13 Observational Methods

13.1 Telescopes as light buckets

Stars are so far away that, of the several hundred *billion* in our galaxy, only about 5000 are visible to our naked eye. Even when the pupils in our eye are dark adapted, they have a maximum diameter of only about 7 mm, limiting the light reaching our retina. Telescopes provide a way to greatly improve on this by collecting the light from a much greater aperture, effectively acting as "light buckets". For a circular aperture of diameter D, the amount of light gathered scales in proportion to the collection area,

$$A = \frac{\pi}{4} D^2 \, . \quad (13.1)$$

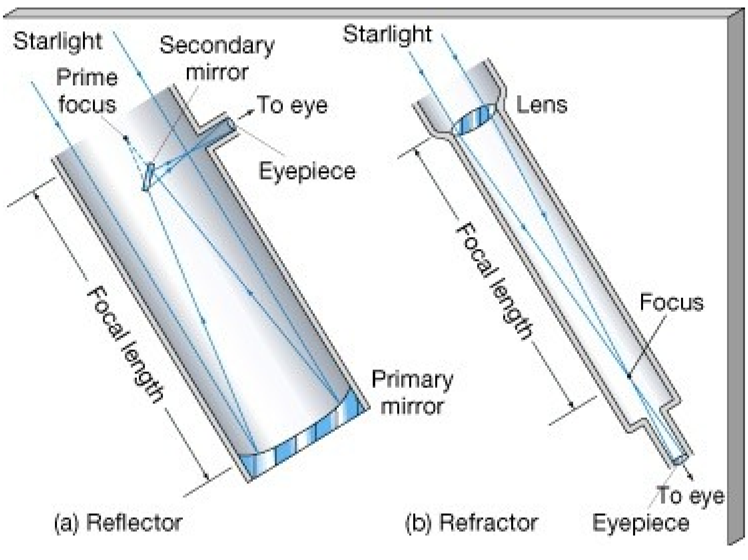

Figure 13.1 Illustration of basic differences between a refracting vs. reflecting telescopes.

As illustrated in figure 13.1, telescopes generally can be categorized as *refractors* vs. *reflectors*. Much like our eyes, refractor telescopes use a lens to bend incoming light into a focus; but such lenses can have a diameter up to about 100 times larger than our pupils, thus collecting 10,000 times as much light. For even larger lenses, housing the long focal length becomes unwieldy, and so this is near the practical upper limit for refractor telescopes.

But reflector telescopes, wherein light is collected by large primary mirror, can be built with much larger total apertures. The largest optical reflectors currently in operation have diameters about 10 meters[1], formed by combining ∼100 meter-size hexagonal mirror seqments. For example, a 7 m diameter mirror that is now a thousand times the aperture of our pupil can collect a *million* times as much light as our eyes.

Using the definition of magnitude from §3.3, this can be used to derive a general formula for the increase in limiting magnitude resulting just from an increased aperture,

$$m_{\rm lim} \approx 7.5 + 5\log(D/{\rm cm})\,. \tag{13.2}$$

Eqn. (13.2) does apply directly to amateur telescopes that are used to view the sky by eye. But in practice, large research telescopes use modern digital camera detectors with efficiencies that well exceed that of our retina. By also integrating the exposure for many minutes or hours, they can detect much fainter objects with magnitudes much larger than the aperture-based limit (13.2). In practice, the limit is often set by the background darkness of the local sky, one reason modern telescopes are built at remote sites, well away from the light pollution of cities.

Quick Question 1:

The human eye has an integration time $t_{\rm int} \approx 0.1$ sec, and a photon detection efficiency $\epsilon \approx 0.1$. Generalize equation (13.2) to estimate the $m_{\rm lim}$ for a telescope detector with higher values of $t_{\rm int}$ and ϵ.

13.2 Angular resolution

Another advantage to a large mirror diameter is that it enables a higher angular resolution. For light of wavelength λ, the diffraction from a telescope with diameter D sets a fundamental limit to the smallest possible angular separation that can be resolved,

$$\alpha = 1.22\frac{\lambda}{D} = 0.25\,{\rm arcsec}\,\frac{\lambda/\mu{\rm m}}{D/{\rm m}} = 2.5\,{\rm arcsec}\,\frac{\lambda/{\rm cm}}{D/{\rm km}}\,, \tag{13.3}$$

where the latter two equalities are scaled respectively for optical and radio telescopes.

For ground-based optical telescopes, this ideal diffraction limit is not generally reached, because turbulence in Earth's atmosphere blurs the image over

[1] The Extremely Large Telescope (ELT) currently under construction in Atacama desert in Chile will have diameter of 39 meters! First light is planned for 2025.

$\sim$1 arcsec or more, an effect known as "astronomical seeing". But this can be reduced to resolutions approaching 0.1 arcsec through a technique called *adaptive optics*, wherein reflection from a laser beam shot up into the sky is used to estimate these seeing distortions, and then dynamically deform secondary mirrors to correct for them.

The sharpest focus requires the primary mirror to have a *parabolic* shape. The primary mirror of the Hubble Space Telescope (HST) was mistakenly (and quite infamously) ground instead to a spherical form, leading then to a "spherical aberration" in images that had to be subsequently corrected by secondary optics. But with this correction, and despite the modest 2.4 m diameter of its primary mirrors, HST's location in orbit above atmospheric distortions and light pollution has helped it revolutionize observational astronomy[2].

Since radio waves can propagate even through the clouds that block visible light, large radio telescopes have been constructed even in locations with poor weather conditions. The radio reflector is now called a 'dish', with the largest ones (e.g., the 300-meter Arecibo telescope in Puerto Rico) built into natural depressions in the terrain, extending over hundreds of meters. Such dishes are not steerable, but by positioning the receiver around the focal plane they can effectively aim at a range of positions within 30^o from the local zenith. The largest steerable dishes range up to 100 m in diameter.

The Very Large Array (VLA) in New Mexico consists of 27 individual dishes that are each 25 m in diameter, positioned on tracks that can spread them over a baseline of up to 30 km. While the sensitivity is set by the combined collective area of the many dishes, a technique called *interferometry* combines their signals to give angular resolution associated with this wider baseline. An extension of this technique, called Very Long Baseline Interferometry (VLBI) can even combine signals from telescopes spread all around the globe; their diffraction limit can thus in principle approach that of a telescope the size of the entire Earth!

An impressive recent example is the Event Horizon Telescope (EHT), which used an array of two dozen telescopes to image the mm-wavelength emission around a black hole, with angular resolution near 25 *micro*-arcsec! The Atacama Large Millimeter Array (ALMA) consists of 66 antennas spread over up to 16 km of the very dry Atacama desert in Chile; the limited water vapor reduces the absorption of mm and sub-mm waves enough to allow detection in this intermediate waveband, which is key for, e.g., diagnosing conditions in star-forming regions that have many magnitudes of extinction (sectionss 12.3, 21.3, 22) at shorter wavelengths in the visible.

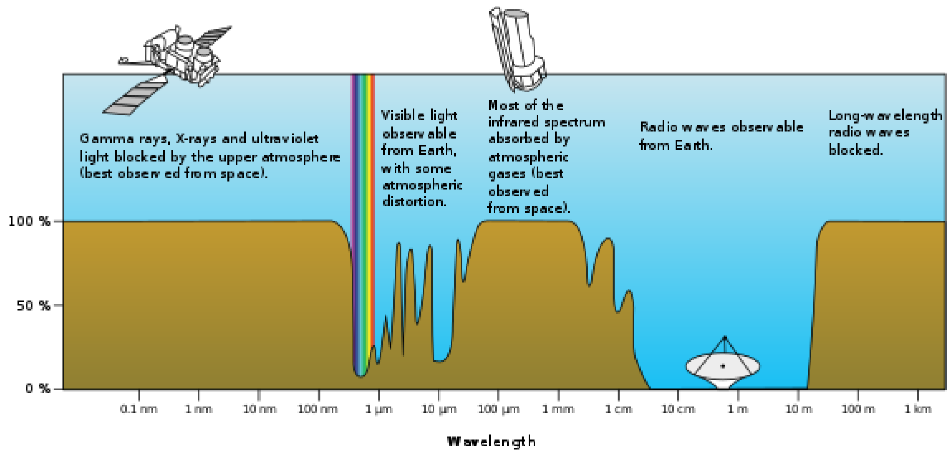

Figure 13.2 The percentage of electromagnetic radiation that is blocked by Earth's atmosphere, plotted as function of wavelength. Image credit: NASA.

13.3 Space-based missions

More generally, as illustrated in figure 13.3, Earth's atmosphere effectively *blocks* radiation in some spectral bands, e.g., at shorter wavelengths ($\lambda < 350$ nm) below the visible. Thus observations in these UV, X-ray, and gamma-ray regions can only be done from orbiting spaced-based platforms above the atmosphere.

The Hubble telescope has been a principal instrument in the near UV ($100\,\text{nm} < \lambda < 400\,\text{nm}$), allowing improved study of hot stars and warm interstellar gas with temperatures $10{,}000\,\text{K} < T < 100{,}000\,\text{K}$. (In the far and extreme UV ($10\,\text{nm} < \lambda < 92.1\,\text{nm}$), ionization by Hydrogen in the local interstellar medium largely attenuates radiation from any more distant sources).

At X-ray wavelengths ($0.10\,\text{nm} < \lambda < 10\,\text{nm}$), corresponding to high-energy photons ($0.1\,\text{keV} < E < 100\,\text{keV}$), telescopes probe very energetic regions with temperatures heated to millions of Kelvin, e.g. from accretion onto compact objects like neutron stars and black holes (§20.5), or hot interstellar bubbles that are shock heated by supernova explosions (§21.2).

At still shorter, gamma-ray wavelengths $\lambda < 0.01$ nm, with still higher photon energies ($E >$ MeV), detectors have discovered mysterious gamma ray bursts. The longer duration (> few sec) ones are now thought to arise from "hypernovae" associated with collapse of rotating cores of massive stars, while the shorter-duration bursts are understood to originate from the "kilonovae" associated with merger of neutron stars (§20.6).

Finally, orbiting telescopes have also been used for the part of the infrared

[2] Particularly noteworthy are the weeklong exposures allowed by its uniquely dark sky background; known as the Hubble Deep Fields, these exposures revealed huge numbers of very faint, very distant galaxies up to 10 Gly away.

blocked by the atmosphere. Such infrared observation are particularly key to studying cool dense regions of the interstellar medium where dust absorption leads to many magnitudes of extinction in visible light; these are often regions of active star formation (sections 12.3, 21.3, 22).

A full list of space-based telescopes is given at:
https://en.wikipedia.org/wiki/List_of_space_telescopes.

13.4 Questions and Exercises

Quick Question 1: a. The VLA works at radio frequencies 1-30 GHz. Work out associated wavelength range in cm. b. Then for D=30 km, work out the associated angular resolutions α, in arcsec.