

1 Lecture Telescopes and Instruments

- Read chapter 5
- Exercises: Do all “Review and Discussion” and all “Conceptual Self-Test”)

1.1 Optical Telescopes

- telescope is a “light bucket” – capture photons
- optical telescopes collect photons in the visible part of the spectrum
- long history – Galileo (early 17th century), primary astronomical instrument for over 350 years
- optical telescopes (lenses), best known by public, thus our starting point
- optical telescopes come in two main categories: Refractors and Reflectors
- Refractors
 - Based on the optical principle of refraction
 - think of the appearance of a straw bent in a glass of water (See Pic. 5.1)
 - lens in a refractor gathers and “concentrates” light – acts as many tiny prisms all bending the light to a Focus Point (See Pic. 5.2)
 - light “slows down” in glass – the speed of light is faster in air than in glass
 - the “speed bump” causes light to bend
 - eye piece used to magnify the image created at the focus point
 - cannot arbitrarily magnify for a number of reasons (we will see more details later)
 - light bucket can only collect a limited number of photons
- Reflectors
 - uses a mirror instead of a lens to gather light
 - light reflects off polished surface at the same angle at which it arrived (angle of incidence equals angle of reflection)
 - light rays all reflect to the (prime) Focus Point (see Pic. 5.3)
 - again, eyepiece required to magnify image at the prime focus
- Comparison of Refractors and Reflectors
 - light must pass through a lens for light gathering purposes with a refractor – leads to problems: attenuation (some of the light is “lost” by the glass, and chromatic aberration (it turns out that the “light speed bump” bump is different for different frequencies (wavelengths, or colours), blue light travels faster than red light thus creating a rainbow effect)

- reflectors do not suffer from these effects
 - large lenses for refractors can be very heavy, can deform with weight over time
 - refractors require that both surfaces of the lens be accurately machined – expensive and difficult
 - for these reasons *all* large optical telescopes for scientific investigation are based on reflector design (see Pic 5.6)
- Types of Reflectors
 - prime focus can be in an inconvenient place – need to move it
 - Newton (again!) used a secondary mirror – Newtonian reflector
 - Cassegrain, Nasmyth/Coude, Schmitt-Cassegrain – all move the focus with the use of secondary mirrors (and others) so that a viewing instrument (sometimes an eye) can more conveniently view the image (see Pic 5.7 5.8)
 - Keck – mirror arrangement can be made at the Cassegrain, Nasmyth or Coude focus depending on the viewing needs
 - Hubble Space Telescope (HST) – Cassegrain telescope launched by the space shuttle Discovery, 1990 (optical, infrared, and ultraviolet (see Pic 5.9)
 - Telescope Size
 - modern instruments much larger than Galileo’s simple design
 - increases in ability come from two main sources: light gathering power (how big the light bucket is), and resolving power (angular separation of small details)
 - large telescopes by construction have large collecting areas – the larger the primary mirror, the more photons can be gathered from the source
 - more photons means more information from the radiating source
 - observed brightness \propto area of “light bucket”
 - until 1880s, astronomers thought that telescopes with mirrors larger than 5m or 6m would be too expensive/difficult to make
 - new technologies and mirror design have led to effective surfaces in the 8m to 12m range! – e.g. Keck has 36 hexagonal mirrors that lead to an effective surface area of 10m (see Pic. 5.11), Subaru, 8.3m European Southern Observatory (VLT) uses four 8.2m reflecting to give an effective diameter of 16m!
 - large telescopes – more light but also solve other problems – resolving power
 - large telescopes can separate images that are close together in the field of view (see Pic. 5.13)
 - limits to resolution – diffraction, wave property of light
 - angular resolution $\propto \lambda/D_{\text{mirror}}$

- quest: to construct instruments that are diffraction limited (not limited by other problems) – hard to do!
- Imaging
 - need to store images – imaging and detectors
 - early days – sketches in notebooks
 - late 1800s most of 1900s – photographic plates
 - computers today play a critical role: image with the whole EM spectrum
 - CCD (charged coupled devices technology) – the photoelectric effect at work!
 - solid state devices that record light by building up electric charge in pixel arrangement
 - computers used to eliminate noise clean up image (systematic effects etc.)
 - astronomers also use colour filters to examine narrow parts of the spectrum so that blackbody curves can be determined
 - recall that the spectrum from the object allows astronomers to determine chemical composition (see Pic 5.16)
 - high resolution astronomy has other problems – earth’s atmosphere!
 - atmosphere causes blurring of star light – refraction causes by temperature gradients (turbulence) in the air cause the starlight to “dance”
 - astronomers use the term seeing to refer to the turbulence in the atmosphere
 - light from object is spread over a seeing disk
 - additional problems – light pollution
 - reduce both effects by building telescopes on secluded mountain tops
 - HST diffraction limited at $0.05''$, while best telescopes on earth are limited by the atmosphere at about $1''$ ($20\times$ worse)
 - just because the atmosphere won’t cooperate doesn’t mean defeat!
 - active optics and real time control systems
 - computers can correct for noise in real time, compensating for the atmosphere
 - the methods also correct for mechanical vibration and thermal fluctuations and other instrument effects
 - some methods use a laser to create an artificial star that allows astronomers to gauge the atmosphere and compensate with mirror adjusting software (mostly used with IR instruments because atmospheric effects are smaller – visible band experiments underway, approaching the diffraction limit of the instruments themselves)

1.2 Radio Astronomy

- earth also receives radio band radiation
- not limited to viewing the sky with the light our eyes can detect
- radio window wider than visible window – atmosphere presents little challenges as compared to optical frequencies (see Pic. 3.9)
- radio astronomy started in 1931 with the work of Karl Jansky at Bell Labs
- experimenting with shortwave radio he found that the centre of our galaxy is a source of radio radiation
- William Herschel in the early 1800s had discovered “dark regions” absent of stars
- by 1940s scientists realized that the space between stars was filled with low density diffuse gas and that this gas was also a source of radio waves
- most radio telescopes have a huge curved metal dish that collects radio waves and focuses them onto a receiver at a focus point – signals processed by a computer
- large size required because sources are faint – need large collecting areas
- radio dishes need not be as smooth as optical mirrors – wavelengths in the 1cm range (smoothness required at the scale of the wavelength studied); see Pic 5.23, 5.24
- radio astronomy gives poor resolution compared to optical instruments – but still very valuable, another window into the universe
- not limited to night-time studies – can view while the sun is above the horizon
- can map gas clouds around objects – interstellar medium; see Pic 5.26
- can also see through dusty areas that obscure other forms of radiation – complementary observations
- radio studies reveal interesting quantum phenomena too difficult to produce in the lab
- 21cm line allows astronomers to study interstellar gas
- hyperfine structure, spin flip produces 21cm wavelength – metastable state too difficult to set up in the lab!
- radio astronomy suffers from lack of angular resolution
- solution: Interferometry
 - use a number of radio telescopes together to view the same object at the same wavelength at the same time – combine all observations

- more than just a combination – use interference effects (see Pic. 5.27, 5.28)
- create an effective huge antenna from array – increase angular resolution, in some cases 0.001”!
- interferometry possible at other wavelengths, VLT in IR spectrum

1.3 Space Based Astronomy

- optical and radio astronomy oldest types – today entire EM range studied
- atmosphere not transparent to most forms of radiation – need to get above the atmosphere
- study radiation sources that we otherwise could not
- Infrared
 - possible to study with ground base equipment – greater range in space
 - HST has IR capability – other examples: IRAS (1983) SITF (2003) – IR telescopes must be cooled, limit thermal noise (telescope is a noise source)
 - see Pic. 5.32
- Ultraviolet
 - higher frequency than visible light – earth’s atmosphere almost totally opaque to UV radiation
 - space based observations required e.g. IUE (1978), EUVE (1992), GALEX (2003), HST (see Pic. 5.34)
- High energy astronomy: X-rays and Gamma rays
 - highest energy photons – atmosphere opaque – direct study requires space based observations
 - high energy photons difficult to focus
 - X-ray telescopes use grazing optics to focus X-rays (see Pic. 5.35)
 - CCDs or photographic plates do not work well with hard photons – individual photons counted by electronic detectors on satellite
 - Chandra X-ray observatory – study X-ray emitting gas: Bullet cluster, important discovery – dark matter!
 - need a lot of time to build up images – few photons
 - Gamma ray astronomy studies the highest energy sources in the Universe
 - e.g. Compton Gamma-ray Observatory (1991)

- gamma ray astronomy often undertaken indirectly – gamma rays colliding in the atmosphere create a shower of charged particles
- charge particles leave a special shower trail of light in the sky (Cherenkov radiation) that allows astronomers to re-construct the gamma ray event
- projects include HESS and MAGIC
- gamma ray astronomy used to help understand the origin and phenomenology of the production regions – connection with particle physics
- now see the sky with the entire em spectrum (see Pic. 5.39)
- The new frontier: neutrinos and gravity
 - new ideas/methods to observe the universe – no longer confined to em radiation
 - neutrinos – fundamental particles that only interact through the weak nuclear force – very weakly interacting!
 - neutrinos produced in nuclear reactions – can be detected with large amounts of material (e.g. water, heavy water, dry “cleaning fluid”)
 - difficult but possible – noble prize 2002 for detection of astrophysical neutrinos
 - help us understand supernova events, the processes in the sun, and even neutrinos themselves (neutrino mass)!
 - observatories include super-kamiokande, SNO (see Pics in class)
 - according to Einsteins theory of gravity, gravitational waves should be produced by certain types of astrophysical processes
 - LIGO – current observatory looking to detect gravitational radiation!
 - perhaps one day, view the universe with neutrinos and gravitational radiation in the way we make observations with em radiation!