Sofi Martínez Fortis ASTR 8060 HW 2

1) Hβ emission line of binary Supermassive BH

$V_r = 5000$ km/s (BH radial velocity)

Goal: Find redshifts at which this line will fall in the J, H, K windows

$\lambda_{H\beta} = 4861$ Å (astronomy.swin.edu.au/cosmos/b/Balmer+series)

J = 12200 Å H = 16300 Å K = 21900 Å (Bessel et al. 1998)

$V_r = 5 \times 10^{16}$ Å/s

$$\frac{V_r}{c} = \frac{\lambda_{BH} - \lambda_{H\beta}}{\lambda_{H\beta}} = \text{doppler shift}$$

constant

$$Z_{dopp} = \frac{5000 \text{ km/s}}{3 \times 10^5 \text{ km/s}} \qquad 1 + Z = \frac{\lambda_{J,H,K}}{\lambda_{H\beta}}$$

$$Z_{cosmo} = \left[\frac{1 + Z_{dopp}}{1 + Z}\right] - 1$$

For J band:

$\lambda_J = 12200$ Å

$\boxed{Z_{cosmo} = -0.59}$

For H band:

$\lambda_H = 16300$ Å

$\boxed{Z_{cosmo} = -0.70}$

For K band:

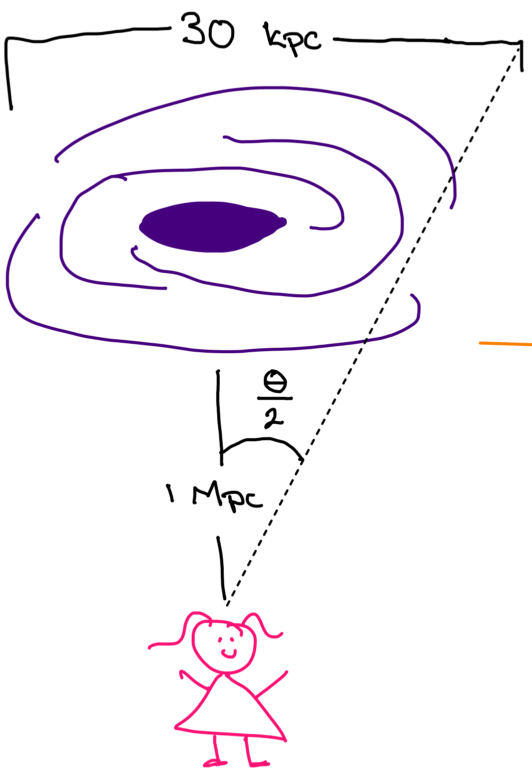
$\lambda_K = 21900$ Å

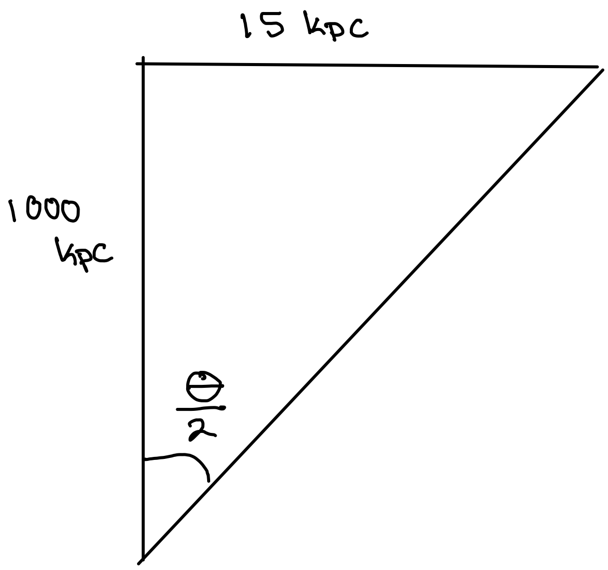
$\boxed{Z_{cosmo} = -0.77}$

2) Size of a galaxy

r = 1 MPC (distance from us) d = 30 kpc (diameter of galaxy)

* How large is it in the sky?





$$\tan\left(\frac{\theta}{2}\right) = \frac{15 \text{ kpc}}{1000 \text{ kpc}}$$

* Using small angle approximation...

$$\frac{\theta}{2} = \frac{15 \text{ kpc}}{1000 \text{ kpc}}$$

$$\theta = 2 \cdot \frac{15 \text{ kpc}}{1000 \text{ kpc}} = 0.03 \text{ radians}$$

$$\theta = 0.03 \text{ rad} \times \frac{180^\circ}{\pi \text{ rad}} \approx \boxed{1.72^\circ}$$

3) Size + Field of View

$D = 8\,m$ (diameter of optical telescope)
$R_p = f/3$ (prime focus)
$R_N = f/12$ (Nasmyth focus)
Typical seeing $= 0.5''$ FWHM

Goals:
i) Find physical size (in microns) of CCD pixels to Nyquist sample a star image at prime focus

ii) Do the same for Nasmyth focus

iii) Find resulting field of view for each case if CCD has 2048^2 pixels

i) Prime Focus

$$\text{Nyquist Sampling} = \frac{FWHM}{2} = \boxed{0.25''}$$

$$f = R_p D = (3)(8\,m) = \boxed{24\,m}$$

$$s = \frac{206265''}{24 \times 10^6\,\mu m} = 0.0086\,''/\mu m$$

$$\text{Pixel size} = \frac{1\,\mu m}{0.0086''} \times 0.25'' = \boxed{29\,\mu m}$$

ii) Nasmyth Focus

$$f = R_N D = (12)(8\,m) = 96\,m$$

$$s = \frac{206265''}{96 \times 10^6\,\mu m} = 0.0021\,''/\mu m$$

$$\text{Pixel size} = \frac{1\,\mu m}{0.0021''} \times 0.25'' = \boxed{116.36\,\mu m}$$

iii) Resulting field of view

If CCD has 2048 pixels × 2048 pixels and Nyquist Sampling = 0.25",

$$FOV = 2048\,pix \times \frac{0.25''}{pix} \times 2048\,pix \times \frac{0.25''}{pix} \approx \boxed{512'' \times 512''}$$

4) Converting Flux of Star

B-magnitude → B = 9.5

Goals:

i) Convert to $\frac{erg}{s \cdot cm^2 \cdot Å}$

ii) Convert to $\frac{photons}{s \cdot cm^2 \cdot Å}$

iii) Convert to Jy

* Assumption: $m_{vega} = 0$

i)

$$9.5 = -2.5 \log\left(\frac{f}{f_{vega}}\right)$$

$$\frac{-9.5}{2.5} = \log\left(\frac{f}{f_{vega}}\right)$$

$$10^{-9.5/2.5} = \frac{f}{f_{vega}}$$

B band

$$f_{vega} = 63.2 \times 10^{-12} \frac{W}{m^2 \cdot nm}$$ (Chromey)

$$f = 1 \times 10^{-14} \frac{W}{m^2 \cdot nm} = 1 \times 10^{-14} \frac{J}{s \cdot m^2 \cdot nm} \times \frac{1\,erg}{10^{-7}\,J} \times \frac{1\,m^2}{100^2\,cm^2} \times \frac{1\,nm}{10\,Å}$$

$$\boxed{f = 1 \times 10^{-12} \frac{erg}{s \cdot cm^2 \cdot Å}}$$

iii) To Jy

$f_{vega} = 1880$ Jy (from notes)

$$9.5 = -2.5 \log\left(\frac{f}{1880\,\text{Jy}}\right)$$

$$f = (1880\,\text{Jy}) \cdot 10^{\frac{-9.5}{2.5}} \rightarrow \boxed{f = 0.30\,\text{Jy}}$$

ii) To $\frac{\text{photons}}{s \cdot cm^2 \cdot Å}$

Energy of 1 photon $= h\nu$ or $h\frac{c}{\lambda}$

$h = 6.626 \times 10^{-34}$ J·s or 6.624×10^{-27} erg·s

For Vega in B band:

$\lambda_{eff} = 436$ nm $= 4360$ Å

$$E_{photon} = (6.626 \times 10^{-34}\,\text{J} \cdot s) \frac{3 \times 10^{18}\,Å/s}{4360\,Å} = \boxed{4.56 \times 10^{-19}\,\text{J}}$$

$$f_{vega} = \frac{63.2 \times 10^{-12}\,\text{J}}{s \cdot m^2 \cdot nm} \times \frac{1\text{ photon}}{4.56 \times 10^{-19}\,\text{J}} \times \frac{1\,m^2}{100^2\,cm^2} \times \frac{1\,nm}{10\,Å} = \boxed{1386.2 \frac{\text{photons}}{s \cdot cm^2 \cdot Å}}$$

Therefore,

$$f = \left(1386.2 \frac{\text{photons}}{s \cdot cm^2 \cdot Å}\right) 10^{-9.5/2.5} = \boxed{0.220 \frac{\text{photons}}{s \cdot cm^2 \cdot Å}}$$

5) Flux conversions

AB mag = 20 $\qquad \lambda = 5500$ Å

Goals:

i) Convert into standard Johnson V mag

ii) Convert to $\frac{\text{photons}}{\text{s} \cdot \text{cm}^2 \cdot \text{Å}}$

ii) $\frac{\text{photons}}{\text{s} \cdot \text{cm}^2 \cdot \text{Å}}$

$$E_{photon} = h\frac{c}{\lambda} = (6.626 \times 10^{-34}\ \text{J} \cdot \text{s}) \frac{3 \times 10^{18}\ \text{Å/s}}{5500\ \text{Å}} = \boxed{3.16 \times 10^{-19}\ \text{J}}$$

$$f_\nu = (3631\ \text{Jy}) \cdot 10^{-0.4(20)} = 3.631 \times 10^{-5}\ \text{Jy}$$

$$3.631 \times 10^{-5}\ \text{Jy} \times \frac{10^{-26}\ \text{J}}{(1\ \text{Jy})\ \text{s} \cdot \text{m}^2 \cdot \text{Hz}} \times \frac{1\ \text{m}^2}{100^2\ \text{cm}^2} = \boxed{3.631 \times 10^{-35}\ \frac{\text{J}}{\text{s} \cdot \text{cm}^2 \cdot \text{Hz}}}$$

$$f_\lambda = f_\nu \left| \frac{\delta \nu}{\delta \lambda} \right|$$

$$\nu = \frac{c}{\lambda} \rightarrow \frac{\delta \nu}{\delta \lambda} = -\frac{c}{\lambda^2} = -\frac{3 \times 10^{18}\ \text{Å/s}}{5500^2\ \text{Å}^2} = \boxed{9.92 \times 10^{10}\ \frac{\text{Hz}}{\text{Å}}}$$

$$f_\lambda = \frac{3.631 \times 10^{-35}\ \text{J}}{\text{s} \cdot \text{cm}^2 \cdot \text{Hz}} \times \frac{9.92 \times 10^{10}\ \text{Hz}}{\text{Å}} \times \frac{1\ \text{photon}}{3.16 \times 10^{-19}\ \text{J}} = \boxed{9.96 \times 10^{-6}\ \frac{\text{photons}}{\text{s} \cdot \text{cm}^2 \cdot \text{Å}}}$$

i) Standard Johnson V-mag

From notes,

$$f_{vega,v} = 3540 \text{ Jy}$$

$$f_v = f_{vega,v} \cdot 10^{-0.4 m_v}$$

$$\log\left(\frac{f_v}{f_{vega,v}}\right) = -0.4 m_v$$

$$m_v = \frac{\log\left(\frac{3.631\times10^{-5}\text{ Jy}}{3540\text{ Jy}}\right)}{-0.4} \Rightarrow \boxed{m_v = 19.97}$$

6) Even more conversions

$$\mu = 1\times10^{6}\ \frac{\text{Jy}}{\text{sr}} \qquad \lambda = 5500\ \text{Å}$$

i) $\dfrac{\text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Hz}\cdot\text{arcsec}^2}$

$$\frac{1\times10^{6}\text{ Jy}}{\text{sr}} \times \frac{10^{-23}\text{ erg}}{(1\text{ Jy})\text{ s}\cdot\text{cm}^2\cdot\text{Hz}} \times \frac{1\text{ sr}}{4.25\times10^{10}\text{ arcsec}^2} = \boxed{2.35\times10^{-8}\ \frac{\text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Hz}\cdot\text{arcsec}^2}}$$

/

ii) $\dfrac{\text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}\cdot\text{arcsec}^2}$

$$\nu = \frac{c}{\lambda} = \frac{3\times10^{18}\ \text{Å/s}}{5500\ \text{Å}} = 9.92\times10^{10}\ \frac{\text{Hz}}{\text{Å}}$$

$$\mu = \frac{2.35\times10^{-8}\ \text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Hz}\cdot\text{arcsec}^2} \times \frac{9.92\times10^{10}\ \text{Hz}}{1\ \text{Å}} = \boxed{2333.5\ \frac{\text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}\cdot\text{arcsec}^2}}$$

iii) $\dfrac{\text{mag}}{\text{arcsec}^2}$

$$\mu = m + 2.5\log\Theta, \quad \Theta = 4.25\times10^{10}\ \text{arcsec}^2\ (\text{arcsec}^2\ \text{per}\ 1\ \text{sr})$$

$$m_{AB} = -2.5\log(10^6\ \text{Jy}) + 8.9$$

$$\mu = m_{AB} + 2.5\log(4.25\times10^{10}\ \text{arcsec}^2)$$

$$\boxed{\mu = 20.47\ \frac{\text{mag}}{\text{arcsec}^2}}$$

iv) $\dfrac{\text{Photons}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}\cdot\text{arcsec}^2}$

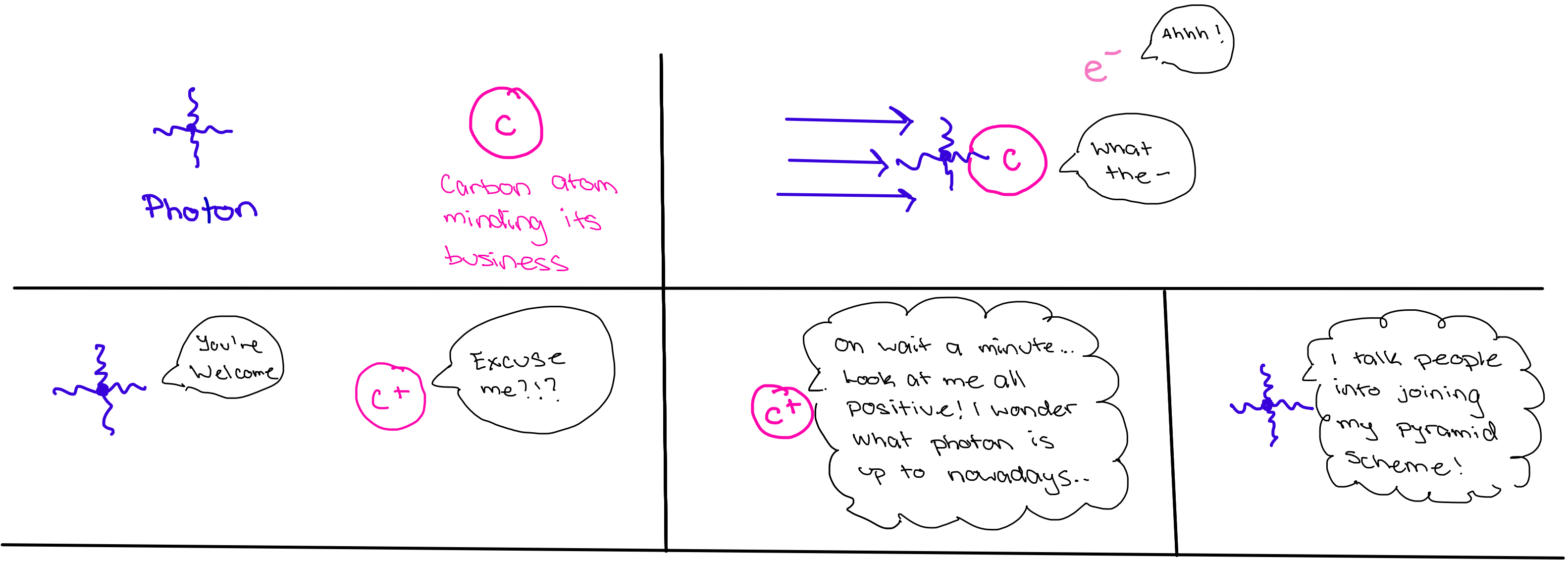
$$h = 6.624\times10^{-27}\ \text{erg}\cdot\text{s}$$

$$E_{photon} = 6.624\times10^{-27}\ \text{erg}\cdot\text{s}\cdot\frac{3\times10^{18}\ \text{Å/s}}{5500\ \text{Å}} = 3.61\times10^{-12}\ \text{erg}$$

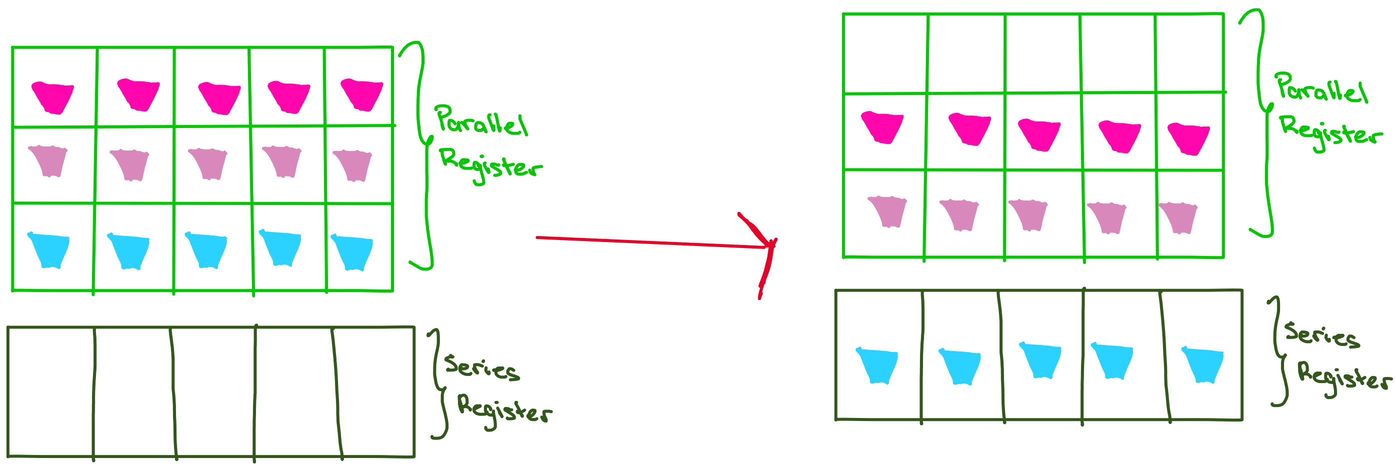
$$\mu = \frac{2333.5\ \text{erg}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}\cdot\text{arcsec}^2} \times \frac{1\ \text{photon}}{3.61\times10^{-12}\ \text{erg}} = \boxed{6.46\times10^{14}\ \frac{\text{Photons}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}\cdot\text{arcsec}^2}}$$

7) CCDs

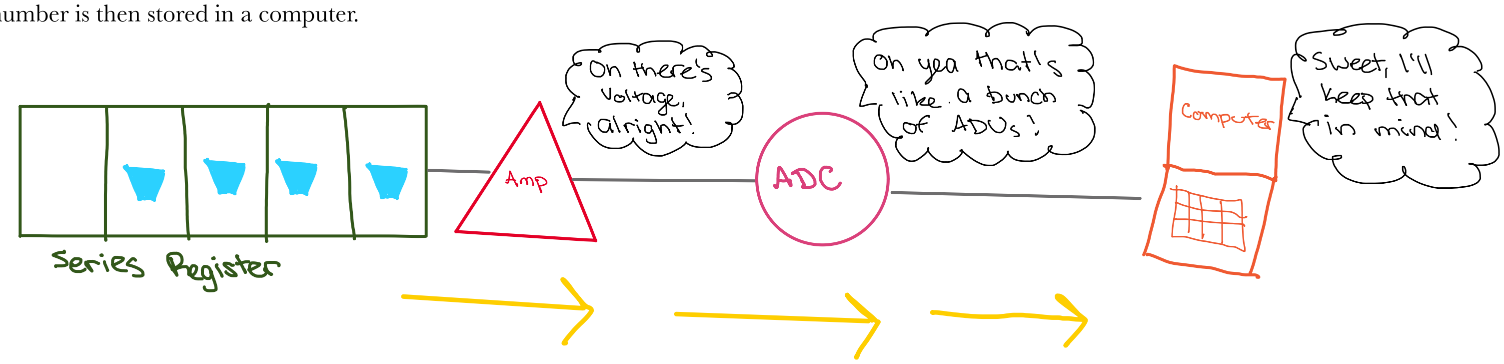
Modern telescopes aren't like in the movies where one physically looks at the sky through one end of the instrument. The main purpose of telescopes today is to collect data, which astronomers then decipher (or at least try to decipher). Telescopes collect data typically in the form of electromagnetic waves such as light. Light particles, called "photons" often hit atoms so energetically, that they knock out one of their electrons, thus ionizing the atom (i.e making it have a positive charge). This process is called "photoionization". Photons are like the mean girls in high school; they really do hit you where it hurts, but you end up having a major glow-up later in life because of it.



Photons do this. A lot. Telescopes have something called a charge coupled device (CCD). CCD's produce a signal that can be analyzed by astronomers using the electrons that were knocked out from atoms via photoionization. CCDs are made from Silicon. Photons that hit the CCD, ionize some of the Si atoms. The free electrons generated from photoionization are then stored in a *metal-oxide superconductor (MOS) capacitor* which is essentially just a very fancy bucket. Each pixel has one capacitor or "bucket". After one exposure (i.e, the time the CCD collects data for one image), all the free electrons are chilling in their buckets and these buckets are nicely arranged in a cute little grid called, the "parallel register". The bottom row then moves down to a new row called the "series register", which is a row of pixels that were not exposed to light.



Then, an amplifier calculates the voltage in the series register one column at a time due to the electrons stored in the buckets. Next, an analog-to-digital converter (ADC) coverts the voltage into a number of analog digital units (ADU), which is directly related to the amount of electrons present. This number is then stored in a computer.



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Once this process is repeated for every column in the series register, the next bottom row in the parallel register will move down to the series register and the amplifier, ADC, and computer get to do their thing all over again!