The *Chandra* X-ray Observatory

A better understanding of the universe

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X-ray Astronomy

- 50 years old discipline
- Must go above Earth atmosphere
- Direct window into the hot, energetic universe
- Probe of extreme physics
- NS equation of state
- Acceleration of cosmic rays
- Relativistic effects near the BH horizon
With *Chandra* X-ray astronomy has come of age

- 100 times better imaging than any other X-ray telescope, with pixel based spectral discrimination
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We can see motion!
Supernova Remnant Cas A - Patnaude et al 2009

$V_{exp} = 4200 \pm 500 \text{ km/s}$

Distance $\sim 10,000$ light years; Diameter $\sim 29$ light years
ΔT/10 years = 2.9% ± 0.5% stat ± 1.0% sys
⇒ 0.2%-0.3% cooling in 10 years expected through neutrino emission in the modified Urca process
⇒ fast cooling suggests superfluidity of nucleons in stellar core

Heinke & Ho 2010; Elshamouty et al 2013
The Crab Nebula

- Blue – Chandra
- Red and purple – Hubble and Spitzer
The Crab Nebula

7 *Chandra* images taken over several months - Hester et al 2002
see Weisskopf 2011 for review
X-ray emission is the natural way to probe the evolution of the universe

Gravity

Feedback
X-ray emission is the natural way to probe the evolution of the universe

- **Gravity**
  - Large masses in cosmic web, clusters, galaxies
    - $10^{12-14} M_\odot$
    - Virial $kT \sim$ keV range
  - Growth of MBH
    - Active Galactic Nuclei / QSO
  - Stellar evolution
    - Supernovae
    - NS, BH in X-ray binaries

- **Feedback**
  - Physical and Chemical
    - Star, SN, XRB
    - AGN
      - Jets
      - Winds
Outline

• 3 Threads through *Chandra* Science
  1. Chemical evolution from Supernovae to the inter-galactic medium
  2. Hierarchical merging evolution of galaxies and MBHs
  3. Large scale structures in the universe and Cosmology

• The Future - SMARTX
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Chandra Observations of SNRs
G292.0+1.8 – Oxygen rich SNR

- Distance: 20,000 light years
- 6 kpc
- 66 light years across

- Oxygen: yellow + orange
- Magnesium: green
- Silicon and Sulfur: blue

Hughes et al. 2001
Chandra/NASA Release 2014
Cas-A – Exploding star turned inside-out

Distance ~ 10,000 light years; Diameter ~ 29 light years

Hwang & Laming 2012
The Antennae
NGC 4038/9
D ~19 Mpc ~ 63 Million light years
~35 K light years across
The Antennae

NGC 4038/9

D ~19 Mpc ~ 63 Million light years

~35 K light years across

~63 Million light years
Chandra observations of the hot ISM of the Antennae
Baldi et al 2006a, b

\[ kT \sim 0.2 - 0.8 \text{ keV} \]
\[ M_{\text{gas(all)}} \sim 1.2 \times 10^7 M_\odot \]
\[ \tau_c \sim 10^{7.8} \text{ yr} \]
Red - Fe
Green – Mg
Blue - Si

Baldi et al 2006a, b
M82
Hot galactic wind

9.5 days of Chandra time
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Galaxy – MBH Evolution

- **Collapse**
  - Galaxy Formation
  - MBH Formation
    - accretion

- **Merging**
  - Galaxy
  - MBH
    - accretion

- **Feedback**
  - Stellar / Supernovae
  - AGN (accreting MBH)

Volonteri 2012 - Science
Merging Evolution.... The stellar View

What you can see through an optical telescope
Merging Evolution...Enter Chandra

NS, BH, and Million K gas
NGC 6240
D ~ 100 Mpc
~330 Million light years
200,000 light years

\[ M_{\text{gas}} \sim 1.3 \times 10^{10} M_\odot \]
\[ kT \sim 0.65 \text{ keV} \]
\[ T_c \sim 4 \text{ Gy} \]
\[ \alpha\text{-elements enriched} \]
• Core
  – steep profile
  – consistent with starburst wind

• Halo
  – cooler, quasi-isothermal
  – pre-existing?
  – Binding mass $\sim 10^{13} M_\odot$

Mgas $\sim 1.3 \times 10^{10} M_\odot$

kT $\sim 0.65$ keV

Tc $\sim 4$ Gy

$\alpha$-elements enriched

Nardini et al 2013
The Double Nucleus of NGC6240 - Merging MBHs
Komossa et al 2003

Distance ~ 330 Million light years
Nuclei separated by ~3,000 light years
NGC 6240
double AGN – *Chandra*
Hard emission
360 Ks ~ 4 days
Wang Junfeng et al 2014
NGC6240

circum-nuclear region

Hard power law + lines:
Fe Kα 6.4 keV
Fe XXV
Fe XXVI + Kβ

Scattered nuclear emission + kT~6 keV thermal emission

Strong winds/shocks
$V_{\text{shock}} \sim 2200 \text{ km/s}$
The shocks $V_{\text{shock}} \sim 2200$ km/s are from an extended region where intense star formation is occurring (Wang et al. 2014).

M$_{\text{FeXXV}} \sim 4 \times 10^5$ M$_\odot$

$\sim$ 10$^6$ SN

SN II rate $\sim$3/yr

Contours are H2 2.12 μm
Max 2005
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Inside Clusters of Galaxies –
Examples from Chandra Press Releases

ESO 137-001
A galaxy being stripped by the hot cluster medium
Tail ~100,000 light years

M87 – the central galaxy of the Virgo Cluster
Erupting MBH

Hydra A - 840 Mly
Cavities being blown by the MBH
Abell 520 cluster of galaxies – 2.4 Billion Light Year away – 5.2 Million light years across

Optical light – HST & CFHT
Abell 520 cluster of galaxies – 2.4 Billion Light Year away

Average galaxy density
Abell 520 cluster of galaxies – 2.4 Billion Light Year away
Hot Gas from Chandra – merging collision shocks – centered on DM clump
Abell 520 cluster of galaxies – 2.4 Billion Light Year away
Mass from lensing HST data
Abell 520 cluster of galaxies – 2.4 Billion Light Year away

DM and Galaxies do not trace each other

Jee et al 2012, 2014
X-ray emission line at 3.56 keV from the decay of sterile neutrinos?

From a new study of the central region of the Perseus galaxy cluster using NASA's Chandra X-ray Observatory and 73 other clusters with ESA's XMM-Newton

Bulbul et al 2014

Image is ~770,000 light years across
Cluster Mass Function consistent with $\Omega_\Lambda = 0.75$

Vikhlinin et al 2009
Dark energy constraints in a flat universe from the combination of all cosmological data sets. 

Vikhlinin et al 2009

\( w_0 = -0.991 \pm 0.045 \) (±0.04 systematic) and \( \Omega_X = 0.740 \pm 0.012 \)
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The Way Forward

We need to preserve *Chandra’s* resolution and band-width, while *increasing* effective area and spectral resolution

➡️ Square Meter Arcsec Resolution Telescope

➡️ http://smart-x.cfa.harvard.edu/doc.html
• SAO (Lead, Optics, Program Management)
• PSU (Piezo)
• MIT (Gratings)
• GSFC (Microcalorimeter)
• MSFC (Optics)
• JHU, Stanford, NIST/Boulder, U. Chicago
The X-Ray Telescope to Follow *Chandra*

- Angular resolution comparable to *Chandra*
- $\sim 2.5 \, \text{m}^2$ Mirror Effective Area
  - 30 – 100 times the Effective Area of *Chandra*
- Sub-arcsec imaging over $15' \times 15'$ f.o.v.
  - $\sim 50 \times$ *Chandra* survey f.o.v.
The Way Forward – SMART-X ‘straw-man’

**CMOS camera**
- 0.33” pixel
- 22’×22’ f.o.v.
- 33 ev @ 0.5keV – 120 eV @ 6keV

**Calorimeter**
- 1” pixel
- 5’×5’ f.o.v.
- <5 eV res.

**Gratings**
- A=4000 cm²
- Res. Power =5000

~10 × Chandra
Resolves thermal line widths

Vikhlinin et al
SMART-X mirror optical design

Fig. 1

- ×30 higher sensitivity: 4Msec Chandra Deep field depth reached in 80 ksec
- ×10 larger solid angle for sub-arcsec imaging
- Entire 20′×20′ field of view not source-confused down to CDFS limit
- ×500 higher survey speed at the CDFS limit
• **Map the high z universe** spatially and spectrally
  – The hot web, clusters and groups

• **Study MBH formation, merging and feedback**
  – Intense X-ray emission of ‘point-like’ sources will identify obscured AGNs out to $z = 10$
    • $10 \text{ keV} / (1+z) = 0.9 \text{ keV}$ for $z=10$

• **Study group evolution** out to $z=6$

• **Study galaxy evolution** out to $z=3$
  – Hot halo formation and physical/chemical evolution
  – AGN merging
  – Faint AGN
  – Evolved stellar population via compact binaries

• **Uncharted Local Universe**
  – Hot baryons in the Cosmic Web in emission and absorption
X-ray Deep Surveys
Angular Resolution is essential

- to go deep
- for matching the new class of large telescopes
X-ray Deep Surveys
Angular Resolution is essential

• to go deep
• for matching the new class of large telescopes

~ Athena
Path to large-area sub-arcsec mirrors

Vikhlinin et al
Piezo-controlled X-ray optics simulation

Current state of mirror development

ZnO transistors for row-column addressing

Strain gauges to control sub-arcsec imaging in flight
Piezo-controlled X-ray optics simulation

Aldcroft 2012 SPIE

Input distortion X

Adjustment using X

Residual

Mirror performance improved by a factor of 5 to 10

400mm x 200mm mirror segment with 20 x 20 grid of piezoelectric actuators

Factor of 30 zoom in color scale

Uncorrected

Corrected

Scatter intensity

Arcsec

SPIE 8503 T. Aldcroft 2012-Aug
Piezo-controlled X-ray optics simulation

Mirror performance improved by a factor of 5 to 10

Now × 10-30
From 12” to 0”.39
In summary....

• **With Chandra X-ray Astronomy has come of age**
  – We can directly study the hot evolving universe
    • Observe chemical evolution in the hot gas
    • Hierarchical merging evolution of galaxies and MBHs
    • Cosmology and large scale structures in the universe

• **Starting to plan for the next X-ray telescope**
  – We need a significant step forward