Astrophysics in the 2020's

AXIS the Advanced X-ray Imaging Satellite
axis.astro.umd.edu/
**AXIS in a Nutshell**

**Advanced X-ray Imaging Satellite**

R. Mushotzky, UMD

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**Galaxies over Cosmic Time**

- New lightweight single-crystal silicon optics with high angular resolution and collecting area and a modern CCD with higher sensitivity and spectral resolution than Chandra

- LEO orbit minimizes background, allows rapid slewing for TOOs and extends detector lifetime (>5 yrs, no consumables)

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**Merging black holes**

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**Feedback in galaxies**

- Angular Resolution: ~0.3 arc sec
- Bandpass: ~0.1-12 keV
- Effective Area:
  - 4500 cm$^2$ @1 keV;
  - 1500 cm$^2$ @ 6 keV
- Energy Resolution: 150 eV @ 6 keV (CCD resolution)
- Total count rate / source: 10x Chandra's at launch
- Detector Background: 5x lower than Chandra
Top Level Science Goals

- Image galaxies at the peak of star formation
- Probe regions within $10R_{\text{s}}$ of black holes via gravitational lensing
- Understand how accretion occurs in active galaxies via imaging the Bondi radius
- Constrain star formation and AGN feedback out to very high redshifts
- Measuring black hole mergers by obtaining the largest sample of 'dual' AGN
- Search for the first black holes
- Provide rapid response for transient/time variability science
- X-ray binaries in nearby galaxies

Other science: a vast increase in sample size of objects with “exciting” structure, such as clusters of galaxies, SNR, PWN, spatially resolved SNR in local group galaxies, jets, and star forming regions in the Milky Way and the local group.

Figure 2. HST images of $z \sim 0.7$-8 galaxies, image is 2x2" from http://astronomy.nmsu.edu/cwc/Research/MgIIreview/.
Goals and Implementation

- High Angular Resolution + large collecting area + large field of view + broad band + timing capability

Minimum 10x Chandra's collecting area at 1 keV and similar or better angular resolution with wider field of view.

- Rapid Response capability like Swift but 60x more sensitive

Baseline Design
Programmatic Constraints

AXIS is a funded Probe class mission study being considered for submission to the 2020 NAS Decadal Survey In Astronomy and Astrophysics

Probe class <$1B (strong limit)- One telescope, one detector, no moving parts

Desire to be selected by Decadal for a launch in ~2028

Technology has to be ready and vetted by 2022
Astronomy is in a golden age with spectacular discoveries such as the first extrasolar planets, pinning down the age of the Universe, dark energy, galactic and extra-galactic black holes, gravitational waves, extra solar neutrinos, and galaxies formed only a few hundred million years after the Big Bang as just some of the drivers for new missions.

Adapted from John Huchra
What does the 2020's Promise for U.S. Astrophysics

Major advances in the 2010-2017 period
• Evolution of black holes over cosmic time
• Exo-planets and the search for life
• Opening of 'non-photon' astronomy (neutrinos and gravitational waves)
• Incredible increase in precision of cosmological parameters- CMB, BAO etc
• Study of galaxies at redshifts greater than 4

Next decade
• Time domain astronomy (LSST and others)
• The first galaxies (JWST)
• Cosmology (DESI, DEC, WFIRST, Advanced CMB)
• Exo-planets (TESS etc)

*Missing*- The Hot and Energetic Universe!
What is Needed??

One of most spectacular achievements of astronomy in the last 50 years has been opening up the entire electromagnetic spectrum for study from long wavelength radio to the highest energy $\gamma$-rays.

However due to the earth's atmosphere much of this relies on access to space and with constrained budgets of the last decade this has been restricted.

NASA has focused on optical astronomy with JWST and WFIRST but that is only a small part of the picture.
The range of High Energy Astrophysics...
Q: How do black holes accrete?
A: Resolve the SMBH sphere of influence
Imaging the gravitational sphere of influence in SMBHs

How does accretion work, where does the gas come from?

\[ R_{\text{Bondi}} = \frac{2GM}{c_s^2} \]; the radius within which the Black Hole will accrete.

Chandra can only measure Bondi* radius in 3 galaxies...

Bondi accretion - spherically symmetric, steady state accretion of a non-self-gravitating gas.

AXIS Science Lead: Helen Russell
Imaging the gravitational sphere of influence in SMBHs

AXIS will measure Bondi radius in ~60 Galaxies
Q: How and when did SMBHs grow?

A: Hierarchical structure formation with Dual AGN+ Sensitive Surveys of High Z Universe
Dual Nuclei In Highly Absorbed AGN

Keck adaptive optics

Koss + submitted, using Swift BAT selected luminous absorbed AGN
Hidden Nuclear Mergers in Nearby Obscured Quasars (X-ray Detect Obscured AGN+High resolution Imaging)

Hard X-ray selected AGN in <3 kpc mergers, ~15% of obscured luminous AGN
Scales of 200 pc to kpc

Puzzling given dynamical friction timescales, don’t expect to find these sources
Are these obscured AGN with nuclear mergers the prototypes for GW sources?

Koss et al. Submitted
Comparing AXIS and Chandra for Imaging

An average AXIS pointing of 100ks will have as many serendipitous sources as a Chandra 1Ms pointing but the median flux is ~10x fainter.
Limits of Present Surveys

AXIS 1 Ms

$M_{\text{BH}} \sim 5 \times 10^4$

$M_\odot$ at $z=9$
Q: How does gas get into and out of galaxies?

A: Probe galaxies over Cosmic Time

M82

red = x-ray outflow

A: Probe galaxies over Cosmic Time
Galaxies over Cosmic Time

NGC 6240 rapidly star forming galaxy at z=0.02
x-ray and optical composite

x-rays in red

Soft x-ray is wind escaping from galaxy
AXIS will resolve starburst galaxies at $z \sim 1$, the peak of star formation in universe, imaging the outflows in moderate exposures.

NGC 6240
ULIRG at $z=0.02$
simulations by Edmund Hodges-Kluck
Sizes of Galaxies

AXIS can measure the sizes of galaxies in the x-ray out to $z \sim 5$ and can locate the x-ray source inside the galaxy.

3x3'' HST images of $z \sim 7$ galaxies Bunker et al 2010
HST Images of z~2 Galaxies

Images are 2x2"

AXIS will position the x-ray sources inside the galaxy
– distinguishing AGN, ULXs and starburst complexes
Q: How does gas get into and out of galaxies?

A: Peer into the heart of AGN feedback in clusters
Looking at the heart of the feedback process

Perseus cluster

Chandra Image Perseus Core
~1Msec- 100ks 100 ks exposure with AXIS

Fabian et al. 2011

Sanders et al. 2016
Sampling of the PSF

AXIS will sample the telescope PSF taking full advantage of the imaging information.

Chandra image of the central region of an AGN- Imaging of the hot outflow which maybe responsible for feedback.

THE ASTROPHYSICAL JOURNAL, 844:69 (24pp), 2017 J

Maksym et al.
Q: How does large scale structure evolve?

A: Connect cluster outskirts to the Cosmic Web
Growth of Structure

Most of the cosmic web at $z<1$ is hot and emits and absorbs x-rays.

But the emission has a very low surface brightness and has been observed in only a few cases.
\[ \frac{A}{F^2 B} = \text{figure of merit for background limited observations} \]
e.g. observations of low surface brightness objects
\( A = \text{effective area} \)
\( F = \text{local length} \)
\( B = \text{detector background} \)

**AXIS** will provide \(~100\times\) the Chandra sensitivity for measurement of the low surface brightness outskirts of clusters.

**Linear features such as shock fronts easily seen in high-resolution images.**
Structure Near the Event Horizon
Quasar Microlensing

AXIS Science Lead: George Chartas
Lensing also allows measurement of broad Fe Lines at high redshift. The scale of flux magnification during a microlensing caustic crossing episodes is determined by the ratio of the source size to Einstein radius \[ \sqrt{\frac{R_{\text{source}}}{R_{\text{Einstein}}}} \]

allows estimate of the energy dependent size (Neronov et al 2016)

The 10x larger source size in optical leads to a lower amplitude to variability.

Lensing also allows measurement of broad Fe Lines at high redshift.
Constraints on X-ray emitting region from Chandra lensing data

X-ray emission occurs within $10R_G$

Gravitationally redshifted emission lines seen in lensed source during caustic crossing

Chartas+16,17
Numerical Simulations of Microlensing Events

Chartas+ 2016, 2017; Krawczynski+ 2017
Energy shifts of the Fe Kα line energy during caustic crossing in HE 0435 imply $3r_g < r_{ISCO} < 4r_g$.

**AXIS can do MANY more**

- The Large Synoptic Survey Telescope will discover ~ 4000 gravitationally lensed quasars.
- Analysis of LSST image light-curves can provide reliable triggers for caustic crossing events.
- These microlensing triggers allow dense X-ray monitoring of caustic crossing events using AXIS ability to have a flexible program.
Imaging SMBHs in Quasars

AXIS will obtain constraints on the ISCO and spin parameter of many quasars with redshifts in the range of \(~1\) testing theories of the joint evolution of black holes and their spins across cosmic time and probe dark matter distribution in the lensing galaxies on small scales.
AXIS comes at the perfect time!

LSST (2023-2033)

- LSST will find 4000 new lensed quasars
- Daily monitoring will determine which sources have active caustic crossings

Athena (2028 - 2033)

- Prime science of Athena is to measure black hole spin in distant quasars
Time Domain Astronomy

- With LSST, LOFAR and other facilities the 2020's will be the epoch of time domain astronomy.

- Swift has shown the potential of rapid x-ray response to transients and other time domain alerts made possible by a rapid response spacecraft and flexible mission operations.

With ~60x the sensitivity of Swift and 10x better timing than Chandra in the x-ray and rapid response capability, AXIS will extend and enhance this area of science. TDEs, GRBs, gravitational wave sources, flare stars, novae and supernovae shock break-outs, x-ray binaries in 300 galaxies.
AXIS will have \(~10\text{-}30\text{x}\) the Chandra counting rate and \(6\text{-}30\text{x}\) the time resolution of Chandra \((\sim0.02 \text{ sec})\)

For luminous x-ray binaries in M31/M33 the AXIS counting rate will be \(\sim6\text{x}\) the Ariel-V All Sky Monitor flux for x-ray binaries \((\sim0.1 \text{ of RXTE ASM})\)

Detect young pulsars e.g. X279 = SN1957D in M83 D=4.6Mpc
Eddington limited sources will give $10^4$ cts/100ks at D~5 Mpc.

Detailed spectra and timing studies for x-ray binaries in over 300 galaxies compared to ~10 for Chandra.
AXIS and Jets

AGN jets may carry as much energy as radiation, and be responsible for feedback in massive systems from $z>6$ to $z=0$

But still do not know how jets are formed, what they are made of, why they occur in some AGNs, how long they live, and where they deposit most of their energy. –

Need spatially resolved good quality x-ray spectra and time variability (only 2 flares seen with Chandra: M87 + Pictor-A)

AXIS will find many new X-ray jets, providing high quality spectra of the best candidates

High-resolution X-ray images are an important counterpart to next-generation radio surveys

X-ray variability is a smoking gun for in situ particle acceleration (shock acceleration in M87) and the synchrotron mechanism
AXIS Detects Distant Jets

Centaurus A (Weaker jet) - Deep Chandra (600 ks; Worrall+2007)

1 arcmin = 1 kpc = 3,300 ly

Pictor A (Powerful jet) - Deep Chandra (450 ks; Hardcastle+2016)

1 arcmin = 42 kpc (137,000 ly)

Jets projected to z=3 (1” = 8 kpc)

Most jets are 1-30 kpc (0.1”-4” at z=1). Next-generation radio telescopes (SKA, ngVLA) will achieve θ<1” resolution, but ATHENA will only have θ=5”.
Why Jets* with AXIS

AGN jets may contribute to feedback in massive systems from $z>6$ to $z=0$, however we do not know

- How jets are formed
- What jets are made of
- Where jets deposit their energy
- When jets are active
- Why jets occur

- Detecting jets and resolving knots requires high spatial resolution. With ~10x Chandra Aeff, AXIS will
  - Find many new X-ray jets with less selection bias
  - Better characterize known jets

- High-resolution X-ray imaging is an important counterpart to next-generation radio surveys

* Jets are: relativistic, hyper-luminous beams of energy from a giant black hole that can disrupt a galaxy.
X-ray and Radio Image of Cygnus-A

environment is important

Red is radio emission, blue is x-ray emission from hot gas
Jets are a fantastic place to study particle acceleration and propagation.

3C273 jet
X-ray blue, optical white, radio red
strong variations in spectral shape with position
After deconvolving with a model of the Chandra psf, the X-ray jet is resolved in the transverse direction with a width of ~500 pc

X-ray

Spine-sheath?
Jets may have a slower boundary layer, which accelerates particles via plasma turbulent waves and entrains material. **AXIS will provide a statistical sample of jets with transverse structure, which will have complementary radio data** (there are not many resolved CXO jets due to lower sensitivity). This will constrain how jets decelerate.
An Example of Jet Science

IC/CMB vs. Synchrotron in X-ray Jets

X-ray jets often too bright to be synchrotron from the same population that emits in radio.

- Inverse Compton scattering of the CMB predicts stronger GeV flux than is seen
- Are X-rays are synchrotron from a second, more energetic population?
  - Prediction that there should be a $z > 2$ population of X-ray jets with no radio counterpart
- AXIS will find these jets, or not, and also test the expected $(1+z)^4$ brightening to determine whether quenched radio jets explain the high ratio of blazars to radio galaxies at $z > 2$ (Volonteri+2011, Ghisellini+2015)
• highest redshift clusters to form in the universe
• Ultra-luminous x-ray sources at z~1
• $10^5$ M black holes at $z$~9 (0.5 Gyr after the Big Bang)
• Chemical abundances in galaxies, clusters, nearby galaxies

AXIS will extend the reach of x-ray astronomy at high angular resolution
Top Level Science Goals of NWNH
Galaxies Across Cosmic Time Panel

• How do cosmic structures form and evolve?
• How do baryons cycle in and out of galaxies, and what do they do while they are there?
• How do black holes grow, radiate, and influence their surroundings?
• What were the first objects to light up the universe and when did they do it?

AXIS can trace the growth of $M_{BH} > 10^4 M_\odot$ to $z \sim 9$
Universe as a Laboratory

The universe serves as an unparalleled laboratory for physics, providing extreme conditions and unique opportunities to test theoretical models. Astronomical observations yield invaluable information for physicists across the entire spectrum of the science, studying everything from the smallest constituents of matter to the largest known structures. Astronomy is the principal player in the quest to uncover the full story about the origin, evolution and ultimate fate of the universe.

NSF Web page

In addition astronomy has shown time and time again the ability to discover new and previously unknown and unimagined phenomena...

The universe is not only stranger than we imagine, it is stranger than we can imagine. J.S. Haldane
Advantages of AXIS for Spectroscopy

The enhanced collecting area at low energies and better energy resolution allows accurate measurement of oxygen abundances and constraints on carbon and nitrogen.

Simulation of emission of ISM of MW galaxy at D~20 Mpc 100 Ks
Summary

AXIS will provide breakthrough capabilities in many areas of astrophysics

Will be compatible in sensitivity to the next generation of astronomical observatories

Can be developed and flown in ~12 years
Backup Slides
Test of type Ia SN Models

Seitzenzahl et al. 2015 the delayed-detonation model synthesizes \( \sim 3.5 \) times more radioactive \(^{55}\text{Fe}\) than the merger model: the peak Mn K\(\alpha\) line flux of the delayed-detonation model exceeds that of the merger model by a factor of \( \sim 4.5 \). (250ks exposures for Chandra and AXIS)

![Type Ia SN at 1 Mpc, 250ks Chandra simulation](image1)

![Type Ia SN at 1 Mpc, 250ks AXIS simulation](image2)
Radio Galaxies

to maintain luminosity of lobe need $\sim 10^{42-45}$ ergs/s in jet (energy of particles); lifetime base on loss arguments $\sim 10^7$ yrs ($10^{56}-10^{61}$ ergs; rest mass energies up to $10^8 M_\odot$)

For many objects jet energy $> photon$ radiated energy

A minimum value - assumes all of the energy supplied is radiated away:
- minimum energy requirement for the black hole lower limit since all of energy does not go into radiating particles (relativistic electrons) (e.g. energy into protons or magnetic fields)
What Does 10x the Area Do

• can conduct quick 'finding' surveys to select objects from a sample for future study

• For jets have e-Rosita catalog and next generation VLA survey to provide catalog for high z jet survey
High Redshift Jet with No Radio Counterpart

- B3 0727 at z=2.5 (Simonescu et al 2016) shows a clear x-ray jet (~12" long and narrow) and no radio counterpart
- Thought to be due to (1+z)4 amplification expected from the inverse Compton radiative model.
- Confirms the existence of an entire population of similar systems with bright X-ray and faint radio jets at high redshift,

Important for the cosmological evolution of supermassive black holes and active galactic nuclei in general.

B30727 z=2.5 Jet Chandra

radio contours in blue
AXIS Observation of High Z Jets

\[ z=2.5, \text{ CXO 20 ks} \]
Quasar \( L_X = 2 \times 10^{45} \text{ erg/s} \)
Jet \( L_X = 1 \times 10^{44} \text{ erg/s} \)

\[ z=2.5, \text{ AXIS 10 ks (simX)} \]
Quasar \( L_X = 2 \times 10^{44} \text{ erg/s} \)
Jet \( L_X = 1 \times 10^{43} \text{ erg/s} \)

Quasar \( L_X = 2 \times 10^{43} \text{ erg/s} \)
Jet \( L_X = 1 \times 10^{42} \text{ erg/s} \)

This is comparable to luminosities in \textit{local} jets, so lower selection bias.
Multi-Wavelength Astrophysics

Almost every astrophysical object from comets to quasars emits/absorbs radiation over a very wide range of wavelengths.

Major advances in astrophysics requires complementary sensitivity and angular resolution across the entire electromagnetic spectrum to answer the fundamental questions posed by Astro2010.

Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes?
The Origin of Galaxies and Large-Scale Structure
New Worlds: Seeking Nearby, Habitable Planets
Understanding the cosmic order
X-ray ejecta discovered in a microquasar evolved over a month.

AXIS resolution + effective area lead to 0.01-0.03" centroiding for similar brightness, exposure time as CXO observations (cf. JVLA).

Monitoring these systems for state transition (through standing ToO) probes jet formation, ISM interaction.
Galactic Source Astrophysics

AXIS will have ~10-20x the Chandra counting rate and 6-30x the time resolution of Chanda.

For luminous x-ray binaries in M31 the AXIS counting rate will be ~ 1/6 of the Uhuru flux for x-ray binaries.

Detect young pulsars e.g. X279 = SN1957D in M83.
Spectra and images of SNR at 5 Mpc (>300 galaxies).
AXIS survey capabilities
The new AXIS technology...
AXIS Optics

Requirements

Angular resolution  – 0.3” HPD
Field of view      – 15′ diameter with best PSF
Effective area     – 10–30x Chandra

AXIS Optics Lead: Will Zhang
AXIS Optics

Under reasonable assumptions:
   Focal length: 9 meters
   Outer diameter: 1.5 meter
   Mirror thickness: 0.5 mm

• AXIS can have effective areas (optics + detector)
  – >5,000 cm² at 1 keV
  – >1,000 cm² at 5 keV

• AXIS’s PSF and FOV
  – More or less uniform 0.5” HPD in a 15-armin dia. FOV
  – Better PSF on-axis at expense of off-axis PSF.
    For example, 0.1” on-axis, 1.5” at 6-arcmin off-axis
AXIS Optics

The Meta-Shell Paradigm

- Each mirror segment is fabricated, qualified, and then aligned by and bonded to four spacers which kinematically constrain it.
- Several hundred mirror segments are aligned and bonded to form a meta-shell.
- A dozen or so meta-shells of different diameters form the final mirror assembly.

AXIS Optics Lead: Will Zhang
AXIS Optics

Fabrication Process

Monocrystalline silicon block
Conical form generated
Light-weighted substrate
Etched substrate
Polished mirror substrate
Trimmed mirror substrate

AXIS Optics Lead: Will Zhang
AXIS Optics

Fabrication Process

Accomplished as of May 2017
Single pair of mirrors aligned, bonded, and X-ray tested.

Expected to be accomplished by December 2017
Multiple pairs of mirrors aligned, bonded, and X-ray tested.

AXIS Optics Lead: Will Zhang
AXIS Optics

Summary of Engineering

- **Meta-shell approach**
  - Advantages of full shell optics but with an order of magnitude more collecting area
- **Preliminary structural, thermal, and optical analysis completed to mature the system design**
  - Shows 0.5” mission is feasible
- **Prototype load testing demonstrates the meta-shells are robust**
- **Development continues: design, analysis, testing**

This work has been funded by NASA through ROSES/SAT and ROSES/APRA.

AXIS Optics Lead: Will Zhang
AXIS Detectors

Requirements

Angular resolution – small pixels (8–16 μm)
Field of view – large format
Effective area – fast readout, high QE at 0.2 keV

CCD

CMOS

Monolithic

Hybrid

- Pixel electronics and detectors share area
- Control and support electronics placed outside of imaging area
- Fill factor loss
- Co-optimized fabrication

- 100% fill factor detector
- Fabrication optimized by layer function
- Local image processing
- Scalable to large-area focal planes
(figure usage pending MIT/LL approval)
AXIS Detectors

Digital CCDs

4 BI 2600x2600 pixel CCDs in 2x2 array, 4.2 cm (15’)
FOV
8 µm (0.17”) pixels
50–100 µm depletion (0.1–10 keV sensitivity)
128 outputs @ 5 MHz
70 frames/sec (200x Chandra)
QE with filters: 25% (0.2 keV), 75% (0.5 keV), >90% (>1 keV)
challenges: charge splitting with small pixels, huge data rate

(will reformat with some pictures)
AXIS Detectors

Background

M. Markevitch

(some version of this with Athena WFI)

AXIS Detectors Lead: Eric Miller
### AXIS Trades

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
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<td>Orbit</td>
<td>equatorial LEO vs. HEO</td>
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<tr>
<td></td>
<td>background</td>
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<tr>
<td></td>
<td>observing efficiency</td>
</tr>
<tr>
<td></td>
<td>data rate</td>
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<tr>
<td>Optics</td>
<td>PSF vs. field of view</td>
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<td>Detectors</td>
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<td>QE, spectral resolution</td>
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<td>Design</td>
<td>single telescope vs. several modules</td>
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<td>focal length</td>
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<td>slew rate</td>
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<tr>
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<td>focal length</td>
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AXIS Cheat Sheet
1. 1.10x area of Chandra ACIS
2. 10x lower background
3. New CCD technology
4. Rapid response capability

What do YOU want?
1) 3” over entire 40’ FOV
2) 0.5” over entire 14’ FOV
3) 0.1” at central 6’; 15’ total FOV

Thank you!
axis.astro.umd.edu
AXIS Optics

Three Basic Elements

• **Segment or Substrates**
  – Figure quality, including micro-roughness
  – Thickness and mass

• **Coating**
  – High reflectance
  – No figure degradation

• **Alignment and Bonding**
  – Locating and orienting each mirror segment
  – Keeping it there for good
  – Doing so without causing figure distortion
AXIS Optics
Substrate Fabrication

• **Material:** mono-crystalline silicon
  – Free of stress
  – Low density: 2.35 g/cm³
  – High thermal conductivity: 150 W m⁻¹ K⁻¹
  – High elastic modulus: 130 – 188 GPa
  – Low thermal expansion: 2.6 ppm/K
  – Commercial availability
  – Best studied and understood material

• **Fabrication process:** polishing
  – Grinding, lapping, slicing, acid etching, full-aperture polishing, & sub-aperture polishing, etc.
  – Best possible figure and finish quality
  – Mass production and robotics to minimize cost

AXIS Optics Lead: Will Zhang
### AXIS Optics

**Optics Top Level Error Budget**

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<tr>
<th>Parameter or Process</th>
<th>Contribution to HPD (&quot;&quot;)</th>
<th>Notes</th>
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<tr>
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<tr>
<td>Axial figure (sag)</td>
<td>0.1</td>
<td>Shown as of June 2017</td>
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<tr>
<td>Axial figure (other than sag)</td>
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<td><strong>Integration of segments to meta-shells</strong></td>
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<tr>
<td>Alignment</td>
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<td><strong>Bonding</strong></td>
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<td>Difficult to assess. Emphasis of work in coming years. Tallest pole!!</td>
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<td>RSS of above two numbers.</td>
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**AXIS Optics Lead: Will Zhang**
Chandra 4 Day Exposure on Redshift 1.6 Cluster of Galaxies
Centaurus-A
Jet, hot gas, binaries and a shock

NASA/CXC/CfA/R.Kraft et al.
AGN Feedback in Clusters

Perseus cluster

Fabian et al. 2011

AXIS Science Leads: Chris Reynolds, Andy Fabian

Gaussian Gradient Magnitude filtered image (map the gradients in image to reveal fine structure)

Sanders et al. 2016
Main Science Questions from NWNH- Galaxies Panel

• How do cosmic structures form and evolve?
• How do baryons cycle in and out of galaxies
• How do black holes grow, radiate, and influence their surroundings?
• What were the first objects to light up the universe and when did they do it?
Connecting cluster outskirts to the Cosmic Web

Chandra Mosaic of A133 with point sources identified

Unsharp mask image showing excess surface brightness

AXIS Science Lead: Maxim Markevitch
Lots of other cool science!

Do you have ideas?

The Galactic Center

Tidal Disruption Events

Supernova Remnants

Relativistic Jets

Ultraluminous X-ray Sources

Deep fields
Wide Variety of Other Exciting Science

- Ultra luminous x-ray sources
- Searching for first black holes
- Relativistic Jets
- Deep fields
- Tidal Disruption Events
- Supernova Remnants
- The Galactic Center
Arp 220

PSF Deconvolution

1"
350 pc

6-7 keV
VLA 33 GHz

6-7 keV
IRAM PdBi CO 2-1

PSF Deconvolution

1"
350 pc

6-7 keV
LOFAR 150 GHz

6-7 keV
ALMA 2.6 mm
Sampling the PSF- NGC1068

Figure 1. (a) HRC image of the 7 arcsec across (500 pc) nuclear region of NGC 4258 frame time) of the same region, displayed at the native pixel (0.425). (d) The subpix of the native pixel (0.125). A 1'' scale bar is shown in all panels, corresponding to 1''. (A color version of this figure is available in the online journal.)

Wang et al 2012
X-ray Missions are Aging!

US 'x-ray' astronomy has
1 large mission (Chandra, 18 years old)
1 medium (Swift 13 years old)
2 small (Nustar and NICER)

Need to prepare proper successors to Chandra and Swift
**Dual AGN - The Progenitors of LISA Signals**

Out of 3114 VLBI imaged AGN, only one pc scale binary found

But most AGN are not radio loud...

Graham+15

Burke-Spolaor et al. 2011

AXIS Science Lead: Mike Koss
Multi-Wavelength Astrophysics

Almost every astrophysical object from comets to quasars emits/absorbs radiation over a very wide range of wavelengths.

Major advances in astrophysics require complementary sensitivity and angular resolution across the entire electromagnetic spectrum to answer the fundamental questions posed by Astro2010:

- How do cosmic structures form and evolve?
- How do baryons cycle in and out of galaxies?
- How do black holes grow, radiate, and influence their surroundings?
- What were the first objects to light up the universe and when did they do it?
Radio emission and Jets from AGN

Jets seem to be easy to form- fundamental assumption is that jets 'feed' the radio lobes

even when they are 'invisible'

random set of radio images (E. Hodges-Kluck)

Wide variety of shapes size, energies
• Jets occur in a wide variety of astrophysical sites (black holes, neutron stars, young stars, white dwarfs)
  – AGN
  – High and Low Mass Young Stars
  – Low Mass X-ray Binaries
  – Black Holes X-ray transients
  – gamma-ray bursts
  – symbiotic stars

• The jets size $\sim 10^{17}$ cm (young stars)
  $\sim 10^{24}$ cm very massive BHs
  – range of $10^7$ in size and more in energy

• jet formation mechanisms similar?
  but energetics and nature of jet (relativistic, non-relativistic) are very different

Direct evidence in x-ray emitting black hole binaries and young stars for a disk-jet connection

Often (where it can be measured) jet speed is $\sim$ escape speed from the object

Vela Pulsar
X-ray emission comes from within $10R_G$ around supermassive black holes.

X-ray half-light radii of quasars as determined from Chandra microlensing analysis versus their black hole masses. Chartas+2016
Building high redshift QSOs - constraints on growth rates and seed masses

- Assuming Eddington limited growth, black hole mass grows as:

\[ M_{\text{BH}}(t) = M_0 \exp \left( \frac{1 - \epsilon}{\epsilon} \lambda_{\text{Edd}} \frac{t}{0.45 \text{Gyr}} \right) \]

- The seed of ULAS J1120 (z=7.083, \( M_{\text{BH}} \approx 2 \times 10^9 M_\odot \)) could have formed by direct collapse at z~15, but requires growth at \( \sim \)Eddington limit for entire lifetime

- Pop III seed requires super-Eddington growth for substantial fraction of age of the Universe

N.B. extreme, rare object - not representative of bulk of early SMBHs and their growth
SMBH seed formation mechanisms

Gas

Dark matter

Pop III star remnants

First stars: maybe one star per galaxy, up to several hundred times larger than the sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

M_{BH} \sim 100 M_\odot
z\sim 20-30

Direct gravitational collapse

Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

The stellar core collapses into a small black hole, embedded in what is left of the star

M_{BH} \sim 10^5 M_\odot
z\sim 15

Stellar cluster collapse

Locally unstable gas flows toward the galaxy center

Gas fragments into stars, and a dense star cluster forms

Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

M_{BH} \sim 1000 M_\odot
z\sim 10

Grow by merging and accretion

M_{BH} \sim 10^6 - 10^{10} M_\odot
z\sim 6 and below

from Volonteri (2012)