Some Chandra Facts

- The only X-ray observatory amongst those currently flying (and planned) that features sub-arcsecond angular resolution
- 2979 distinct PIs and CoIs in cycles 1-11
  - ~200 new PIs and Co-Is per year
- Involved more than 1350 students and postdocs
- After initial buildup now averaging over ~500 papers per year
- Has had a major impact (Trimble & Ceja 2008)

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Citations</th>
<th>Papers</th>
<th>Cites/paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra</td>
<td>16936</td>
<td>723.5</td>
<td>23.41</td>
</tr>
<tr>
<td>HST</td>
<td>15390</td>
<td>1063.1</td>
<td>14.48</td>
</tr>
<tr>
<td>VLA</td>
<td>8478</td>
<td>582.2</td>
<td>14.60</td>
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<tr>
<td>Keck</td>
<td>8122</td>
<td>356.6</td>
<td>23.33</td>
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<tr>
<td>XMM-Newton</td>
<td>7993</td>
<td>332.0</td>
<td>24.08</td>
</tr>
<tr>
<td>VLT</td>
<td>5696</td>
<td>345.5</td>
<td>16.49</td>
</tr>
<tr>
<td>AAT</td>
<td>4592</td>
<td>170.2</td>
<td>26.98</td>
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The atmosphere poses problems.
The early history

- Solar Studies in late 40’s
- Discovery of first extra-solar source in 1962
Where is the beef?

We know now that most of the matter that we “see” is from its X-ray emission.
The bulk of this matter is the hot X-ray-emitting gas in the great galaxy clusters.
How the optics work

Field of View ± 0.5 Deg
Focal Surface

Doubly Reflected X-rays
4 Nested Paraboloids
4 Nested Hyperboloids

10 meters

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter
How the optics look
The Observatory

- Solar Array (2)
- Spacecraft Module
- Sunshade Door
- Aspect Camera Stray Light Shade
- High Resolution Camera (HRC)
- Integrated Science Instrument Module (ISIM)
- Transmission Gratings (2)
- Low Gain Antenna (2)
- Thrusters (4) (105lbs)
- CCD Imaging Spectrometer (ACIS)
- High Resolution Mirror Assembly (HRMA)
The Crab never ceases to give us new insights!
The Crab never ceases to surprise!
The hunt for the site of the gamma-ray flare!
Chandra & Spitzer show radiation-driven implosion triggers star formation

- Gravitational collapse of cold gas common driver for star formation

- Collisions, tidal forces, supernova explosions, jets, and radiation from massive stars also trigger star formation.

- Can radiation trigger rich star formation?

- Cepheus B molecular cloud at 750pc

- Spitzer (red) detects diffuse emission and hundreds of stars

- Chandra (violet and white) selects young stars based on x-ray brightness

- IRAC and 2MASS colors identify young stars with proto-planetary disks

Chandra & Spitzer show radiation-driven implosion triggers star formation.

- **INNER LAYER**
  - 70-80% with disks
  - Age ~1 million yrs

- **INTERMEDIATE LAYER**
  - 60% with disks
  - Age ~2-3 million yrs

- **OUTER LAYER**
  - 30% with disks
  - Age ~3-5 million yrs

Chandra LETG spectra of Nova KT Eri explore nucleosynthesis under extreme conditions

- Nucleosynthesis in stellar interiors normally hidden
- Classical nova explosion due to thermonuclear runaway with $T \sim 10^8$
- Ejecta expand and thin with time revealing deeper layers, while photosphere evolves to lower R and higher T
- C, N, and O absorption features provide abundances
- N abundances several times C - reversal of usual ratio
- Data are fingerprints for TNR, testing models based on lab cross-sections
- High res spectra map complex velocity structures and inhomogeneities in outflow

Drake and Ness (2010)
Chandra's sub-arcsecond imaging reveals previously unseen features in SNR Cas A

Cassiopeia A

3-D reconstruction using Chandra, Spitzer, and optical telescopes indicates that asymmetries are intrinsic to explosion.

- Assume ejecta freely expanding from single point
- Distance proportional to velocity
- 3-D positions of features seen from different viewing angles
- See spherical component, torus-like tilted thick disk, and jets/pistons
- Asymmetries intrinsic to explosion

Delaney et al. (2010)
Chandra and SOAR/Gemini data show that ram pressure stripping of ESO 137-001 in Cluster A3627 transforms galaxy and leads to star formation in the ICM.

- Galaxy ISM stripped via ram pressure
- X-ray tails (blue) extend ~80kpc, \( L_X \sim 10^{41} \), \( M_{\text{gas}} \sim 10^9 \), \( T \sim 0.8 \) keV
- Outer layers of tails heated by 6 keV cluster gas via conduction, mixing, etc
- Stripping slows star formation in galaxy
- Follow-up H\( \alpha \) (pink) and GMOS show star formation in tails/ICM

Sun et al (2010)
Jets filling X-ray cavities
Jet enriches ICM with Fe from central galaxy

Kirkpatrick et al (2009)
Jet enriches ICM with Fe from central galaxy

Metallicity enhanced by ~60% along direction of radio jets and lobes extending from ~20-120 kpc

20% ±10% of Fe transported from central galaxy to ICM (2-7 $10^7$ M$_\odot$)

Energy required to lift gas is 1~5% of AGN output

AGN outbursts can enrich ICM

Kirkpatrick et al (2009)
Missing baryons imprint absorption signature on X-ray spectrum of background AGN

Key features are OVII and OVIII (1s-2p transition at 574 eV, Lyα line at 654 eV)
Demonstration of non-interacting dark matter

Clowe, Gonzalez, & Markevitch (2004)
Previous Chandra and XMM observations produced marginal WHIM detection.

![Graph showing normalized counts per second per Angstrom for XMM and Chandra observations. Peaks are labeled as OVII z=0 and OVII z=0.03.](image)
Deeper Chandra exposure provides firm detection of WHIM hot component (OVII)

Counts s$^{-1}$Å$^{-1}$

Wavelength (Å)

OVII $z=0$

OVII $z=0.03$

Fang et al (2010)
Chandra measures the cluster mass function demonstrating the impact of dark energy on the growth of structure.

\[ \Omega_M = 0.25, \Omega^\Lambda = 0, h = 0.72 \]

\[ \Omega_M = 0.25, \Omega^\Lambda = 0.75, h = 0.72 \]

\[ Z = 0.025 - 0.25 \]
\[ Z = 0.55 - 0.90 \]

\[ N(>M), h^{-3} \text{Mpc}^{-3} \]

\[ M_{500}, h^{-1} M_\odot \]

Vikhlinin et al (2009)
Chandra measurements of cluster mass function to constrain cosmological parameters

Vikhlinin et al (2009)
Chandra measurements of cluster mass function to constrain cosmological parameters

Vikhlinin et al (2009)
Combining all data sets yields $w = -0.991 \pm 4.5\% \text{ (stat)} \pm 4\% \text{ (sys)}$

For alternative gravity model $f(R)$ range of "fifth force" reduced by factor of $\sim 100$ to scales $\leq 40$ Mpc

Limits summed mass of light neutrinos to $\leq 0.33$ eV
In Sept 1963 laid out a proposal calling for, amongst other things 10m-focal length, ~arcsec angular resolution telescope of area > 400 cm²
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<th>Science</th>
<th>Goal</th>
<th>Observations</th>
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<td><strong>Dark Energy</strong></td>
<td>Measure the expansion history of the universe for 0.5&lt;z&lt;1</td>
<td>Take X-ray images &amp; spectra for massive clusters selected using SPT, ACT, and Planck Surveys</td>
</tr>
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<td><strong>Dark Matter Decay</strong></td>
<td>Search for evidence of decaying dark matter particles</td>
<td>Take X-ray images and spectra of galaxy clusters to test the evolution of $f_{\text{gas}}$ to z~1.2</td>
</tr>
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<td><strong>Missing Baryons</strong></td>
<td>Measure WHIM features to constrain the baryon overdensity</td>
<td>Obtain high-resolution spectra of quiescent blazars along lines of sight selected using COS and other instruments.</td>
</tr>
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<td><strong>AGN Feedback</strong></td>
<td>Determine how AGN feedback operates in galaxies and clusters of galaxies</td>
<td>Obtain deeper images of both galaxies and clusters as well as high-resolution spectra of selected bright AGN</td>
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<tr>
<td><strong>Accreting SMBHs, AGN unification, and the Cosmic X-ray Background</strong></td>
<td>Measure the luminosity and evolution functions for obscured and unobscured AGN</td>
<td>Extend the CDFS survey from 2 to 4 Mseconds to extend the survey to lower luminosities and higher z.</td>
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<td><strong>Metal Enrichment in Starburst Galaxies</strong></td>
<td>Trace evolution of temperature, density pressure and velocity of shocked material in very young SNR</td>
<td>Obtain deep images and spectra of a number of starburst galaxies to trace the metals and hot gas</td>
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<tr>
<td><strong>Evolution of Young Supernova remnants</strong></td>
<td>Measure mass and radius for bursting neutron stars</td>
<td>Take grating spectra of X-ray binaries in outburst</td>
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<tr>
<td><strong>Equation of state for Ultra-Dense Matter</strong></td>
<td>Extend mass and radius measurements for a number of neutron stars</td>
<td>Perform high-resolution spectroscopy to determine distances with burst data from other satellites</td>
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<td><strong>Formation of Protoplanetary disks</strong></td>
<td>Determine the lifetimes of the disks</td>
<td>Make simultaneous Chandra and ALMA observations of young star clusters</td>
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Observatory status

• Spacecraft is in excellent health – almost in the 13\textsuperscript{th} year
  – No safe-modes since first year of operations
• All redundant systems are available except one pair of gyro rotors that has been swapped to a backup.
  – One of the switched gyro rotors is fully healthy and the second has reserve life. Chandra can operate with one rotor from each set.
• Thermal insulation has slowly degraded
  – Some systems are warming
  – Requires increased pitch restrictions and limits on constrained observations
  – Focused mission planning effort has managed impacts
• There will (no doubt) be new challenges as Chandra ages
• However, overall observatory performance remains superb
• No known limitations to > 20-yr mission
The opportunity for exploration and discovery with Chandra remains as high as it was at launch.

http://chandra.harvard.edu