PHY2003 ASTROPHYSICS I

Lecture 4. Non-optical observing

The E/M spectrum

Thin gas will emit line radiation (atomic,molecular)

The radiation emitted by an opaque body (gas, liquid or solid) at a temperature T has a black-body spectrum. The wavelength at which most radiation is emitted is given by Wien's Law:

$$\lambda_{max} T = 2.9 \times 10^{-3}\,\mathrm{mK}$$

T	λ	Spectral range	Example
50K	60μm	Far-Infrared	Pluto
300K	10μm	Mid-Infrared	Earth
1,000K	3μm	Near-Infrared	Mercury
6,000K	500nm	Visible	Solar surface
30,000K	100nm	Ultraviolet	Hottest stars
1,000,000K	3nm	Far-UV/X-ray	Neutron stars/black holes

The Earth's atmosphere is only transparent to radiation in certain windows; optical, radio, parts of the near-IR and mid-IR.

Solution: Either use very high mountains, or space telescopes.

Sub-mm to Radio Telescopes

Radio emission has large wavelengths ($\lambda \sim 10$ cm), so therefore need large telescopes ($\theta = 1.22\lambda/D$)

Example: A typical optical telescope has an effective resolution of 1 arc-sec. What diameter radio telescope would you need to match this if observing at a wavelength of $\lambda = 21$ cm?

Jodrell Bank has a 76m dish, but $\theta_{min} \simeq 331$ arcsec!

To get better resolution, multiple telescopes are used together as interferometers. The largest UK radio interferometer is the MERLIN array, with antennae up to 217 km apart.

The telescopes "see" the sky as a series of interference fringes.

Two telescopes are separated by a distance L, which is a multiple of the observing wavelength λ, so $L = n\lambda$.

Take a source at a large distance. The pathlength from the source to antenna 2 is P_2 and to antenna 1 is $P_1 = P_2 + P'$.

$$P' = L \sin\theta$$

For constructive interference, P' must be an integer number of wavelengths, so

$$L \sin\theta = m\lambda$$

$$\sin\theta = m\lambda/L$$

As the Earth turns, θ also changes.

The fringes are evenly spaced at the angle for which $m = 1$. As θ is small:

$$\sin\theta \simeq \theta = \lambda/L = \lambda/n\lambda = 1/n$$

$$\theta = 1/n\,\mathrm{radians}$$

So the achievable resolution is dependant on the distance between the antennae alone. In Very-Long Baseline Interferometry (VLBI), radio telescopes around the globe are linked: $\theta \simeq 0.005$ arcsec.

Infrared Telescopes

IR telescopes are the same as optical telescopes, so use mirrors and photon-counting detectors. However beyond $\lambda = 2 \times 10^{-6}m\equiv 2\mu$m, thermal IR radiation from the detectors, telescope and the sky can swamp the faint signal from celestial objects. So sensitivity is the main problem, not resolution.

To get around this, we need to baffle optics, to make sure that only radiation from the sky enters the detector, not from the telescope. Also the detectors must be cooled using Liquid He ($T \simeq 4$K).

The largest IR telescopes are 8-m Gemini telescopes, but even at 14,000 feet they are heavily limited by the atmospheric background. The Stratospheric Observatory for Infrared Astronomy (SOFIA) uses a 2.5-m telescope within a Boeing 747 to observe at 40,000 feet.

The largest IR telescope in orbit now operating is the Spitzer Space Telescope (SST), with a 0.85m mirror. The successor to the 2.4-m Hubble Space Telescope will be the 6.5-m optical +IR James Webb Space Telescope.

X-ray/Far-UV Telescopes

At very short wavelengths, normal reflection optics do not work. This is because the wavelength of the photons $\lambda \leq 10^{-9}$m, so the incoming radiation 'sees' a rough surface and either scatters in random directions or is absorbed into the mirror.

X-ray telescopes using grazing incidence optics, where the photons hit the surface at a high angle of incidence and hence 'see' the atoms in the mirror much closer together.

The largest X-ray telescopes so far constructed are Chandra (NASA) and XMM-Newton (ESA), which have resolutions of $\sim 1 - 5$ arcsec.

γ-ray Telescopes

Gamma-rays are the highest energy photons recorded, and are often a signature of matter-antimatter annihilation. The same detectors are used as found in particle physics experiments. Largest recent space telescopes are Fermi (NASA) and Integral (ESA). The image resolution is ~ 30 arcseconds.

Non-E/M Telescopes

Cosmic rays - These are high energy protons, electrons and atomic nuclei that reach our Earth from interstellar and intergalactic space. The highest energy cosmic rays recorded have energies $> 10^{20}$eV, it is unknown how such energies are created, but acceleration of particles near super-massive black holes is the most plausible source.

Neutrinos - These are regularly detected from the Sun, and were detected from supernova SN1987A in 1987. The first dedicated neutrino telescopes are now operational, with the largest (called IceCube) forming a detector array 1km^3 under construction at the South Pole. Neutrinos have been recorded with energies $> 10^{15}$eV!

On 22 September 2017, IceCube detected an extremely high energy 290 TeV neutrino (2.9×10^{14}eV). Gamma rays with energies > 100GeV were detected coming form the same direction, galaxy TXS 0506+056 containing an AGN (active galactic nucleus). This showed that high-energy neutrinos are somehow generated by supermassive black holes.

Gravitational Waves - Einstein's General Theory of Relativity predicts that objects in high gravity fields can lose energy in the form of gravitational waves. Three ground-based gravitational-wave telescopes are now operational, using laser interferometers to measure changing path differences. The first detection of gravitational waves (from colliding black holes) was made on 15th September 2015. A space-based telescope (LISA) is planned for the 2020's or 2030's.

On 17 August 2017, a 100-second long gravity wave passed through Earth, 1.7 seconds before a burst of gamma-rays was also detected. These were tracked back to a collision between two Neutron Stars in the galaxy NGC4993, 44 Mpc distant. Analysis of the fireball spectra showed evidence for the thermonuclear production of heavy elements (heavier than Zirconium).