**Stars and Galaxies: Observational Techniques**
**Lecture 1 – Introduction**

## Aims

To motivate the need for astronomical instrumentation and observations, and to review basic observational techniques.

## Objectives:

By the end of the lecture you should be able to:
- justify why astronomy instrumentation is important
- develop appreciation of range of todays astronomical images
- describe the historical advances in astronomy instrumentation
- describe basic observational techniques of:
  - star coordinates
  - angular sizes
  - fluxes and magnitudes

## Important Facts:

- Star and Galaxy Coordinates – Right Ascension (RA) is equivalent of terrestrial longitude. RA is measured in degrees ($0 < RA < 360\,\mathrm{deg}$) or hrs, mins, secs ($0 < RA < 24\,\mathrm{hr}$). Declination (Dec) is equivalent of terrestrial latitude and measured in degrees ($-90 < \mathrm{Dec} < +90\,\mathrm{deg}$).

- Angular size of celestial objects (e.g. moon, galaxies) on the sky are measured on great circles on the celestial sphere. Angular size measured in degrees, arcminutes and arcseconds (1 degree = 60 arcminutes = 3600 arcseconds).

- The flux of a star or galaxy is measured in $\mathrm{W\,m^{-2}}$. Flux is also commonly expressed on the (relative) logarithmic "magnitude" scale.

- The apparent magnitude system relates the intensity (or flux) from one astronomical object to another using a logarithmic scale. The absolute magnitude relates to the luminosity of an object. The absolute magnitude defines how bright an object would be if placed at a distance of 10 parsecs.

## Important Formulae:

**Angular Size:** Using the small angle approximation, the actual size of an object, (D) = distance to object ($d$) × Angular size. i.e. $\mathrm{D} = d\theta$ (where $\theta$ must be in radians).

**Apparent Magnitude** If two stars have fluxes, $f_1$ and $f_2$, then their apparent magnitude difference is $m_1 - m_2 = -2.5 \log(f_1 / f_2)$.

Absolute Magnitude ($M$) is related to apparent magnitude ($m$) by:
$M = m + 5 - 5 \log(d)$
where $d$ is the distance in parsecs.

**Important numbers:**
$G = 6.67 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$
Suns mass: $\mathrm{M_\odot} = 1.99 \times 10^{30}\,\mathrm{kg}$
Suns luminosity: $\mathrm{L_\odot} = 3.84 \times 10^{26}\,\mathrm{W}$
Suns absolute magnitude ($V$-band) = 4.8mag
1 parsec = 3.26 light years = $3.09 \times 10^{16}$ m
1 light year = $9.5 \times 10^{15}$ m

## Lecture 2 – Telescopes

**Aims:**

To briefly review the basics of ray diagrams for lenses and mirrors and their application to telescopes, and then to review the design of modern ground based observatories and telescopes.

**Objectives:**

By the end of the lecture you should be able to:
• recall basic geometric optics; focal length; real and virtual images; lens makers equation; magnification and their application to telescopes.
and have some understanding of:
• why we build large telescopes
• why modern telescopes all reflective
• what the main two telescope mounts are and how they compare (advantages / disadvantages)
• what are the Prime, Cassegrain, Coude and Nasmyth telescope foci and how do they compare
• what is meant by angular resolution, plate scale, effective focal length

**Important Facts:**

• Why do we build large telescopes? In the mid-1990s astronomers started building larger telescopes since this was only way to gather more light (e.g. the Keck 10-meter telescope on Mauna Kea in Hawaii, or the ESO VLT 4-meter Telescope at Cerro Paranal in Chile).

• Large aperture improves spatial resolution since in the diffraction limited case, $\theta = 1.22\,\lambda\,/\,D$. Large aperture + high resolution results in high signal-to-noise (S / N).

• Energy / unit area in image $\propto$ Light Grasp / Resolution$^2 \propto \mathrm{D}^4$ where $D$ is mirror diameter)

• Refractors: Large lenses are not fast therefore refractors are very long and so rarely used as big telescopes. Lenses also sag under their own weight and it is difficult to keep refractive index constant over large piece of glass. Glass also suffers from dispersion (chromatic aberration) + absorption.

• Reflectors: Only one surface needs to be of good quality, and full area can be supported. Single mirrors up to 8 m diameter have been built (e.g., Gemini and VLT). Segmented mirrors have been built up to 10 m (e.g., Keck); modern primary mirrors can be fast (f/3) (and hence relatively compact).

• Reflectors have parabolic mirrors to avoid spherical aberration.

• Telescope foci include: Prime (wide field), Cassegrain (multi-purpose), Coude (equatorial, heavy instruments), Nasmyth platform (Alt-Az, heavy instruments).

• Effective focal length of a telescope is the focal length of a single lens / mirror with the same f-ratio as the final beam.

• Equatorial Telescope Mount: One axis points at Celestial Pole and rotates to track star at fixed Declination. Other axis moves to change Declination.

*Advantages*: only 1-axis must be controlled (RA); tracking rate is constant; star field does not rotate with time.

*Disadvantages*: large, bulky, expensive; gravity-vector on attached instruments is harder to predict.

• Alt-Azimuth Telescope Mount: One axis moves in horizontal direction (azimuth) and one in vertical (altitude)

*Advantages*: simpler and more compact to construct; Nasmyth platform available,

*Disadvantages*: Non-uniform tracking speed; requires 2 axes controlled; requires image de-rotator.

**Important Formulae:**

**Lens makers equation:** $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$ where $f$ is the focal length of the lens, $u$ is the object distance and $v$ is the image distance ($v$ negative if image is virtual).

**Linear magnification:** $M = -v \,/\, u$

**Angular magnification:** $M = \beta \,/\, \alpha$ where $\alpha$,$\beta$ are the incoming and outgoing angles for a source at infinity.

**focal length of of lenses:** $\frac{1}{f} = \left(\frac{n-1}{R_1}\right) + \left(\frac{n-1}{R_2}\right)$ where $n$ is refractive index of glass and $R_1$ and $R_2$ are radii of surfaces.

**$f$-ratio:** f / # = focal length / aperture= = $f \,/\, D$

**Angular Resolution:** For circular aperture, the Rayleigh limit is $\theta = 1.22\,\lambda\,/\,\mathrm{D}$

**Plate scale:** $d\theta \,/\, ds = 1 \,/\, f$

**Important numbers:** 1 radian $= (180\,/\,\pi) \times 3600 = 206265$ arcseconds.

**Lecture 3 – Atmosphere and Detectors**

**Aims**

To study the effect of the atmosphere on astronomical observations and to review the key specifications of CCD detectors.

**Objectives:**

By the end of the lecture you should understand the meaning of the terms:
• Atmospheric absorption
• Atmospheric refractive index
• The emission of light by the atmosphere
• Atmospheric Seeing
and also be able to describe CCD specifications:
• quantum efficiency; read noise; bias; dark noise; well depth; resolution, system gain and ADUs and Quantum efficiency

**Important Facts:**

• **Effects of the atmosphere:** The atmosphere scatters, absorbs, refracts and disperses the electromagnetic radiation passing through it. The atmosphere also emits thermal and also fluorescent radiation.

• **Scattered Light:** Scattered light occurs from Rayleigh scattering (atomic X-section) the amplitude of which is proportion to $1 / \lambda^4$; i.e. blue light scatters more than red (hence the sky is blue).

• **Seeing** Optical images are "smeared" by atmospheric turbulence.

• **Atmospheric absorption:** absorption of radiation is dominated by $CO_2$ and $H_2O$ molecules in the atmosphere. The atmosphere is transparent in the optical, near-infrared and radio windows, but opaque almost everywhere else.

• **Atmospheric refraction:** depending on the zenith distance, there is an apparent shift in position of stars due to refraction. This is important for astrometry, and causes 4 extra minutes of daylight as the Sun crosses the horizon. This also causes the apparent flattening of the Sun (and moon) at the horizon.

• **Atmospheric dispersion:** is caused by variation of refractive index with wavelength, and elongates image by dispersing light into a spectrum.

• **Atmospheric Emission:** Fluorescent airglow (emission from molecules in the atmosphere) is major cause of atmospheric emission. Thermal black body emission from sky and the telescope also important in the infrared.

• **Atmospheric turbulence:** Temperature fluctuations lead to refractive index fluctuations which distorts initial plane wave from a source at infinity. An image of a point is no longer an Airy disk but lots of (moving) point sources due to the atmosphere. This causes a severely blurred spot, which is known as atmospheric seeing.

• **Observatory sites selection:** needs clear skies, good seeing, dark sky, little water vapour. Best sites are therefore remote, dry, mountain top sites.

**CCD Technology:**
• **CCD detector:** Charge Coupled Device, Silicon (Si) microcircuit with pixels with typical sizes 10–30 $\mu$m. This is the standard detector for optical wavelengths ($\lambda < 1\,\mu$m). A CCD is an array of MOS capacitors which accumulate photo-electrons generated by the photo-electric effect.

*Advantages of CCDs:* excellent Quantum Efficiency; high dynamic range, no damage from over-exposure, photon arrival rate unimportant, excellent linearity, excellent stability.

*Disadvantages of CCDs:* Still not enough pixels, usually need mosaics to build large images; time resolution costs; readout noise.

• **CCD Characteristics:**
quantum efficieny (QE) up to 90%.
Bias – electronic offset added to pixel intensities.
Read read-noise – generated in reading out electrons.
Dark dark current – accumulation of thermal noise during exposure.
Well depth – number of photoelectrons that can be stored before saturation.
System gain – number of ADUs per photoelectron.

• **CCD Bandwidth:** – wavelength range a CCD is sensitive to photons (typically 350 nm–1000 nm). The upper cut-off is governed by bandgap energy in the silicon semiconductor. The lower cut-off governed by absorption of the photons in Silicon.

**Important Formulae:**

• Atmospheric absorption: $m_{corr} = m_{obs} - A_\lambda(z = 0)\sec(z)$ where $z =$ zenith distance. $A_\lambda(0)$ is the absorption in magnitudes at wavelength $\lambda$ and $z = 0$.

• Atmospheric refraction: $r = (n - 1)\tan(z)$ where $r$ is refracted angle and $z$ is (small) zenith distance. Value of $n$ depends on wavelength which gives rise to atmospheric dispersion.

• Atmospheric dispersion: Dispersion $= (n_{blue} - n_{red})\tan(z)$

• Quantum Efficiency (QE) = Number of photons converted to photo-electrons / number of incident photons.

## Lecture 4 – Photometry

### Aims

To measure the magnitude of a star or galaxy and its uncertainty using a CCD detector.

### Objectives:

By the end of the lecture you should understand the meaning of the terms:
- Noise in the context of an astronomical image
- Poisson counting statistics
- CCD processing in terms of removal of pixel sensitivity variations (flat-fielding), bias, dark current and sky background
- Photometric signal-to-noise (S / N)
- Photometric correction for atmospheric absorption

### Important Facts:

- Photometry: the process of obtaining quantitative (numerical) values for the brightness of celestial objects.

- Noise: any source of photons which are not desirable in the experiment.

- Signal-to-noise ratio (SNR): the ratio of useful to non-useful data.

- CCD Photometry: correct the number of photons per CCD pixel for pixel sensitivity variations (flat-fielding), bias, dark current and sky background. Also need to correct for atmospheric absorption.

- Poisson statistics: arrival of photons at a detector is a Poisson process – random independent events.

- CCD reduction: need Bias frame (0 sec exposure), Dark frame (same exposure as object but shutter closed), Flat field (uniform field eg inside of dome) and sky frame (same exposure as object but on blank sky).

- CCD noise sources: readout noise (Gaussian, $\sigma_{rd}$), Photon noise on object signal (Poisson, $\sqrt{f_{obj}t}$) where $t =$ time; Photon noise on sky background (Poisson, $\sqrt{f_{bg}t}$); Photon noise on dark current ($d$) (Poisson, $\sqrt{dt}$).

- Noise approximations – SNR can be calculated in several approximations: object photon noise limited, sky limited, read-out noise limited.

**Important Formulae:**

• Poisson statistics: P(N;$\bar{N}$) = $\frac{e^{-\bar{N}}\bar{N}^N}{N!}$. For large mean value, $\bar{N}$, standard deviation = $\sigma = \sqrt{N}$, variance = $\sigma^2 = \bar{N}$ and the fractional error = $\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$

• Errors in quadrature: If $s_1 = x_i \pm \sigma_1$ and $s_2 = x_2 \pm \sigma_2$ then $s_1 + s_2 = x_1 + x_2 \pm \sqrt{\sigma_1^2 + \sigma_2^2}$ and $s_1 - s_2 = x_1 - x_2 \pm \sqrt{\sigma_1^2 + \sigma_2^2}$.

• Signal-to-noise ratio: $\mathrm{SNR} = \frac{Signal}{\sqrt{Signal+Background+Dark+Read^2}}$

or, $SNR = \frac{\sum_{i=1}^{m} f_{obj,i}t}{\sqrt{\sum_{i=1}^{m}(f_{obj,i}+f_{bg,i}+d)t+\sum_{i=1}^{m}\sigma_{rd}^2}}$

• Gain: all terms in SNR equation have to be in photons = ADU × gain.

• Calibrated Magnitudes: $m = -2.5\log(electons\,/\,s) + m_{zp}$ where $m_{zp}$ is the magnitude corresponding to 1 electron / second.

**Lecture 5 – Spectroscopy**

## Aims

To describe the basic techniques of astronomical spectroscopy, focussing on diffraction and reflections grating spectrographs.

## Objectives:

By the end of the lecture you should be able to describe:
- What are the key components of a spectrograph
- What are the angular and linear dispersions of a spectrograph
- What is the grating equation
- What is the spectral resolution of both a theoretical and a real spectrometer

## Important Facts:

- Spectroscopy is defined as the measurement of the intensity of a light source as a function of wavelength.

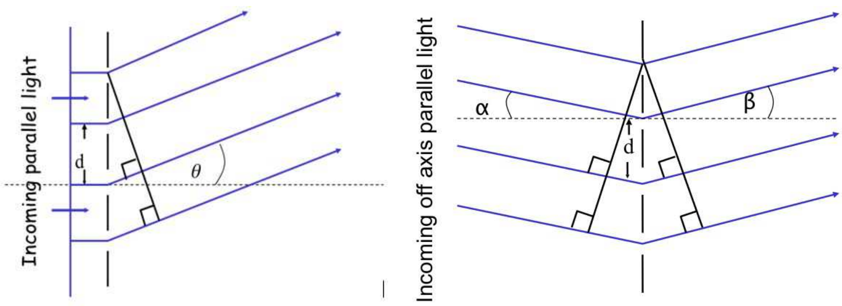
- A spectrometer or spectrograph is the instrument used to measure spectra.

- Spectroscopy important route to measure the composition star and galaxies via emission and absorption spectra, measure stellar velocities, galaxy dynamics and galaxy redshifts via Doppler effects.

- Spectrograph components: Slit, collimator, diffraction grating, camera.

- Usually use a diffraction or reflections grating for dispersing element but also prisms (refraction) and Fabry-Perot (interference) can be used for spectroscopy.

- Basic concept of a transmission grating (*left*) versus Reflection Grating (*right*).



**Important Formulae:**

**Diffraction condition for constructive interference**: $d\sin\theta = n\lambda$ where $n$ is spectral order, $d$ is line spacing and $\lambda$ is wavelength.

**Diffraction grating angular dispersion:** $d\theta \,/\, d\lambda = n \,/\, d\cos\theta$ (rad / nm).

**Reciprocal linear dispersion:** $d\lambda \,/\, dx = (d\lambda \,/\, d\theta)\,(d\theta \,/\, dx) = d\cos\theta \,/\, nf_{cam}$ (nm / mm) since $d\theta \,/\, dx = 1 \,/\, f_{cam}$ is spectrograph camera plate scale and $f_{cam}$ its focal length.

**Intensity from N lines** distance $d$ apart: $I \propto \left(\frac{sin(N\pi d\theta/\lambda)}{sin(\pi d\theta/\lambda)}\right)^2$

**Grating Equation:** $n\lambda = d\,(\sin\alpha + \sin\beta)$ i.e. $n\lambda\rho = d\,(\sin\alpha + \sin\beta)$ where $\rho = 1 \,/\, d$ is the ruling density (lines / mm).

**Spectroscopic resolution:**
Theoretically, $R = \lambda \,/\, \Delta\lambda = nN$ where $n =$ spectral order and $N =$ number of grating lines.

The higher the number, $N$, of diffraction grating lines, the higher the spectral resolution. Higher spectral order $n$ also means higher resolution.

In practice, $R = n\rho\lambda W \,/\, \chi D_T$ where $\rho$ is the ruling density (lines / mm), $\lambda$ is the wavelength, $W$ is the grating width, $\chi$ is the angular size of the image of a star on the slit and $D_T$ is the telescope diameter. Slit width should be matched to the seeing. The narrower the slit, higher the spectral resolution.

## Lecture 6 – Measuring Stars

### Aims

To describe the key stellar observables, and how they can be measured and used to construct a HR-diagram.

### Objectives:

By the end of the lecture you should be able to describe:
- How stellar temperature is measured.
- How stellar luminosity is measured.
- How stellar distances are measured.
- How stellar radii are measured.

### Important Facts:

- Stellar black body temperatures as required for Hertzsprung-Russell diagram are usually measured using broad-band colours e.g. (B-V).
- Blue stars have higher temperatures than red stars.
- Stellar distance measured with parallax.
- Parallax is the angle a star apparantly moves against "fixed" background of distant stars in 6 month period due to Earths motion around Sun.
- Parsec is defined by the distance of a star which has a parallax of $1''$. $1\text{pc} = 206265\,\text{AU}$.
- Proper motion ($\mu$) is the motion of star in plane of sky (arcsec / year).
- Stellar radii can be measured using a Michelson stellar interferometer.
- For binary star [resolved source] with angular separation [size] $\theta$ is derived from the minimum fringe visibility; i.e. fringes disappear when $\theta = \lambda / 2D$ where $D$ is the telescope separation.

### Important Formulae:

**Wiens law:** For a black body, $\lambda_{max}\,\mathrm{T} = 2898\mu\mathrm{m\,K}$

**Stellar colour in magnitudes:** $B - V = -2.5\log(f_B / f_V)$

**Stellar parallax:** $\mathrm{d[pc]} = 1 / \theta('')$

**Stellar Luminosity:** $L = 4\pi R^2 \sigma T^4$ where $R$ is stellar radius, $T$ is effective temperature.

**Lecture 7 – Multiwavelength Techniques**

## Aims

To review how and why we study stars and galaxies at wavelengths from the X-ray- to the radio- regime and what physical proccesses produce the radiation.

## Objectives:

By the end of the lecture you should be able to describe:

• Why we need to take images at different wavelengths and what they teach us about the physical processes occurring within star-forming regions and galaxies.
• Some of the differences in the technology required to record images in the X-rays, UV, optical, near/mid-infrared, sub-mm and at radio wavelengths.
• Where the neutral Hydrogen 21 cm emission comes from.

## Important Facts:

• X-ray photons are high energy (few keV) and arise from hot ($\sim 10^6$ K) gas in the diffuse ISM and from the dense gas in binary stars (star-neutron star; star–white dwarf or star–black hole).

• X-ray satellites detect high energy photons using grazing incidence telescopes (which have long focal lengths).

• Most of the light from galaxies in the UV comes from the youngest, hottest stars. CCDs are used, but must be made "blind" to the optical (where they are most sensitive).

• Emission in the infrared comes from older stars, but also hot dust in/around star-forming regions.

• In the (sub)-millimeter, the radiation comes from cold dust (few kelvin), from the most densely shielded inter-stellar medium. This is where stars are born.

• To detect radiation in the (sub)-millimeter, subtle changes in temperature (resistence) are recorded using bolometers.

• At (sub-)millimeter and radio wavelengths, we often use interferometers since the resolution ($\theta = 1.22\,\lambda\,/\,\mathrm{D}$) of a single dish telescope is very poor.

• The 21 cm radiation from neutral hydrogen arises from the spin-flip of the ground state of the electron from anti-parallel to parallel.

**Lecture 8 – Frontiers in Technology**

**Aims**

To describe the most recent advances and planned future developments in astronomy instrumentation.

**Objectives:**

• What is the technique of adaptive optics?
• What is the technique of integral field spectroscopy?
• What new ground and space telescopes are planned?

**By the end of the lecture you should be able to describe:**

• Multi-Object Spectroscopy: observing multiple spectra simultaneously greatly improves observational efficiency.

• Integral field spectrographs: take spectra of several contiguous "pixels" simultaneously via lenslets or fibres.

• Adaptive Optics: plane wavefront randomly distorted by moving cells of air with different refraction indices.

• Fried parameter, $r_0$: characterises size of turbulent cells - length over which a wavefront remains unperturbed. Typically, $r_0 \sim 10$cm at 500 nm and increases roughly proportional to wavelength. The larger $r_0$ the better the seeing.

• Coherence time or lifetime of turbulent cell depends on wind velocity and $r_0$. Typically, $\tau_0 \sim 10$ ms.

• Isoplanatic angle, $\theta_0$: is angle over which guide star correction still works.

• Laser guide stars now in routine use where no natural guide star available.

• Size of image (seeing)$\sim \lambda \,/\, r_0$ (cf $1.22\lambda \,/\, \mathrm{D}$) so seeing improves at longer wavelengths.

• Future Space Telescopes James Webb Space Telescope (JWST) – will have a 6.5 m mirror and work mainly in the near-infrared. Huge cost (6.8 billion USD).

• Future ground-based telescopes ESO ELT 42-m. Started construction in August 2014 at a total cost of 1.1 billions Euros.

**Important Formulae:**

**Fried parameter wavelength dependence:** $r_0 \propto \lambda$

**Size of image (seeing):** $\propto \lambda \,/\, r_0 \propto \lambda^{-1/5}$ (c.f. $1.22\,\lambda \,/\, D$)

**Atmosphere coherence time:** $\tau_0 \propto r_0 \,/\, v$ measures time for turbulent cell to move across its own length. $v$ is wind velocity; (typically $v_0 \sim 10\,\mathrm{m}\,/\,\mathrm{s}$ and $r_0 \sim 10\,\mathrm{cm}$ thus $\tau_0 \sim 10\,\mathrm{ms}$).

**Isoplanatic angle:** $\theta_0 \propto r_0 \,/\, h$ where $h$ is height of turbulent layer and $\theta_0$ is angle over which guide star correction works (again $r_0$ is Fried parameter).