The Imaging Chain in X-Ray Astronomy
Pop quiz (1):
Which is the X-ray Image?

A.

B.
Answer: B!!! (But You Knew That)
Pop quiz (2):
Which of These is the X-Ray Image?

A. B. C.

The dying star ("planetary nebula") BD +30 3639
Answer = C!
(Not So Easy!)

n.b., colors in B and C are “phony” (pseudocolor)
Different wavelengths were “mapped into” different colors.
1. X Rays from source are absorbed (or scattered) by dense structures in object (e.g., bones). Much less so by muscles, ligaments, cartilage, etc.
2. Most X Rays pass through object to “expose” X-ray sensor (film or electronic)
3. After development/processing, produces shadowgram of dense structures
   (X Rays pass “straight through” object without “bending”)
Lenses for X Rays Don’t Exist!

It would be very nice if they did!

Nonexistent X-Ray “Light Bulb”

X-Ray Lens

X-Ray Image
How Can X Rays Be “Imaged”

- X Rays are too energetic to be reflected "back", as is possible for lower-energy photons, e.g., visible light.
X Rays (and Gamma Rays “γ”) Can be “Absorbed”

- By dense material, e.g., lead (Pb)

Sensor
Imaging System Based on Absorption ("Selection") of X or $\gamma$ Rays

- Input Object (Radioactive Thyroid)
- Lead Sheet with Pinhole
- "Noisy" Output Image (because of small number of detected photons)
How to “Add” More Photons
1. Make Pinhole Larger

⇒ “Fuzzy” Image

Input Object
(Radioactive Thyroid w/ “Hot” and “Cold” Spots)

“Noisy” Output Image
(because of small number of detected photons)

“Fuzzy” Image
Through Large Pinhole
(but less noise)
How to “Add” More Photons
2. Add More Pinholes
• BUT: Images “Overlap”
How to “Add” More Photons
2. Add More Pinholes

• Process in Computer to Combine “Overlapping” Images

Before Postprocessing

After Postprocessing
BUT: Would Be Still Better to “Focus” X Rays

• Could “Bring X Rays Together” from Different Points in Aperture
  – Collect More “Light” ⇒ Increase Signal
  – Improves “Signal-to-Noise” Ratio of Measured Image
    • Easier to See Details
X Rays CAN Be Reflected at Small Angles (Grazing Incidence)

X Ray at “Grazing Incidence is “Deviated” by Angle $\theta$ (which is SMALL!)
Why Grazing Incidence?

- X-Ray photons at “normal” or “near-normal” incidence (photon path perpendicular to mirror, as already shown) would be transmitted (or possibly absorbed) rather than reflected.

- At near-parallel incidence, X Rays “skip” off mirror surface (like stones skipping across water surface)
Astronomical X-Ray Imaging

X Rays from High-Energy Astronomical Source are Collected, Focused, and Detected by X-Ray Telescope that uses Grazing Mirrors
X-Ray Observatory Must Be Outside Atmosphere

- X Rays are absorbed by Earth’s atmosphere
  - lucky for us!!!
- X-ray photon passing through atmosphere encounters as many atoms as in 5-meter (16 ft) thick wall of concrete!

[Diagram showing various observational techniques at different altitudes]

http://chandra.nasa.gov/
Chandra

Originally AXAF
Advanced X-ray
Astrophysics Facility

http://chandra.nasa.gov/

Chandra in Earth orbit (artist’s conception)
Chandra Orbit

- Deployed from *Columbia*, 23 July 1999
- Elliptical Orbit
  - Apogee = 86,487 miles (139,188 km)
  - Perigee = 5,999 miles (9,655 km)
- High above Shuttle ⇒ Can’t be Serviced
- Period is 63 h, 28 m, 43 s
  - Out of Earth’s Shadow for Long Periods
  - Longer Observations
Nest of Grazing-Incidence Mirrors

Mirror Design of Chandra X-Ray Telescope
Another View of Chandra Mirrors

Paraboloid Surfaces

Hyperboloid Surfaces

X-rays

Focal Point

X-rays
...And are “Gently” Redirected Toward Sensor...

n.b., Distance from Front End to Sensor is LONG due to Grazing Incidence
Sensor Captures X Rays to Create Image
(which is not easy!!)
X-Ray Mirrors

- Each grazing-incidence mirror shell has only a very small collecting area exposed to sky
  - Looks like “Ring” Mirror (“annulus”) to X Rays!

- Add more shells to increase collecting area: create a nest of shells
X-Ray Mirrors

- Add more shells to increase collecting area
  - Chandra has 4 rings (instead of 6 as proposed)

- Collecting area of rings is MUCH smaller than for a Full-Aperture “Lens”!
4 Rings Instead of 6…

• Budget Cut$ !!!
• Compensated by Placement in Higher Orbit
  – Allows Longer Exposures to Compensate for Smaller Aperture
  – BUT, Cannot Be Serviced by Shuttle!!
    • A Moot Point (at least for the moment)…
Resolution Limit of X-Ray Telescope

- ☺: No Problems from Atmosphere
  - But X Rays do scintillate much anyway

- ☹: $\lambda$ of X Rays is VERY Short
  - Good for Diffraction Limit to Angular Resolution

- ☹: VERY Difficult to Make Mirrors that are “Smooth” at Scale of $\lambda$ for X Rays
  - Also because $\lambda$ is very short
  - Mirror Surface Error is ONLY a Few Atoms “Thick”
  - “Rough” Mirrors Give Poor Images
**Chandra Mirrors Assembled and Aligned by Kodak in Rochester**

“4 Rings”
Mirrors Integrated into spacecraft at TRW, Redondo Beach, CA

(Note scale of telescope compared to workers)
On the Road Again...

*Travels of the Chandra mirrors*
Chandra launch: July 23, 1999

STS-93 on “Columbia” 😊
Sensors in Chandra

• “Sensitive” to X Rays
• Able to Measure “Location” [x,y]
• Able to Measure Energy of X Rays
  – Analogous to “Color” via:

  – High E \Rightarrow \text{Short } \lambda
X-Ray Absorption in Bohr Model

Incoming X Ray (Lots of Energy)
CCDs as X-Ray Detectors

1. Incident x-ray produces shower of electrons in selected pixels
2. Voltage moves electrons to the right to "count-out" row
CCDs as X-Ray Detectors

(3) Clocked voltage moves electrons out of count-out rate
(4) Computer reconstructs image (9 pixels)

CXC CCD's will have ~1 million pixels
Sensor

Advanced CCD Imaging Spectrometer (ACIS)
CCDs in Visible-Light Imaging

• Many Photons Are Available to be Detected
• Each Pixel “Sees” Many Photons
  – Up to 80,000 per pixel
  – Lots of Photons
    ⇒ Small Counting Error
    ⇒ “Accurate Count” of Photons
• Can’t “Count” Individual Photons
CCDs “Count” X-Ray photons

• X-Ray Events Occur Much Less Often:
  1. Fewer Available X Rays
  2. Smaller Collecting Area of Telescope

• Each Absorbed X Ray Has Much More Energy
  – Deposits More Energy in CCD
  – Generates MANY Electrons (1 e⁻ for every 3000 electron volts in X Ray)

⇒ Each X Ray Can Be “Counted”
  – Attributes of Individual Photons are Measured Independently
Measure Attributes of Each X Ray

1. Position of Absorption \([x, y]\)
2. Time when Absorption Occurred \([t]\)
3. Amount of Energy Absorbed \([E]\)

- Four Pieces of Data per Absorption are Transmitted to Earth:
Why Transmit Attributes \([x,y,t,E]\) Instead of Images?

• Too Much Data!
  – Up to 2 CCD images per Second
  – 16 bits of data per pixel \((2^{16} = 65,536\) gray levels\)
  – Image Size is \(1024 \times 1024\) pixels
    \[\Rightarrow 16 \times 1024^2 \times 2 = 33.6\) million bits per second\]
  – Too Much Data to Transmit to Ground

• Instead Make “List” of “Events” \([x,y,t,E]\)
  – Compiled by on-board software and transmitted
  – Reduces Necessary Data Transmission Rate
Image Creation

• From “Event List” of $[x,y,t,E]$
  – Count Photons in each Pixel during Observation
    • 30,000-Second Observation (1/3 day), 10,000 CCD frames are obtained (one per 3 seconds)
    • Hope Each Pixel Contains ONLY 1 Photon per Image

• Pairs of Data for Each Event are “Graphed” or “Plotted” as Coordinates
  – Number of Events with Different $[x,y] \Rightarrow “Image”$
  – Number of Events with Different $E \Rightarrow “Spectrum”$
  – Number of Events with Different $E$ for each $[x,y] \Rightarrow “Color Cube”$
First Image from Chandra: August, 1999

*Supernova remnant Cassiopeia A*
Processing X-Ray Data (continued)

• Spectra (Counts vs. $E$) and “Light Curves” (Counts vs. $t$) Produced in Same Way
  – Both are 1-D “histograms”
Example of X-Ray Spectrum

Gamma-Ray “Burster”
GRB991216

http://chandra.harvard.edu/photo/cycle1/0596/index.html
Chandra/ACIS image and spectrum of Cas A
Light Curve of “X-Ray Binary”

http://heasarc.gsfc.nasa.gov/docs/objects/binaries/gx301s2_lc.html
Processing X-Ray Data (cont.)

- Can combine either energy or time data with image data, to produce *image cube*
  - 3-D histogram
X-Ray Image Cube example: Space vs. Time

Central Orion Nebula region, X-ray time step 1
X-ray image cube example:
space vs. time

Central Orion Nebula region, X-ray

time step 2
Multiwavelength Astronomy

What do different wavelength regimes allow astronomers to “see”?
Electromagnetic radiation is everywhere around us. It is the light that we see, it is the heat that we feel, it is the UV rays that gives us sunburn, and it is the radio waves that transmit signals for radio and TVs.

EM radiation can propagate through vacuum since it doesn’t need any medium to travel in, unlike sound. The speed of light through vacuum is constant throughout the universe, and is measured at $3 \times 10^8$ meters per second, fast enough to circle around the earth 7.5 times in 1 second. Its properties demonstrate both wave-like nature (like interference) and particle-like nature (like photo-electric effect.)
A temperature-dependent “hierarchy” of states of matter

• Coldest (T < 100K)
  – dense molecular gas, ice-coated dust
• “Warm” (100K ≤ T ≤ 1000K)
  – warm dust & molecules
• Hotter: (1000K ≤ T ≤ 10000 K)
  – atomic gas (molecular bonds break down)
• Hotter still: (T > 10,000K)
  – ionized gas (electrons separated from nuclei ⇒ plasma)
Radio/Microwave Radiation

• Long $\lambda$
• Very penetrating
  – most matter is transparent to radio waves
• Probe of “coldest” matter (dense gas & dust)
  – Afterglow of “Big Bang” ($T \approx 2.7$ K)
• Probe of molecular gas
  – Many molecules were first detected in interstellar space via their radio radiation
    • carbon monoxide, water, hydrogen cyanide, ammonia, alcohol…
Mid- to Far-Infrared Radiation

- Very “penetrating,” e.g., through dust and gas
- Probe of “dust grains”
  - huge variety known, from giant molecules to grains of glass
- Most of known dust in universe emits in mid- to far-IR
  - Dust forms around dying stars
  - Dust congeals into planetary systems now forming around young, recently formed stars
  - Dust surrounds the massive centers of many galaxies
- Planets emit most strongly in mid- to far-IR wavelengths
M17 Star Cluster: Combination of Visible and Far Infrared Image
Near-infrared radiation

- Probe of “hot” dust and molecular gas
- Somewhat penetrating
  - $\lambda = 2 \, \mu m$ penetrates matter 10 times as far as visible light
- Probe of stars that are cool and/or surrounded by dust clouds
  - e.g., stars that have just formed and stars that are “kicking off” (starting to emit light)
Visible                Near-Infrared
Hot molecules and dust

Image mosaic of the NGC 6334 star formation region obtained with SPIREX/Abu telescope at the South Pole
Visible light

• Easily scattered by dust clouds

• Visible-light universe dominated by stars
  – Starlight can be detected directly (the stars themselves) or reflects from dust grains near stars
  – Stars are a primary constituent of galaxies, so distant galaxies are usually first detected in visible or near-IR light

• Gas ionized by UV from hot stars (and heated to about 10,000 K) also emits brightly in visible light
  – e.g., Great Nebula in Orion (M42)
Our Nearest (Galactic) Neighbor in visible light: a twin to the Milky Way?

M31
Andromeda Galaxy, Visible Light
Ultraviolet Light

• Short λ, easily scattered by atomic gas and by dust clouds
• Probe of hottest stars and ionized gas
  – Matter spiraling into massive objects (collapsed stars or centers of massive galaxies) emits strongly in the UV as it gets heated to T>10000 K
X Rays

• Highly energetic photons ⇒ highly penetrating
  – dust is nearly transparent to X rays
• Probe of cosmic "collisions" that produce plasma with $T > 1,000,000$ K
  – e.g., gas ejected at high speed from rapidly dying stars collides with gas that was ejected earlier and at lower velocity by same star
  ⇒ gas heated to X-ray-emitting temperatures
  – Most stars, especially young stars, have tenuous outer atmospheres (corona) that is sufficiently hot to emit X-rays
  – Many compact, massive objects thought to be black holes display X-ray emission
X Rays Indicate Explosive Events

Supernova remnant Cassiopeia A
Supernova Remnant Casseopeia A

X ray

Visible

Infrared

Radio
A Noisy “Neighbor” Galaxy

“Starburst” Galaxy M82 in Ursa Major
Images at Many Wavelengths are Needed to Find Newborn Stars

X Ray

Infrared

Central Region of M42 (Orion Nebula)
Exploding Sun-like Stars

Planetary Nebula BD +30 3639

Visible (Hubble Space Telescope)
Infrared (Gemini 8-meter telescope)
X Ray (Chandra)
New Discoveries of X Rays from Planetary Nebulae

NGC 6543
(The Cat's Eye Nebula)

NGC 7027

X Ray (Chandra)  Visible (HST)