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Memorie della

Wide Field X-ray Telescope (WFXT)

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Abstract. The Wide Field X-ray Telescope is the latest in a series of mission concepts to carry out a large area X-ray survey with sensitivity orders of magnitude fainter than the ROSAT All Sky Survey, and with angular resolution of 5 arcsec over the entire survey area. The science that can be addressed by such a mission and the technical readiness are discussed. The conclusion is that WFXT addresses many of the science issues raised in the 2010 New World New Horizons decadal survey and is well matched to the next generation of optical, IR and radio surveys currently being planned. The technologies needed for WFXT have all been demonstrated, and only the mirrors have a technical readiness level (TRL) that is less than 6. Three independent cost estimates for this mission, covering life-cycle costs, launch services and a GO program are below $1B (FY12), and suggest that the mission concept is mature and ready for implementation.

Key words. X-ray Astronomy

1. Introduction

A wide field X-ray telescope mission has been studied in great detail over several decades, starting in the early 1990's, and in its present form now in 2012. The Wide Field X-ray Telescope (WFXT) mission concept (Murray, et al. 2008, 2010) is the result of the work of many individuals, too many to be listed in their entirety here (see the WFXT Web sites[1]). However, it is only proper to acknowledge that

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[1] http://www.wfxt.eu and http://wfxt.pha.jhu.edu

this has been a team effort, and many individuals have been instrumental in keeping this effort moving forward.

The last all sky X-ray survey was carried out with ROSAT nearly 20 years ago (*e.g.*, Voges, et al. 1999). This survey, generated a catalog of about 100,000 sources, and reached a typical sensitivity of about 10^{-12} to 10^{-13} $\mathrm{erg\,s^{-1}cm^{-2}}$, 4 to 5 orders of magnitude brighter than the faintest sources now detected with the Chandra deep fields. The eROSITA instrument, part of the Russian-German Spectrum X-Gamma mission (Predehl, et al. 2011), is scheduled for launch in late 2013 or early 2014. It will conduct a four year all sky survey that will reach about two orders of magnitude fainter than ROSAT, ~4×10^{-15} $\mathrm{erg\,s^{-1}cm^{-2}}$ (0.5-2 keV) at the orbit poles, and ~1×10^{-14} $\mathrm{erg\,s^{-1}cm^{-2}}$ over most of the rest of the sky, and also extend to higher energy than ROSAT. However, the angular resolution of eROSITA, $25-30$ arcsec (HEW), and the relatively small effective area, about 1,500 cm^2 at 1 keV, will present some limitations with regard to source identification and studies of clusters at redshifts beyond ~1. Faint source locations will be poor, making optical identifications difficult, and the extraction of cluster parameters (*e.g.*, temperature) will be subject to systematic uncertainties due to background AGN, cool cores, and possible non-hydro static conditions in the cores. Even in pointed mode, the eROSITA on-axis HEW is ~15 arcsec.

WFXT is designed to be the follow up mission to eROSITA, optimized to have a wide field of view (~1 deg diameter) with an angular resolution of ~5 arcsec (HEW) over the entire field, and a collecting area of ~7,000 cm^2 at 1 keV and ~2,000 cm^2 at 4 keV. WFXT will carry out a series of surveys, wide and shallow, medium and moderate, and narrow and deep as listed in Table 1. The comparison of the WFXT surveys with others is illustrated in Fig. 1, and as noted, WFXT will approach the CDFS faint limit over about 100 square degrees, ~800 times the solid angle of these Chandra deep surveys. With this performance, WFXT will enable a broad range of science studies such as detecting the first supermassive black holes, measuring galaxy/AGN coevolution, studying feedback mechanisms, observing the cosmic cycle of baryons, understanding structure formation, and carrying out precision cosmology. All of these studies require X-ray observations with high sensitivity, good angular resolution and a wide survey area. These properties can all be achieved with a specific X-ray optic and mission design, and require only modest technical developments in order to be ready for flight.

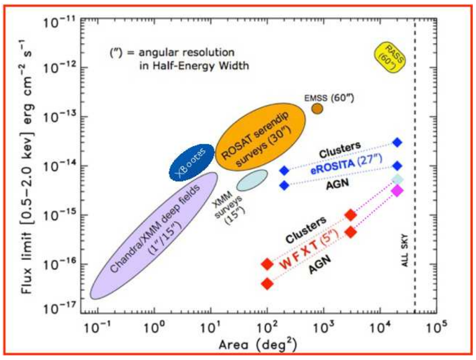


Fig. 1. Comparison of X-ray Surveys. The plot shows the limiting flux versus the survey area. In parentheses the typical angular resolution (HEW) is shown. The eROSITA and WFXT plots separate the AGN (or point-like source) performance from the Cluster (or extended source) performance.

2. Science with WFXT

As a survey mission, WFXT science will be focused on the discovery space opened through having large numbers of sources with well measured properties. For example, we estimate that WFXT will detect about 10 million AGN in the three surveys. About 500,000 will have more than 400 detected counts, which is sufficient for spectral fitting (N_H and γ), the detection of an Fe-K line, and a determination of redshift from the centroid line energy (Fig. 2). WFXT will be able to detect up to 10,000 obscured AGN ($\mathrm{N}_H > 10^{23}$), and 300 Compton thick AGN beyond redshift of 1. WFXT will detect QSOs at high redshift. A pessimistic model predicts at least 2,000 QSOs beyond

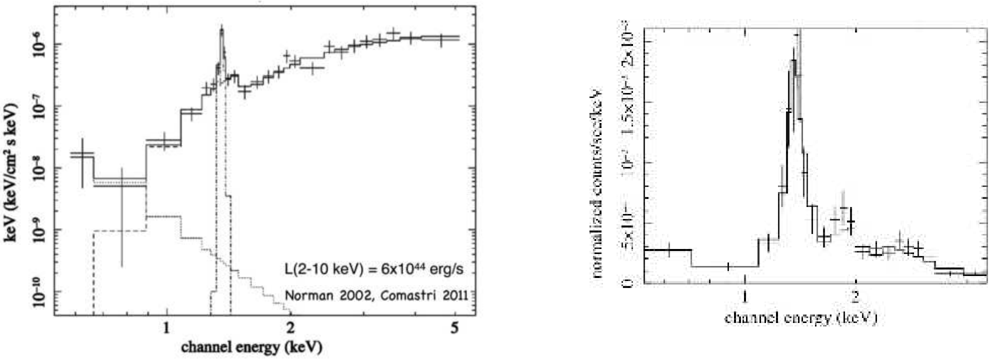
Table 1. Description of WFXT surveys

Quantity	Survey		
	Narrow/Deep	Moderate/Medium	Wide/Shallow
Ω (deg^2)	100	3,000	15,000
Exposure (ksec)	400	13-20	2-3
Total Time (yr)	1.5	1.5	2.0
S_{min} (0.5-2 keV) erg s^{-1}cm^{-2} point-like at 3σ	4.0×10^{-17}	4.5×10^{-16}	4.0×10^{-15}
Total AGN Detected	$\sim 4.7 \times 10^5$	$\sim 4.4 \times 10^6$	$\sim 7 \times 10^6$
S_{min} (0.5-2 keV) erg s^{-1}cm^{-2} extended at 5σ	1×10^{-16}	1×10^{-15}	5×10^{-15}
Total Clusters/Groups	$\sim 5 \times 10^4$	$\sim 3 \times 10^5$	$\sim 2 \times 10^5$

redshift of 6, of which a large fraction (perhaps 1/2) may be heavily obscured. With these very large data sets it is possible to carry out statistical studies with high precision. For example the AGN correlation function (clustering) can be used to study the halo mass associated with the host galaxies. With such a large total sample, the correlation functions can be calculated for different classes of AGN (e.g., luminosity) and at various cosmic times (i.e., redshift bands). AGN clustering on smaller scales informs their merger history and interactions over time, an area where large numbers are needed to reduce statistical errors sufficiently to distinguish amongst theoretical models.

The WFXT surveys for AGN are well matched to the next generation of wide field optical and infrared surveys currently underway or planned for the near term. This is illustrated in Fig. 3, where we have plotted the spectral energy distributions (SED) for radio loud (QSO2) and radio quiet (QSO1) type sources and the corresponding limiting sensitivity for various surveys. The high angular resolution of WFXT across its entire 1 degree field of view allows X-ray source locations to be known with 1-2 arcsec accuracy. Good positions allow cross matching to surveys in other bands yielding single candidates for most of the X-ray sources, and greatly improving the chances for proper identification. X-ray surveys are efficient in identifying AGN and at high redshifts are particularly good for detecting obscured AGN, which are also detectable with Euclid and LSST, but are 'lost' in the high density of sources in these surveys. Using WFXT we will detect close to 2,000 AGN at redshift greater than 6 with sufficient counts to measure their redshifts directly and classify them as obscured or unobscured. Combined with their LSST and/or Euclid (or WFIRST) counterparts, these identifications will make follow up spectroscopic observations efficient (observing the right object) and help in interpreting the spectra since the redshifts are already known.

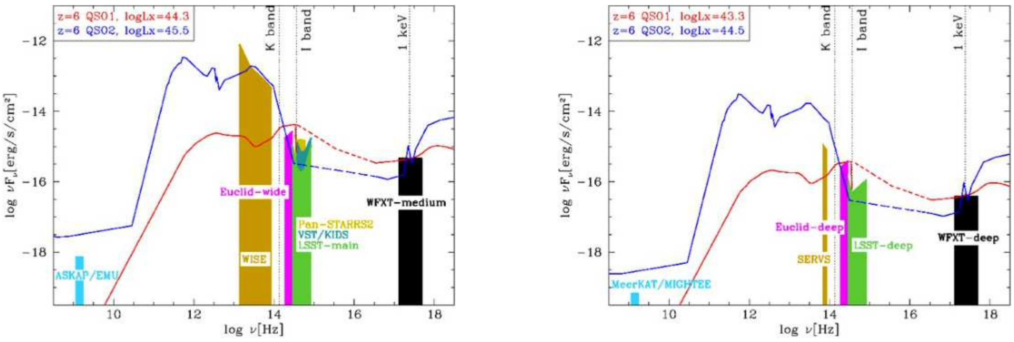
The 5 arcsec HEW of WFXT, essentially flat across the field of view, enables identifying extended X-ray sources such as clusters and groups of galaxies with high efficiency. We estimate that about 200,000 clusters or groups will be detected over the three survey areas, more than half will be at redshifts greater than 0.5, and ~50,000 will be at redshifts greater than 1. More than 5,000 clusters (with ~2000 at redshift of 1 or more) will be detected with enough photons to fit a spectrum and accurately determine the average cluster temperature and the redshift from the energy of the iron emission line commonly found in clusters. The high resolution of WFXT is needed to remove fore/background AGN from the data as well as excising the inner core region in obtaining reliable cluster temperatures. Even a small contamination at high energies due to unrecognized AGN emission can result in a significant over estimate of a cluster's temperature. Similarly, cluster structure and merging are easily observable with 5 arcsec image resolution. Fig. 4 shows simulated images of



(a) High redshift Compton thick AGN

(b) Detail of Iron-K line

Fig. 2. Simulated spectrum of a Compton thick, high redshift, AGN based on the parameters of CDFS202, a z=3.7 AGN with $N_H = 10^{24}$, $\Gamma = 1.82$, and $F_X = 3 \times 10^{-15}$ erg s^{-1}cm^{-2}. The equivalent width of the iron line is 1 keV and the centroid can be estimated to ±2%. For a 400 ksec (Deep) observation there are 530 total counts. The dashed lines show the various model components used for the spectral fitting, the solid line is their sum, and the crosses are the simulated data points.



(a)

(b)

Fig. 3. Synergy of WFXT surveys with other wide area surveys: (a) Redshift 6 QSOs detected in the WFXT Moderate/Medium survey, (b) Redshift 6 QSOs detected in the WFXT Narrow/Deep survey

the "Bullet Cluster" at various redshifts using WFXT.

The WFXT cluster survey will generate a "golden" sample of more than 500 clusters at redshift 0.5 or higher, for which accurate temperature profiles can be made as well as profiles of metallicity. These can be used for a variety of studies including precision cosmology (growth of structure) and the growth and evolution of clusters through merging and accretion. For the brightest clusters detailed studies of the intercluster medium (ICM) will help to trace the evolution of entropy injection and metal enrichment.

The WFXT narrow/deep survey will be carried out as a series of ∼ 40 ksec observations spaced about 6 months apart over 5 years to build up the final 400 ksec depth. This procedure enables a range of time domain studies on the variability of AGN to be made involving very large numbers of sources. Sampling about 10 different regions provides statistical studies of cosmic variance in source distribution and their properties.

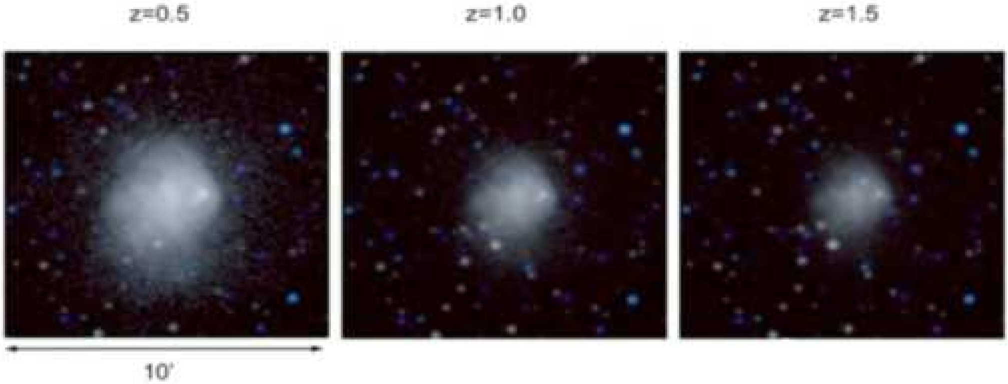


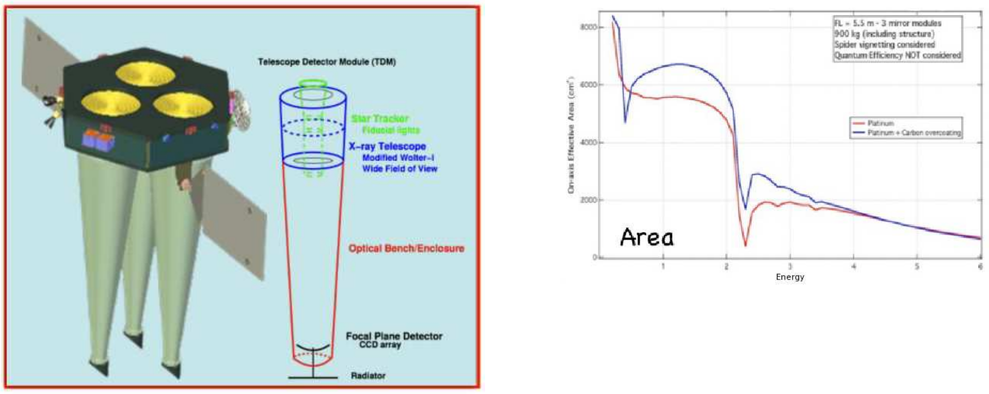
Fig. 4. Simulated images of the "Bullet Cluster" at redshifts of 0.5, 1.0 and 1.5 as seen with WFXT in a deep 400 ksec exposure (Santos, Tozzi & Rosati 2011). These images are 10 arminutes on a side. The point-like objects give the scale of the point spread function (5 arc second HEW) and show that even at high redshifts only relatively small areas of the cluster would be removed to avoid AGN contamination for spectroscopic analysis. Similarly, the cluster cores can be excised and still leave most of the cluster emission for analysis.

All of the WFXT survey data will be made public in a series of data releases, similar to that done with the Sloan Digital Sky Survey, and on a time scale of 6-12 month intervals as data are processed and catalogs are created. We will provide these data to a suitable archive site in standard X-ray data formats and with the necessary additions to the suite of data analysis tools already in use by the community.

We include a substantial Guest Observer program for this mission, with about 40% of the total time over the first five years of operation for peer reviewed observations. WFXT will operate in a pointed mode to allow studies of individual targeted sources with high throughput and 5 arcsec image quality. Our mission cost model includes funding for implementing this program and includes a grant program for observers using WFXT data. After the WFXT core surveys are completed (about 5 years), the entire mission will become a GO facility supporting the entire astronomy community.

3. The WFXT mission concept

WFXT consists of three identical wide field X-ray telescopes that are approximately co-aligned, each with a small array (2 x 2) of CCD detectors at the focus in an inverted pyramid geometry to best match the curved focal plane typical of X-ray telescopes. As shown in Fig. 5, each of the telescope modules includes a bore-sighted star camera with a fiducial light system to accurately map the X-ray detector positions to the sky. Since WFXT operates in a photon counting mode, each individual event can be projected onto the sky correcting for any small changes in the telescope pointing direction relative to some nominal direction. Three identical telescope/detector assemblies are used to achieve the desired collecting area, particularly at high energy. The co-alignment requirement for the telescopes is only at the arcmin level due to the uniformity of the point spread function over the large field of view. The star tracker and fiducial light system is integrated into the X-ray telescope assembly using a pair of back-to-back Danish micro-Advanced Stellar Compass star trackers. The forward looking tracker provides the pointing knowledge needed to reconstruct X-ray images. The backward facing tracker monitors the locations of an array of fiducial lights that are mounted at the X-ray focal plane (and thus the X-ray detector), and therefore motion of the focal plane with respect to the X-ray telescope. This technique has been used successfully on



(a) (b)

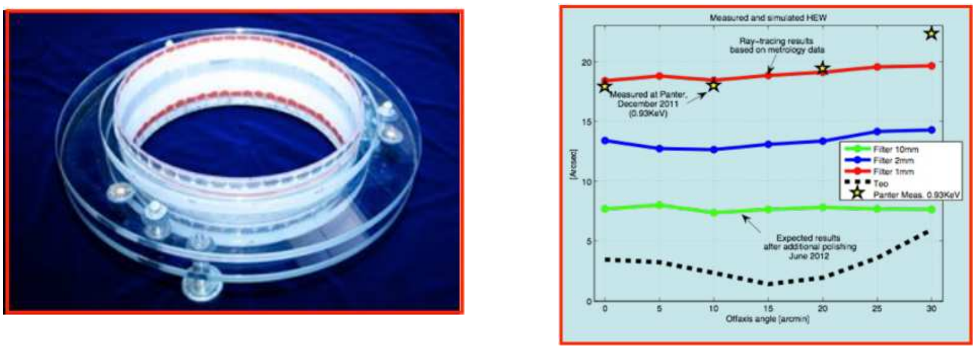
Fig. 5. WFXT Design Concept: (a) Three co-aligned X-ray telescope/instrument modules, (b) Overall mirror effective area for the three telescopes

several X-ray missions (e.g., Einstein, ROSAT, XMM-Newton and Chandra).

The enabling technology to develop WFXT is essentially in hand. The design of wide field X-ray optics is well understood (Burrows, Burg & Giacconi 1992). An early SiC prototype mirror shell using epoxy replication from a polished mandrel was fabricated in 1999 (Ghigo, et al. 1999), and tested at both the Panter Facility of MPE and the XRCF at NASA's MSFC. This mirror achieved 10 arcsec (HEW) resolution over a full 1 degree field of view. Since then there have been several modifications to the fabrication process ultimately evolving from replication to grinding and polishing as new technologies have become available. A more recent prototype glass mirror shell is shown in Fig. 6. It was fabricated at Brera and tested at Panter (Citterio, et al. 2012). While the performance was only about 17 arcsec HEW, constant across the 1 degree field of view (Fig. 6), this first test of a new manufacturing process has been a critical test-bed for process development and improvement. Unfortunately this shell was damaged during a handling accident at Brera while it was being reworked. A new shell is in fabrication, and the lessons learned from the first should lead to faster processing, and ultimately to better performance. In parallel with the efforts at Brera, there is a technology program at MSFC studying thin nickel replica mirror shells and possible nickel coated beryllium shells as alternatives to glass.While more work is needed to demonstrate the desired performance for WFXT, there do not appear to be any fundamental limits to prevent achieving them provided there is adequate funding.

The X-ray CCDs needed for WFXT are well within the current state-of-the-art. MIT Lincoln Laboratory CCDs similar to those flown on both Chandra, and more recently, Suzaku meet the performance specifications for WFXT, except for their size (Bautz, Foster & Murray 2010). These CCDs are 1k x 1k devices and for WFXT a 2k x 2k array (still with 25 micron pixels) is needed to cover the large field of view with sufficient oversampling of the PSF. CCDs of this size have been fabricated routinely at Lincoln Labs and no new technologies are needed. However, new mask sets will need to be made and an engineering run fabricated to verify and qualify the larger devices. Alternatively, the rapid developments in CMOS imaging arrays for X-rays may allow their use in WFXT. The CMOS devices offer several advantages over CCDs such as better radiation hardness, lower operating power, and simpler support circuitry (e.g., Janesick, et al. 2010, and references therein).

All of the spacecraft requirements for WFXT have been either demonstrated or ex-



(a) (b)

Fig. 6. Prototype glass shell at Brera: (a) Prototype shell is mounted with stiffening rings for support during fabrication and testing., (b) Measurements from Panter Facility compared with metrology predictions.

ceeded by the Chandra and XMM-Newton missions. Pointing accuracy and control requirements are almost an order of magnitude less stringent than for Chandra. Careful design will be needed to assure the thermal stability requirements for the X-ray telescopes is met, but this can be greatly alleviated if the observatory is placed in a high Earth orbit as is the case for both Chandra and XMM-Newton. A preliminary study for the WFXT spacecraft showed that the observatory fits within the standard Atlas V fairing (Fig. **??**) and there is considerable mass and power margin as shown in Fig. **??**.

There have been three independent studies for the WFXT mission. The first was part of a proposal to Astro-2010 as part of the Astronomy and Astrophysics Decadal Survey process. The second was a study carried out by the X-ray Community Science Team, which included as its third notional mission, N-WFI (Wife Field Imager), that was largely based on the WFXT concept, but evaluated through the GSFC Mission Design Laboratory process. Finally, a third study was conducted at the MSFC Advanced Concepts Office, again based on the WFXT concept submitted to the Decadal Survey, but with expanded trades such as the orbit and mission lifetime. All of these studies arrived at similar total mission lifetime costs (slightly under $1B FY12) that includes not only development, but launch services and mission operations and a guest investigator program.

4. Conclusion

A wide field X-ray telescope mission has been proposed in one form or another for about 20 years. The current version, WFXT, has been studied for several years and provides an excellent match to the next generation of wide field surveys, both ground and space based. The enabling technologies have all been demonstrated, although more work in establishing the best manufacturing process for the wide field telescopes is needed. The overall mission design has been examined in three independent studies with very similar outcomes with regard to cost and schedule.

The science merit of an X-ray survey with high angular resolution (5 arcsec HEW), and large effective area, leading to very large catalogs or point-like (AGN) and extended (Clusters) sources has been discussed in many venues, most recently "The Wide Field X-ray Telescope, A Vast Legacy for Astrophysics and Cosmology" (Rosati, et al. 2011). The US 2010 decadal survey for astronomy and astrophysics, New Worlds New Horizons (NWNH 2010), recognized the importance of multiwavelength surveys, and the NASA X-ray Community Science Team report[2] notes that a

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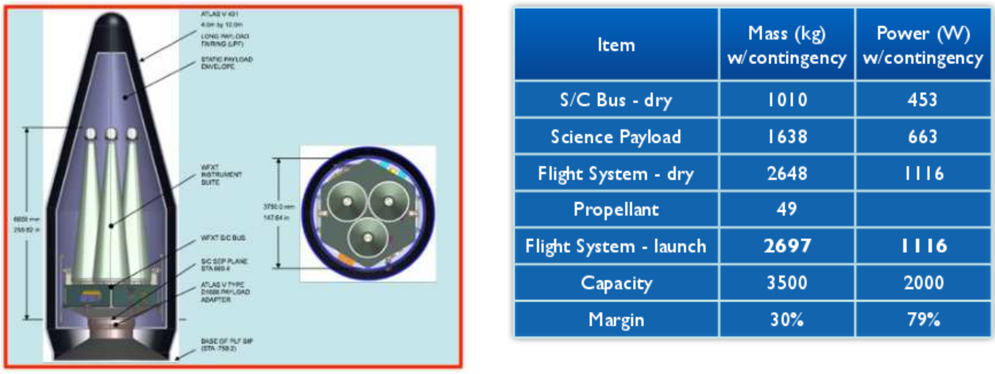
[2] http://pcos.gsfc.nasa.gov/physpag



Item	Mass (kg) w/contingency	Power (W) w/contingency
S/C Bus - dry	1010	453
Science Payload	1638	663
Flight System - dry	2648	1116
Propellant	49	
Flight System - launch	**2697**	**1116**
Capacity	3500	2000
Margin	30%	79%

(a) (b)

Fig. 7. Notional WFXT concept study results: (a) WFXT inside Atlas V fairing, (b) WFXT mass and power budget estimates

wide field X-ray survey would address many of the science areas of NWNH that were specifically associated with X-ray measurements: What happens close to a black hole; growth and evolution of supermassive black holes; formation/evolution of clusters of galaxies and cosmology; and growth of large scale structure and the cosmic web. WFXT is a strategic science mission that will address many science objectives, for example: precision cosmology with clusters of galaxies; the physics of clusters of galaxies and the ICM; AGN growth, evolution and variability; the X-ray source population and properties of nearby normal galaxies. The core survey mission is planned to take about 5 years, during which there is also a concurrent guest observer program using about 40% of the available time. With the conclusion of the core surveys, the mission will become entirely GO driven, providing the astronomical community with access to a powerful X-ray observing facility. Operating in a Chandra-like highly elliptical, high Earth orbit, we can expect WFXT to have a long productive lifetime.

WFXT is technically ready to start and the preliminary design has large mass and power margins beyond the normally required 30% contingency. With the exception of the X-ray telescopes, which are at TRL 4, all other elements of WFXT are at TRL 6 or greater. Three independent cost estimates put WFXT in the sub-$1B (moderate) mission class including full life-cycle costs, launch costs, and a vibrant GO program.

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