The WAXS/WFXT MISSION

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Abstract

I present the science goals and give a brief summary of the Wide Angle X-ray survey with a Wide Field X-ray Telescope (WAXS/WFXT) mission proposal (Phase A) which will be submitted to the Italian Space Agency (ASI) following the call for proposal under the Small Satellite program. The text points out the uniqueness of the mission for the study of the evolution of clusters of galaxies and of the Large-Scale Structure at large redshifts and for the study of the Milky Way. I present, furthermore, the successful result of the metrology of the first wide field X-ray optics ever made.
1 Introduction

The idea of planning a survey aimed especially to the detection of clusters of galaxies came long ago following a suggestion by Riccardo Giacconi. At that time Riccardo, in collaboration with Chris Burrows and Richard Burg, was studying the possibility to design an X-Ray optics having a good resolution over a large field of view. This would optimize the time it would take to carry out a survey over a large solid angle. Once it had been demonstrated that the design was under control, we started to develop the technology to realize the prototype. This took some years and finally we succeeded. In these proceedings we will briefly outline the science goals and the general plan of the mission. Further details are given in the study of phase A that will be submitted to the Italian Space Agency in November 1998 and on specialized papers published especially by the technology X-Ray group headed by Oberto Citterio. At this meeting, however, we present for the first time the excellent results of the X-Ray metrology carried out on the 60-cm shell prototype, the most difficult and critical shell to be made. This is a breakthrough in the field comparable, in all aspects, to the result of the first Ritchey Chretien optics for ground based optical telescopes.

WAXS/WFXT is an excellent and unique survey mission with a strong Italian heritage. The ROSAT all sky survey is too shallow and the ROSAT deep surveys have too small a solid angle. AXAF will not be dedicated to large surveys and does not have the field of view to discover a sizeable number of objects. The disadvantage of the XMM serendipitous survey is that it will be spread over thousands of pointing in different directions, this is not suitable for measuring the Large Scale Structure. ABRIXAS, while being a complement to the proposed mission, will not have the adequate sensitivity and angular resolution for our science goals. (The rather limited resolution makes identification directly from the survey difficult and places a heavy demand on the telescope time needed for the optical follow-up). WAXS will complement the above missions by accomplishing original science and by creating a unique catalogue for follow-up observations.
Both large ground-based telescopes and space missions will make use of the WAXS source
catalogues for many years to come.

A comparison with the most important missions that are ready to fly is significant and
illuminating. This is shown in Fig. I.1, where we plot the area of the survey versus the limiting
sensitivity. The baseline of the mission includes an ultra-deep survey that almost reaches the
sensitivity of the AXAF deep survey, but over an area more than twenty times larger. The
confusion limit is, assuming we reach the optimum resolution as we expect, well below the
XMM confusion limit.

The work I am describing below is the result of the creativity and dedication of many
scientists, Italian and Foreign Institutions. To them goes the merit of the content and however
I am responsible for the form and the eventual inaccuracies of the text. The main contributors
will be acknowledged at the end of the contribution. I would like from the starting, however,
to express my gratitude to the team of the Brera Observatory whom, especially in this last
year, worked with extreme dedication to this project. The collaboration of Steeve Murray, Alan
Wells and Cosimo Chiarelli went beyond duty and could be explained only as a result of true
friendship and very deep interest in the project.

I will discuss part of the science goals in section II and I will illustrate the expected perfor-
mance of the instrument in section III. In section IV I will give a brief summary of the mission
planning. At the time of writing it is not yet known whether the mission will be approved. I
hope to convince the reader in that this mission is a unique opportunity to extend our
understanding of the Structure and Origins of the Cosmos.

2 Science goals

The unique features of the X-ray sky make it possible to select groups, clusters, and AGN from
X-ray images and to use these classes of objects to map the large scale structure of the Universe
at high redshift ($z > 1$). Compared to optical images, X-ray images are relatively sparse and
dominated by the distant, extragalactic sources.

A convincing example is given in Fig. II.1, where we reproduce a patch of sky from the second
generation Digitised Sky Survey plates, $30' \times 30'$ in size and corresponding to a ROSAT-PSPC
pointed observation (targeted at QSO1404+286). In this optical image there are 2176 objects
brighter than the plate limit $m_B \sim 23$, about half of which are galaxies. Contours from the
ROSAT X-ray image are overlaid on the optical picture. The X-ray data reveals two clusters,
‘A’ at $z = 0.36$ and ‘C’ at $z = 0.55$, and a group of galaxies, ‘B’, at $z = 0.12$. About 20 of the
26 detected sources are distant AGNs.

The design of the WAXS/WFXT mission is indeed based on the scientific goal
of detecting clusters of galaxies at high redshifts. Optical surveys are extremely limited,
even if complementary, in detecting clusters. This is because for distant clusters optical surveys
generally detect only the very tip of the luminosity function, that is the brightest galaxies. The galaxy background, however, increases tremendously with distance so that the cluster galaxies are confused in the background and clusters are difficult to detect even at \( z \sim 0.8 \) - 1.0. In the X-ray, clusters of galaxies appear as extended objects and an angular resolution of 15 arcseconds over a large field of view is sufficient to separate clusters from point sources at large redshift. In any cosmology the minimum angular diameter of a cluster is about 30 arcseconds, occurring at about \( z \sim 1.25 \).

Finally it is important to detect clusters at various redshifts and over a very large area. This is necessary to obtain a statistically significant number of bright clusters, which are very rare, and to study their evolution and clustering properties. Thus, the primary mission requirement is to conduct two surveys. A 900 square degree shallow survey to detect the brightest clusters over a large solid angle of contiguous area, and a 100 square degree deep survey to probe more deeply into the cluster X-ray luminosity function to study evolution.

In Fig. II.2 we compare explicitly the effective sky coverages as a function of the X-ray flux limit for the three most representative present surveys and the WAXS Shallow and Deep surveys. Note how in both case, the WAXS surveys represent a step of an order of magnitude with respect to existing surveys. Note also that these flux limits are conservative, as they have been based on the request of collecting 50-100 counts from a cluster at the limit. In practice, we can very probably push our detection limit down by a factor of two in both surveys.

Based on the experience gained with the RDCS survey (Rosati et al. 1998), and the similar survey by Vikhlinin et al. (1998b), we define as “typical” a cluster with an extension of \( \sim 1 \) arcmin radius. This represents the median angular size (roughly twice the 50% power radius) of the clusters in the RDCS sample after de-convolving the ROSAT-PSPC PSF.

In Fig. II.3, we plot the limiting flux as a function of the exposure time, for a signal-to-noise ratio (S/N)=5 and for a source with an extension of 1 arcmin radius. For a cluster described by a Raymond-Smith thermal model, with \( K_T=5 \) keV and 0.3 solar abundance (filtered by a galactic absorbing column density equal to \( 3 \times 10^{20} \) cm\(^{-2}\)), the conversion factor is \( 1 \text{cts s}^{-1} = 1.2 \times 10^{-11} \) erg s\(^{-1}\) cm\(^{-2}\) (between 0.5-2.0 keV), which is accurate within 10% for clusters with temperatures between 2 and 10 keV. We considered an instrumental and cosmic background of \( 10^{-3} \) cts s\(^{-1}\) arcmin\(^{-2}\), which is about two times the diffuse X-ray background in the WFXT energy band and should provide a conservative upper limit. In Fig. II.3 we also show the S/N sensitivity curve in the case of a total background two times lower and the S/N = 10 and S/N = 50 sensitivity curves.

If we take an exposure time of \( > 10^5 \) s for the deep area (100 sq.deg.) and \( > 10^4 \) s for the shallow area (900 sq.deg.), from Fig. II.3 we can estimate a limiting flux (0.5 - 2.0 keV) for our “typical cluster” of \( \sim 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\) and \( \sim 5 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) for the deep and shallow area, respectively. These exposure times ensure that, at the faintest fluxes here
considered, at least 50 to 100 net counts will be accumulated from a typical cluster. Based on the RDCS survey, the corresponding signal-to-noise is enough to discriminate between a point-like and an extended source, thus allowing a robust list of cluster candidates to be defined by using X-ray data alone. This clearly implies that we shall also be able to detect clusters at fainter fluxes.

**A very important cosmological probe is provided by the evolution of clusters.**

The main reason for this is that clusters correspond to the high peaks of the primordial density field (e.g. Kaiser 1984), so that their abundance (i.e. the number of clusters within a given mass range), is highly sensitive to the details of the underlying mass density field. The typical mass of rich clusters (\( \sim 10^{15} \ M_\odot \)), is close to the average mass within a sphere of 16 Mpc radius in an unperturbed Universe, so that the local \((z < 0.2)\) abundance of clusters is expected to place a constraint on the r.m.s. fluctuations on the same scale, what is called \(\sigma_8\) (being normally expressed using \(H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}\)).

This is basically a measure of the normalization of the power spectrum, and the Press-Schechter (1974) theory, easily shows that the cluster abundance is highly sensitive to \(\sigma_8\) for a given value of the density parameter \(\Omega_0\) (see Borgani et al. 1998 for details). At the same time, once the local abundance of clusters (i.e. \(\sigma_8\)) is fixed, its evolution back in time will mainly depend on \(\Omega_0\). **Therefore, if we are able to trace the cluster abundance to high redshifts in a reliable way, we shall directly constrain the value of the cosmological density parameter.**

The problem is that we cannot observe directly the abundance of clusters within a defined mass range, as required by the theory, and have to resort to some kind of observable which can be connected as closely as possible to mass. Cluster masses can be measured through galaxy velocity dispersions, but this is very time-consuming and for the moment limited to local samples. Weak-lensing maps are also a promising technique, but again it is difficult to collect systematic observations for large samples. **In this respect, X-ray selected clusters offer the best opportunity, as they have measurable properties that can be linked to mass in a more direct way than optically-selected systems.** The best parameter would be X-ray temperature, which offers the most direct route to mass. Although the situation is improving (Henry 1997), X-ray temperatures are however still not available in a systematic way for large samples of clusters. An easier way is to use X-ray luminosities. Considerable efforts have therefore concentrated in the last few years on trying to detect signs of evolution with redshift in the **X-ray luminosity function** (XLF), to be then related to the mass function through the Luminosity-Temperature relation.

After the pioneering results from EMSS survey (Gioia et al. 1990), in the last couple of years there has been a major burst of works tackling this problem, all based on serendipitous searches of clusters over deep ROSAT pointed observations from the public archive (Rosati et al. 1998,
Vikhlinin et al. 1998b; see Rosati 1998 for a review). These studies, that were able to reach fluxes as faint as $2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, have shown how there is practically no evolution between $z = 0$ and $z = 0.8$ in the abundance of clusters of moderate luminosity ($L < L_* \sim 4 \times 10^{44}$ erg s$^{-1}$), while there is a hint for evolution in the abundance of very luminous systems. Vikhlinin et al. (private comm.), in fact find no luminous cluster in their distant redshift bin ($z > 0.5$), while 9 would be predicted on the basis of the local XLF. Fig. II.4 shows a comparison of the XLF in local and distant samples. Note how in this figure, prior to the latest Vikhlinin et al. result, the only evidence for evolution is the $\sim 2 \sigma$ deficiency in the EMSS XLF at high $z$ (starred symbols).

These serendipitous surveys are in general limited by the difficult compromise between depth (i.e. flux limit) and sky coverage, as we further show in Fig. II.5 for the RDCS: the data cover different ranges of luminosity at different redshifts and direct comparison is difficult. The only way to improve significantly on these measures of evolution is to enlarge the covered area at similar fluxes, and to go fainter on comparable areas. This is exactly what the Shallow and Deep WAXS surveys will do. Determining the existence of luminous clusters at $z > 1$, providing a robust measure of the XLF at different redshifts and establishing firmly the evolution of clusters of galaxies is a primary goal of the mission.

The full power of the survey concerning the statistics of large-scale structure will be exploited through the measurements of redshifts for WAXS groups and clusters. While “local” ($z < 0.2$) surveys of rich clusters, as the REFLEX survey, give a coarse view of the large-scale distribution of matter, the WAXS survey will be unique in producing a large sample of groups at $z < 0.1$, that will give a more detailed description of local large-scale structure. Even more important, this will be based on objects selected through a clean tracer of mass as X-ray emission is. The Shallow survey will detect nearly 500 groups within $z < 0.1$.

A direct example of the power of using X-ray selected clusters for studying the large-scale structure of the Universe has been recently provided by the ROSAT-ESO Flux Limited X-ray cluster survey (REFLEX, Guzzo et al. 1995, Boehringer et al. 1998). While the above mentioned ROSAT deep surveys are all based on searches of serendipitous cluster sources on archival pointed observations (see Rosati 1998 for a review), the REFLEX survey is a wide-angle project based on the ROSAT All-Sky Survey (RASS), which is about two orders of magnitude brighter in flux limit ($\sim 1 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ for clusters). The preliminary results from REFLEX represent a very good example of the effectiveness of X-ray selected clusters as tracers of large-scale structure. In Fig. II.6 we plot the estimate of the power spectrum from a preliminary version of the REFLEX data. This is computed using only 230 clusters with $z < 0.1$, while the whole survey is going to contain 475 clusters with $z < 0.3$ and flux brighter than $3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, over an area of 4.24 sr.

The WAXS surveys will be able to both increase the detail of this measure in the
local \((z < 0.2)\) Universe, by using X-ray selected groups and poor clusters, and, most importantly, to perform the same measure as a function of redshift, out to \(z \sim 1\), using X-ray luminous rich clusters. This will represent an unprecedented probe of the evolution of the large-scale structure of the Universe, constraining the cosmological parameters.

Very little is known about the physics of the intercluster medium in superclusters, primarily because these systems are rare (only 3 superclusters are known with masses comparable to Shapley 8) and because they are very hard to map due to their large angular size. Possible detection of a significant number of rich superclusters in the WAXS surveys provides a unique opportunity for their detailed study. A 30 Mpc diameter supercluster will subtend approximately 1 deg at \(z = 0.5\). With the large contiguous survey area of the WAXS surveys, available only to this specific mission, we can readily map the X-ray background and provide strong limits on any diffuse emission within the core of such a supercluster. A very conservative estimate of the minimum detectable surface brightness enhancement is 30% of the X-ray background brightness around 1 keV. For a 0.5-1 keV plasma filling a 10 Mpc supercluster, this corresponds to the central density of \(1 - 2 \times 10^{-5}\) cm\(^{-3}\). The diffuse intercluster gas in these superstructures can be detected in the WAXS surveys out to substantial redshifts. According to our visibility simulations, the diffuse gas in a Shapley-like supercluster would be detected out to \(z \sim 0.5\) in the Deep survey and out to \(z \sim 0.2\) in the Shallow survey. While other X-ray missions (e.g., XMM) may detect comparable numbers of clusters and superclusters, they will be randomly spread over the sky and the primary science objective – studying large scale structure – is feasible only with the large contiguous surveys proposed here.

A sensitive X-ray survey like WAXS should also be able to map directly the warm/hot gas present between clusters, trapped inside the potential filaments and superstructures. In fact, at redshifts below 0.5 also the diffuse gas filling the deepest parts of the supercluster and filament potential wells is starting to be detected in the X-rays (see, e.g., Wang et al. 1997, Connolly et al. 1996). This allows to map directly the large scale distribution of the warm/hot baryons, the dominant baryonic component of the matter in the Universe (Cen & Ostriker 1998). The volume fraction of the warm/hot gas is only a few percent while the relative mass fraction is up to \(\sim 50\%\) at \(z > 0.5\) (see Fig. 2 in Cen & Ostriker 1998) indicating that the filamentary Cosmic Web is the repository of such abundant baryonic material. At the same redshifts the overall emission of the warm/hot gas with \(kT > 0.5\) keV is just a factor \(\sim 3\) below the overall emission of the hot gas in rich clusters (see Fig. 4 in Cen & Ostriker) indicating that such warm/hot gas is a major contributor to the soft \((kT > 1\) keV) diffuse X-ray background. Also, Colberg et al. (1998) showed that clusters accrete matter from a few preferred directions, defined by the filamentary structures, and that the accretion persists over cosmological long times. A spectacular example is shown in Fig. II.7.

The observational study of AGNs, along with the theoretical study of their
formation, is another avenue to better understanding the origin of structures.

AGNs dominate the deep X-ray images, comprising approximately 80% of all the sources (Hasinger et al. 1998; Schmidt et al. 1998) at high galactic latitude. Once the clusters (and the bright stars) have been identified, one can reasonably assume that most of the remaining sources are AGNs. In the present baseline for the two high latitude WAXS surveys (∼ 100 sq.deg. at $S_X > 4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ and ∼ 900 sq.deg. at $S_X > 3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ at 5σ) we expect to detect ∼ 30,000 – 40,000 AGNs, approximately equally divided in the two surveys. These numbers will increase by about 50% pushing the detection limit down to 4σ. While most of these AGNs will be the “classical” broad-line quasars, a not negligible fraction is expected to be constituted by absorbed AGNs, with $N_H > 10^{21}$ cm$^{-2}$ (Comastri et al. 1995).

At the 5σ limiting fluxes quoted above, we will detect ∼ 15 and ∼ 200 AGNs per square degree in the Shallow and Deep surveys, respectively. The surface density of AGNs in the Deep Survey is significantly higher than those which will be obtained in the forthcoming optical surveys on large areas. For example, the Sloan Digital Sky Survey (SDSS) will measure redshifts of ∼ 105 QSO in $10^4$ sq.deg. (Margon 1998), while the expected surface density of AGNs in the 2dF sample is 30-40 sq.deg. It should be noted that the optical surveys will select magnitude-limited samples of AGN with colors as a primary selection criterion. Since in the optical band AGNs are a small fraction of the total number of objects, the statistical uncertainties in the colors at faint magnitudes and the difficulty in separating the point-like objects from the much more numerous faint, extended galaxies makes very difficult the assessment of the level of completeness of faint optically selected samples. From this point of view, the X-ray selection is highly superior because a very large fraction (> 70%) of X-ray sources are known to be AGNs.

The comoving spatial density of AGNs detected in WAXS surveys will be ∼ $10^{-5}$ Mpc$^{-3}$, i.e. comparable to that of galaxy groups at low redshift. Thus, AGNs are promising tracers of the large scale structure, although they cannot be substituted to clusters for a quantitative measurement of the matter power spectrum. The physical cause of AGN activity is not well understood yet and therefore AGNs can be arbitrarily biased (or anti-biased) with respect to the total matter distribution. Nevertheless, AGNs should be suitable for qualitatively mapping the large scale structure. For this purpose, the high spatial density of X-ray selected QSOs and our square survey geometry is highly desirable.

The evolution with redshift of the clustering strength is much more controversial, with contradictory results obtained by different groups using samples of ∼ 1000 quasars spanning the entire redshift range (see, for example, Andreani & Cristiani 1992). These results will be soon improved by the analysis of the forthcoming 2dF quasar sample, which ultimately will contain about 30,000 quasars with $m_B < 21.0$ in 750 sq.deg. Even this sample, however, will not provide much information for $z > 2.5$, because of the relatively bright limiting magnitude and, therefore, the relatively small number of objects at such high redshifts.
Vice versa, WAXS will allow the detection of a large number of quasars at $z > 2.5$. A precise estimate of how many such quasars will be detected is highly uncertain because very little is known about the X-ray luminosity function (XLF) at these redshifts. While most of the AGNs will be in the range $0.5 < z < 2.5$, more than 2,000 quasars (most of them in the deep survey) are expected to be detected at $z > 2.5$. More pessimistic models, with a decreasing comoving density beyond $z = 2.5$, still predict about 1,000 such objects. These estimates are consistent with the available optical identifications in the deep ROSAT survey in the Lockman Hole (Schmidt et al. 1998). Note that in this survey, covering only $\sim 0.2$ sq.deg., it has been detected the highest redshift, X-ray selected quasar ($z = 4.45$; Schneider et al. 1998), with a flux higher than the limit of the WAXS Deep survey.

**WAXS is an excellent and unique mission for such a project.** The ROSAT all-sky survey is too shallow and the ROSAT deep surveys have too small solid angles. Serendipitous surveys with AXAF and XMM eventually will cover a large area at a limiting flux similar to that of the WAXS. The disadvantage of a serendipitous survey, however, is that it will be spread over of thousands pointings in different directions, which complicates the optical follow-up and makes the detailed study of the AGN spatial distribution impossible.

**Rapid and large amplitude variability is common among AGNs,** both for radio-quiet Seyfert galaxies and for radio-loud objects, and it is the main defining property of blazars. For the shallow survey, each field of view will be observed in a single passage for approximately $10^4$ seconds, while for the small area deep survey each field will be observed $\sim 10$ times, within a total period of a few months. In this area we will therefore have the possibility to detect variability on both short timescales (of the order of hours) and long timescales (from a few weeks to a few months). The latter timescales are particularly interesting, since they have not been well sampled yet, except for a few selected sources. Time variability studies on these scales will be impossible with other missions (with the exception of a small number of “famous” sources). The number of AGNs subject to this variability analysis is huge (essentially, the brightest 30% of all objects), allowing us to define for the first time the variability properties of all classes of AGNs.

**We will also include in the mission plan, a Galactic Plane survey to better understand the structure of the Milky Way and its X-ray properties.**

Given the strong dependence of coronal activity on rotation and age, any flux limited X-ray survey will preferentially detect active stars which are observable to larger distances than low-activity ones. This explains why flux limited surveys carried out with Einstein, EXOSAT and ROSAT have typically shown a large fraction of active stars, either young stars or RS CVn binaries (Favata et al. 1993, 1995; Tagliaferri et al. 1994; note that for RS CVn binaries the high rotation and high coronal activity is due to tidal interaction rather than young age). X-ray observations thus provide a unique way to investigate the distribution of active stars, and in particular of young stars, in the Galaxy up to distances of few kpc.
There are several factors that are expected to influence the distribution of X-ray active stars in the solar neighborhood, all of which are still poorly understood. A first dominant component is expected to arise from the structure of the galactic disk, with young stars strongly concentrated on the galactic plane and rapidly decreasing at higher galactic latitudes. To first approximation, this distribution should be only weakly dependent on galactic longitude, provided the sampled volume remains sufficiently close to the Sun (up to few hundred parsec, as in most X-ray surveys carried out so far). However, as soon as we increase the sensitivity, we will start exploring larger and larger volumes and the radial distribution of stars on the disk (e.g. the spiral arm structure) will become increasingly important. For sufficiently high sensitivity, a clear asymmetry between the directions of the galactic center and anticenter should become readily apparent. Even at limited sensitivity, the distribution of young active stars should be markedly different at different galactic latitudes, owing to the finite scale-height (∼ 100 pc) of their density perpendicular to the galactic plane.

A cross-correlation of the RASS survey (at a flux limit of ∼ 2 × 10^{-13} erg s^{-1} cm^{-2}) with the Tycho catalogue (which is complete down to $m_V = 10.5$) has recently shown an additional structure in the spatial distribution of X-ray active stars besides the general decrease with galactic latitude (Guillout et al. 1998a, b; see Fig. II.8). This density enhancement, which is particular prominent in the third and fourth quadrants of galactic longitudes (i.e. between $l = 180$ deg and $l = 360$ deg), is in very good agreement with the expected position of the so-called Gould Belt (GB). This is a large-scale ring structure of recent star formation which had previously been identified on the basis of the spatial distribution of OB associations and which appears to be inclined by about 20 deg to the galactic plane. Fig. II.9 shows a model prediction at a sensitivity a factor 4 higher and for stars down to $m_V = 15$ (simulation courtesy of P. Guillout); the galactic plane structure and the GB are now detectable much more clearly.

For a few selected regions at low galactic latitudes in Cygnus and in Taurus covering respectively 64.5 sq.deg and 70 sq. deg, a complete optical identification program of the RASS sources has been carried out (Motch et al. 1997), showing that ∼ 85% of the RASS sources at low galactic latitudes are indeed stars. A GPS at a sensitivity of ∼ 1 − 2 × 10^{-14} erg sec^{-1} cm^{-2} has been carried out (cf. Morley et al. 1996, Pye et al. 1997, Sciortino et al. 1998) using a number of individual PSPC pointings in the range of galactic longitudes from $l = 180$ deg to 270 deg and at very low galactic latitudes $|b| < 0.3$ deg. The sensitivity is much larger than that of the RASS but the total survey area is only 2.5 sq.deg and makes the results statistically uncertain and dependent on local fluctuations.

With the current scan rate of 0.3 arcsec/sec and a FOV of 1 deg × 1 deg, current estimates of the WFXT sensitivity indicates that a limiting sensitivity of ∼ 2 × 10^{-14} erg s^{-1} cm^{-2} (appropriate for moderately absorbed - $N_H < 10^{21}$ cm^{-2} - thermal sources with a temperature of ∼ 10^7 K) in the spectral band 0.35 - 8 keV can be reached for point sources with a single scan.
(i.e. for an exposure time of 10 ksec). With the goal to survey $\sim 500$ sq.deg. at this limiting sensitivity and assuming a 15% overlap between adjacent strips we estimate that the overall observing time will be of $7 \times 10^6$ s equivalent, for a 65% average observing efficiency, to $\sim 4$ months of elapsed time to be devoted by WFXT to the GPS.

Hence, at the same limiting sensitivity, WFXT will cover an area 200 times larger than the ROSAT GPS based on pointed observations. With respect to the areas studied in detail by Motch et al. (1997) in Cygnus and Taurus, the improvement in area coverage by WFXT will be only a factor 3.7, but the sensitivity will be an order of magnitude higher, making accessible a volume 100 times larger than with the RASS. In all these cases, the step forward with respect to previous observations allowed by the proposal WFXT GPS will be enormous.

An ultra-deep survey of a few square degrees has been included in the mission plan, for detecting the faintest possible sources before being limited by source confusion. This survey requires that we reach the goal of better than 15-arcsecond angular resolution for the optics. Should this not be the case, the ultra-deep survey will not be made, and we will instead extend the area of the shallow and deep surveys.

We have simulated a very deep WFXT image using the BeppoSAX simulator, assuming an Half Energy Width of 12 arcsec over the whole field of view (1 deg) and to this we have applied the Wavelet Transform algorithm already developed at OAB. At $10^6$ seconds integration time (see Fig. II.10) we are getting close to the confusion limit. However, we still see the sources quite well. In Fig. II.11 we show the comparison between the input sources and those detected by the algorithm. Although we did not spend too much time in refining the algorithm to the WAXS case, the agreement is excellent. We can recover all sources down to a flux limit of $< 6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$. Moreover, our simulations have also shown that we are accurately able to distinguish between point-like and extended objects for sources with only 50 counts.

### 3 The Instrument

The configuration of the satellite as shown on Fig. III.1 is the result of the trade-off and detailed configuration design and analysis.

The WFXT is the assembly of several structural and functional elements, in the following we describe the mirror module and illustrate the overall response. The Mirror Support Adapter (MSA) is the outermost element, its main function is to support WFXT connecting the telescope to the satellite structure. The next element, moving towards the core is the case: it connects the top of the MSA to the front spider. The front spider is the element supporting the mirror shells. In the front spider two circular rings, “C” shaped, are connected by 16 radial spokes. The spokes have a rectangular cross section; moving from the inner ring to the outer ring, their height decreases linearly while their width increases. Underneath the front spider are placed two flat masks (X-ray pre-collimator). They are connected to the case through a circular “C”
shaped ring - X-ray pre-collimator support. On the other side, the front spider supports 25 mirror shells (MSs). The connection between the mirror shells and the front spider is by means of glue. The 25 MSs are concentrically disposed, they are divided into two groups: the outermost ones, formed by the MSs from #1 to #9, while the innermost range from #10 to #25. The front spider supports also a cylindrical element: the fiducial light mechanical interface. The MSA top is connected to the rear spider. The rear spider is the assembly of two circular rings, having a rectangular cross section, connected by means of 16 spokes. The main function of these spokes is to support the thermal baffles and the electron diverter. The thermal baffles are three concentric cylindrical shells.

The final mirror module consist of the MSS, thermal pre- and post-collimators and an X-ray pre-collimator (see Fig. III.2).

In the Phase A study we considered in detail three models for the WFXT Mirror Module based on different technologies:

- Mirror Module with Nickel Mirror Shells (named Model A);
- Mirror Module with SiC Mirror Shells (named Model B);
- Mirror Module with Al2O3 Mirror Shells (named Model C).

All the models have the same interfaces with respect to the tube of the satellite and the fiducial light system. The design of each model has been done taking into account:

- The optical specifications;
- The interface requirements;
- The experience that Media Lario has accumulated as responsible for the mirror module design and manufacturing of other X-ray astronomy projects (JET-X, XMM).

For each Model we performed a Finite Element Model (FEM) and a thermo-structural analysis (with the impact on the optical performance of the Mirror Module).

A prototype SiC carrier has been manufactured by Morton International (USA) and C. Zeiss (D) has made the replica. This corresponds to the largest mirror shell of the WFXT telescope. This shell has been tested at the X-ray PANTER facility. Measurements were carried out with the PSPC and CCD detectors at 0.5 and 1.5 keV. The results of these tests are very encouraging; we have obtained values of the $HEW \leq 15''$ (Fig. III.3). The breakthrough is that we have fully demonstrated that by adopting the polynomial design it is possible to have almost constant HEW on a large field of view ($\pm 30'$). This is an outstanding result if compared with the performances of, e.g., the JET-X Wolter I design.

We point out, however, that the HEW values are higher than what we would expect from the design and manufacturing errors. We have identified an epoxy variation thickness at the front and back entrance of the mirror shell, which has caused a variation in the mirror profile and in turn the image blur. This problem can easily be solved and a new mirror shell is under manufacturing to confirm our analysis.
In particular, extra- and infra-focal position PSPC images show that the image degradation took place in a limited azimuth sector of the mirror shell. By extrapolating the performances of the azimuth portion of the mirror not degraded by the epoxy variation thickness we are able to derive an approximate value of the best HEW that can be obtained once solved this problem. The procedure involves the de-convolution of the PSPC resolution and provides a HEW of \( \leq 12 \) arcsec. This demonstrates that the mirror technology fabrication meets the requirement for the WFXT program.

The collecting area of the telescope at 1.5 keV is \( \sim 360 \text{ cm}^2 \) (\( \sim 310 \text{ cm}^2 \) after convoluting with filter and CCD response). The energy resolution, at 1.5 keV, is \( \Delta E/E \leq 10\% \). The CCD focal plane is based on the heritage of the technology developed for JET-X, XMM and AXAF using the best technology and detectors available today. The convolution of the mirror shells with the filter and detector shows that we have a rather good response in the range of interest (0.2 - 8 keV). The response curve of the instrument is plotted in Fig. III.4. The high angular resolution distinguishes extended clusters of galaxies from point-like sources at any redshift, and the good sensitivity reaches a large number of very faint and distant objects as required to achieve the science goals of the mission.

4 A simulated mission

A typical mission plan has been computed for the two possible orbital inclinations: 3.5 and 50 deg. The purpose here, is to show that the scientific goals can really be accomplished in the minimum mission baseline of approximately two years. The proposed mission plans are computed with the purpose to keep the amount of large satellite movements (e.g. switching among different targets) as low as possible. All factors reducing the observing efficiency (Earth and solar interference, radiation belt crossing, etc.) have been taken into account. For simplicity in the table we list only the simulation for the 3.5 degrees orbit. Note that in the last column, total, we give the percentual accumulation time achieved after each pointing to reach the full integration time at the specified target, 100%.

The data will be promptly released after completion of the observations and in any case within one year of the end of the mission. They will enter the public domain through the delivery of the calibrated data to the appropriate centers. The final calibration will be implemented and released at the end of the mission when all LMC data will be available. Copy of the archives will be set up in Italy, USA, UK and Germany and will be regulated by common rules. The clean, calibrated data will be kept available online on disks; at the end of the mission this service could be under the responsibility of the ASI-SDC. When justified a large set of data could be transferred to the requesting group by the most convenient means of data transfer (DAT tapes, CD-ROMs). The WFXT Science team, coordinated by the PI, will release at the end of the mission
the final and official catalog of the detected sources, along with information such as coordinates, fluxes, source extension, etc.

5 Acknowledgements

The Scientific Institutes involved in the hardware aspect during the Phase A study are: Brera Astronomical Observatory (OAB), Smithsonian Astrophysical Observatory (SAO), University of Leicester (UL), Max-Planck-Institute für Extraterristische Physik (MPE). The Industries participating are: ALENIA, MEDIA-LARIO, TELESPAZIO, OFFICINE GALILEO. P.I: G. Chincarini (OAB); co-PI: S. Murray (SAO); Co-I J. Trümper (MPE), A. Wells (UL), Telescope PI: O. Citterio (OAB); PM: G. Tagliaferri (OAB); PS: S. Sciortino (OAPA). Six panels headed by S. Sciortino coordinated all the work for the science proposal. The panels were chaired by: Colafrancesco (LSS), Chincarini (Clusters of galaxies), Zamorani (AGN), Forman (Galaxies) Pallavicini (Stars) and Watson (Compact Objects). Contribution to this work came from Antonuccio-Delogu, Arnaboldi, Bandiera, Bardelli, Boehringer, Bonometto, Borgani, Campana, Catalano, Cavaliere, Covino, Della Ceca, De Grandi, De Martino, Fiore, Garilli, Ghisellini, Giacconi, Giommi, Girardi, Giuricin, Governato, Guillout, Guzzo (who revised the final version of the science proposal), Iovino, Israel, Lazzati, Le Fevre, Longo, Maccacaro, Maccagni, Mardirossian, Matarrese, Micela, Molendi, Molinari, Moscardini, Murray, Norman, Perola, Osborne, Pye, Ramella, Randich, Robba, Rosati, Scaramella, Stella, Stewart, Tagliaferri, Tozzi, Trinchieri, Vikhlinin, Vittorio, Wolter. Members of the following Institution expressed direct interest in the mission: ASI (SDC), Bologna (OA), Catania (OA), Firenze (OA), Milano (IFCTR,UNI), Napoli (OA), Padova (UNI,OA), Palermo (OA,UNI), Perugia (INFN), Roma (OA-UNI), Trieste (OA), Marsiglia (CNRS,LAS), Baltimore (IHU), Cambridge (MIT), Princeton (UNI), Munich (ESO,MPE), Copenhagen (DSRI).

Indeed this paper is the result of cutting and pasting part of the Phase A proposal.

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Figure I.1: Comparison of the survey area versus the limiting sensitivity. The baseline of the mission almost reaches the sensitivity of the AXAF deep survey over an area more than twenty larger. The confusion limit is well below the XMM confusion limit.

Figure II.1: 30'x30' optical image from the DSS plates, with superimposed the X-ray contours from a pointed ROSAT observation. There are 26 X-ray sources in this area. 20 are distant AGNs. Sources 'A' and 'C' are two clusters of galaxies at \( z = 0.36 \) and \( z = 0.55 \) respectively, while 'B' is a poorer group at \( z = 0.12 \).

Figure II.2: The effective area covered on the sky by the three most representative X-ray deep cluster surveys, the EMSS (Henry et al. 1992), the RDCS (Rosati et al. 1998) and CfA (Vikhlinin et al. 1998a), compared to the areas of the WAXS Shallow and Deep surveys. Note that the flux limits for the WAXS surveys are rather conservative (adapted from Rosati 1998).

Figure II.3: The limiting flux reachable as a function of the integration time for a typical cluster, at a given S/N ratio.

Figure II.4: Comparison of the local \((z < 0.3)\) and distant \((0.3 < z < 0.8)\) cluster X-ray luminosity function. Filled circles and the dot-dashed line represent the local XLF as measured by De Grandi et al. (1998), filled triangles and stars are, respectively, the RDCS (Rosati et al. 1998) and EMSS (Henry et al. 1992) results in the \( 0.3 < z < 0.6 \) range; lozenges are the RDCS estimates for the \( 0.5 < z < 0.85 \) bin.

Figure II.5: The filled circles give the cluster X-ray luminosity function from the RDCS survey (Rosati et al. 1998), in three redshift bins at a median redshift (top to bottom) of 0.17, 0.31, 0.58. The three XLF have been displayed with a vertical shift \( \Delta \log(\phi) = 2 \) for clarity. The two panels refer to two different cosmological models: an Einstein-deSitter model, and a flat model with \( \Omega_0 = 0.3 \) and a cosmological constant. Note how the data from the more distant bin marginally overlap those at smaller redshifts (Borgani et al. 1998).

Figure II.6: A preliminary estimate of the power spectrum of cluster density fluctuations from the REFLEX survey, currently the best available sample of X-ray selected clusters from the ROSAT All-Sky Survey. Note how using clusters, the sampling of density fluctuations is optimal on large scales \((k < 0.2)\), i.e. specifically where more information is needed and where this becomes difficult when using galaxy redshift surveys. (Schuecker et al., in preparation; Boehringer et al. 1998).

Figure II.7: Output of a hydrodynamic/n-body simulation of the formation of a cluster of galaxies and the surrounding filamentary structures, within a 32 Mpc size cube (Bode et al. 1998). The pictures show different quantities projected from a slab of 8 Mpc deep at the center of the cube. Clockwise from top-left, they show the distribution of (a) the dark matter, (b) the gas, (c) the X-ray emission, and (d) the corresponding temperature field. Note how well the cluster and surrounding groups in the X-ray image trace the overall mass distribution.

Figure II.8: All sky distribution in galactic coordinate of the 8593 Tycho stars detected as
PSPC sources above the limiting flux of $\sim 2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The density enhancement at low galactic latitude is clearly visible as well as an evident enhancement that has been associated with a physical structure, the so-called Gould Belt. This has an ellipsoidal shape with a semi-major axis of about 500 pc and a semi-minor axis of about 340 pc, and with the Sun located inside it about 150 to 250 pc off center (from Guillout et al. 1998a).

**Figure II.9:** A simulation of the projected all-sky angular distribution (in galactic coordinates) of the X-ray emitting stars down to $m_V = 15$ and to $f_X = 5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ according to the model of the spatial distribution of young stars recently proposed by Guillout et al.(1998b). Note that both the galactic disk population and the Gould belt populations will be adequately sampled by the proposed low-latitude surveys (Simulation is courtesy of P. Guillout).

**Figure II.10:** Detection by the wavelet algorithm on a simulation of an ultra deep WAXS field. The size of the circles is related to the physical dimension of the detected sources.

**Figure II.11:** Comparison between the input log $N$ − log $S$ and that derived from the analysis.

**Figure III.1:** View of the WFXT parts.

**Figure III.2:** WFXT Mirror Module conceptual design.

**Figure III.3:** Image spot of the outermost WFXT mirror shell tested at the PANTER facility. The four images (from left to right and top to bottom) refer to off-axis positions of 0’, 10’, 20’ and 30’ off-axis angles. Images were taken at energy of 1.5 keV and with a CCD detector.

**Figure III.4:** Effective area (mirror + CCD + filter) for the WFXT telescope. Different curves refer to the different material used to coat the mirror surfaces.
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| From      | To          | Field | Partial $\times 10^6$ sec | Total % |
|-----------|-------------|-------|--------------------------|---------|
| Jan 1st   | Jan 14     | Cal   | 0.7                      | 100%    |
| Jan 15    | Feb 2nd    | HLS   | 1.0                      | 10%     |
| Feb 3rd   | Feb 17     | LMC   | 1.0                      | 25%     |
| Feb 18    | Apr 30     | GPS   | 3.4                      | 49%     |
| May 1st   | Aug 4      | HLS   | 4.9                      | 59%     |
| Aug 5     | Aug 19     | LMC   | 1.0                      | 50%     |
| Aug 20    | Oct 19     | GPS   | 3.0                      | 91%     |
| Oct 20    | Nov 7      | UDS   | 1.0                      | 50%     |
| Nov 8     | Jan 29     | HLS   | 4.1                      | 100%    |
| Jan 30    | Feb 13     | LMC   | 1.0                      | 75%     |
| Feb 14    | Feb 25     | GPS   | 0.6                      | 100%    |
| Feb 26    | Mar 21     | any   |                          |         |
| Mar 22    | Apr 9      | UDS   | 1.0                      | 100%    |
| Apr 10    | Apr 26     | any   |                          |         |
| Apr 27    | Aug 7      | HLD   | 5.2                      | 52%     |
| Aug 8     | Aug 23     | LMC   | 1.0                      | 100%    |
| Aug 24    | Oct 29     | any   |                          |         |
| Oct 30    | Feb 5      | HLD   | 4.9                      | 100%    |