EXECUTIVE SUMMARY

We propose the Advanced X-ray Imaging Satellite (AXIS) as the premier high angular resolution X-ray mission for the mid-2020s. AXIS will follow in the footsteps of the spectacularly successful Chandra X-ray Observatory with similar or higher angular resolution and ~10x Chandra count rates, allowing considerably more science per unit time and the accomplishment of science objectives not possible with Chandra (Table 1). This mission will vastly enhance the study of the unique science of the high-energy universe, which requires X-ray observations, and complement the next generation of astronomical observatories (such as JWST, WFIRST, LSST, SKA, ALMA, TMT, ELT, CTA). Finally, as seen by the strong synergy between Chandra and XMM-Newton, having a high throughput spectroscopic mission (Athena) flying at the same time as a high resolution X-ray imager vastly increases the science phase space.

We will build on the mirror technology program started by the Constellation-X/IXO program, whose goal was to produce high angular resolution lightweight X-ray optics with low weight and reasonable cost, utilizing precision polishing and light weighting of single-crystal silicon mirrors. At present this technology has achieved 3 arcsec angular resolution for individual mirror segments and builds on recent developments in the semiconductor industry: (i.) the inexpensive and abundant availability of large blocks of monocrystalline silicon; and (ii.) revolutionary advances in rapid, deterministic, precision polishing of mirrors. The baseline detector is similar to the Chandra CCD but benefits from 25 years of technology development, allowing smaller pixels, which better sample the PSF, in turn allowing higher effective angular resolution.

As required by the Probes program we will design to obtain the best science for a fixed cost. The study will focus on the science drivers of the mission, the technology development plan for the mirrors, detector tradeoffs and orbit choices (modulo available launchers), and will be open to participation by the entire astronomical community.

Our goal is to achieve the Chandra angular resolution or better at the central focus and to have a considerably better off axis point spread function and considerably larger collecting area, with a goal of 10 times the Chandra count rates for most categories of source and to detect enough photons in reasonable exposure times to make use of the high spatial resolution.

AXIS can be developed using proven spacecraft components and methods for attitude reconstruction that are compatible with the angular resolution. CCD detectors with the needed pixel size are available today and smaller pixel sizes should available in the mid 2020s. The single technology area needing development is the construction of a high-throughput, lightweight, high angular resolution X-ray mirror. Since the mirror needed for this mission is simply a smaller version of the one envisioned for X-ray Surveyor (XRS), the necessary mirror technology development is already underway and successful development of AXIS will pave the way for the larger XRS mirror.

Historically, it has taken more than 15 years to develop and build a strategic (e.g. >$2B) mission, it is clear that X-ray Surveyor could not fly before 2035 (15 years after it is selected by the 2020 Decadal survey). Thus it is highly likely that without the selection of a mission like AXIS, more than 15 years will pass without a high angular resolution X-ray capability. With the selection of a mission like AXIS, a high angular resolution X-ray mission could fly within 10 years.

The AXIS science objectives are directly responsive to the goals set forth by the Astro2010 Decadal Survey and the NASA Astrophysics Roadmap. Some of our proposed science highlights include: probing the regions within 20 Schwarzschild radii of accreting black holes via gravitational lensing, determining the rate of black hole mergers by measuring the rate of dual AGN, understanding why most black holes in the local universe are not active by imaging the Bondi...
accretion radius, measuring feedback and star formation by X-ray imaging of normal galaxies to \( z > 2 \), vastly enlarging the sample of high signal-to-noise high angular resolution images of supernova remnants and clusters of galaxies.

### AXIS Science

The need for high angular resolution (sub-arc sec) in astrophysics is evident across the entire electromagnetic spectrum from sub-arc sec imaging and spectroscopy in the radio and millimeter bands (VLBI, ALMA), to the infrared (JWST), optical (HST) and X-ray (Chandra). It is essential for resolving the critical physical scales of virtually all classes of objects and the desire to extend such studies to the highest redshift. These goals have driven the development of virtually all new telescopes in the radio (EHT, SKA), infrared and optical (interferometers, coronagraphs and adaptive optics on large ground based telescopes and WFIRST), but so far there has been no development of new high-resolution telescopes in the X-ray band. Astronomy is a multi-wavelength science with almost every class of astrophysical object having critical diagnostic information available only with multi-wavelength data.

Chandra has produced exciting and unexpected results across the entire spectrum of astrophysical objects: comets, planets, stars, supernova remnants, galaxies, black holes, neutron stars, clusters of galaxies and cosmology. However, after 15 years of highly successful operation Chandra is reaching the limits of its capabilities (due to continued degradation of ACIS) and further progress requires higher sensitivity. The main reason that there is the lack of a successor mission to Chandra anywhere in the world is the difficulty and expense of making X-ray optics with the desired characteristics. However, recently it has become possible due to developments initially designed to produce the mirrors for the International X-ray Observatory (IXO). A relatively low cost, high angular resolution, large collecting area Chandra successor can now be built within

<table>
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<tr>
<th>Table 1: Key AXIS Performance Parameters</th>
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<tr>
<td><strong>Area</strong></td>
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<tr>
<td>Angular Resolution</td>
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<td>Bandpass</td>
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<td>Effective Area</td>
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<td>Energy Resolution</td>
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<td>Total count / source</td>
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<tr>
<td>Detector Background</td>
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### Table 1: AXIS Addresses Key NASA Science Goals

<table>
<thead>
<tr>
<th>Science Question</th>
<th>Observation</th>
<th>Requirements</th>
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<tbody>
<tr>
<td>What happens close to a black hole?</td>
<td>Observations of gravitational lensed QSOs and inside the Bondi radius</td>
<td>High angular resolution and sensitivity</td>
</tr>
<tr>
<td>When and how did SMBH grow?</td>
<td>Deep surveys of the high z universe</td>
<td>10x Chandra sensitivity for deep surveys</td>
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<tr>
<td>How does large scale structure evolve?</td>
<td>Observations of high z clusters with the ability to detect merging and effects of feedback</td>
<td>Field of view, low background, broad band pass</td>
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Additional NWNH (Astro2010) Science Enabled by AXIS

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<thead>
<tr>
<th>Science Question</th>
<th>Observation</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>How do stars form &amp; flares impact planet-hosting stars?</td>
<td>Survey of stellar nurseries in Milky Way and nearby galaxies</td>
<td>Field of view, angular resolution, high sensitivity, bandpass</td>
</tr>
<tr>
<td>How does gas exchange in galaxies and the IGM?</td>
<td>Observations of star-forming and passive galaxies out to ( z \sim 2 )</td>
<td>Low background, high angular resolution, high sensitivity</td>
</tr>
<tr>
<td>How do rotation and magnetic fields affect stars?</td>
<td>Survey of main sequence stars</td>
<td>Large effective area between 0.2-3 keV with high-resolution spectroscopy</td>
</tr>
<tr>
<td>How do massive stars and Type Ia SNe explode?</td>
<td>Large samples of spatially resolved SNR in nearby galaxies to drastically increase the sample of SNR physics</td>
<td>Deep observations of nearby galaxies</td>
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</table>
the next 10 years and thus is an excellent candidate probe mission for consideration by the 2020 Decadal Report.

We have baselined the lowest cost mission that meets the science case and does not exceed the Probe cost cap. As shown by the 2012 NASA-sponsored X-ray Mission Concepts Study it is not possible to develop a high resolution X-ray imaging mission in an Explorer budget. We have designed AXIS to fit within the probe cost range, trying to obtain the best possible high angular resolution science in the X-ray band while foregoing additional capabilities. AXIS will also be a crucial step towards a strategic class mission such as X-ray Surveyor that would achieve the trifecta of high-throughput, high-resolution imaging and high-energy-resolution spectroscopy.

A quantitative measure of the need for high angular resolution X-ray imaging is the number of papers that have combined data from Chandra and other major observatories. The impact is stunning: 831 papers with HST (roughly 5% of all HST papers since 2000), 116 with the VLT, 179 with the VLA, 82 with Keck, and lately 27 with ALMA. Furthermore, the over 1650 papers using both Chandra and XMM-Newton data (~1/3 of all XMM-Newton papers) emphasizes the need for a high angular resolution X-ray imager concomitant with Athena in the late 2020s. While it is unknown if Chandra can operate for another decade, no space-based astronomical satellite has operated for 25 years (with the exception of HST which was refurbished 5 times), and thus it is unclear if Chandra (in orbit since 1999) will continue to operate for another decade. Regardless the continued degradation of ACIS is reducing the capabilities of Chandra significantly. The absence of high angular resolution X-ray capability in the post-2025 era would be a major hole in scientific capability, undermining US investments in all other astronomical facilities.

Below we present a small subsample of the high profile science possible with AXIS. We have focused on science results which are at the limit of the Chandra capabilities and probe new areas of physics and which take advantage of the $2-4\times$ better effective PSF, the $10\times$ larger count rates and the much better soft response than Chandra. AXIS will also be better than Chandra for the vast array of science that Chandra has already pioneered.

**Galaxies across cosmic time**

As noted in the 2010 Decadal report the evolution of galaxies is one of the most important areas in all of astrophysics. Galaxies are complex systems that evolve dramatically across cosmic time. Their critical constituents – stars, gas and dust, supermassive black holes and dark matter – are strongly coupled to one another and all of them have critical parameters that can only be studied in the X-ray band. While galaxies exhibit an enormous range of structures, a detailed study of them to high redshifts requires both high angular resolution and high sensitivity. In star-forming galaxies, the X-ray emission provides an unobscured tracer of star-formation activity, galactic winds and the black hole and neutron star population. In passive galaxies, the X-ray emission...
measures the gas and dark matter mass of the galaxy, compact object population and, with sufficient-signal to-noise, the metallicity of the gas.

Recent Chandra and HST observations allow us to establish the scales required. Over a wide range of redshift the size of “normal” galaxies (as expressed by their exponential scale length for spirals or half light radius for elliptical galaxies) lies in a narrow range around 2.5−4.5 kpc out to $z\sim 2$ where Hubble imaging resolves most galaxies with an angular size of ~0.4 arcsec (Ferguson et al. 2004; Figure 2). Separating out the emission from the X-ray binaries, weak AGN, ultraluminous X-ray sources, and hot gas requires high angular resolution and sufficient sensitivity to detect them. These considerations translate to an angular resolution requirement for AXIS of <0.5 arcsec, and a sensitivity requirement of $\sim 10^{17}$ erg/cm$^2$/sec in a 1 Ms exposure time, if AXIS is to measure the flux (~50 photons) of a “typical” rapidly star forming galaxy at $z\sim 2$, the peak of star formation in the universe enabling a robust measurement of the SFR independent of reddening. At $z\sim 2$, the effective temperature of the hot gas in rapidly star forming galaxies should be $T\sim 0.7/(1+z)$~0.25 keV, where the much larger sensitivity of AXIS compared with Chandra will make a crucial difference.

X-ray observations measure the star formation rate free from the effects of obscuration (Mineo et al. 2014) with the X-ray flux linearly related to the star formation rate(SFR) by $SFR\sim L_x/(5\times10^{39}$ erg/s). This simple relation seems to hold out to $z>1$, and the relation may extend all the way up to objects with SFRs of several thousand solar masses per year, (Cowie et al. 2016, ApJ, submitted). Thus AXIS would provide a reddening free probe of the most violent star formation events in the universe.

The X-ray luminosity of elliptical galaxies follows a simple relation where $L(x)\sim M_{\text{Halo}}^{1.85}$ and $L(x)\sim M_{\text{star}}^{2.6}$ (Anderson et al 2015). Basic X-ray imaging observations therefore make possible a measurement of the mass of the host galaxy and in turn constraints on feedback models. For massive galaxies, future S-Z instruments will be able to measure the Sunyaev-Zeldovich (S-Z) effect for individual galaxies; the combination of the X-ray and S-Z data will strongly constrain possible sources of feedback.

These possible sources include jets, blast waves, and gentle heating (as is required to explain the distribution of baryonic vs. dark matter and for galaxies to lie on the best fit X-ray luminosity vs. halo mass relation (Choi et al. 2016). AXIS will determine the hot gas luminosity and density distribution, as well as the AGN luminosity, allowing direct comparison with theoretical models for elliptical galaxies to $z\sim 0.5$ when they assumed their present mass and form. For a typical X-ray luminosity of $3\times10^{41}$ ergs/sec for a massive galaxy, AXIS will obtain ~600 cts per Ms at $z=0.5$, enabling a robust measure of the density distribution, average temperature of the gas and X-ray luminosity. AXIS’s low background, soft response and large collecting area are crucial for detecting the extended emission. AXIS’s angular resolution allows the measurement of the density distribution of the gas the point sources in the host galaxies and unrelated background and foreground sources. Because of its high background, Chandra can only detect elliptical galaxies out to ~0.1 of the virial radius. At low energies, around the emission peak from $T\sim 5\times10^6$K gas, the AXIS detector background should be ~10-20 times less than Chandra’s and the effective area 40× larger.

**Feedback in galaxies**

Theoretical models of galaxy formation require physics beyond just gravity and hydrodynamics. This is called “feedback”: the influence of the objects themselves on their formation. Despite
15 years of intensive study, the physics of how this actually occurs has eluded observation, and neither the mechanisms by which feedback occurs nor the physical processes involved (e.g., mass motion, heating, ionization) are understood. For massive galaxies, it is thought that the main cause of feedback is the influence of the supermassive black hole on star formation, either expelling gas from the galaxy or preventing it from falling in.

Recent work has shown that AGN-driven winds are detected in both the X-ray and in molecular lines (Tombesi et al. 2015), and it seems as if these winds are a major contributor to feedback, having the right amount of energy in the right objects. In addition to the spectral indication of feedback, there is also Chandra imaging of a few objects (Wang et al. 2012) that reveals the presence of extensive photoionized gas in the central regions of AGN (Figure 3,4).

This gas might be the long sought for AGN wind and/or jet interaction driving an outflow. However, Chandra has performed only a few such observations due to its limited collecting area, lack of soft response, and resolution and thus these results are thus tentative. AXIS would dramatically increase the sample, surveying objects over a wide range in AGN luminosity, star formation rate, and Eddington ratio, and perhaps allow direct measurements of AGN feedback.

In elliptical galaxies, Chandra observations have detected the interaction of relativistic plasma with the X-ray emitting gas (Diehl & Statler, 2007), indicating feedback of the same type as seen in clusters of galaxies. But again, the limited resolution and collecting area have severely limited the exploration of feedback. The best examples are extremely local, M84 (Figure 5) and NGC 4636, in the Virgo cluster. These observations can be extended to the more distant universe by AXIS, which can detect similar phenomena at $z$-0.06. In summary, AXIS can study star formation and feedback in galaxies to high redshifts and across a wide range of parameters in both spiral and elliptical galaxies.
Black holes

A) Structure close to the event horizon

1) Gravitational lensing

Chandra has allowed break-throughs in the study of gravitational lensing of supermassive black holes (Figure 6). If the geometry is just right, gravitational lensing by a foreground galaxy can produce several images of a background quasar, separated by a few arc-seconds or less. Each image then flickers due to the action of microlensing by individual stars within the lensing galaxy, and a statistic analysis of this flicker reveals information about the micro-arcsecond scale structures of the inner accretion disk. Analysis of observation of ~10 strongly lensed quasars, which are at the limit of Chandra’s present day sensitivity (Pooley et al. 2012; Chartas et al. 2009, 2012, 2016), shows that the X-ray emission originates within 20 Schwarzschild radii and that the Fe K emission structure is different from the X-ray continuum (Pooley 2009, Chartas 2016). These spectacular results beg for extension and enhancement.

The Chandra sample is limited to the few quasars that are X-ray bright enough to produce high S/N spectra and with image separations large enough to be resolved with Chandra’s ~1 arcsec effective resolution. AXIS will drastically increase the sample size and the signal-to-noise ratio in each object. It will directly image the central regions near a black hole, which, when combined with the Athena high signal-to-noise, high-resolution spectra of non-lensed sources will produce a major breakthrough in our understanding of these extreme regions.

Due to the very small angular size of the X-ray source, X-ray emission gives rise to the largest amplitude microlensing signals. X-ray observations thus place the strongest constraints on the mean surface density of the lensing galaxy, the dark matter fraction in the lensing galaxies, the mean surface density in the stars of the lensing galaxy, and the mean mass <M> of the stars in the lens. As shown in Pooley et al. (2009), even the small number of Chandra observations constrains the ratio of stellar matter to dark matter. AXIS’s higher signal-to-noise data and a larger sample can drastically improve these constraints.

In addition, observations of Fe emission from lensed AGN (Reis et al. 2014), which have their flux amplified by lensing effects, provide a strong constraint on the spatial origin of the Fe K line. In a similar fashion, observations of two lensed QSO’s have confirmed the presence of extremely fast outflows at high redshift. AXIS will drastically increase the number of objects with such measurements, obtaining a moderate sized sample of such ultrafast outflows at high redshift where theory indicates that feedback is dominant.

LSST will find 4000 lensed quasars, most of which will be significantly dimmer than the presently known systems, potentially allowing a vastly larger sample but requiring increased sensitivity at high angular resolution. AXIS overlaps LSST’s ten-year survey period allowing simultaneous monitoring of lensed AGN in multiple optical and X-rays bands. This will place tight constraints on the inclination angle and the spin parameter of the black hole (Popovic et al. 2003; Neronov et al. 2016). The much larger sample allows the study of accretion disk structure as a function of AGN luminosity, black hole mass, redshift, and host galaxy properties, achieving a fundamental breakthrough in our understanding of accretion disks, the hot X-ray emitting corona, the mean surface density of the lensing galaxy, the dark matter fraction in the lensing galaxies, the mean surface density in the stars of the lensing galaxy, and the mean mass <M> of the stars in the lens and the geometry of the Fe K emission region.
2) Bondi Radius

A supermassive black hole sitting in the hot X-ray emitting atmosphere of a giant elliptical galaxy will accrete a nearly spherical inflow of hot gas, via “Bondi accretion” (e.g., Bagbinoff et al. 2003). The temperature and density of the gravitationally captured, inflowing material are expected to increase as it approaches the black hole in a simple, predictable fashion (e.g., Humphrey et al. 2008), producing a deterministic accretion rate onto the black hole. For the central density and temperatures seen in many nearby elliptical galaxies and Sgr A*, the observed luminosities are many orders of magnitude smaller than predictions based on the Bondi accretion rate assuming a standard 10% radiative efficiency (Loewenstein 2001). Either the radiative efficiency is significantly overestimated or considerably less gas is accreted than predicted. This discrepancy highlights a major gap in our understanding of accretion and the quiescence of the local black hole population, and is important for understanding the origin and evolution of black holes across cosmic time.

Resolving the structure and dynamics of the inflowing gas once it falls within the gravitational influence of the black hole is essential for creating an accurate model of the accretion flow. This region is bound by the Bondi radius \( R_B = \frac{2GM_{BH}}{c^2} \sim 0.4T_{\text{keV}}^{-1}M_9(D/20\text{Mpc})\text{arcsec} \), where \( M_9 \) is the mass of the black hole in units of \( 10^9 \) solar masses and \( T_{\text{keV}} \) is the temperature of the gas near \( R_B \). In the absence of angular momentum, the black hole is predicted to gravitationally capture the ambient ISM surrounding it at a rate \( \frac{dM_{\text{Bondi}}}{dt} = 4\pi\lambda(GM_{BH})^2n_c \), where \( \lambda = 0.25 \) for an adiabatic process and \( n_c \) is the density of the gas at \( R_B \) (Figure 8).

The Bondi region can be resolved by Chandra in only very few of the nearest objects. Although these systems were targeted in two Chandra visionary projects, the angular resolution and spectral capabilities were barely adequate to the task and produced ambiguous results. In Sgr A*, the flat density profile of the gas inflow implies the presence of an outflow that expels >99% of the matter initially captured at the Bondi radius (Wang et al. 2013). Flattening of the density profile within the Bondi radius of NGC3115 also indicates the presence of an outflow (Wong et al. 2014). However, the temperature structure appears to be complex and is not well resolved by the Chandra data. The gas may be cooling out of the X-ray hot phase and feeding the rotating gas disk, rather than free falling onto the black hole. In M87 (Russell et al. 2015), there is no evidence for the expected temperature increase within ~0.25 kpc due to the gravitational influence of the black hole. This suggests that the hot gas structure is not dictated by the SMBH’s potential and,
together with the shallow density profile, shows that the classical Bondi formalism may not be applicable. In strong contradiction to most theoretical calculations, these observations suggest that the gas flows within the Bondi radius are a complex mixture of inflow fueling the black hole and powerful outflows.

With an effective angular resolution of 0.2” and increased sensitivity there are at least 25 supermassive black holes in the local universe (Figure 8, Garcia et al 2010, Van den Bosch 2016) for which the Bondi radius can be resolved. AXIS will obtain definitive results on the density and temperature profile of hot gas flowing within RB providing the first information on which accretion flow model is appropriate.

B) Dual AGN

The general theory of structure formation predicts that mergers are a major component of galaxy growth and evolution. Since almost all massive galaxies at low redshift contain central supermassive black holes, it has long been predicted that when the galaxies merge, so should their black holes. This is the major science driver for the ESA L3 gravitational wave mission eLISA and pulsar timing arrays. However, the timescales for the BH merger to occur are very uncertain and one of the few observational tests of this idea other than gravitational waves is to search for ‘dual black holes’ in nearby galaxies (Steinborn et al. 2016). Theoretical calculations indicate that a significant fraction of these sources would be active galaxies, which has stimulated an intensive search for dual AGN (Koss et al. 2015), but despite intensive work there is little information about the occurrence rate of dual AGN for a large sample of objects covering a wide range in mass, luminosity and nature of the host galaxy.

Dual AGN are extremely rare in the radio (Burke-Spolaor et al. 2011) and, optical selection techniques for dual AGN are extremely inefficient, producing a very large fraction of “falses” (Nevin et al 2016). In contrast, Chandra X-ray observations have discovered all three of the “dual AGN” with the closest separation and have found a significant fraction of all the believable candidates (Koss et al. 2015). However, the limited Chandra resolution and sensitivity have severely restricted the redshift range in which duals can be found and the range of relative intensities in which they can be detected (e.g., if the 2 sources are closer together than 1.5” and have a relative intensity ratio of greater than 30:1 the signal is not recognizable in the Chandra images). Recent high resolution NIR observations of the host galaxies of obscured AGN have found that very close mergers may exist in a larger fraction obscured luminous AGN (Figure 9). With improved signal to noise and better PSF sampling AXIS would answer the critical questions: (i.) is the low observed rate of dual AGN consistent with the theoretical predictions upon which eLISA is based?; (ii.) what is the frequency, environment, and luminosity dependence of dual AGN?; (iii.) is the obscuration level of the AGN correlated with merger stage?; (iv.) How are mergers related to the luminosities of the sources?; and (v.) how does accretion rate correlate with merger stage and the dual AGN rate? The kpc-scale dual AGN population that will be well sampled by AXIS provides key constraints for the SMBH mass merger function for the expected eLISA and pulsar timing array SMBH merger rates (Kelley, Blecha, & Hernquist 2016). Additionally, high resolution X-ray observations will provide the best constraints on offset AGN from recoiling black holes another prediction of the black hole merger process.

Feedback at High Redshift

X-ray cavities, filled with relativistic plasma, act as “calorimeters” of the total power emitted by the cluster central black hole and at low redshift are a direct indicator of AGN feedback (Hlavacek-Larrondo et al., 2012). At low redshift the cavities are seen as ‘holes’ in the X-ray surface...
brightness. However, because they are filled with relativistic plasma (detected as radio emission) at high redshift they become X-ray bright spots radiating via inverse Compton emission (Smail and Blundell 2013) because the CMB energy density grows as $(1+z)^4$. To study cluster level feedback at $z>1$ requires the ability to detect and measure these ‘anti-cavities’ in the cores of clusters. Detection of these unique features of AGN feedback in the high redshift universe is a severe technical challenge with Chandra, because the X-ray brightness contrast of the subtle “ghost bubbles” is very low and they are of small angular size. AXIS will open up this field.

C) The Highest Redshift Universe

The very high-redshift universe has largely been beyond the sensitivity limits of Chandra and XMM-Newton. Only a small number of X-ray AGNs have been directly detected beyond $z>5$. In combination with WFIRST data, AXIS has the potential to generate much larger samples of $z>5$ AGNs, allowing the study of how the AGN luminosity function changes at high redshifts and comparison with the star formation history, which may drop off more slowly than the AGN luminosity function. This is a key measurement in understanding the sequencing of the growth of supermassive black holes relative to the growth of galaxies.

At even higher redshifts, $z=6-8$, stacking analyses have only placed upper limits of $\sim2\times10^{41}$ erg/s on the average X-ray luminosity of optically selected galaxies a limit an order of magnitude higher than the X-ray emission from low redshift star forming galaxies. Some models predict that rapidly forming high $z$ galaxies might be considerably more luminous, thus the extra factor of 10 in sensitivity provided by AXIS might allow the detection of X-ray emission from normal galaxies at these redshifts. If there are also significant AGN contributions, one should be able to detect individual sources. These observations are key to understanding the early growth of supermassive black holes and what typical masses they have grown to at these redshifts. Angular resolution may provide a key diagnostic allowing us to separate compact AGNs from the more extended star-forming contributions and allow unique optical/IR counterparts to be determined.

Figure 9: Adaptive optics images of potential dual AGN in merging galaxies (Koss et al 2016 Nature sub) The white bar shows 1 kpc at the redshift of the sources.
Complementary and expansion of phase space

AXIS would provide a vast increase in sample size of objects with “exciting” structure, such as clusters of galaxies, SNR, plerions, spatially resolved SNR in local group galaxies, jets, and star forming regions in the Milky Way and the local group. For many of these kinds of object, only 1-3 objects are accessible to Chandra, and typically require very long exposures. AXIS would increase sample sizes by factors of (angular resolution)$^3$ (e.g., to study the same physical scale at a larger distance, the number of targets increases as $d^3$), but to get same S/N need $d^2$ more area. So improvement of a factor of 3 in resolution and a factor of 10 in area gives 30 times more targets. As is very common in astrophysics it is only by studying physical phenomena with a reasonable sized sample that strong conclusions can be reached. With the $\geq 0.5$Ms Chandra exposures required for detailed studies of almost every extended source, the Chandra samples are small and highly biased to the highest surface brightness members of the population.

AXIS will have complementary angular resolution and sensitivity to next generation observatories in other bands. All of the next generation observatories (ALMA,WFIRST, JWST, SKA, adaptive optics on 30m telescopes) have <1 arcsec angular resolution. In addition, many of these facilities have vastly improved sensitivity compared with the previous generation of telescopes for which Chandra was a good match. Without a Chandra successor with adequate capabilities operating at the same time as these new observatories, the rate of major advances will drastically diminish from the number we have made over the last two decades.

Other Important Science

There are many other science topics that could be discussed but for which we did not have space in this proposal. We hope that the community will join in the discussion as we start the study. Amongst these are detailed study of star clusters, resolving supernova remnants in nearby galaxies, the astrophysics of jets, detailed maps of starburst galaxies, deep X-ray surveys, pulsar wind nebulae, star formation regions in the local group, cluster cooling fronts, galaxy interactions, bubbles in clusters, ram pressure stripping of galaxies in groups and clusters, particle acceleration in SNR, cluster structure at high z and comparison with the S-Z effect, observations of planets, interaction of AGN with cluster gas at moderate to high z, identification of X-ray binary hosts in the local group, and expansion of SNR in the LMC/SMC. The few topics we have stressed are those that, at the present time, seem to be the most exciting, but this is a ephemeral statement and we anticipate that the study team will come up with a large set of different science topics that can be addressed in a set of White Papers. Those topics discussed here capture the driving technical requirements for AXIS.

TECHNICAL SECTION

Instrumentation

The AXIS instrumentation consists of a high resolution X-ray mirror and a focal plane CCD or similar type detector. As described below, the primary technology development driver is the mirror, while the detector requirements are similar to the capabilities of present day devices.

Mirror

In order accomplish the AXIS science objectives, the X-ray mirror for AXIS needs to combine large throughput with high angular resolution. A Chandra-type mirror, with a small number of thick substrates, can provide the angular resolution but has inadequate effective area; growing a Chandra-type mirror to provide the needed area would introduce a substantial mass, technology, and cost challenge. Thin shell mirror technology currently under development for X-ray Surveyor and other applications holds the promise of providing the needed combination of properties at a reasonable mass and cost.

We base the AXIS mirror design on the N-CAL mirror design (Petre et al. 2012), with a 9.5 m focal length, a 1.3 m diameter, 178 nested shells with 20 cm segment length and a mass of 325 kg. The shells are Ir coated, providing $\sim 4500$ cm$^2$ of effective area at 1 keV and $\sim 1100$ cm$^2$ at 6
AXIS – Advanced X-ray Imaging Satellite

keV (see Figure 1). The short axial length mirror segments and mounting the mirror pairs so that the principal surface of the array is a spherical surface improves off-axis imaging performance compared with Chandra.

The mirror technology development at GSFC initiated by the Con-X project in the early 2000s was continued by the subsequent IXO project until 2011 and has continued to be funded through the PCOS/SAT program to enable missions like the X-ray Surveyor and AXIS. The use of single crystal silicon as the mirror substrate material enables the use of direct surface figuring and polishing, which was used for the Chandra mirror, but makes possible the fabrication of thin (<1mm) and lightweight (areal density <2kg/m²) mirrors with the highest possible angular resolution. The primary technical challenge lies in perfecting a process, which reduces the production cost and weight by more than a factor of 20 on a per unit area basis with respect to Chandra’s mirror. Individual mirror segments with ~3 arcsec angular resolution have been fabricated; it is expected that individual segments meeting X-ray surveyor or AXIS requirements can be demonstrated by 2020. A mirror alignment and bonding process is being developed in parallel. The basic elements of this process have been demonstrated by optical metrology and mechanical testing. Further precision and throughput need to be improved to meet the X-ray Surveyor’s and AXIS’s requirements. It is reasonable to expect this technology will be at TRL-6 for the X-ray Surveyor and AXIS by 2025.

One of the primary objectives of our study is to develop a technology roadmap that leads to a demonstration of the required mirror performance, using Si shells, as well as identifies possible alternate paths within the budget constraints of a probe.

Detector

The focal plane detector will be a CCD or related device, qualitatively similar to those flown on Chandra, Suzaku, and other recent X-ray observatories, but taking advantage of recent technical improvements. The relatively modest 15’ field of view translates to an active focal plane area of 3 cm x 3 cm, which can be provided by either a single CCD or a mosaic of a small number of devices, dramatically simplifying the focal plane. The key technical challenges are pixel size, readout rate, and low energy quantum efficiency. The plate scale of a 9.5 m focal length mirror is ~46 µm/arcsec. In order to adequately sample the 0.2 arcsec HPD beam, the CCD pixels must be 4-8 µm (0.09-0.17 arcsec).

CCDs with 8 µm pixel size are already produced by US imager manufacturers; during the study we will investigate the feasibility of fabricating CCDs with smaller pixels. Smaller pixels will substantially reduce the particle background through superior multi-pixel filtering of the larger charge clouds produced by cosmic rays and significantly reduce pile-up from bright point sources. The detector readout rate translates directly into spacecraft specifications; the faster the readout rate, and the less restrictive the jitter requirement, the brighter the source that can be measured without pile-up. Current CCD technology achieves 5 Mpix/s transfer rates with readout noise less than 5 e− giving good spectral resolution and low energy capability. A single 3cm x 3cm CCD with 4 µm pixels and four readout nodes (the most conservative case), has an integration time of 3 secs, shorter than the Chandra ACIS. By using multiple CCDs and additional readout nodes, the integration time can be reduced by a factor of at least 10.

Backside-illuminated (BI) CCDs as flown on Chandra and Suzaku have good QE over the entire AXIS energy range, and NASA R&A programs are underway to minimize the thickness of the filters required to block unwanted visible/UV radiation to give higher low

<table>
<thead>
<tr>
<th>Description</th>
<th>N-CA L</th>
<th>AXIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Lifetime</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Orbit</td>
<td>L2 Halo</td>
<td>L2 halo, LEO equatorial, TESS-like</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1775</td>
<td>1550</td>
</tr>
<tr>
<td>Average Power (W)</td>
<td>1006/1127</td>
<td>650</td>
</tr>
<tr>
<td>Average/Peak Data Rate (kbps)</td>
<td>76/1800</td>
<td>TBD</td>
</tr>
<tr>
<td>Required Pointing Accuracy (arcmin)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pointing Knowledge (arcsec)</td>
<td>1</td>
<td>~0.1</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Falcon 9</td>
<td>Falcon 9</td>
</tr>
<tr>
<td>Margin to L2</td>
<td>137%</td>
<td>171%</td>
</tr>
</tbody>
</table>
energy throughput than Suzaku. Present optical blocking filters give a combined total QE of 25% at 0.2 keV, 75% at 0.5 keV, and greater than 90% above 1 keV. A QE of 90% up to 10 keV is achievable as demonstrated with the SXI CCDs aboard Hitomi (Tsunemi et al. 2016, Proc. SPIE 9905, 990510). Readout rate could become a technology driver. We will study amelioration of this problem, either using another technology such as an APS or via use of a small sub-window for bright, targeted sources as on Chandra and other missions and incorporate these into our technology development roadmap.

Mission Design

We use the N-CAL parameters (Petre et al. 2012) as the starting point for the AXIS conceptual mission design. N-CAL had a calorimeter detector system which is replaced here with a CCD detector, offering a substantial reduction in mass, power, complexity and cost. N-CAL was designed for a 3-year lifetime, with sufficient consumables to last for five. Mission parameters were established via a study at the GSFC Mission Design Lab (MDL).

The N-CAL conceptual spacecraft has similar pointing requirements, and has substantial margins for the AXIS power and telemetry needs (Table 2). The only required additions would be an onboard metrology system to ensure the attitude reconstruction accuracy is attained and a focus mechanism for the detector. Both of these systems have heritage from Chandra. The AXIS MDL study will be used as the basis for refining the spacecraft design based on the AXIS needs.

The most severe system requirement arises from the high angular resolution: the attitude must be reconstructed (not controlled) to ∼0.1 arcsec. Only modest (∼0.5 arcmin) pointing accuracy is needed, but maintaining the needed knowledge accuracy requires a stable thermal design (Chandra heritage – already built into the N-CAL concept), plus a focus mechanism and metrology system to monitor and remove structural variation. The key requirement is jitter, which in turn is driven by the CCD readout rate (the faster the readout rate, the more relaxed the jitter requirement). The attitude control knowledge error budget, particularly the jitter term, will be refined during the study.

N-CAL was designed for an L2 orbit, primarily because of the constant thermal environment and the desire to maximize observing efficiency. It is not immediately obvious that this is the best orbit for AXIS: meeting the low background requirement suggests that an equatorial low earth orbit (∼600 km) would be preferred. Another possible orbit is the TESS 13.7 day HEO in a 2:1 resonance with the moon. An orbit trade will be carried out during the study. A Falcon 9 can easily place AXIS into any of these orbits. For N-CAL, the mass margin to L2 was over 100% percent (1775 kg vs. 4200 kg), and replacement of the massive calorimeter plus cooler with a CCD reduces mass substantially.

TRL estimates

The X-ray mirror has the lowest TRL. The segmented Si technology is at TRL 5 for a ∼5 arcsec angular resolution system. CCDs with 8 µm pixel size are at TRL 6; reducing the pixel size to 4 µm is a straightforward but nontrivial extension of current technology. The baseline spacecraft consists entirely of heritage components (TRL > 6); no technology development is needed.

Cost Estimate

The AXIS mission cost can be estimated based on N-CAL, whose cost was estimated by applying PRICE-H to the MDL spacecraft design, instrument, and mirror. For the costing of the instruments, mirrors, and spacecraft components, a minimum TRL of 6 will be assumed. During the study, we will pay close attention to the AXIS cost. The mission we propose to the Decadal Survey will be sized such that the overall cost is well within the nominal $1B Probe envelope. If in our judgment an affordable mission falls below the science threshold (to be determined by the science team), we will not submit AXIS to the Decadal Survey.

MANAGEMENT PLAN

The study will be led by the PI, Prof. Richard Mushotzky (U. Maryland). He will direct all elements of the statement of work, and control the expenditure of funds. The technical aspects of
the study (instrumentation and spacecraft definition, and technology roadmap) will be led by the science Co-I’s at GSFC (Ptak, Zhang, Petre) with input on CCDs from Eric Miller (MIT). They will also serve as the interface between the study team and the GSFC MDL. Prof. Mushotzky, assisted by Dr. Francesco Tombesi (U. Maryland), will organize the science inputs in response to the possible changes in mission design caused by the technical study.

The study will be conducted using the very successful 2012 NASA-sponsored X-ray Missions Concept Study that produced the N-CAL design. The key to the success of this study was involvement of the entire team in all scientific and technical aspects of the study, and in regular tracking and reporting of all activities and action items. Regular team telecons (weekly or biweekly) will be held, with face-to-face meetings at strategic times (kickoff, prior to MDL run, to review the study report first draft), as well as opportunistic meetings afforded by AAS, HEAD, or SPIE conferences.

**Statement of Work**

AXIS study will consist of the following elements. It is constructed as one would construct a Science Traceability Flowdown matrix: first determine the driving science requirements, flow them down through instrument and spacecraft requirements, and then develop a conceptual design that accommodates all requirements. Figure 10 shows a rough schedule of the 18-month study.

1. The science team will refine the AXIS science requirements and develop the science justification to guide the mission design. In order to develop the strongest possible justification, we will (i.) broaden the team through an open invitation to the community; (ii.) host a community workshop early in the study to formulate the driving scientific objectives; and (iii.) organize task groups from the science team to explore and elucidate science drivers and observatory science, and synergy with contemporaneous observatories.

2. Based on the refined science requirements, we will refine the baseline and minimally acceptable instrument performance requirements.

   Telescope parameters that will be studied include, but are not restricted to: (i.) effective area vs. energy; (ii.) field of view; (iii.) angular resolution, on and off axis; (iv.) the maximum source brightness required; and (v.) mirror scattering. These telescope requirements will be iterated as the instrument and mission conceptual design progresses to ensure consistency with the final configuration proposed in the study report. In particular, focal length trades off against mass of the spacecraft, energy range of the system and detector background.

   Detectors: We baseline “CCD-like” detectors but we will examine alternative technologies as appropriate. The trade studies will include (i.) bandpass; (ii.) quantum efficiency at both low and high energies; (iii.) energy resolution; (iv.) pixel size; (v.) readout rate; (vi.) background (vii) radiation damage; and (viii) TRL level.

3. We will use these instrument and telescope performance requirements to refine the baseline and minimum technical parameters through trade studies. These parameters include, but are not restricted to: (i.) mirror focal length, which determines bandpass and plate scale; (ii.) mirror diameter, which determines effective area; (iii.) detector size which determines field of view; (iv.)
detector readout speed, which determines bright source limit and flows down to the observatory jitter requirement; (v.) need for onboard processing, which flows down to downlink telemetry rate.

4. These parameters will be used to refine the baseline spacecraft and mission parameters. We will use N-CAL design as our starting point. Parameters to be refined include: (i.) pointing accuracy and angular resolution error budget; (ii.) telemetry rate; (iii.) orbit (equatorial LEO vs. L2 or TESS-like); (iv.) mission operations strategy (e.g., incorporation of rapid TOO response); (v.) minimum mission configuration; (vi.) launch vehicle (any need to consider alternative to Falcon 9); and (vii.) mission operations strategy.

5. We will then validate these design decisions using the GSFC Mission Design Laboratory, and formulate a preliminary cost estimate. If the MDL cost estimate proves unsatisfactory, we will make adjustments to the configuration as necessary, iterating with the science team to preserve the key science objectives.

6. In parallel with the science objectives and mission definition, we will write a technology development roadmap, offering one or more technical approaches for producing a high angular resolution, high throughput mirror and detector (if necessary). If X-ray Surveyor has similar mirror performance requirements, then the XRS mirror technology roadmap might preclude the need for a separate AXIS mirror technology roadmap.

7. Finally, we will compile the science case, the requirements flowdown, and the resulting mission design into a study report to be submitted to NASA at the conclusion of the study in preparation for input to the decadal survey.

REFERENCES

• Choi, Ena 2016 arXiv:1610.09389
• Loewenstein, M., Mushotzky, R.F., Angelini, L., Arnaud, K.A., Quataerett, E., 2001, 555, L21
• Neronov, A., & Vovk, I. 2016, Phys. Rev. D, 93, 023006
• Nevin, R., Comerford, J., Müller-Sánchez, F., Barrows, R. S., Cooper, M. 2016 arXiv:1609.04018 201
• Smail, I., Blundell, K.M. 2013, MNRAS, 434, 3246S
• Steinborn, L., Dolag, K., Comerford, J., Hirschmann, M, Remus, R 2016 MNRAS. 458. 1013S
• Wang, Q. D. et al., 2013, Science, 341, 981
• Zhang, W. W., et al. 2016 SPIE, 9905, 99051