scattering models and the simultaneous hard x-ray spectra from *EXIST,* we can probe the total redshifted output of starlight and re-radiation by dust which measures the nuclear burning luminosity of the universe.

The total accretion luminosity (L_{acc}) of the Universe rivals that from nuclear burning in stars (L_{nuc}). L_{acc} is at least 5%, and may be as high as 50% of L_{nuc}. How has this major energy source been missed? Radio loud quasars were found to be ~10% of blue radio-quiet quasars and these in turn are now recognized to be a similar fraction of the whole AGN population, most of which is hidden by gas and dust. The result is that probably 80-90%, of the luminosity of the Universe is generated from the release of gravitational energy via accretion and has been hidden from our view. A simple pointer to this fact is that three of the four AGN nearest to us - Cen A, NGC 4945 and the Circinus Galaxy - are heavily obscured. Such a gross undercounting of the contents and energetics of the Universe needs correcting, if we are to understand how galaxies evolve.

EXIST employs the only method that directly explores L_{acc}: hard x-ray emission provides an unambiguous measure whereas both radio and IR emission are likely confused by jet or reprocessed (or stellar) emission. Hence *EXIST* will give the first good accounting of the bulk of the accretion luminosity of the universe and the first accurate comparison of this with nuclear burning luminosity.

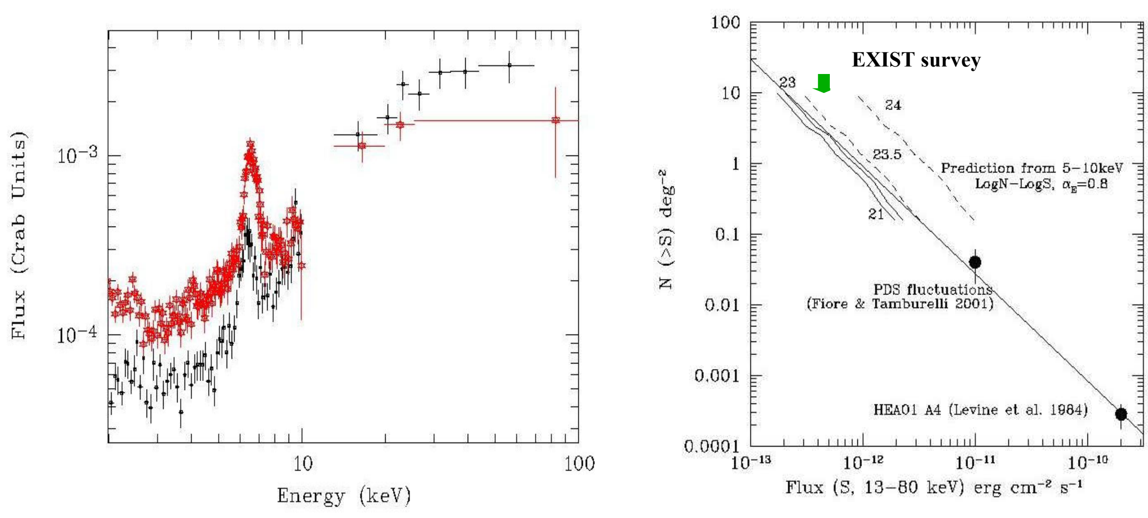

Figure 2-1: Hard X-ray spectra of two obscured AGN and estimated number counts vs. absorption.

2.2 ***Gamma Ray Bursts at the Limit: Pop III Stars?***

EXIST is the optimal next generation Gamma Ray Burst (GRB) observatory, providing 10-

50" locations for 2-3 GRBs each day. *EXIST* will conduct the most sensitive search and subsequent measurements of GRBs at high redshifts (z~5-20), thus allowing GRBs to reach their full potential as probes back to the dark ages and the first Pop III stars, illuminating the origin of structure in the high redshift universe. Furthermore, *EXIST*'s expected spectral resolution enables searches for short timescale spectral variations, critical for constraining the fireball and internal shock models for GRBs.

While we now know that at least one of the two major classes of GRBs are at cosmological distances, the central engine that powers the bursts and the radiation mechanisms are yet to be determined. GRBs likely include the highest observable energy densities and the most extreme physical conditions in the Universe since the Big Bang. The long-duration bursts, for which the initial afterglows were discovered using ~5' images from BeppoSAX, are consistent with the collapsar model, in which the collapse of the interior of a very massive star forms a black hole in a "hypernova" explosion. Pop III stars, almost certainly very massive, are prime GRB sources, which could be readily detected at their likely redshifts (z ~10-20). The broad energy band coverage of *EXIST* and the very large collection area for optimum statistics, will enable "photometric redshifts" to be derived from the observed relation between GRB time-lags and absolute luminosity. *EXIST* could constrain the star formation rate to large z as well as provide the initial GRB detection and redshifts of "orphan afterglows" likely to be found with the LSST.

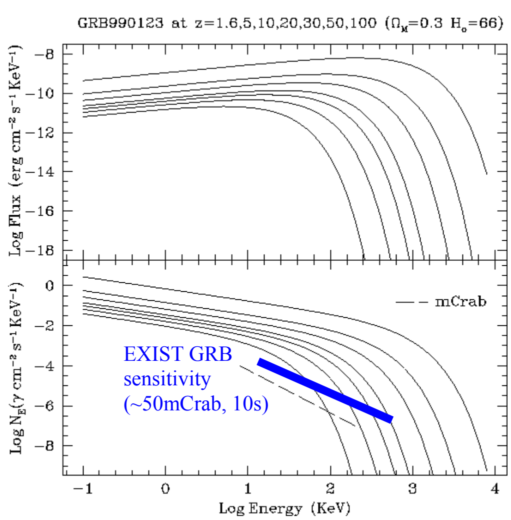

Figure 2-2. *EXIST* sensitivity for high z GRBs.

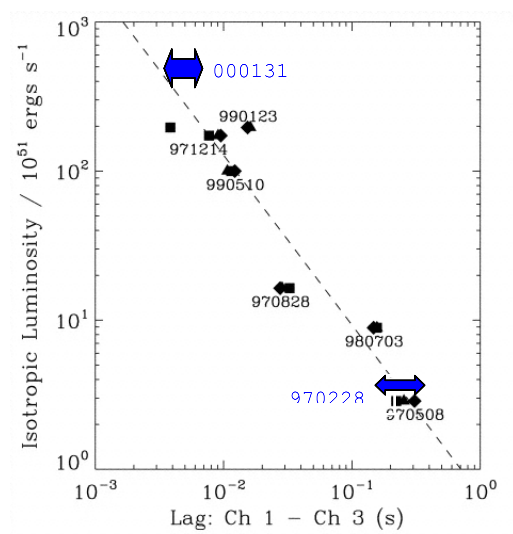

Figure 2-3: GRB luminosity-lag relation.

2.3 Matter at the Extreme: Galactic Black Holes & Neutron Stars

EXIST will extend the RXTE and BATSE studies of accretion powered compact binaries to a complete galactic census of the neutron star (NS) and black hole (BH) populations in our Galaxy, as well as studying the possible bright, transient intermediate mass BH in the Local Group. Pulsars, burst sources, microquasars and transients are natural targets for

EXIST; all provide considerable time-varying emission in the hard X-ray band. Magnetic field strengths derived from cyclotron lines detected with *EXIST* and combined with continuous spin-luminosity measures, will constrain the moment of inertia for the entire NS population. *EXIST's* continuous sky coverage will detect the giant flares from Soft Gamma Repeaters out to Virgo, hence constraining the nature and formation of the strongest magnetic field NSs, the magnetars. And in pointed observations, *EXIST* will study the high frequency quasi-periodic oscillations recently discovered with RXTE at >13keV from black holes in binaries and microquasars, further constraining the accretion physics as well as the mass, spin and radii of these objects. For black holes, determining these parameters tests the fundamental physics of strong field gravity.

2.4 Hidden Supernovae and Novae: Rates from Nuclear Lines

EXIST's survey will reveal supernova remnants obscured by dust in the Galactic plane by resolving hot spot emission sources resolved in the 68 and 78 keV decay lines of ^{44}Ti that are ejected in Type II supernovae explosions. Scaling from the recent BeppoSAX detection of the combined line emission from Cas A, *EXIST* will provide a measure of the galactic Type II supernova rate by detecting and locating all supernova remnants within ~8 kpc which have occurred within the past ~500 years. Stellar novae can be discovered by a flash of 511 keV emission from ^{18}F, which emits positrons as it decays with a 158-min half-life. This transient 511 keV emission is only detectable with an all-sky imager like *EXIST*, and will provide new measures of the nova rate in the Galaxy as well as constraints on the origins of Type Ia supernovae.

3. EXIST Mission Requirements

The high sensitivity and temporal coverage needed to achieve the *EXIST* science demand a very large area, wide-field coded aperture imager. The *EXIST* telescopes will consist of 50° × 40° coded aperture imagers overlapped in 3 × 3 arrays to form a single 75° × 60° telescope. Three such telescopes will then be mounted adjacent to one another, oriented for a combined 180° × 75° field of view. This enables *EXIST* to image the full sky with each orbit, with an energy range overlapping ROSAT or a 2-10keV (ABRIXAS-like) survey on the low end while extending up beyond the 511 keV annihilation line.

The science discussed in the previous section also requires a 1 year all-sky survey 5σ sensitivity of 0.05 mCrab (~5 x 10^{-13} erg cm^{-2} s^{-1}) over the ~10-200 keV band with significant sensitivity to 600 keV (or ~2mCrab each orbit.) This sensitivity matches the ROSAT all-sky soft X-ray survey, and is 10-30 times as sensitive as the planned Swift hard X-ray survey. The sensitivity goal requires *EXIST* to possess a very large total detector area (8 m^2) of imaging CdZnTe (CZT) detector arrays. The need to minimize charged particle background effects gives rise to the need for large active shielding (CsI) and collimation; this shield will also extend the spectra of GRBs to ~10-30MeV, allowing overlap with GLAST (for which *EXIST* will provide precise positions).

The original *EXIST* concept was a payload mounted on the International Space Station (*EXIST*-ISS). However, our most recent studies have indicated that the *EXIST* mission would be best conducted as a free flyer: after an initial 1-2 year survey, *EXIST* would conduct follow-up pointed observations simultaneous with continued surveying. The baseline mission parameters for this free-flying *EXIST* are summarized in Table 3-1.

Figure 3-1: *EXIST* detectors and telescopes (3)

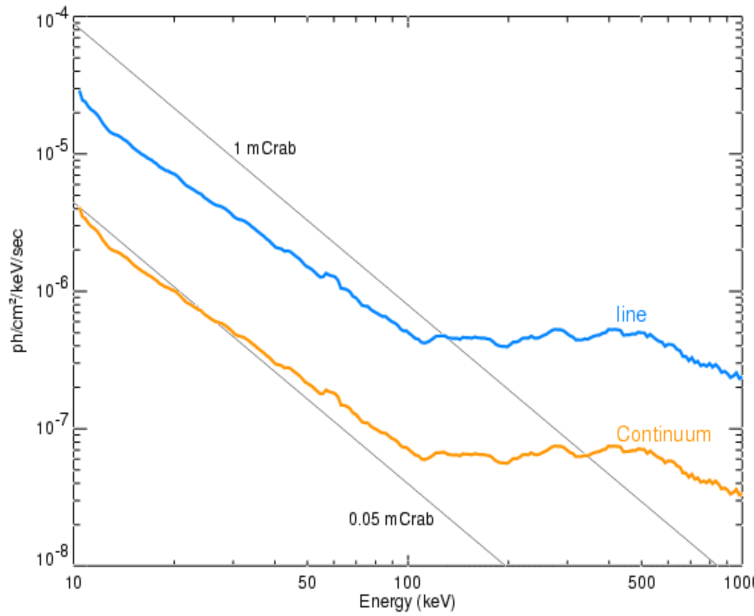

Figure 3-2: Survey sensitivity (5σ, ~10^7 s)

Table 3-1. *EXIST* Mission Parameters

Energy Range	10 - 600 keV
FOV	180° × 75°
Angular Resolution	2-5' (10 - 50" source locations)
Energy, Temporal Resolution	<2-6 keV (<100 - 600 keV), 2 μsec
Sensitivity (5σ, ~10^7 s)	0.05 mCrab (10-100 keV); 0.5 mCrab (>200 keV)
Telescopes, Detectors	Coded aperture, 8 m^2 CZT
Pointing, Aspect	~1° pointing, 5" instantaneous knowledge
Mass, Power, TM, Launch, Cost	8500kg, 1500W, 1.5Mbs, Delta IV, $330M

4. Mission Development Status

The principal technology challenge is the development of the very large array of CZT imaging detectors. The CZT and readout (ASIC) technology has advanced recently and two prototype imaging detectors have been designed and flown in balloon experiments.

EXIST's mission has been studied as both an attached ISS payload and as a free flyer: the latter concept has been baselined, and a full cost estimate has been derived. The following sections address EXIST's development, partnerships and organization.

4.1 Detector Development

EXIST's baseline design requires an 8 m^2 array of CZT. CZT is a high Z, large-bandgap semiconductor with good electron transport properties; its spectroscopic resolution can approach that of Ge detectors without the need for cooling. The Burst Alert Telescope (BAT) on the upcoming Swift mission is employing a 5200 cm^2 array of 4 mm × 4 mm × 2 mm CZT detectors. For BAT, each detector is a pixel; however, for *EXIST*, larger (20mm), thicker (5-10mm) CZT detectors will have segmented electrical contacts for pixel sizes of 1.2 mm. By adding orthogonal strip electrodes on two faces, or an array of pixel electrodes on one face, a single wafer can be segmented into a position sensitive detector for use in an imaging telescope. A CZT detector development collaboration has been formed between the Harvard-Smithsonian Center for Astrophysics and NASA's Goddard Space Flight Center to develop thicker, pixelated CZT detectors for *EXIST*.

Development of a two-scale coded aperture mask is underway, which will enable simultaneous low and high energy imaging, with 2' and 5' resolution, for the central portion of the central telescope (Figure 3-1). This will allow increased resolution and sensitivity for the narrow-field imaging (<100 keV) in *EXIST's* pointed observatory mode.

4.2 EXIST Technology Balloon Flight Program

Technology development for *EXIST* is being done through laboratory work and balloon flight test programs at Harvard, Caltech, GSFC, MSFC and UCSD. A small (1 x 2cm) tiled CZT imager fabricated at GSFC (Figure 4-1) and ASIC readout (32 pixels) was tested on a Harvard-MSFC balloon flight, and a 8 x 8cm (1024 pixel) prototype (Fig. 4-2) and coded mask will be flight tested. Development and flight testing of a complete *EXIST* CZT array (visible in Figure 3-1), with active shield and coded mask, is needed to qualify flight hardware and the final imager-readout design and integration/test procedures.

4.3 Mission Implementation Studies

EXIST has undergone systems engineering studies at GSFC for two types of mission implementations. In April 2000, an initial study was carried out with the ISAL (Instrument Science Analysis Lab) at GSFC for an implementation on the International Space Station (*EXIST*-ISS). A full mission study for *EXIST* as a free flyer was conducted by the IMDC (Integrated Mission Design Center) at GSFC in November 2001. Based on these studies, *EXIST* is baselined as a free-flying intermediate class satellite mission.

In the free-flyer implementation, *EXIST's* large, imaging telescopes will cover the full sky with each orbit, with a pointing accuracy of ~1° and a pointing knowledge of ~10". *EXIST* will be launched into a 500 km-altitude, ≤20°-inclination angle orbit by a Delta IV, with an orbital lifetime greater than 10 years. An equatorial ground station will be in place for primary data dumps, plus NASA's TDRSS will be used for low bit rate real-time data for prompt GRB positions. The estimated sensitivity for *EXIST* (shown in Figure 3-2) has been derived from both internal background in the CZT (scaled from the CZT2 balloon results) and the expected (dominant) cosmic diffuse flux in the large field-of-view.

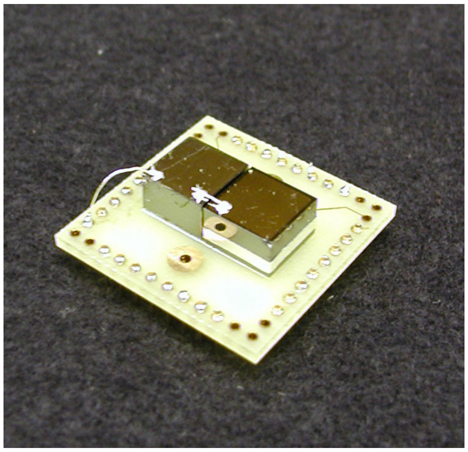

Figure 4-1: CZT2 flown in May 2001

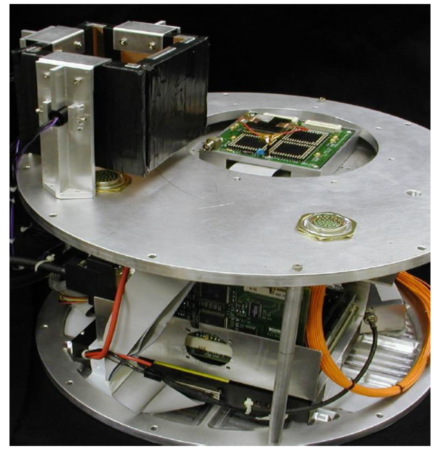

Figure 4-2: CZT3 & 40° active collimator (removed)

The other studied implementation of *EXIST* is well suited for the International Space Station (ISS). *EXIST*'s large mass and payload footprint could be fixed to the ISS P3 site, and the space shuttle would be capable of bringing *EXIST* up to ISS in a single structure occupying ~50% of the STS cargo bay. However, the much lower inclination orbit achieved by a free flying satellite will have a significantly lower background than the ISS's 51.6° inclination orbit, and the free flyer can point as an Observatory (for higher sensitivity spectral-temporal studies in the narrower FOV of the central telescope) while continuing the survey in the remaining off-axis telescopes. Nevertheless, *EXIST*-ISS could achieve most of the key science objectives and should be considered as a backup option.

4.4 Development Schedule and Estimated Cost

EXIST can readily achieve the recommendation of the Decadal Survey and be in orbit by 2010. Support for technology development for demonstration of a complete flight detector module is required. Mission development, 5 years of operations and the Guest Observer

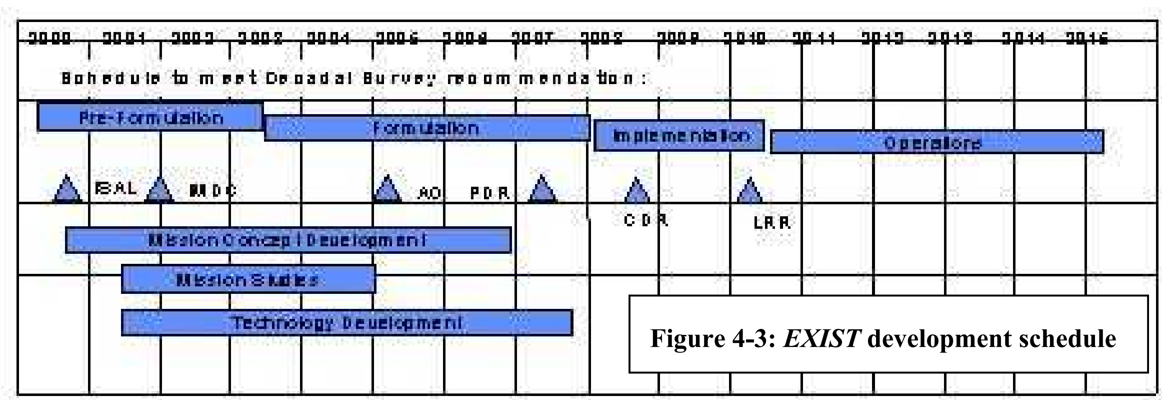

Figure 4-3: *EXIST* development schedule

program were estimated in the November 2001 GSFC/IMDC study to total $330M.

4.5 International Partners

Several groups have expressed interest in contributing to the *EXIST* mission. The Italian Rome and Bologna groups from BeppoSAX are considering the active shield system as well as possibly an auxiliary instrument; they would also provide the important contribution of use of the Malindi ground station. The German MPE and Tubingen groups are interested in contributing to the imager as well as possibly including a small co-aligned telescope (ABRIXAS-2) to conduct a long-planned medium energy (2-10keV) survey. Discussions have also been held with two groups in the UK and Netherlands.

4.6 Team/Organization

The *EXIST* Science Working Group (EXSWG[1]) was formed in 1999 and is chaired by Josh Grindlay. The EXSWG meets about three times a year with the purpose of providing scientific guidance in the development of the *EXIST* mission. *EXIST* is managed at Goddard Space Flight Center with the support of a study scientist (Neil Gehrels), study manager (Ruth Carter) and technical team. The *EXIST* web site can be found at http://exist.gsfc.nasa.gov/.

5. EXIST's Strategic Role

EXIST's science goals are strongly aligned with the recommendations by the four recent NAS survey committees for science priorities in the next decade. For example, the NAS Committee on Gravitational Physics (1999) recommends "the use of gamma-ray, X-ray?. telescopes?. in space? to detect new black holes in orbit around companion stars, and to explore the extraordinary properties of the geometry of space in the vicinity of black holes that are predicted by general relativity." The Committee on the Physics of the Universe, in its 2001 Phase 1 report asks the following two questions that will be addressed by *EXIST* observations: "Did Einstein have the last word on gravity?" and "How do cosmic accelerators work and what are they accelerating?" The NAS Physics Survey Overview Committee Report (2001) contains an entire chapter entitled "Structure and Evolution of the Universe" with lengthy sections emphasizing the promise of future studies of gamma-ray bursts, cosmic laboratories for explosive nucleosynthesis such as supernovae, and black holes: all main targets of *EXIST* science. And last but not least, there is the previously mentioned endorsement of *EXIST* as a moderate initative for the next decade by the NAS Astronomy and Astrophysics Survey Committee (2001.)

EXIST builds on the accomplishments of previous NASA experiments such as HEAO A-4, CGRO (BATSE and OSSE), and RXTE. *EXIST's* science requirements also flow from European missions such as ROSAT and BeppoSAX. *EXIST* science extends and surpasses

[1] Lars Bildsten, Roger Blandford, Deepto Chakrabarty, Martin Elvis, Andy Fabian, Fabrizio Fiore, Jerry Fishman, Neil Gehrels, Josh Grindlay, Chuck Hailey, Fiona Harrison, Dieter Hartmann, Chryssa Kouveliotou, Tom Prince, Brian Ramsey, Rick Rothschild, Gerry Skinner, Stan Woosley, Lynn Cominsky (EPO). The EXSWG will be expanded, with both science and mission specific discipline teams

the expected results from near-term future missions such as INTEGRAL and Swift, while complementing missions that will be in contemporaneous orbit such as NGST, Con-X and GLAST and LISA. And finally, *EXIST* science will appeal to the public, helping to improve science literacy by engaging students of all ages with its views of exploding stars, blazing galaxies and monstrous black holes.

5.1 Comparison with other missions

Only a fuzzy glimpse of the hard X-ray sky is available from the HEAO A-4 broadband hard X-ray survey conducted more than two decades ago. *EXIST* will perform the first full sky, deep imaging survey in the hard X-ray band. Other missions with sensitivity in this band have had only coarse imaging capabilities or narrow fields of view. The OSSE instrument on CGRO had both coarse angular resolution and no sensitivity below 50 keV (and only limited sensitivity below 100 keV). The BeppoSAX PDS instrument is a sensitive hard X-ray detector, but has only a narrow field (~1°), without imaging, and so is not suited for a full-sky survey. The upcoming IBIS instrument on INTEGRAL will be capable of partial sky surveys, but has a smaller field of view (~15°), so it cannot attain the all-sky coverage of *EXIST*. As part of its Core Program, INTEGRAL will conduct a galactic plane survey as a series of points which require ~1 week to cover the inner 160° of latitude of the galactic plane. The *EXIST* survey will achieve greater depth and temporal coverage for galactic plane survey sources: ~0.5 mCrab sensitivity for one day's observation versus ~15 mCrab for *IBIS* for a given point in the 160° region of the galactic plane surveyed once each week. The Swift mission will also conduct a hard X-ray survey with a sensitivity of ~1-2 mCrab in the 15-100 keV band over 3 years. Swift will conduct long stable pointings on gamma-ray burst positions determined initially by its Burst Alert Telescope (BAT), and thus will not have the rapid all-sky survey coverage or the extended bandwidth of *EXIST*.

Table 5-1. Comparison of *EXIST,* Swift and INTEGRAL capabilities.

Parameter	*EXIST*	*Swift*/BAT	INTEGRAL/IBIS
Energy range	10 - 600 keV	15 - 150 keV	15 keV - 10 MeV
FOV (instantaneous)	5 steradian (180° × 75°)	2 steradian	9° × 9° (fully coded)
Detector area	8 m^2 (5 mm thick CZT)	0.5 m^2 (2 mm thick CZT)	2600 cm^2 (CdTe) 3100 cm^2 (CsI)
GRB sensitivity	~ 20 × BATSE	~ 5× BATSE	--
Full sky imaging	Each orbit (95 min)	~ 1 month (?)	--
Angular resolution	2 - 5'	22'	12' (FWHM)
Localization	<10 - 30"	<5'	<4'

5.2 EXIST's Outreach to the Public

As the first deep survey of the sky for black holes and other extreme objects in the universe, *EXIST* will have broad public appeal. Viewing exciting images in an entirely new band of exploration will fascinate people of all ages. *EXIST* will reveal unseen objects such as obscured black holes, historical but hidden supernova remnants, flashes of hard x-rays from GRBs signalling the birth of black holes in the distant universe, and cataclysmic quakes from enormously magnetized neutron stars in nearby galaxies. *EXIST* will be an ongoing movie of the variability of the energetic universe; the public can (and will) tune in with webcast images of GRBs, galactic transients, and the steadily increasingly deep view of the last imaging frontier of the electromagnetic spectrum.

NASA is committed to bringing the excitement of space into the classroom and to the general public, using space science as an engagement to improve science literacy. This is an important national priority, as studies have shown a decrease in science competency in recent years, extending across all grade levels. Few missions will showcase more exciting and energetic phenomena than *EXIST*, which has the potential to capture the public's imagination, to instill a love for science in the general populace, and to energize the learning environment in the science classroom.

Finally, the development of a rugged extremely large area hard X-ray imaging detector system for *EXIST* will have application for both medical imaging (for which CZT cameras are under commercial development) and homeland security. Airport scanners and large area nuclear security/inspection imaging systems could be derived from the technologies developed for the mission.