Future NASA X-ray Astronomy Missions and Concepts

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NASA X-ray missions in the 2020’s: Takeaways

• NASA has one new X-ray mission under development for 2020’s – IXPE (Weisskopf talk)
• NASA is relying primarily on its existing fleet of missions and on collaborations with ESA and JAXA to advance X-ray astronomy
• Promising concepts exist for MIDEX class X-ray missions for the latter half of the decade
• CubeSats and SmallSats are emerging as a new opportunity
• NASA funded X-ray instrumentation has made substantial progress over the past decade
• The future of large NASA X-ray missions depends on the outcome of the 2020 decadal survey, now underway
  – Lynx
  – X-ray probe-class missions
NASA has only one X-ray mission under development – IXPE, scheduled for a 2021 launch and a two-year nominal mission. Mission extension likely if the baseline mission is successful. See M. Weisskopf talk.
NASA X-ray missions in the early 2020’s

- NASA has four X-ray missions in extended operations – Chandra, Swift, NuSTAR, NICER
- All were awarded three-year extensions until 2022 in 2019 Senior Review
- Fleet is aging: Chandra is 20 years old, Swift is 15
NASA is relying on foreign partnerships

- NASA relies on its successful partnerships with foreign space agencies like ESA and JAXA
- Partnerships on XRISM and Athena allow NASA to fulfill 2010 Decadal Survey goals related to IXO
Potential NASA missions in the 2020’s

- NASA’s astrophysics portfolio consists of competed and directed missions
- Competed missions are SMEX (~$145M), MIDEX (~$250M), MOO’s (~$70M), and SmallSats
  - Two SMEX and two MIDEX calls per decade, with accompanying MOO/SmallSat call
- Directed missions are large missions (e.g., Chandra) or medium (“probe-class”) missions (e.g., Fermi)
  - Directed missions are strategic, defined through the decadal survey process
- Any future NASA X-ray mission must be selected through either a MIDEX/SMEX call or by the decadal survey
Potential NASA missions - MIDEX

- NASA solicits Explorer mission proposals every 2.5 years
- One mission selected per solicitation
- Next call is for a MIDEX (PI led; ~$250M cost cap) in late 2021
- Several X-ray missions are likely to be proposed
- Two X-ray missions did well (but were not selected) in the 2016 round:
  - Arcus – high resolution grating spectroscopy in 0.2-1.5 keV band
  - STAR-X – 1 degree field of view, 5 arcsec imager for transient followup and surveys
Proposed Mission: *Arcus*
Exploring the Formation and Evolution of Clusters, Galaxies, and Stars

**SAO-led effort with an experienced team of institutions, scientists, and engineers:**

**Key Hardware Institutions**
NASA/Ames, MIT, Penn State, MPE & FAU

**Science Objectives**
- Where are the ‘missing baryons,’ and more generally, how does matter cycle in and out of galaxies?
- What powers the black hole winds that can impact entire galaxies and clusters?
- How do stars & circumstellar disks form and evolve?

**Why Arcus?**
*An Order of Magnitude Improvement in X-ray High-Resolution Spectroscopy*

- 2010 Decadal Review made X-ray spectroscopy high priority.
- Key science requires gratings; next large X-ray mission (ESA’s *Athena*, 2028) has no gratings
- Uses Silicon Pore Optics developed for Athena together with nanotech Critical Angle Transmission gratings to achieve efficient high-resolution X-ray spectroscopy.

Arcus will find the ‘missing matter’ at and beyond the edges of galaxies & clusters of galaxies.
Potential MIDEX – STAR-X

- Powerful telescope for discovering faint transients
- Mirror has 1° diameter FOV with uniform 5 arcsec HPD; 1,800 cm$^2$ @ 1 keV and 1,270 cm$^2$ @ 0.5 keV – best figure of merit for finding transients (like GW events)
- Fast slewing spacecraft to enable high cadence observations and fast response to ToO
- Low inclination orbit for low background and fast uplink
Smallsats and Cubesats

- CubeSats (<$5M) and SmallSats (<$35M) have become attractive throughout NASA – highly focused science objectives with modest mission lifetime at low cost
- X-ray astrophysics examples include:
  - HaloSat: CubeSat mapping the Galactic halo in OVII (deployed July 2018)
  - Cal X-1: SmallSat to provide absolute on orbit calibration of X-ray observatories
  - XQCSat: Calorimeter based SmallSat to study IGM

HaloSat
- Instrument
- Observed spectrum

XQCSat
- Simulated spectrum

Cal X-1
- Operations concept
Technology development towards a strategic NASA X-ray mission

- NASA has invested in technology development that can be used on a future strategic X-ray mission – met goals for IXO set in 2010

**Calorimeters**

Lynx prototype array (GSFC)

Resolution of ≤ 1 eV achieved

**Mirrors**

Single crystal Si mirror testbed (GSFC)

1.2” HPD measured

**Gratings**

CAT gratings (MIT)

Resolution of 10,000 achieved
Prospects for a strategic NASA X-ray mission

• Beyond the Explorer program and international partnerships, the future of NASA X-ray astronomy in the 2020’s depends on the outcome of the 2020 Decadal Survey of Astronomy and Astrophysics
• The 2020 Decadal Survey of Astronomy and Astrophysics is underway
• Report expected in late 2020
• The report will rank large (> $1B) and medium (~$0.5B-$1B) space and ground facilities
• Previous top ranked large missions include WFIRST (2010), JWST (2000), Spitzer (1990), Chandra (1980)
• NASA instituted studies for four large mission candidates:
  • Origins Space Telescope – large far IR observatory
  • LUVOIR – very large successor to HST with substantial terrestrial planet finding component
  • HabEx – terrestrial planet finder
  • Lynx – successor to Chandra
• NASA also instituted studies of 10 “Probe-class” (< $1B) missions, including two X-ray missions (AXIS, STROBE-X) and a multiband mission with an X-ray telescope (TAP)
Candidate Large NASA Missions for 2020 Decadal

- NASA supported thorough studies of four large missions.
- The 2020 decadal will prioritize these.
- Each mission costs $\geq 5B$

- Origins Space Telescope (far IR)
- Habitable Planet Explorer
- Large UV Optical Infrared Telescope
- Lynx (X-rays)
Lynx Capabilities

**Payload & Mission Characteristics**

- **Lynx Mirror Assembly**
  - 0.5" on-axis PSF, 2m² effective area at 1 keV, sub-arcsec PSF over a 22"x22" field of view.

- **High Definition X-ray Imager**
  - An active pixel array of fine pixels covering a 22"x22" field of view with subarcsecond imaging and providing moderate spectral resolution.

- **Lynx X-ray Microcalorimeter**
  - An array of 1" pixels covering a 5"x5" field of view and providing a 3 eV spectral resolution. Two additional arrays optimized for finer imaging and higher spectral resolution (0.3 eV in soft band).

- **X-ray Grating Spectrometer**
  - Gratings with resolving power of $R > 5000$ and $\sim 4000$ cm$^2$ of effective area across the critical X-ray emission and absorption lines of C, O, Mg, Ne, and Fe L.

**The Mission**

- Orbit: Sun-Earth L2
- Field of regard: 85% of the sky
- Consumables: sized for a 20 year mission
- JWST-like data volume
- Communication 3x daily with DSN
- >85% Observing Efficiency
**X-ray Probe Concepts**

- NASA funded 10 probe studies (out of >25 proposed)
- Two are X-ray specific; a third is multiband, including X-ray
- Several other X-ray probe concepts were submitted in white papers to decadal
- All probe missions will be considered equally

<table>
<thead>
<tr>
<th>Probe Study</th>
<th>Band</th>
<th>Closest Predecessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXIS</td>
<td>X-ray</td>
<td>Chandra</td>
</tr>
<tr>
<td>CDIM</td>
<td>Near-mid-IR</td>
<td>SPHEREx, JWST</td>
</tr>
<tr>
<td>CETUS</td>
<td>UV</td>
<td>GALEX, HST</td>
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<tr>
<td>Earthfinder</td>
<td>Near-IR</td>
<td>Ground-based radial velocity</td>
</tr>
<tr>
<td>GEP</td>
<td>Mid-IR, Far-IR</td>
<td>Herschel, Spitzer</td>
</tr>
<tr>
<td>PICO</td>
<td>CMB</td>
<td>Planck</td>
</tr>
<tr>
<td>POEMMA</td>
<td>Cosmic rays, neutrinos</td>
<td>Auger</td>
</tr>
<tr>
<td>Starshade</td>
<td>Optical/NIR</td>
<td>WFIRST</td>
</tr>
<tr>
<td>STROBE-X</td>
<td>X-ray, IR, gamma</td>
<td>RXTE, NICER</td>
</tr>
<tr>
<td>TAP</td>
<td>X-ray</td>
<td>WFIRST</td>
</tr>
<tr>
<td>Farside#</td>
<td>Radio</td>
<td>LWA, MWA, LOFAR, SunRISE</td>
</tr>
<tr>
<td>Exo-C*</td>
<td>Optical/NIR</td>
<td>WFIRST</td>
</tr>
<tr>
<td>Exo-S*</td>
<td>Optical/NIR</td>
<td>WFIRST</td>
</tr>
</tbody>
</table>

(From M. Elvis white paper)
Advanced X-ray Imaging Satellite (AXIS)

- X-ray imager with 10x Chandra area, much larger field of view
- Low earth orbit, low background for surface brightness studies; rapid response for transient studies

AXIS concept study at https://arxiv.org/abs/1807.02122
• Combines huge collecting area, high X-ray throughput, broad energy coverage, and excellent spectral and temporal resolution in a single facility.
• Characterize the behavior of X-ray sources over an unprecedentedly vast range of time scales.

STROBE-X concept study at https://arxiv.org/abs/1903.03035
• Rapid response, multi-band observatory for following up GW sources and other transients
• X-ray telescope and X-ray Lobster-eye, along with gamma-ray transient monitor and UVOIR telescope

**Table 2: Estimated rates of sources discovered by the TAP instruments.**

<table>
<thead>
<tr>
<th>Transient Type</th>
<th>WFI Rate (yr⁻¹)</th>
<th>XRT Rate (yr⁻¹)</th>
<th>IVUT Rate (yr⁻¹)</th>
<th>GTM rate (yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective 1 – X-ray, UV and IR Counterparts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to Gravitational Wave Sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW NS-NS (on-axis)</td>
<td>20</td>
<td>14</td>
<td>--</td>
<td>20</td>
</tr>
<tr>
<td>GW NS-NS (off-axis)</td>
<td>--</td>
<td>7</td>
<td>70</td>
<td>56</td>
</tr>
<tr>
<td>GW SMBH-SMBH (10⁷ Mₖ)</td>
<td>--</td>
<td>≥ 1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>GW SMBH-SMBH (10⁸ Mₖ)</td>
<td>Several in 5 yr</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Objective 2 – Highest Sensitivity Time-Domain Survey of the Transient Soft X-ray / UV Sky</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eSN shock breakout</td>
<td>1</td>
<td>19</td>
<td>--</td>
<td>6</td>
</tr>
<tr>
<td>Jetted TDEs</td>
<td>106</td>
<td>1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Non-jetted TDEs</td>
<td>1</td>
<td>48</td>
<td>--</td>
<td>40</td>
</tr>
<tr>
<td>AGN (daily / weekly)</td>
<td>120 / 660</td>
<td>1600 / 8700</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>High-z GRBs (z&gt;5)</td>
<td>25</td>
<td>--</td>
<td>22</td>
<td>--</td>
</tr>
</tbody>
</table>
• White papers for a number of other probe concepts were submitted for consideration by the decadal survey.
• Submitted concepts include:
  • The X-ray Grating Spectroscopy Probe
    • Similar science to Arcus – missing baryons, AGN outflows, stellar coronae
    • $\lambda/\Delta\lambda > 5000$, effective area > 1000 cm$^2$, at 653 eV, OVIII Ly$\alpha$
  • The High-Energy X-ray Probe
    • Successor to NuSTAR
    • Response 40 times that of any previous mission in the 10-80 keV band and > 100 times in the 80-200 keV band.
    • Science goals: Black hole growth over cosmic time; probing accreting compact object power sources; constraining stellar evolution endpoints
  • X-ray Polarization Probe
    • Successor to IXPE
    • Science goals: structure of inner accretion flow onto black holes; use neutron stars as fundamental physics laboratories; probe how cosmic particle accelerators work
    • Broadband polarimetry over the wide 0.2-60 keV bandpass in addition to imaging polarimetry from 2-8 keV
• An optimistic scenario leads to a healthy NASA X-ray astrophysics program for decades to come – long-lived extended missions, a MIDEX, a Probe, and Lynx
• Still a worrisome gap in the late 2020’s…
• A pessimistic scenario sees current fleet turned off in 2022, no X-ray MIDEX, no X-ray Probe, and Lynx deferred to a future decade.
• A more realistic scenario lies in between these two.
Prospects for 2020’s not unlike prospects for 2010’s. Then we were:
- Relying heavily on operating missions
- Waiting on small explorers (NuSTAR and GEMS)
- Relying on strong international partnerships (e.g., Astro-H)
- Waiting on decadal survey to recommend IXO

Technology advances over the decade improve the prospects for NASA X-ray missions to make major advances

New mission classes make possible a broader range of investigations
- Astrophysics Probes (assuming Decadal Survey recommendation)
- SmallSats/CubeSats

NASA will continue to rely on a mix of operating missions, small, medium and large new missions and strong international partnerships to maintain a strong X-ray astronomy program

Final note: X-ray astronomy is visible at the highest levels of NASA: weekly report by the Administrator highlighted a NuSTAR image of NGC 6946 featuring a flaring ULX