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Stars and Galaxies

Observational Techniques

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<u>Lecture 1</u>

- *other stuff in notebook*
- Parts of atmosphere are opaque due to water vapour, O_3, etc
- Correcting for atmospheric absorption:

$$\begin{aligned}
X &= 1 \text{ airmass} \\
X &= \sec(z) \text{ airmasses} \\
-\int_{I_C}^{I_O} \frac{dI}{I} &= \int_0^X k\,dX \\
\ln \frac{I_{obs}}{I_{corr}} &= kX + c \\
\frac{I_{obs}}{I_{corr}} &= e^{-kX} \\
m_{obs} - m_{corr} &= -2.5 \log \frac{I_{obs}}{I_{corr}} \\
m_{obs} - m_{corr} &= -2.5 \log e^{-kX} \\
&= 2.5kX \log e \\
m_{corr} &= m_{obs} - A_\lambda(z=0) \sec z
\end{aligned}$$

- Atmospheric refraction
  - 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*
    - $\theta_{dl} = 1.22\frac{\lambda}{D}$
        - 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 ever 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 ≈ 1.1eV

- 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 2

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 quantitive (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

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

Noise Sources

- ➤ Basic sources of noise are:
  1. Readout noise, σ_{rd} electrons (Gaussian)
  2. Photon noise on the signal from the object (Poisson)
     - ➥ $= \sqrt{f_{abj} t}$
  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 3

3.1 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

<u>Lecture 4</u>

4.1 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 = $206265 AU$

4.2 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 5

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

5.1 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 $T = 3 \rightarrow 10\,K$
    - 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 6

6.1 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

6.2 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
    - $r_0 \approx 10\,cm$
    - 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’

6.3 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