Hard X-ray Timing with EXIST

Jonathan E. Grindlay

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138

Abstract. The Energetic X-ray Timing Survey Telescope (EXIST) mission concept is under study as the Black Hole Finder Probe (BHFP), one of the three Einstein Probe missions in the Beyond Einstein Program in the current NASA Strategic Plan. EXIST would conduct an all-sky imaging hard X-ray ($\sim$10-600 keV) survey with unprecedented sensitivity: about 5 $\times 10^{-13}$ cgs over any factor of 2 bandwidth, or comparable to that achieved at soft X-rays in the ROSAT survey. The proposed angular resolution of 5arcmin, temporal resolution of 10microsec, energy resolution of 1-4 keV over the broad band, and duty cycle of 0.2-0.5 for continuous coverage of any source provide an unprecedented phase space for timing and spectral studies of black holes –from stellar to supermassive, as well as neutron stars and accreting white dwarfs. The large sky coverage allows intrinsically rare events to be studied. One particularly exciting example is the possible detection of tidal disruption of stars near quiescent AGN. Super flares from SGRs could be detected out to the Virgo cluster. The large duty cycle and all sky monitor nature of the mission will enable QPOs from luminous AGN and BH X-ray binaries to be studied on timescales not possible before. I provide an overview of the mission concept and Reference Design, the X-ray timing science prospects for EXIST, and how these might be further optimized in the current Study for EXIST as the BHFP so that EXIST might include many of the desirable features of a next-generation timing mission.

INTRODUCTION

At energies above $\sim$10 keV, the sky becomes relatively dark as the thermal emission from the brightest X-ray binaries becomes less prominent and diffuse emission from hot gas can not be maintained. The number of bright sources decreases dramatically, but those that remain are likely to be among the most interesting (at least for high energy astrophysics) as they are either accretion powered or non-thermal. In both cases, variability often becomes increasingly prominent with increasing energy, at least up to 20-30 keV beyond which it has usually been difficult to measure (on short timescales) for persistent sources. These hard X-ray sources are, in general, accreting black holes: at fluxes F_x (10-20 keV) $\lesssim 1 \times 10^{-11}$ erg cm^{-2} s^{-1}, the extragalactic AGN dominate the sky above 10 keV. But even near the galactic plane, the logN-logS relations derived from the RXTE/ASM data for F_x (2-12keV) $\gtrsim 6 \times \times 10^{-11}$ erg cm^{-2} s^{-1}by Grimm, Gilfanov and Sunyaev (2002) (and discussed by Vrtilek in this volume) would suggest that black holes are $\gtrsim 10\%$ of the total for source fluxes at these limits, and probably more so if instead measured at 10-20 keV. This inference requires including transients, and the simple fact that of the $\sim$180 galactic sources detected above the limiting F_x by the ASM, all 16 of the currently known black hole candidates (BHCs) in the Galaxy (cf. McClintock and Remillard 2003) would have been detected.

It could then be argued that a follow-on mission to RXTE, with its highly successful timing studies of accreting black hole (BH) and neutron star (NS) systems, would gain most from greatly increased sensitivity above 10 keV. Obviously, this is countered by the greater source fluxes and thus count rates at lower energies: for a simple power law (with photon index 2) approximation to the spectrum, the counts are 10$\times$ larger in a decade lower energy band. However the relatively non-variable source emission components (e.g. blackbody emission from NS surfaces or the thermal soft continuum from accretion disks around BHs) provide additional 'signal backgrounds' at low energies, and indeed the rms amplitude of quasi-periodic oscillations (QPOs) in both BH and NS accretors increases sharply with energy up to at least $\sim$20 keV (cf. Kaaret, this volume). Thus on balance, the net gains with increased energy band are dependent on the timescale and spectrum of the variable source component(s) to be measured. QPOs can be detected in time T with detection significance n_σ (van der Klis 1998)

$$T = 4\frac{n_\sigma^2 \Delta\nu}{r^4 s^4}(b+s)^2 \tag{1}$$

where s is the source count rate, b is the background, $\Delta\nu$ is the signal bandwidth, and r is the rms amplitude.

We shall use this expression to estimate the approximate sensitivity for QPOs that could be detected at hard X-ray energies with the Energetic X-ray Imaging Survey Telescope (EXIST), now under Study as the proposed Black Hole Finder Probe (one of the 3 Einstein Probe missions) in the Beyond Einstein Program under the current NASA Strategic Plan. In making these estimates, and others for hard X-ray timing science possible with EXIST, we make use of the so-called "Reference Design" for the mission. We first introduce the mission concept and Reference Design and then discuss the principal areas of (hard) X-ray Timing that could be advanced with EXIST. These include: QPOs for bright galactic sources and their long-term trends, QPOs for AGN, stellar encounter events (both stellar disruption and star-disk interactions) with dormant AGN, and super-flare events from soft gamma-ray repeaters (SGRs) in galaxies out to the Virgo cluster. We then describe some of the modifications to the Reference Design which are being investigated in the current BHFP Study and which could further optimize EXIST as a next generation timing mission.

EXIST MISSION CONCEPT: REFERENCE DESIGN

Capsule history of EXIST concept

The EXIST mission has been under study, in several phases, over the past decade. Initially proposed as a MIDEX (Intermediate Explorer) mission (Grindlay et al 1995), it was later studied for a much more sensitive (and larger) configuration that could achieve all-sky imaging survey sensitivities at 10-100 keV comparable to what the only all-sky imaging soft X-ray survey, done with ROSAT in 1990-91 (Voges et al 1999), had achieved at 0.1-2.5 keV. The greatly enhanced survey sensitivity merited the endorsement of EXIST in the Decadal Survey Report[1] as one of the three high energy astrophysics missions recommended for the coming decade (the other two being Constellation-X and GLAST). The "larger" EXIST was first studied (Grindlay et al 2001) for possible implementation on the International Space Station (given its large mass and nominal zenith pointing requirement). However, complexities of planning or (even) accomodating for large attached payloads on ISS made it clear that a lower real cost implementation could be achieved as a free flyer, which could also be more sensitive (given the significantly lower particle backgrounds available in lower inclination, and altitude orbits). Thus EXIST was studied as a free flyer (low earth orbit; range of inclinations) at the Integrated Mission Design Center (IMDC) at the NASA Goddard Space Flight Center in 2001 with additional studies throughout 2002. The resulting design for a free flyer EXIST, the Reference Design (Grindlay et al 2003a), was the basis for our proposal that a sensitive hard X-ray survey be considered for the "Beyond Einstein Program" which was being formulated in 2002 by the advisory committee (SEUS) for the Structure and Evolution of the Universe (SEU) Theme of NASA's Office of Space Science. The Beyond Einstein Program, as finally announced in early 2003 and embodied in the current NASA Strategic Plan, includes the Black Hole Finder Probe (BHFP), one of the three Einstein Probe missions proposed to be conducted in addition to the two primary missions (LISA and Constellation-X) during the Beyond Einstein Program. EXIST is now beginning a Study (as one of two concepts for BHFP) for how the BHFP mission should be defined so that a subsequent competition for its actual development and implementation can be carried out.

Summary of the Reference Design

As a hard X-ray survey mission with primary emphasis on black hole surveys in both space and time, EXIST maximizes the two primary determinants for sensitivity: total detection area and total exposure time, each as appropriate for any given source. This means that the mission design must incorporate very wide field of view (FoV) telescopes and detectors, which in turn means that grazing incidence optics (e.g. with multilayers) are precluded. The basic concept, then, is a scanning array of coded aperture imaging telescopes, each with $60° \times 75°$ fully-coded FoV. The three together combine to form a fully-coded fan beam $180° \times 75°$, with partial coding for imaging (with some loss of sensitivity) out to even larger total solid angle of approximately 5sr (FWHM). The 180° axis of the combined beam is oriented perpendicular to the orbital ram direction so that the full sky is swept out each 95min orbit, and each source on the orbital equator is observed for at least 75/360 $\sim$21% of the total time at full sensitivity (except for those $\sim$5 orbits out of 15 each day where the satellite's passage near the South Atlantic Anomaly (SAA) would cut perhaps 20% of the exposure on those orbits for a nominal 28° inclination orbit. This survey time loss, amounting to perhaps 15%, could be reduced considerably by launching into a lower inclination orbit – at the cost of a larger launch vehicle or smaller payload mass.

The Reference Design telescope and spacecraft structure has the three large area telescopes, each with 2.7m^2 total area of imaging Cd-Zn-Te (CZT) detectors (each fabricated with a 16×16 array of 1.2mm pixels evaporated on the anode side of 2cm $\times$ 2cm $\times$ 0.5cm crystals, and read out by a single ASIC direct-bonded to each crystal), and still larger area (factor of $\sim$2) passive

[1] *Astronomy and Astrophysics in the New Millennium*, National Academy Press (2001)

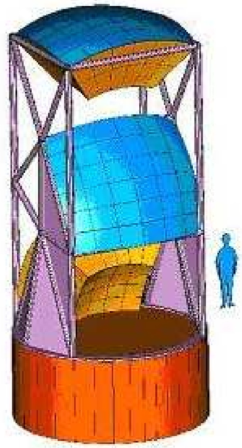

FIGURE 1. Schematic view of EXIST: 3 telescopes, each with curved coded aperture mask 1.5m above its curved detector plane, all mounted above the spacecraft bus.

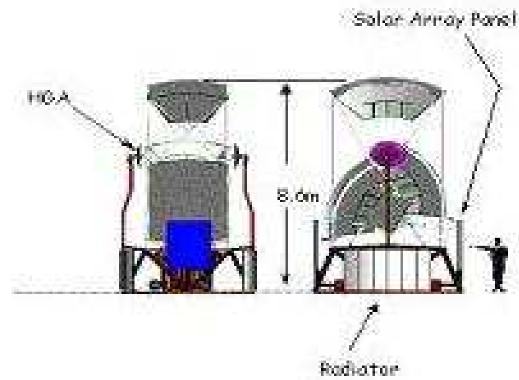

FIGURE 2. EXIST with antennas and solar panels folded for launch.

coded aperture masks at focal length 1.5m above each telescope, “stacked” on the spacecraft (S/C) structure below. This is the minimum mass and envelope configuration for the desired total detector area ($8m^2$) required to achieve the desired survey flux sensitivity of $\sim 5 \times 10^{-13}$ erg cm^{-2} s^{-1}(comparable to that at soft X-ray energies achieved with ROSAT) in any factor of 2 band of energy, from ~10-200 keV, over a 6-12month total exposure time for the fields of view (and thus exposure time per orbit) given. Due to increasing transparencies of the CZT detectors, shields, and coded masks, the sensitivity becomes ~10× lower over the band ~200-600 keV. A view of the EXIST Reference Design (hereafter EXIST-RD), with solar panels deployed and oriented relative to its orbital vector, is shown as Figure 1 in Grindlay et al (2003a). Here we show (Fig. 1) a more schematic view of just the 3-telescope stack on the S/C, with a scale figure along side for comparison.

We also show (Fig. 2) two side views of the telescope-S/C stack (the right view makes the 180° fan beam FoV of the three telescopes combined easier to envision), and finally (Fig. 3) the configuration in the Delta IV fairing for launch. A summary of some of the key parameters for the EXIST-RD is given in Table 1.

KEY TIMING SCIENCE WITH EXIST

EXIST as a component of an XRT mission?

With its heretofore unique capability of all-sky imaging each 95min (or nearly so), and high sensitivity above 10 keV, EXIST would enable a number of new (or com-

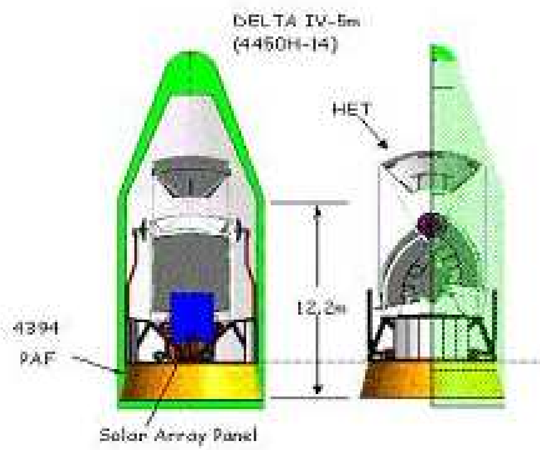

FIGURE 3. EXIST in Delta IV shroud.

plementary) temporal-spectral surveys not yet carried out. The characteristics of the EXIST-RD include at least two, if not three, of the widely-agreed upon requirements for a follow-on X-ray Timing (XRT) mission to succeed RXTE:

Large area: For the EXIST-RD, any given source is imaged by $\sim 1.5m^2$ at any given time, although only half this area is exposed to the source (the other half, occulted by the half-open coded mask, is measuring background simultaneously as well as all other sources in that instantaneous FoV). Thus for fast timing studies (e.g. kHz QPOs, etc.), EXIST-RD is only comparable in area, and thus source count rate, to RXTE at 10 keV. At ~20-30 keV, however, where QPOs are typically a factor of 2-3 larger in rms amplitude (e.g., Kaaret 2004),

TABLE 1. EXIST Reference Design key parameters

Parameter	Value or range
Energy range	10-600 keV ($\lesssim$ 10 – $\gtrsim$ 300 keV)
Sens. (5σ)	50μCrab* (10-200 keV) 500μCrab (200-600 keV)
FoV	180° × 75° (fully coded)
Survey coverage	full sky ea. orbit
Angular resol.	3-5'
Source loc.	10-50"
Energy resol.	1-4 keV
Temporal resol.	10μsec
Detectors	8m^2 imaging Cd-Zn-Te (1.2mm pixels on 2cm crytals)
Telescopes	3, each coded aperture (URAs, 2.5mm pixels)
Mission ops.	zen. scan; & pointings
Mass, power, TM	~8000kg, 1500W, 2Mbs

* 50μCrab= 5 × 10^{-13} erg cm^{-2} s^{-1}in band ΔE=E-0.5E

and the RXTE detector efficiency has fallen by a factor of (roughly 4) while EXIST-RD has maintained (nearly) unit QE, the increase in signal or effective area is closer to the desired factor of ~10. The effects of the higher detector background for EXIST-RD, with its very large FoV, are discussed below.

ASM capability: There is wide agreement that a proper timing mission must include an all sky monitor (ASM) capability as part of its mission plan. The most interesting phenomena, which may be the most rare, will otherwise surely be (usually) missed. Here the EXIST-RD is in its element, with an ASM sensitivity (~500μCrab per day) that is a factor of 10-100× more sensitive than the RXTE/ASM (2-12keV) and $\gtrsim$ 100× more sensitive than the ASM ability achieved by occultation imaging with BATSE, which resulted in the most sensitive hard X-ray (20-100 keV) detection, ~1°locations, and temporal variability studies achieved to date (cf. Harmon et al 2004, Shaw et al 2004).

Hard X-ray response: Given the energy dependence of QPOs just mentioned, as well as the general arguments in the Introduction above, it is clear that temporal variability is often (but not always; see below) best studied above ~10 keV. Here again the EXIST-RD gains on low energy optimized (e.g. focusing optics) approaches to very large areas. True, a grazing incidence large area optic has negligible background in comparison to a large area coded aperture HX imager, but as discussed below this is not an overwhelming advantage if the source(s) being observed (for kHz QPOs, say) are bright: if total background rates, b, are comparable to source count rate s (cf. Eq. 1), then the required integration time is "only" increased by a factor of ~1.4.

For bright galactic sources (e.g. the microquasar GRS1915+105), EXIST-RD can measure the energy dependence of fluctuation amplitudes over a wider range of energies extending well beyond the (typical) 15-20 keV cutoff of the PCA. The nominal background expected in the wide FoV (50°× 60° in each detector module) seen by each CZT detector element is dominated by the diffuse cosmic flux and is comparable to the Crab flux in the ~20-40 keV band and decreasing more steeply at higher energies. For an increase in effective area of the EXIST-RD vs. the PCA at 20-40 keV estimated as a factor of ~10, and correspondingly the increase in signal count rate, s, but now with the non-source background b ~s, Eq. (1) suggests EXIST-RD would detect QPOs at these energies in only ~4% of the time as with the PCA. It is already clear that GRS1915+105 has strong QPOs with rms amplitude increasing with energy up to (at least) 20-30 keV (Rodriquez et al 2002). EXIST-RD would push these studies to higher energies and allow their continuous monitoring (every orbit) for new constraints on the underlying physics of QPOs from stellar mass BHs.

It is also clear that EXIST-RD is competitive, as a timing mission, for temporal measurements of relatively faint sources on long timescales. This regime for QPOs is of course most relevant for AGN and is thus far only studied with the limited coverage of long campaigns of PCA pointings on a half dozen moderately bright AGN (Markowitz et al 2003). EXIST-RD could measure, continuously, AGN fluctuations on minimum timescales of $\delta\tau_{min}$ ~0.5-1day (depending on source orbital latitude) at the ~500μCrab level. For a 10^8 $M_\odot$ BH, this enables detection of QPOs down to the plausible upper frequency cutoffs expected for disks extending down to 3$R_{Schwarz}$, for which τ_{min} ~2.4d is expected. In fact the PCA monitoring campaigns of Markowitz et al (2003) have obtained interesting evidence for high frequency breaks in the power spectra of several of the 6 AGN monitored which are consistent with a scaling $\tau_{min,days}$ ~$M_{BH}/10^{6.5}$ $M_\odot$ which – taken literally – would suggest the (predominantly) 2-10 keV X-ray emission observed with the PCA is arising from regions at ~15$R_{Schwarz}$. Comparison with similar power spectra obtained on these objects (and many more) with EXIST would constrain the origin of variability and the evolution of τ_{min} with source luminosity and accretion rate variations. The continuous coverage that EXIST would provide gives relative immunity from the inevitable aliasing noise in scheduled pointed observations, and would allow the break frequencies to be measured with greater confidence.

Hard X-ray timing objectives for EXIST

We next summarize what are perhaps the most compelling science goals for temporal surveys with EXIST. Each hard X-ray timing objective is described in only broad outline form; the details are being studied as part of the BHFP Mission Concept Study, and results will be reported elsewhere. These temporal surveys are listed in decreasing order of cosmic distance scale without implied corresponding order of interest or priority.

GRBs at the limit

This key objective of EXIST, which potentially has the best chance of locating and studying PopIII BHs giving rise to the very first gamma-ray bursts (GRBs) at z $\sim$15, is of course not really in the category of a hard X-ray temporal survey of BHs (which may otherwise denote surveys or studies of persistent, or quasi-persistent, sources). The science goals for GRBs on EXIST are partly summarized by Grindlay et al (2003b). The GRB survey, and its neutron star cousin – a survey for the most luminous superflares from SGRs in external galaxies (see below) – have similar key attributes: both are possible since the EXIST survey and mission concept are designed to maximize sensitivity, FoV, and temporal coverage to enable detections of faint, rare events. The next objective is perhaps the highest priority example.

Stellar disruption near supermassive BHs

Stellar encounters with supermassive BHs (SMBHs), taken here to be with masses $\gtrsim 10^6 M_\odot$ and so including even that in SgrA*, in the nuclei of galaxies are inevitable and indeed probably of fundamental importance to the buildup of SMBHs. A concise review of many of the developments in this rich subject is provided by Alexander (2003). For stars in the nuclei of galaxies with SMBHs with masses $\lesssim 10^8 M_\odot$, the tidal radius R_t $\sim r(M/m)^{1/3}$ at which stars of mass m and r are disrupted by the SMBH of mass M, lies outside the event horizon. Stellar debris from a star passing close enough to be disrupted on the first or subsequent periastron passages will be accreted by the SMBH and produce an energetic flare. Several such events were very likely detected in the ROSAT all sky survey as soft (kT $\sim$0.1keV), luminous ($L_x \sim 10^{42-44}$erg s^{-1}) events as reviewed by Komossa (2002). Recent followup observations with HST (Gezari et al 2003) of particularly promising events in the galaxies RXJ1242.6-1119 and RXJ1624.9+7554, and with Chandra and XMM-Newton (Komossa et al 2004) of the RXJ1242.6 galaxy, have confirmed they are not in presently active Seyferts, thus further supporting the stellar disruption scenario. Finally, Wang and Merritt (2004) have incorporated the most recent M_{BH} - σ relation for BH masses from central velocity dispersions and calculated the rate of such events as $\sim 10^{-5}$ yr^{-1} Mpc^{-3} for non-dwarf galaxies (with the possibility of even higher rates in dwarf galaxies if they contain intermediate mass BHs), and Alexander and Hopman (2003) have shown that disruption events (as opposed to slow inspiral events) are the dominant conributors to increasing the mass of the SMBH.

Cannizzo, Lee and Goodman (1990) have modelled these stellar disruption events, finding they produce accretion luminosities at approximately Eddington values and with emission likely dominated by EUV and soft X-ray emission from the disk at effective temperatures $\sim 10^5$K. Their predicted accretion rate and thus luminosity remains roughly constant for $\sim$1yr, followed by a powerlaw decay, L $\sim \tau^{-1.2}$. Not calculated by Cannizzo et al (or anyone else, to our knowledge), but quite likely by analogy with other extreme transient accretion events (which these surely would be), is the possibility that in addition to the dominant soft thermal emission there is an underlying hard power law component. Stellar mass BHs in the Galaxy are usually first detected as "soft" X-ray transients but are always accompanied by luminous hard power law emission (or Comptonized blackbody) which dominates the flux from the luminous thermal component at energies above $\sim$10-20 keV (e.g., Tanaka and Lewin 1995). The luminosity in this hard component, broad band, is usually at least 10% of the peak outburst luminosity. *Thus, if even just 1% of the near-Eddington soft L_x from tidal disruption of a star by a SMBH appears in such a hard tail, these events will be readily detectable with EXIST.*

We estimate the detection rate as follows: using the Wang and Merritt (2004) disruption rate of $\sim 10^{-5}$ yr^{-1} Mpc^{-3} and a conservative (10σ) detection flux limit of F_x (20-40 keV) $\sim 1 \times 10^{-12}$ erg cm^{-2} s^{-1}, and "typical" (e.g. L_*) galaxy with central BH of mass $10^7 M_\odot$ and space density $\sim$0.02 Mpc^{-3}, and an assumed hard X-ray luminosity that is L_x ($\gtrsim$ 10keV) $\sim 0.01 L_x$ (soft), with L_x (soft) $\sim L_{edd} \sim 10^{45}$ erg s^{-1}, EXIST should detect these events out to $\sim$100Mpc at a rate of $\sim$30 yr^{-1}! An even more conservative assumption that the peak outburst luminosity, L_x (soft), is instead only $0.1 L_{Edd}$ brings this down to $\sim$1 yr^{-1}.

The recent Chandra and XMM observations of the RXJ1242.6 galaxy by Komossa et al (2004) show that the soft emission has declined even more rapidly, by a factor of $\sim$200 over the intervening decade since the ROSAT observation. Most interesting of all is that the XMM spectrum shows the emission to be a power law (with photon index 2.5$\pm$0.2) detected out to at least

10 keV and with luminosity in the ROSAT band of L_x (0.1-2.4keV) $\sim 5 \times 10^{41}$ erg s^{-1}. This provides at least indirect evidence that the disruption event itself does indeed include a hard component, as required if they are to be detectable with EXIST. In this case, also, it may be that the decay of the outburst is less than the observed (Komossa et al 2004) factor of ∼200 since that is derived by comparing the thermal (outburst peak?) to non-thermal (decade later) components. If the non-thermal component were ∼10% of the thermal (instead of the 1% value assumed above), then it would have decayed by a factor of ∼20, or very close to the factor of $\sim 14 = 9^{1.2}$ predicted from the Cannizzo et al (1990) models for the power law decay over the 9 year interval between the ROSAT and XMM spectra.

Obviously many more such events must be observed. As noted in Komossa et al (2004), planned soft X-ray all sky monitor experiments (e.g. Maxi or Lobster) might do this but only for those galaxies with their central SMBH not obscured. EXIST would allow an unbiased survey of all such events, provided they do indeed produce a hard X-ray component. For encounters of sub-giants (rather than main sequence stars, as assumed above), the disruption is partial and the He WD core will eventually plunge into the SMBH after spiralling in. For these events, EXIST will have provided a trigger for LISA to then record the gravitational wave signature.

AGN and QSO variability and QPOs

We have already discussed the applicability of EXIST to the fundamental problem of measuring the variability spectra of AGN. EXIST would measure minimum variability timescales, which could be $\tau_{min} \sim 0.25$d for emission from $3R_{Scwarz}$ from a $10^7 M_\odot$ SMBH. Given the corresponding flux limit (5σ) of 1mCrab = 1×10^{-11} erg cm^{-2} s^{-1}for a 0.25d or 4 orbit integration on any source, this would allow all AGN containing $10^7 M_\odot$ SMBHs and accreting at 1% of Eddington (thus with L_x ($\gtrsim$ 10 keV) $\sim 10^{43}$ erg s^{-1}to be measured. These would be detected out to distances d ∼100 Mpc. Assuming such Seyferts constitute about 1% of the galaxy distribution, there should be some 80 Seyferts in this lowest mass ($10^7 M_\odot$) AGN sample for which power spectra could be measured. The numbers increase for more massive SMBHs if they are accreting at the same 1% of Eddington rate, despite the fall off in their host galaxy numbers (with increased mass to accomodate the more massive SMBH) since the available detection volume increases faster. QSOs with L_x ($\gtrsim$ 10 keV) $\sim 10^{45}$ erg s^{-1}and SMBH masses $\sim 10^9 M_\odot$ (again assuming 1% Eddington) could be detected on their presumed minimum timescale $\tau_{min} \sim 25$d out to z ∼0.8, or approximately where obscured AGN seem to peak in local number density. Thus a large sample of AGN and QSO light curves and power density spectra should be achieved from which to test models for QPOs and, more fundamentally, to constrain spin of the SMBHs if their mass is inferred independently (e.g. from reverberation mapping) by in effect measuring their innermost stable orbit radii as the radius appropriate to τ_{min}.

Stellar mass BH variability and QPOs

Again, we have partly discussed the stellar mass BH case, where RXTE has done so much. The high background due to the large FoV of EXIST-RD makes it competitive only above ∼20 keV and then only for bright ($\gtrsim$ 100mCrab) sources. However there is physics to be learned by signficantly extending the energy range of variability and QPO studies. Determining τ_{min} over a significantly broader energy band can constrain lags and Comptonization models. Most unique, however, would be the first comprehensive survey of the evolution of QPOs with $\dot{m}$ and spectra. That is, how do QPOs change their "spots" when input parameters (e.g. $\dot{m}$) or output parameters (e.g. spectral shape and thus models) change? The migration of QPO peaks and power spectra slopes and breaks with input/output parameters will require the continuous coverage EXIST would provide; sporadic pointings will not track the full behaviour. As with AGN, this could lead to qualitatively new constraints on BH spin or, at the very least, the underlying physics of QPOs.

A key area for stellar BH timing is of course the detection and study of new (as well as recurring and known) transients. The imaging ASM nature of EXIST is required for discovery and locations of faint transients (e.g. ∼10mCrab) in crowded fields (e.g. the central Bulge). The hard X-ray response is similarly critical for these heavily absorbed regions. The recent hard X-ray images of the galactic center region from INTEGRAL (e.g. Revnivtsev et al 2004) indicate a population of absorbed sources for which timing (and spectral) studies could elucidate their BH (vs. NS) nature.

The imaging of EXIST has two further advantages for timing on relatively faint (for fast timing: ∼10-100mCrab) sources in that fluctuations (power spectra, etc.) can and would be measured simultaneously for background events as well as all other actual sources in the FoV. Coded aperture imaging does not scramble temporal signals or signatures, regardless of how many sources (and background) are in the FoV.

Neutron stars and SGRs

Neutron star timing with EXIST will be optimal for pulsars (both accretion and rotation powered), with their hard spectra which extend out to $\gtrsim$ 20 keV in both cases. The full sky each orbit imaging-ASM nature of EXIST, at high sensitivity per orbit, will facilitate the discovery of faint pulsar transients (e.g. Be-HMXB systems). As with galactic BHs, the study of QPOs from bright LMXBs containing NS primaries is competitive with the PCA or any planned 2-10 keV followon XRT mission by providing the diagnostic coverage above 20 keV. Indeed, one of the many attractive "finder telescope" features of EXIST (not just for timing) is that it could provide the hard X-ray coverage continuously and at no impact and thus allow the XRT to be a large area low mass/low resolution X-ray optic with sensitivity only below 7 keV (for Fe line coverage).

A unique advantage of EXIST for timing studies of NSs is to extend our study of soft gamma-ray repeaters (SGRs), or magnetars, to galaxies well beyond our Local Group. Whereas the normal SGR bursts from the 4 systems known (3 in the Galaxy, 1 in the LMC) have $\sim$1sec duration and $\sim$30 keV exponential spectra with peak luminosities of typically $\sim 10^{41}$ erg s^{-1}, two of the sources have shown "superbursts" or giant flares with shorter duration ($\lesssim$ 0.1sec) initial spikes which reach peak luminosities $\sim 10^3$ times the normal bursts. Such superbursts, with L_x ($\gtrsim$ 10keV) $\sim 10^{44}$ erg s^{-1}, could be seen with EXIST (for which the limiting flux is $\sim 2 \times 10^{-9}$ erg cm^{-2} s^{-1}for a 0.1sec detection) out to the $\sim$16Mpc or the distance of the Virgo cluster. Thus a sample of nearly 10^3 galaxies could be continuously sampled for super-burst SGRs. Given that the two known super-SGR bursts (in the Milky Way and LMC) have each occurred once in about 20y, a plausible detection rate of super-SGR events could be as high as $\sim$50 yr^{-1}. This would allow the first survey for magnetars in external galaxies and enable tests for their formation sites (e.g. presumably in spiral disks), activity cycles and superburst production.

POSSIBLE MODIFICATIONS TO THE REFERENCE DESIGN

We mention a few of the ongoing studies for the BHFP that could further enhance EXIST as a hard X-ray timing mission, with even more capabilities appropriate to a next-generation X-ray timing mission.

Energy range: First, the energy band covered and in particular (for XRT objectives) the lower energy limit E_{min} is being studied. If E_{min} could be reduced from 10 keV to 5 keV, the sensitivity to QPOs could be increased since signal count rates would double (for typical spectra approximated as power laws with photon index 2). However backgrounds would also increase, and by even larger factors if the FoV is maintained at the EXIST-RD value. Thus E_{min} and FoV are correlated study options. Decreasing E_{min} also requires consideration of the detector and readout technologies since noise considerations as well as mass overburden make $\sim$5keV thresholds difficult to achieve with the baseline CZT array technology. One option being considered is to have a portion of the CZT array apportioned to a lower energy E_{min} detector system with total area perhaps 1/4 of the total available (to maintain comparable signal to noise with the primary CZT system).

The upper energy limit, E_{max}, is also a primary design driver (which also affects E_{min} of course) and is being studied for optimum science and impact on mission cost and complexity. E_{max} = 600 keV is the value for EXIST-RD, but values as low as 300 keV (cf. Table 1) are being studied.

Field of view: Decreasing the FoV would of course greatly reduce backgrounds and, for the same detector area, increase timing sensitivities. It impacts the primary survey objectives, and all sky monitor capability, by reducing exposure time per source correspondingly. The present large FoV is chosen to be that value where diffuse sky flux is comparable to (but larger than) detector backgrounds due to shield leakage and other processes. Other options are possible, such as smaller FoV at lower energies (e.g. $\lesssim$ 30 keV) where the effects of bright point sources are largest. One option being studied is to reduce the FoV in the cross-scan direction (to maintain exposure time in the scan direction) at low energies with an interposed thin slat collimator. Other options are also being investigated.

Pointing vs. scanning: The EXIST-RD has a simple mission model: the telescope stack is zenith pointing and scans the full sky around the orbit. The pointing is very forgiving ($\sim$0.5°) but the aspect requirements are tight (5$''$). The S/C control systems to do this can then also allow inertial pointing on a fixed target (or many targets, given the very large FoV). This would increase the exposure time per source or field that is achieved each orbit by a factor of (typically) 2, given the large FoV and thus exposure time per orbit in scanning mode. Nevertheless it is of interest for certain timing objectives and could easily be accomodated.

Re-configurable telescope array: The EXIST-RD has its three telescopes fixed, in the tower-stack configuration (Figs. 1 and 2) that allows each to view $\sim$1/3 of the 180° fan beam unocculted by the others. Alternatively, if the three telescopes were mounted on the same plane (on a long bench; which would require a higher launcher shroud (Fig. 3) to accomodate and was therefore not chosen as the baseline), and they were each allowed to move in elevation (only), the three could be co-aligned to increase the available area by a factor of 3 for fixed pointing or slow scan pointing on a given source or group of sources. This would have the largest impact on timing objectives (particularly if combined with the smaller low energy FoV option) and allow (for the current design) $\sim$4.5m^2 to be pointed on a given field. This option would entail additional mission complexity and (probably) mass, for the larger envelope. However tradeoffs can be considered as part of the current Study for the BHFP.

CONCLUSIONS

EXIST in its current Reference Design configuration already incorporates several key attributes of an optimized hard X-ray timing mission. The X-ray Timing mission or observatory concepts discussed as the needed successor for RXTE are based in large part on the requirements to resolve individual pulse trains in QPOs from galactic BH and NS accretors. EXIST would not do this in its Reference Design but could, in principle, with some of the options being studied now by the EXIST team for the BHFP Study. However EXIST, in its primary survey mode configuration is already a superb ASM and would have sensitivity to conduct pathfinder science on the (much) longer timescales needed for variability studies of galactic BHs and AGN. Break frequencies in the power spectra of AGN, and QPOs in AGN, could be measured by EXIST over a range of interesting BH masses.

Of perhaps the most interest for novel timing studies of SMBHs is the suitability of EXIST to provide an unbiased (by low energy extinction) survey for stellar disruption near SMBHs that almost certainly lurk in bulges of all galaxies, without requiring these be known or detected as persistent sources by virtue of being AGN. Dormant AGN, or long since extinct AGN, are available for this study in sufficient numbers that surprisingly large rates of detection are predicted. More detailed study is needed to assess whether a disruption event will indeed produce an accompanying hard X-ray spectral component (as with galactic BH transients), but the recent XMM detection (Komossa et al 2004) of such a component in the faded “afterglow” of a 1992 likely stellar disruption discovered with ROSAT makes the hard X-ray component even more likely – particularly if this XMM spectrum is later observed to decay with the $\sim \tau^{-1.1}$ possibly expected.

ACKNOWLEDGMENTS

I thank the EXIST Science Working Group for discussions and Roger Blandford and Martin Elvis for discussions of AGN variability and stellar disruption. I thank Bill Craig, Neil Gehrels, Fiona Harrison, Jaesub Hong, Ron Ticker and GSFC engineers for their work on developing the EXIST Reference Design. This work was partly supported by NASA grant NAG5 5-5396.

REFERENCES

Alexander, T. 2003, to appear in Coevolution of Black Holes and Galaxies, L.C. Ho, ed. (Pasadena: Carnegie Observatories)

Alexander, T. and Hopman, C. 2003, ApJ, 590, L29

Gezari, S., Halpern, J., Komossa, S., and Leighly, K. 2003, ApJ, 592, 42

Grindlay, J.E. et al 1995, Proc. SPIE, 2518, pp. 202-210.

Grindlay, J.E. et al 2001, AIP Conf. Proc., 587, pp. 899-908

Grindlay, J.E. et al 2003a, Proc. SPIE, 4851, pp. 331-344

Grindlay, J.E. et al 2003b, AIP Conf. Proc., 662, pp. 477-480

Grimm, H.J., Gilfanov, M. & Sunyaev, R. 2002, A&A, 391, 923

Harmon, C.A. et al 2004, ApJ, in press

Kaaret, P. 2004, these proceedings

Komossa, S. 2002, Rev. Mod. Astron., 15, 27

Komossa, S., Halpern, J., Schartel, N., Hasinger, G., Santos-Lleo, M. and Predehl, P. 2004, ApJ, 603, L17

Markowitz, A. et al 2003, ApJ, 593, 96

McClinock, J. and Remillard, R. 2003, to appear in Compact Stellar X-ray Sources, eds. W.H.G. Lewin and M. van der Klis (astro-ph/0306213)

Revnivtsev, M. et al 2004, A&A, in press (astro-ph//0402416)

Rodriquez, J. et al 2002, A&A, 386, 271

Shaw, S.E. et al 2004, A&A, submitted (astro-ph/0402587)

Tanaka, Y. and Lewin, W.H.G. 1995, in X-ray Binaries, W.H.G. Lewin, J. van Paradijs and E.P.J. van den Heuvel, eds. (Cambridge Press), pp. 126-174

van der Klis, M. 1998, in Many Faces of Neutron Stars, R. Buccheri, J. van Paradijs, and M. A. Alpar, eds. (Kluwer), p. 337

Voges, W. et al 1999, A&A, 349, 389

Wang, J. and Merritt, D. 2004, ApJ, 600, 149