The Chandra X-ray Observatory
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In 1572, Danish astronomer Tycho Brahe recorded a 'new star' in the constellation Cassiopeia.

It was visible to the naked eye until 1574, slowly fading from view.
1 hour with Chandra
Milky Way galaxy: Supernova remnant (X-ray)

- 1 megasecond (11 days)
- Blue: Iron
- Red: Silicon
- Green: outer shock wave

**Cas A** with Chandra (Una Hwang)

11000 light years away

16 light years across
The Chandra X-ray Observatory

Launched 17 years ago 23 July 1999

A revolution in X-ray astronomy and astronomy in general
We are now in the era of multiwaveband astronomy.
Sources of X-rays

- Shock waves in plasma (ionized gas)
- “Synchrotron” caused by energetic particles in magnetic fields (like a natural particle accelerator)
- Energy release from gravity (“accretion” power)

Explosions: Supernovae and their remnants

Particles moving near the speed of light in magnetic fields

Matter falling into deep gravitational wells

In the optical, we see mostly energy from nuclear fusion
In X-rays, we see mostly accreting sources: energy from gravity!
Powerful sources of X-rays

A power source entirely different from the nuclear fusion that drives the Sun and stars

...and much more efficient
Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).

Visible light observable from Earth, with some atmospheric distortion.

Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio waves observable from Earth.

Long-wavelength radio waves blocked.
What is Chandra?

The greatest X-ray telescope ever built!
Orbits the Earth to be above the atmosphere (which absorbs X-rays, *luckily!*)
Goes 1/3 of the way to the Moon
every 64 hours (2 ½ days)
Chandra takes superbly sharp images:
with good spectral resolution (colors) too!
X-ray Telescopes are different

Chandra’s mirrors are almost cylinders
X-rays don’t reflect off a normal mirror – they get absorbed.
Only by striking a mirror at a glancing angle, about $1^\circ$,
do X-rays reflect.
Then they act like visible light
and can be focused

This makes for very long telescopes
The Chandra spacecraft

10 meters (32 ½ ft) from mirror to detector, 1.2 meters (4 ft) across mirror

...but focuses X-rays onto a spot only 25 microns across
Chandra science center
Smithsonian Observatory, at Harvard (Cambridge, MA)

Chandra mission control
Near MIT in Cambridge, MA

DSN control at Jet Propulsion Lab
Pasadena, CA

MAP of DEEP SPACE NETWORK

70km North of Barstow, CA USA
60km West of Madrid, Spain
40km SW of Canberra, Australia
The Milky Way Galaxy: Galactic Center

Milky Way in Sagittarius: 30000 Years Away
Seen as it was when modern humans had just evolved
NGC 1333
(Winston et al 2010)
Galaxy Centaurus A (NGC 5128) - 12 million light years away
Extragalactic Universe: Active Galaxy (X-ray)
Radio data on an even bigger scale

Feain et al
Australia Tel.

1.5 million light years end to end
We also see a big cloud of gamma rays

(Fermi data, Teddy Cheung)
Pictor A  (Hardcastle et al 2016)
MS0735.6+7421
z=0.22
Vantyghem et al
2014
MS0735.6+7421
z=0.22
Vantyghem et al
2014
Extragalactic universe:
Merging galaxy (visible light)
Merging galaxy Arp 220

- $z=0.018$ (250 million light years)
- Energy output: 1 trillion suns
- Most energy output in the infrared
- 20-year controversy: star formation or quasar?
- Answer: both, but mostly star formation
Arp 220 nucleus

- Deep in the galaxy, Chandra reveals:
  - a large region of newly forming stars (yellow)
  - a source of 'hard' X-ray radiation partly obscured by dust and gas, and coinciding with a pair of bright points seen with radio telescopes – at least one (and maybe 2) supermassive black holes at the very center of the galaxy
- Further from the middle, a bright X-ray binary star, probably with a black hole – brighter than any x-ray star in our galaxy
The Bullet Cluster, 1E0657-56

Two clusters in collision: studying this object let us measure the dark matter

Right: what we see directly in X-rays (red) and optical

Below: blue shows the matter distribution we infer

Extragalactic universe: Cluster of galaxies (X-ray, visible and dark-matter model)

Distance: 3.3 billion light years

Size: 3 million l.y.

Data: Maxim Markevitch et al.
Extragalactic universe:
Quasars (X-ray)

The Bootes survey

1000 supermassive black holes
X-ray satellites

SWIFT – Low Earth Orbit

Suzaku – Low Earth Orbit

Chandra

XMM – High Earth Orbit
NuSTAR

Launched June 2012

Just made first definitive measurement of a black hole spin rate – evidence for general relativity effects
ASTRO-H/Hitomi

RIP

Athena  (ESA 2028)

Astrosat  
(India)  
2015

Spektr-RG/ 
eROSITA  
2017??

SVOM (France/China) 2021?