

Stars and Galaxies

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Chapter 1

Observational Techniques

other stuff in notebook

Lecture 3

- Parts of atmosphere are opaque due to water vapour, O_3 , etc
- Correcting for atmospheric absorption:
 - **GET IMAGES FROM SLIDES**

$$X = 1 \text{ airmass}$$

$$X = \sec(z) \text{ airmasses}$$

$$-\int_{I_C}^{I_O} \frac{dI}{I} = \int_0^X k dX$$

$$\ln \frac{I_{obs}}{I_{corr}} = kX + c$$

$$\frac{I_{obs}}{I_{corr}} = e^{-kX}$$

$$m_{obs} - m_{corr} = -2.5 \log \frac{I_{obs}}{I_{corr}}$$

$$\begin{aligned} m_{obs} - m_{corr} &= -2.5 \log e^{-kX} \\ &= 2.5kX \log e \end{aligned}$$

$$m_{corr} = m_{obs} - A_\lambda(z=0) \sec z$$

- Atmospheric refraction
 - **MATHS AND PICS IN SLIDES**
 - plane parallel atmosphere
 - apply laws of refraction
 - basic trig stuff
 - always in small angle approx range
 - $r = (n - 1) \tan(z_0)$
- Refractive index also has wavelength dep
- atmos ref turns into an atmos dispersion
- disperses more for smaller wavelength

- 3 or 4 arcsecs
 - a lot
- Every object appears as a spectrum as colors separate
- atmos emission
 - fluorescent emission
 - * air glow
 - emits thermal radiation for TE
 - Most emission is from OH molecules in upper atmos
 - * vibrational and rotational movement
- want to try and stay away from regions with lots of this emission
- Other sources of emission:
 - light pollution
 - * from ground
 - * from satellites and aircraft
 - zodiacal light
 - * light scattered from interplanetary dust
 - * in plane of the Solar System
 - scattered light
 - * e.g. from the moon
 - * telescope scheduling to dark, grat, and bright time
- more difficult observations at longer wavelengths
 - more background issues
- dust causes lots of interference
 - at longer wavelengths, interaction between dust and photons is smaller
 - interaction cross-section
- easier to see through dust a lot easier and see other galaxies etc at longer wavelengths
- Atmospheric turbulence
 - *twinkle twinkle little star*
 - Stars twinkle due to light getting bounced around in atmos
- Angular resolution of telescope limited by Fraunhofer Diffraction
 - *see last year*
 - Airy disk
 - assume stars as point sources
 - large telescope \implies small airy disk
 - small telescope \implies large airy disk
 - how close before two stars are seen as one?
- Characterise resolution with Rayleigh criterion
 - at some point the principle maximum of one star overlays with the principle minimum of the second
 - * *diffraction limit*
 - $\theta_{al} = 1.22 \frac{\lambda}{D}$
 - * integrate round a cylinder using Bessel fns to get this
 - * covered sort of later on in other module
- Atmos is constantly moving
 - changing size, density, and temperature causes different path lengths over dt for stars
 - sum up over lots of dt for observing
 - * causes blurring though
 - no longer airy disk, severely blurry
- for atmos turbulence, the seeing is defined as minimum angle between two stars that can just be resolved
 - typically in arcsec
 - 50x worse than the diffraction limit
- Detectors
 - Charged Coupled Device
 - little silicon micro-circuits

- little ray of capacitors
- discrete energy bands
 - * conduction band and valence band
 - * difference of $\approx 1.1\text{eV}$
- upper cut-off wavelengths governed by band gap voltage difference
- lower wavelengths cut-off by absorption of photons into the silicon
- excellent Quantum efficiency
 - * $> 90\%$
- high dynamic range
- excellent linearity
- excellent stability
- still not enough pixels

Lecture 4

Back to CCDs:

- Well Depth
 - how many electrons can be stored in the upper state, usually 100s of thousands
- use binary for how many levels for the signal
 - i.e. 8 bit = $2^8 = 256$ levels
- System Gain
 - how many photo-electrons are required for digital output of 1
 - small gain means reduced saturation signal

Photometry

- Process of obtaining quantitative (numerical) values of the brightness of celestial objects
- CCD gives output prop to number of photons incident on each pixel
- Photometry takes raw data and corrects for noise from other sources
- Noise is just any interference for the image
- SNR (signal to noise ratio) defined as ratio of useful to non-useful data
- Poisson stats
 - arrival of photons governed by this
 - studied for how cameras observe sky stuff
 - see stats last year
 - Hughes and Hase and labs stuff

$$P(n, N) = \frac{\exp(-N)N^n}{n!}$$

- High means approximates Gaussian stats
- mean is N
 - also Variance
 - std dev is \sqrt{N}
- Telescope experiments can take eight hours or so
 - so use Poisson errors for easy error in counts
- Small error associated with read out

Basic Data Reduction to Correct for Background in CCD

- Bias
 - a zero second readout which results in a constant offset

- allows for understanding of the “noise” quantity
- Dark
 - CCD band stuff
 - CCD will be in TE so will promote thermal photons
 - thermal photons can hit detector and skew results
 - this will increase in time
- Flat Field
 - variations in sensitivity
 - varied energy ever so slightly across CCD
 - quantum efficiency
 - slight changes across the CCD in efficiency causes a non-uniform field across CCD
- Also have sky background counts
 - these are often the most significant contributor

$$\begin{aligned}\text{Final Frame} &= \frac{\text{Object Frame} - (\text{dark} + \text{bias})}{\text{Flat Field} - (\text{dark} + \text{bias})} \\ \text{Final Frame} &= \frac{\text{Object Frame} - (\text{dark} + \text{bias})}{\text{Flat Field} - (\text{dark} + \text{bias})} - \frac{\text{Sky Frame} - (\text{dark} + \text{bias})}{\text{Flat Field} - (\text{dark} + \text{bias})} \\ \implies \text{Final Frame} &= \frac{\text{Object Frame} - \text{Sky Frame}}{\text{Flat Field} - (\text{dark} + \text{bias})}\end{aligned}$$

Noise Sources

- Basic sources of noise are:
 1. Readout noise, σ_{rd} electrons (Gaussian)
 2. Photon noise on the signal from the object (Poisson)
 - $= \sqrt{f_{obj}t}$
 3. Photon noise on the signal from the sky background (Poisson)
 - $= \sqrt{f_{bg}t}$
 4. Photon noise on the dark current (Poisson)
 - $= \sqrt{dt}$
- Uncorrelated noise sources can be added in quadrature
 - $\sigma_{\text{total}} = \sqrt{\sigma_1^2 + \sigma_2^2}$
- Signal/Noise

$$SNR = \frac{S}{\sqrt{S + D + B + \sigma_{rd}^2}}$$

- S - signal
- B - background
- D - dark
- σ_{rd} - read error
- Prev equation assumes all the terms are in photo-electrons
- Will need to be accounted for if in ADU
- counts in number of photons
- gain can be set to more than 1
 - confuses simple SNR eqn and changes what you plug in

SNR Approximations

- Common approximations:
 1. Photon noise limited on the object

- signal dominates so can ignore other terms for SNR
- 2. Sky Limited
 - sky background dominates, only count background
- 3. Read Noise Limited
 - read background dominates, only count read term

Lecture 5

Spectroscopy

- Most useful tool in astro
- measurement of intensity of a light source
 - function of wavelength
- Different spectra:
 1. light from source straight to detector
 - continuous spectrum
 2. light from source travels through a cloud of gas straight to detector
 - continuous spectrum with dark lines
 3. light from source travels into cloud and scatters through it to detector
 - bright line spectrum on black background
- Types of spectrograph
 1. Refraction (prisms)
 2. Diffraction gratings
 3. Interference (Fabry-Perot interferometer)
 - focus on diffraction grating
- Diffraction grating
 1. Slit
 - need this to focus light from source of interest and block everything else
 2. Collimating lens
 - make sure light lands parallel to diffraction grating
 3. Diffraction grating
 4. Camera
- Condition for constructive interference:

$$n\lambda = d \sin \theta$$

$$\frac{d\theta}{d\lambda} = \frac{n}{d \cos \theta}$$

- $\frac{d\theta}{d\lambda}$ is known as angular dispersion (rad/nm)
 - higher dispersions from higher spectral orders and smaller line spacings
 - more convenient for Reciprocal Linear dispersion ($\frac{d\lambda}{dx}$)
 - measuring wavelength per unit x at detector (nm/mm)
 - multiply $\frac{d\theta}{d\lambda}$ by plate scale $\frac{d\theta}{dx} = \frac{1}{f_{cam}}$

$$\frac{d\lambda}{dx} = \frac{d\lambda}{d\theta} \frac{d\theta}{dx} = \frac{d}{f_{cam} n} \cos \theta$$

Grating Equation

- For angles of incidence to grating
- For diffraction grating or reflection

$$n\lambda = d(\sin \alpha + \sin \beta)$$

$$n\lambda\rho = \sin \alpha + \sin \beta ; \rho = \frac{1}{d}$$

Resolving Power

- Recall angle for blurred star

$$\theta = 1.22 \frac{\lambda}{D}$$

- Resolving power of a spectrograph is wavelength over band pass:
 - λ is the wavelength
 - $\Delta\lambda$ is the minimum discernible difference in λ

$$R = \frac{\lambda}{\Delta\lambda} = nN$$

$$R = \frac{n\rho\lambda W}{\chi D_T}$$

- Where
 - n is diffraction order#
 - N is number of lines
 - ρ is the ruling density (lines/mm)
 - λ is the wavelength
 - W is the grating size
 - χ is the angular size of the image of a star on slit
 - D_T is the telescope size
- Don't want too narrow a slit
 - optimise width of slit for photons from star
 - spectral resolution gets blurred
- Second equation above is for a practical spectrograph
 - At most wavelengths, this value of R is much less than that given by nN

CDs, DVDs, and Blu-Rays

- basically diffractions gratings
- DVDs store more info than CDs based on diffraction types
- Blu-Rays need UV light to make sense

Lecture 6

Measuring Stars

- Black body radiation

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

- Characteristic temperature is where $\frac{dE}{d\lambda} = 0$, bump at top of curve

- Colours of stars depends on plot, nearest colour to peak is visible colour

$$L = 4\pi R^2 \sigma T^4$$

- Calc distance to star?
 - use parallax
 - define 1 parsec as distance corresponding to parallax of $\theta = 1''$
 - 1 psc = 206265 AU

Interferometry

- Combines light from two telescopes
 - makes it possible to measure stars
 - interfere the light and measure phase difference
 - diffraction limit: $1.22 \frac{\lambda}{D}$
- As star tracks across sky, path length changes
 - phase will shift in and out of phase with movement
 - more complicated for two light sources
 - get a more complex fringe pattern
 - * modulated by $\frac{\lambda}{D}$ for each telescope
- Moving telescopes apart changes fringe pattern
 - at some point apart, the fringe pattern will disappear and will resolve the star
 - can then use maths to find θ and find the radius using that and the distance away
 - VLT uses more than two telescopes
- Aperture synthesis
 - a trick we need for observations
 - path length will not change between two telescopes, if they come over parallel
 - Will have a 'y' pattern of telescope arrays so that path length will always be changing no matter what way it is passing over the sky

Lecture 7

- Zero-point mag gives one count
- See example sheet from Lecture 6 for some good notes

Multi-Wavelength Techniques

- Missing a huge fraction of images outside visual
 - how do we see the rest of it?
- X-ray radiations
 - electrons wizzing around
 - Accelerated to high energies in plasma state
 - effectively in about a million K
 - protons will make electrons change path, and emit energy
 - accretion disks generate some of this
- Difficulties
 - X-rays have too high energies
 - mirrors absorb it and don't work
 - very shallow angle mirrors focus instead
 - Grazing incidence

- UV radiation
 - temperatures of around 50 kK
 - massive stars
 - clumpy as all around clumps of new big stars forming in groups
- Difficulties
 - CCDs have lower QE for these lower energies
 - hard to move energy level difference in CCDs to measure UV accurately
 - swamped by other photons
 - use a blocking filter to try and filter visual photons away and just get UV
- Infra-red radiation
 - begin to suffer from sky background here
 - to do it accurately, you need to be in space
 - see a ‘fuzz’ tracing spiral arms on galaxies
 - * hot dust in the interstellar medium being heated by stars
 - * emission from cooler stars
 - * globular clusters of old stars
- Sub-millimeter radiation
 - looking at $T = 3 \rightarrow 10\text{ K}$
 - challenging to detect such low energies
 - very sensitive thermometers
 - liquid helium at a few micro-Kelvin
 - changes resistance and allows current to flow for a second
- Why
 - Pillars of Creation
 - lots of dusty regions
 - * actively forming stars in the dust clouds
 - * carbonaceous material - graphite, diamonds etc
 - * silicates
 - * ices
 - optical photons increases dust temperature slightly, still around 10 K though
 - * emits 100 micron wavelength photons to lose temperature
 - looking at Pillars in sub-millimeter shows clouds glowing now
 - can observe nebulae very differently in sub-millimeter
- Radio radiation
 - 3 components
 - * local thunderstorms
 - * distant thunderstorms - radio waves bounce round atmosphere
 - * constant hiss with period of 23 hours 56 minutes and 4.1 seconds
 - * sidereal day
 - This hiss is the galactic emission
 - surface of telescopes need to be ‘smooth’
 - smoothness isn’t as necessary for radios
 - * easy to build big telescopes for radio without this concern
 - very difficult to get a high resolution radio telescope

Lecture 8

Radios Ctd

- Biggest telescope is FAST
 - 500m diameter
- Why observe in radio?

- 21cm
 - * Neutral H emission
- electron can have parallel or anti-parallel spin
 - * two sub ground states
- anti-parallel is lower energy than parallel so will eventually flip to this one
 - * very small energy difference
 - * hyper-fine energy splitting
 - * this takes a few millions years though
- lots of H in galaxies
 - * probability adds up to observe this
 - * pointing radio telescopes sees this

Telescope Tech

- ‘Twinkling star’
 - caused by atmosphere moving around and bumping image around
 - break it up into sub-images
 - * speckles
 - whole image will also move around
- Fried parameter
 - $r_0 \approx 10\text{ cm}$
 - size of turbulent cells
 - coherence time
 - * $t_0 = \frac{r_0}{v}$
 - * v is wind speed
 - * this means that a star will only be stable for about 10 ms
- Correcting this
 - light comes in normally
 - hits third mirror that can change angle with actuators
 - then hits a beam splitter
 - * 50% to computer analyser
 - * 50% to somewhere else
 - computer constantly measures image and changes actuators to correct image for turbulence
 - * uses fast Fourier transforms to get back to real image
 - * happens every millisecond or so
 - this requires bright star though
 - shine lasers up to 15 km into atmosphere to focus
 - * this creates a fake star for corrections - ‘natural guide star’

Exoplanets

- How do we observe planets against photon noise of stars?
 - observe stellar spectrum and planet spectrum for comparison
 - heavier molecules are more difficult to observe as they’re lower down
 - * refraction issues
 - detecting O_3 would be a key trigger for life
 - * not able to do it yet