ASTR469 Lecture 12: High Energy Astrophysics

1 High Energy Astrophysics

At this point we have covered wavelength regimes that use CCDs (optical, infrared, ultraviolet) as well as the radio regime. High energy astrophysics in the X-ray and gamma-ray regimes necessarily uses different detection techniques, and a few new emission processes.

1.1 Detection Techniques

The main difference in high energy astrophysics is that each photon is dealt with individually. For the other techniques we've discussed, we sum the emission from all the photons into one data set (image, spectrum, etc.). For high energies, we treat each photon as a quantum of data, an "event." We can measure the direction it came from using the location on the detector, its energy, and its time of arrival (among other properties). There are far fewer photons compared to other regimes, so retaining all these data for each event is feasible.

1.2 X-ray detectors

Just getting photons to the detector can be a challenge, however. We have previously treated the index of refraction as a given. Your book derives in Equation 8.62 the actual expression. In Chapter 11, your book notes that the refractive index for soft X-rays $\mu \simeq (1-\epsilon)^{0.5}$, where ϵ is some small value. We see from this expression that the index of fraction is slightly less than one. In this case, materials are transparent and X-rays simply pass through a mirror (as they do for your soft tissue). So how can we build a telescope? The most obvious answer would be to use lenses, but the focal lengths required are too great. Mirrors then! The solution is to use mirrors at low indices to gently guide the photons to the detector.

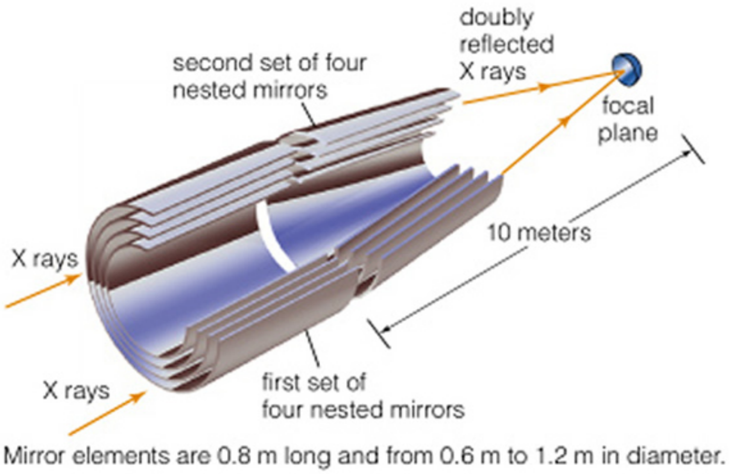


Figure 1: The mirror design for Chandra.

Real X-ray telescopes are built with "grazing indidence" angles of $\theta \simeq 89^\circ$. There are multiple sets of mirror surfaces that together focus the X-rays onto the detector. X-ray telescopes are generally not diffraction limited (diffraction limit is really small in the X-ray regime), and since they must be in space are also not seeing limited; the resolution limit instead comes from the optics and hardware. It's difficult to machine and align the mirrored surfaces with sufficient accuracy.

1.2.1 Notable X-Ray Telescopes

The Chandra X-ray Observatory Launched 1999
0.2 – 10keV
four pairs of nested mirrors
angular resolution of $0.5''$

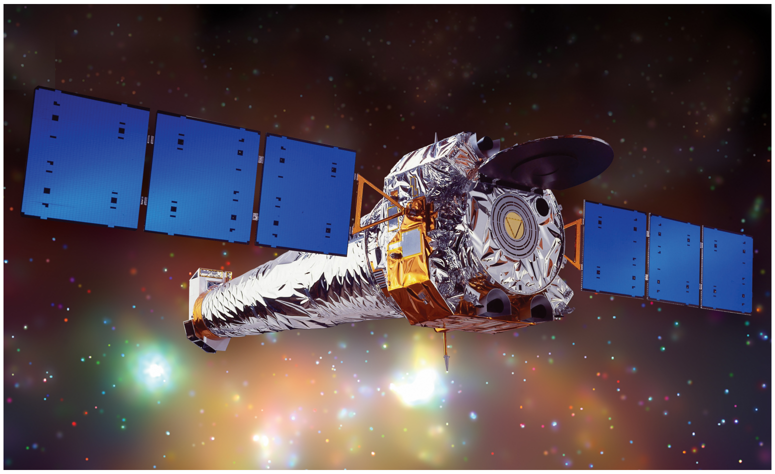


Figure 2: Chandra

XMM-Newton Launched 1999
Resolution $6''$
0.1 – 15keV
Larger field of view than Chandra

1.2.2 Gamma-ray detectors

Mirrors and lenses also don't work with gamma-rays very well, and we can't even use grazing mirrors. When a gamma-ray hits matter (like in a mirror or lens), it will interact with the material in such a way as to destroy the gamma-ray or change its energy by a large amount. This means that images we have from the gamma-ray region are not as sharp (that is, they have poorer angular resolution) than images taken in the visible or most other wavelengths.

The Compton Gamma Ray Observatory (CGRO) The CGRO was part of NASA's Great Observatories series, with the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope, was a space observatory detecting light from 20 keV to 30 GeV in Earth orbit from 1991 to 2000. It featured four main telescopes in one spacecraft covering x-rays and gamma-rays, including various specialized sub-instruments and detectors.

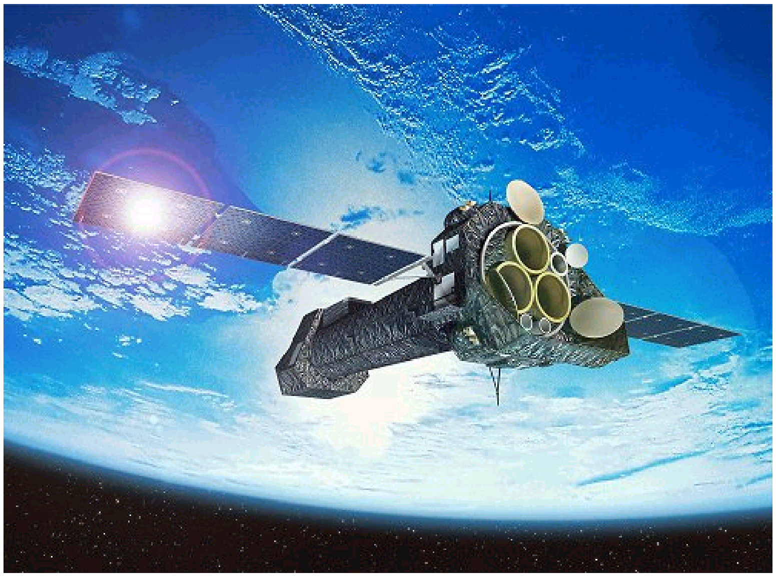


Figure 3: XMM-Newton

Fermi Gamma Ray Space Telescope
Launched 2008
150 keV to 300 GeV

Here, from Wikipedia on the detector for Fermi:
Large Area Telescope The Large Area Telescope (LAT) detects individual gamma rays using technology similar to that used in terrestrial particle accelerators. Photons hit thin metal sheets, converting to electron-positron pairs, via a process termed pair production. These charged particles pass through interleaved layers of silicon microstrip detectors, causing ionization which produce detectable tiny pulses of electric charge. Researchers can combine information from several layers of this tracker to determine the path of the particles. After passing through the tracker, the particles enter the calorimeter, which consists of a stack of caesium iodide scintillator crystals to measure the total energy of the particles. The LAT's field of view is large, about 20% of the sky. The resolution of its images is modest by astronomical standards, a few arc minutes for the highest-energy photons and about 3 degrees at 100 MeV.

1.3 Sources of High Energy Photons

Sources of cosmic gamma-rays produce relatively few gamma-ray photons for us to detect in the vicinity of Earth and thus require long observations, sometimes several weeks, to get a significant detection or accurate measurement of a source. A few processes that you hopefully are somewhat familiar with:

- Bremsstrahlung (free-free), discussed in radio lecture. The hotter the plasma, the higher the energy of the emitted photons.

$$\epsilon_{ff} = 1.4 \times 10^{-27} T^{0.5} n_e n_i Z^2 g_B \tag{1}$$

Figure 4: Compton

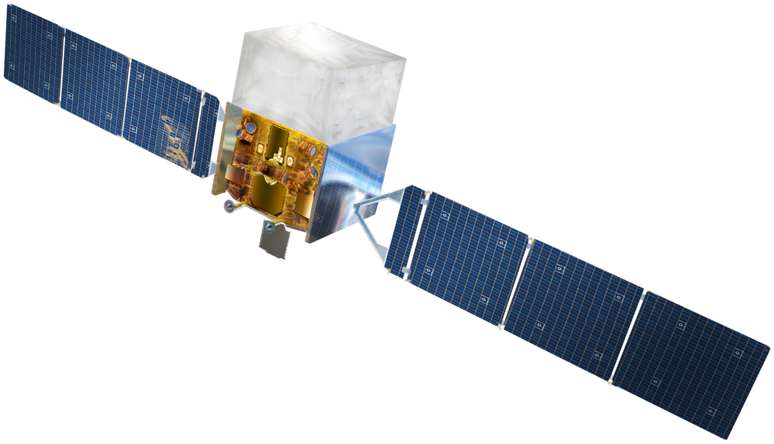


Figure 5: Fermi

- (Inverse) Compton scattering. You undoubtedly learned about Compton scattering in modern physics. In Compton scattering, a photon's wavelength changes after interaction with a free particle, usually an electron (they are moving much faster). Depends on energies of particles, photon production rate, particle density. If the photon loses energy, this is Compton scattering. If the photon gains energy, Inverse Compton.

- Synchrotron, discussed in radio lecture. Synchrotron is a non-thermal process, so the temperature of the electrons is not strongly related to the emission. Instead, we get

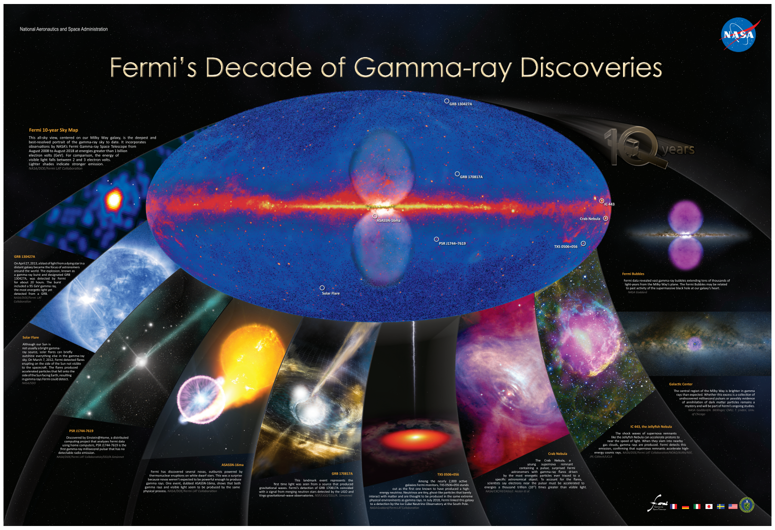


Figure 6: Fermi discoveries

X-ray emission from synchrotron if the magnetic field is strong.

- Electronic transitions. The electronic transitions we have talked about before have been relatively low energy. The higher the energy gap between levels in the electronic transition, the greater the photon energy. Large transitions result in high energy photons. We get large transitions from highly ionized species.

- Interactions between these processes. Of course, nature doesn't fit all emission into these neat categories and we often have multiple processes simultaneously. Synchrotron self-compton is probably most obvious where inverse-Compton scattering of synchrotron radiation by the same relativistic electrons that produced the synchrotron radiation.

What could cause such emission?

- Pulsars and magnetars.

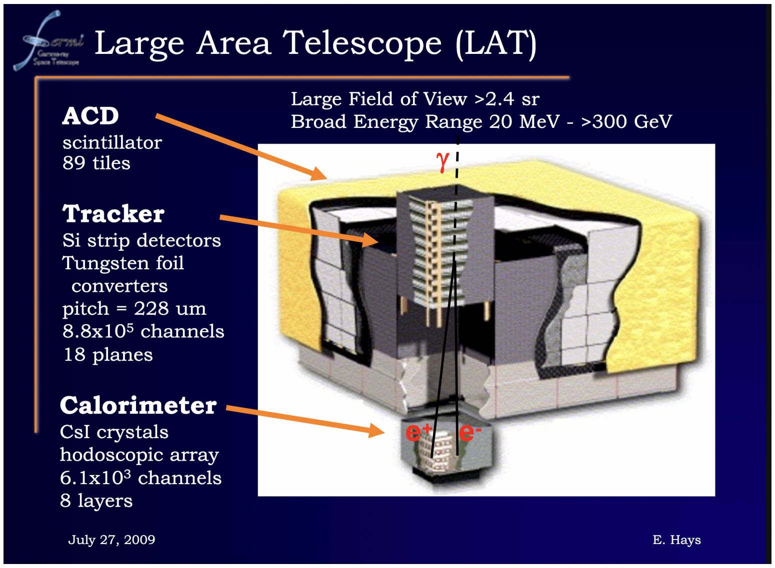
- Supernovae or neutron-neutron star collisions, neutron star/black hole collisions. These lead to "Gamma-ray bursts."

- "Active Galactic Nuclei," the actively accreting black holes at the center of galaxies.

- Massive stars (X-rays only) due to the interactions between stellar winds and ambient material.

- Supernova remnants

- Hot, free electrons



Large Area Telescope (LAT)

Large Field of View >2.4 sr
Broad Energy Range 20 MeV - >300 GeV

ACD
scintillator
89 tiles

Tracker
Si strip detectors
Tungsten foil
converters
pitch = 228 um
8.8x10^5 channels
18 planes

Calorimeter
CsI crystals
hodoscopic array
6.1x10^3 channels
8 layers

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Figure 7: LAT on Fermi