

GeCAA – Data Analysis

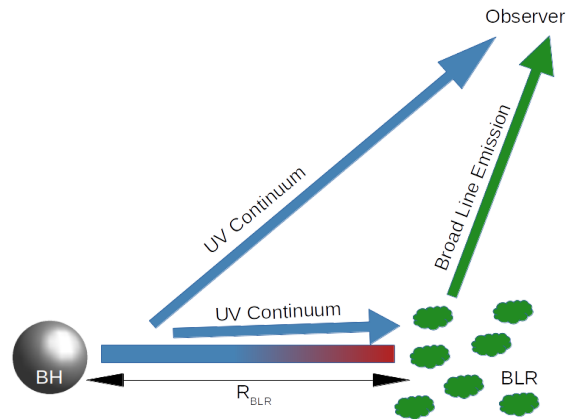
Final Question Sheet

(Total 120 points)

1. AGN

It is believed that the accretion disc around supermassive black holes (BH) at galactic centres gives rise to UV thermal emission. This emission is associated with Active Galactic Nuclei (AGNs).

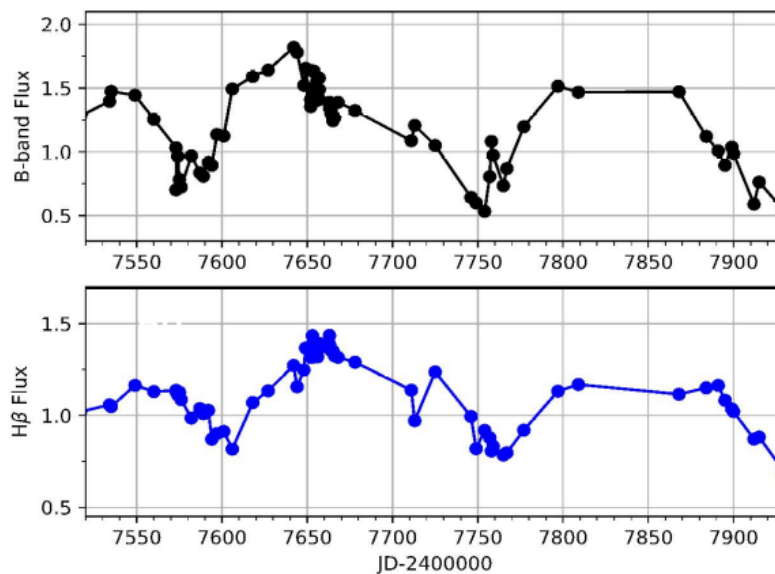
The optical spectra of bright AGNs show additional bright broad emission lines. Those emission lines arise from the dense gas in the Broad Line Region (BLR), which is ionized by the UV photons from the accretion disc. See the sketch to visualise this model.



We can assume that the flux of broad emission lines varies in response to the variation of the UV continuum with a time delay. This time delay should be proportional to the separation R_{BLR} between the BH and the BLR.

Assume that the size of the accretion disc is negligible as compared to R_{BLR} .

- a) **(1 point)** Estimate the time lag (days) between the B-band continuum and broad emission line (H_{β}) using the light curves shown below. The x-axis is in reduced Julian Dates (JD).



- b) **(3 points)** Estimate R_{BLR} in parsecs (pc).
- c) **(2 points)** Estimate the angular separation of this region θ_{BLR} (in arcsec) from the blackhole, if this AGN is $100 Mpc$ away from us.

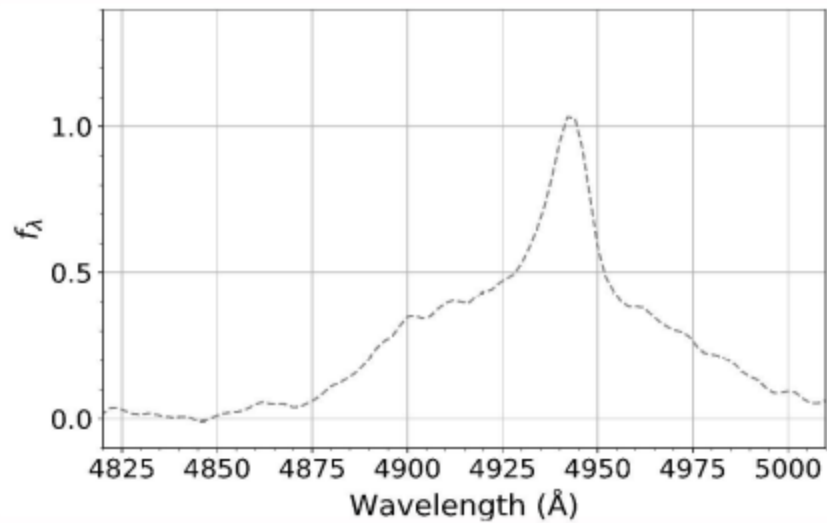
It is possible to estimate the mass of the system using the Virial theorem, if the velocity dispersion of the gasses in the BLR and the size of the system are known. Assume that the masses of the accretion disc and broad line region are negligible, as compared to the black hole.

The velocity dispersion v_σ may be estimated from the broadening of the given emission line. We will take the corresponding wavelength dispersion to be

$$\sigma = \frac{FWHM}{2.35}$$

where FWHM is the full width at half maximum of the broad emission line.

- d) **(5 points)** Calculate the velocity dispersion v_σ in units of $km s^{-1}$, from the spectral line shown below.



- e) **(4 points)** Calculate the mass of the central BH ($M_{vir,BH}$) in units of M_\odot .

2. Minor Planet

Table 1 gives the ecliptic longitude (λ) and parallax (ρ) at different times (t), for a certain hypothetical minor planet. The baseline for the parallax measurement is the diameter of the earth. The time is expressed in years and, for your reference, the ecliptic longitudes of the Sun (λ_{\odot}) for the same dates are also given the table. Let us assume that the orbital inclination of this minor planet, with respect to the ecliptic, is negligible and the eccentricity of the Earth's orbit is negligible.

- a) **(38 points)** Calculate the coordinates of the minor planet in the heliocentric polar coordinate system and put them in an approximately sketched polar plot. The x-axis in the plot should be directed towards the initial position of the minor planet. Draw the major axis of the orbit of the minor planet.
Identify erroneous observation(s), if any.
- b) **(6 points)** Assuming the heliocentric orbit of the minor planet to be elliptical, determine
- i) the semi-major axis length a_p ,
 - ii) eccentricity e .
 - iii) the period P .
- c) **(6 points)** Estimate the errors in the values of P , a_p , e and the solar mass.

Table 1: Minor planet data.

t [year]	λ [°]	λ_{\odot} [°]	ρ ["]
2012.3	336.73	40.95	3.82
2012.6	3.44	134.83	7.24
2012.9	50.71	242.08	7.09
2013.4	94.52	64.84	2.40
2013.6	121.40	134.59	2.16
2013.9	154.31	241.82	2.75
2014.2	25.33	353.29	3.16
2014.5	148.51	99.04	1.99
2014.8	176.26	205.45	1.83
2015.0	216.33	280.19	2.03
2015.3	187.5	28.55	2.897

3. Hypervelocity Stars

In recent years, a new field of research has emerged, that of Hypervelocity Stars (HVS for short). These are stars in our Galaxy (mostly at its outskirts), which are moving with excessive velocities and may be escaping from the Milky Way.

In this question, you will use spectroscopic and astrometric measurements in order to calculate the velocity of one such star, called “HVS1”, consider its origin and whether it may escape the Galaxy.

Figure 1 shows a spectrum of HVS1 in the blue to UV part of the spectrum:

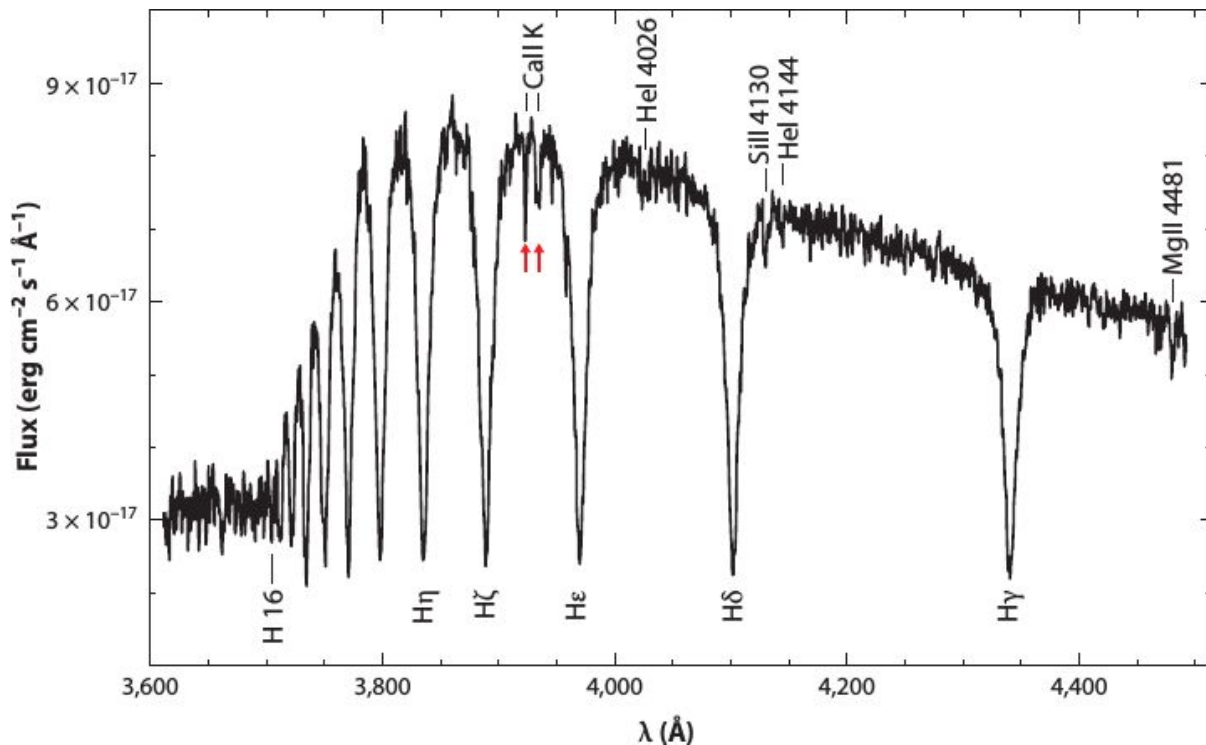


Figure 1. The spectrum of HVS1 shifted to the rest frame of the star (i.e., there is no Doppler shift due to the motion of the star along the line of sight).

- a) **(7 points)** Determine the spectral type of the star using the standard spectra in Appendix 3 and the absorption lines identified on the spectrum of HVS1. (Note that the spectrum above contains both stellar and interstellar absorption lines.)

- b) **(18 points)** Detailed modeling of the spectral lines places the star between luminosity classes V (Main Sequence) and IV (subgiant).
 - i. The apparent magnitude of the star in the visual band is $m_v = 19.84$. Find the absolute magnitude M_v of the star using Appendix 1 for the two possible luminosity classes.

You may ignore the uncertainty in m_v , since the uncertainty in your calculation will be dominated by the uncertainty in M_v .

- ii. For both these possible luminosity classes, calculate the star's distance from the Sun, ignoring interstellar extinction.
- iii. The Galactic coordinates of HVS1 are $\ell = 227.33537267^\circ$, $b = 31.33199386^\circ$. Is the assumption of ignoring interstellar absorption justified? Write "YES" or "NO".
- iv. The Gaia mission of the European Space Agency has been mapping the Milky Way since 2014, measuring the parallax and proper motion of 1.5 billion stars to an accuracy between 0.04 and 0.1 milliarcseconds (mas).
Could Gaia have measured the parallax of HVS1,
A) if it is a MS star? Write "YES" or "NO".
B) If it is a subgiant? Write "YES" or "NO".

For the rest of this question, adopt the larger of the two distances you have calculated above.

- v. Assume that the distance of the Sun from the Galactic center is $R_\odot = 8.0 \text{ kpc}$.
Make a roughly proportionate sketch of the relative positions of HVS1, the Sun and the Galactic center. Use it to calculate the distance (r) of HVS1 from the Galactic center.
- c) **(17 points)** Here, you will calculate the actual velocity of HVS1.
- i. The spectrum in Fig1 shows two absorption lines due to Ca II. One is caused by the atmosphere of the star and the other is due to the interstellar medium. The shift of this line is due to the motion of the star with respect to the interstellar medium.
Measure this Doppler shift and calculate the radial velocity of HVS1 with respect to the Sun.
 - ii. We are interested in the velocity with respect to the Galactic center. For this, we first need to take into account the velocity of the Sun due to the rotation of the Galaxy. The following equation transforms the velocity of a star with heliocentric radial velocity v_{hc} to one in the Galactic rest frame (rf), v_{rf} :

$$v_{rf} = v_{hc} + 11.1 \cos \ell \cos b + 247.24 \sin \ell \cos b + 7.25 \sin b$$

where the speeds are measured in km s^{-1} .

Find v_{rf} for HVS1.

- iii. HVS1's proper motion has been measured as:

$$(\mu_\alpha, \mu_\delta) = (+0.08 \pm 0.26, -0.12 \pm 0.22) \text{ mas yr}^{-1}$$

Calculate the tangential velocity component (in km s^{-1}) of HVS1. (You may ignore the correction for declination as the star is near the celestial equator).

- iv. Calculate the velocity (v_r) of the star with respect to the Galactic center (magnitude measured in km s^{-1} and angle with respect to direction of the Galactic center).
 - v. Assuming this star was born within the Galactic disc, use your calculation of the velocity to estimate where in the Galactic disc it is more likely to have come from:
 - A) near to the Galactic center
 - B) further out in the Galactic disc
- d) **(6 points)** From the energy considerations,
- i. Give an expression for the escape speed (v_{esc}), as a function of the distance from the Galactic center and the enclosed mass of the Galaxy.
 - ii. Calculate the mass of the Galaxy (in solar masses) within the radius of the distance of HVS1.

$$M(r) = 4\pi\rho_0 r_c^2 \left[r - r_c \arctan\left(\frac{r}{r_c}\right) \right]$$

Where $r_c = 8 \text{ pc}$ and $\rho_0 = 1.396 \times 10^4 M_\odot \text{ pc}^{-3}$ are constants of the equation.

- iii. Calculate the magnitude of the escape velocity at the distance of HVS1.
 - iv. Is this a runaway star? Write "YES" or "NO".
- e) **(2 points)** How long has it taken for HVS1 to reach this position?
- f) **(3 points)** On the basis of the spectral type and the luminosity class of this star, estimate the age of HVS1 and compare this with your result in the previous part. Which one of the following statements about the origin of the star is true:
 - (A) the star was ejected when or shortly after it was formed
 - (B) the star was ejected mid-way through its time on the Main Sequence
 - (C) the star was ejected towards the end of its time on the Main Sequence
- g) **(2 points)** Astronomers looking for HVS-s start by finding a sample of stars in the Galactic halo which are of a spectral type similar to that of HVS1. Explain why by choosing which one of the following statements is true:
 - (A) Stars of this spectral type are young and so belong to the native population of the halo
 - (B) Stars of this spectral type are old and so belong to the native population of the halo
 - (C) Stars of this spectral type are young and so **do not** belong to the native population of the halo
 - (D) Stars of this spectral type are old and so **do not** belong to the native population of the halo

Appendix 1: Spectral types, luminosity class and absolute magnitude M_v

Classification and absolute magnitude of stars (M_v)

Sp	Supergiants		Bright giants II	Giants III	Sub- giants IV	Main sequence dwarfs V	ZAMS ^(a) V	White dwarfs VII	Population II			
	Ia	Ib							Sub- dwarfs VI	Red branch	Horiz. branch	
O5	-6.4			-5.4		-5.7						
B0	-6.7	-6.1	-5.4	-5.0	-4.7	-4.1	-3.3	+10.2				
B5	-6.9	-5.7	-4.3	-2.4	-1.8	-1.1	-0.2	+10.7				+2.3
A0	-7.1	-5.3	-3.1	-0.2	+0.1	+0.7	+1.5	+11.3				+0.8
A5	-7.7	-4.9	-2.6	+0.5	+1.4	+2.0	+2.4	+12.2				+0.5
F0	-8.2	-4.7	-2.3	+1.2	+2.0	+2.6	+3.1	+12.9				+0.4
F5	-7.7	-4.7	-2.2	+1.4	+2.3	+3.4	+3.9	+13.6	+4.8	+4.8		+0.4
G0	-7.5	-4.7	-2.1	+1.1	+2.9	+4.4	+4.6	+14.3	+5.7	+4.1		+0.3
G5	-7.5	-4.7	-2.1	+0.7	+3.1	+5.1	+5.2	+14.9	+6.4	+2.0		-0.1
K0	-7.5	-4.6	-2.1	+0.5	+3.2	+5.9	+6.0	+15.3	+7.3	-0.2		-0.6
K5	-7.5	-4.6	-2.2	-0.2		+7.3	+7.3	+15	+8.4	-2.2		-2.2
M0	-7.5	-4.6	-2.3	-0.4		+9.0	+9.0	+15	+10	-3		-3
M2	-7		-2.4	-0.6		+10.0	+10.0		+12			
M5				-0.8		+11.8	+11.8		+14			
M8						+16			+16			

Appendix 2: Spectral Lines

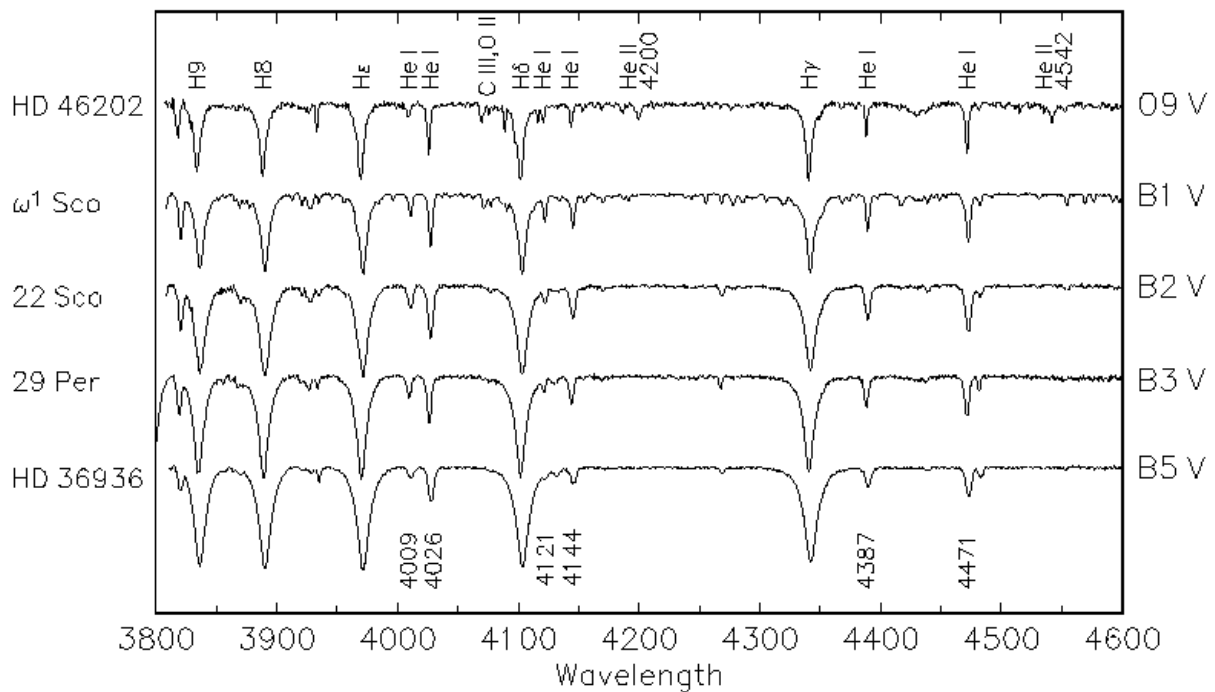
Spectral lines useful in the spectral characterization of low resolution stellar spectra of different stars.

Species and ionization	Identification	Wavelength/nm	Species and ionization	Identification	Wavelength/nm
Ca II	K	393.4	TiO		545–570
Ca II	H	396.8	Na I	D doublet	589.0,589.6
H I	Balmer H ϵ	397.0	TiO		590–610
Fe I		404.6	CH ₄	methane band	619
H I	Balmer H δ	410.1	TiO		620–640
Ca I	g	422.7	H I	Balmer H α	656.3
CH	G	430–432.5	TiO		665–700
H I	Balmer H γ	434.0	O ₂	B (telluric band)	686.7
He II		454.2	H ₂ O	a (telluric band)	716.0
TiO		475–490	CH ₄	methane band	725
H I	Balmer H β	486.1	H ₂ O	(telluric band)	732–738
TiO		495–510	O ₂	A (telluric band)	759.4
[O III]	oxygen	495.9	H ₂ O	Z (telluric band)	790–840
[O III]	oxygen	500.7	CH ₄	methane band	798
TiO		515–540	CH ₄	methane band	887–911

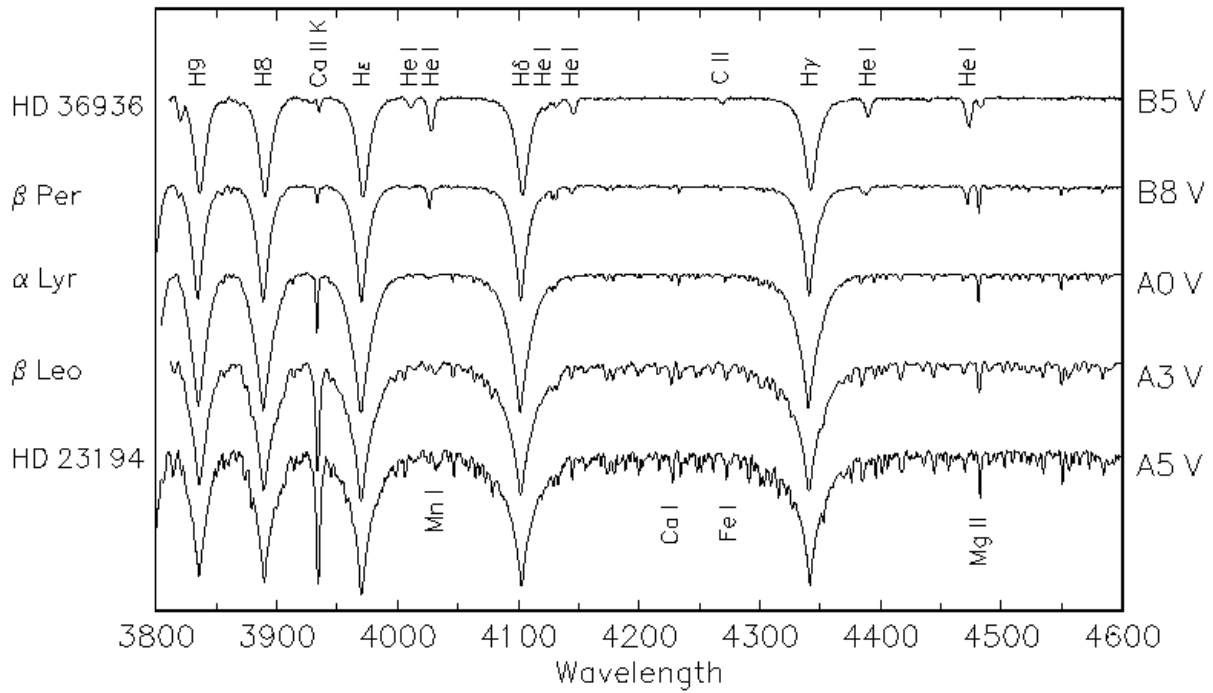
Appendix 3: Absorption spectra typical of different spectral classes^[3]

Spectra of main sequence stars of different spectral classes, at the blue end of the spectrum (where there are many absorption lines due to atomic transitions). The spectra have been divided by the respective continuum so that the lines are more easily discernible. The first six panels correspond to MS stars. The seventh panel shows how the lines change for different luminosity classes for the same spectral type.

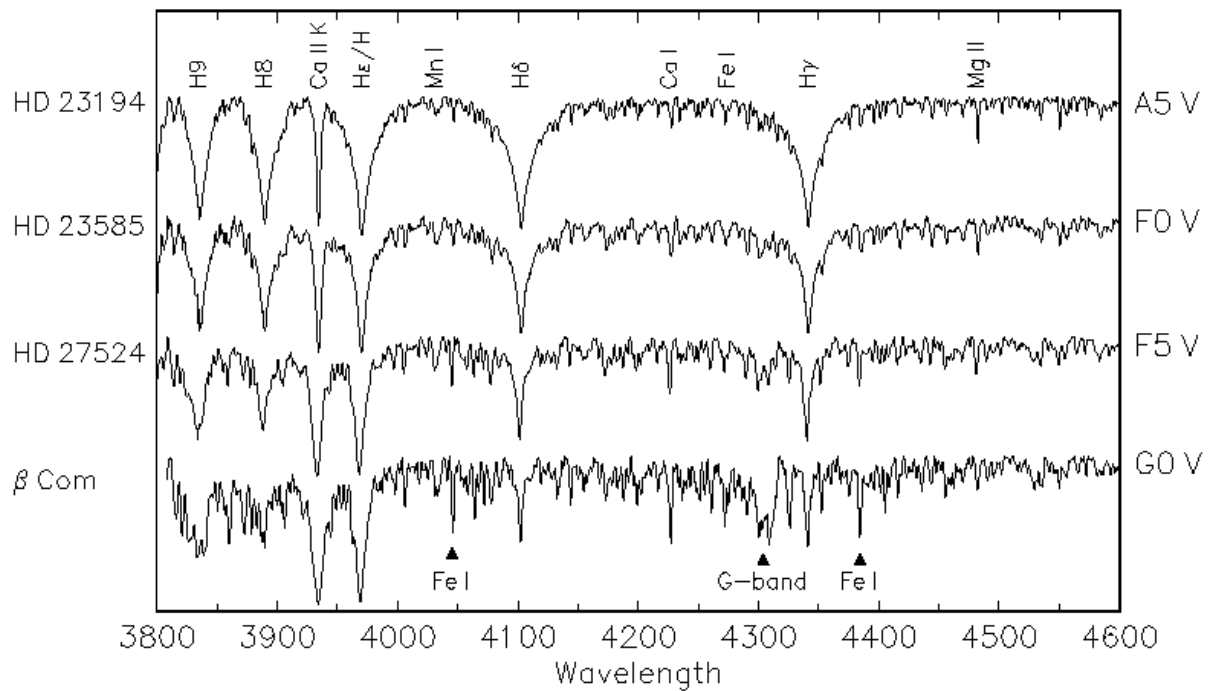
Main Sequence O9 – B5



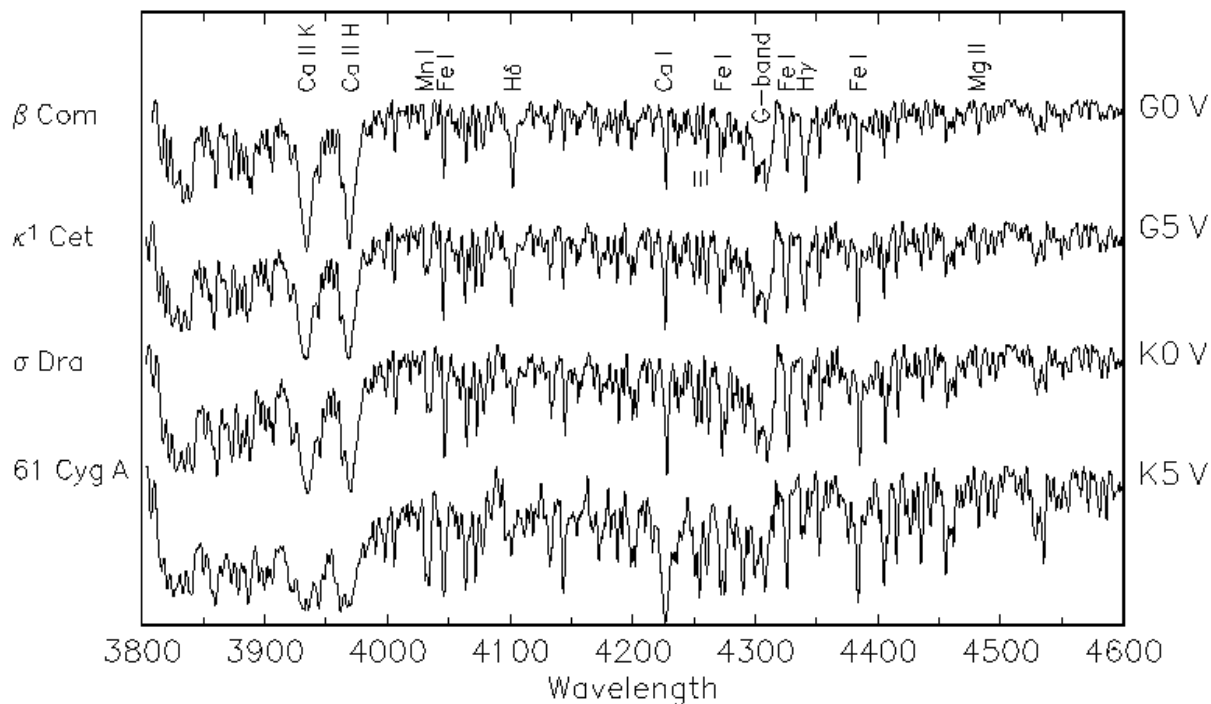
Main Sequence B5 – A5



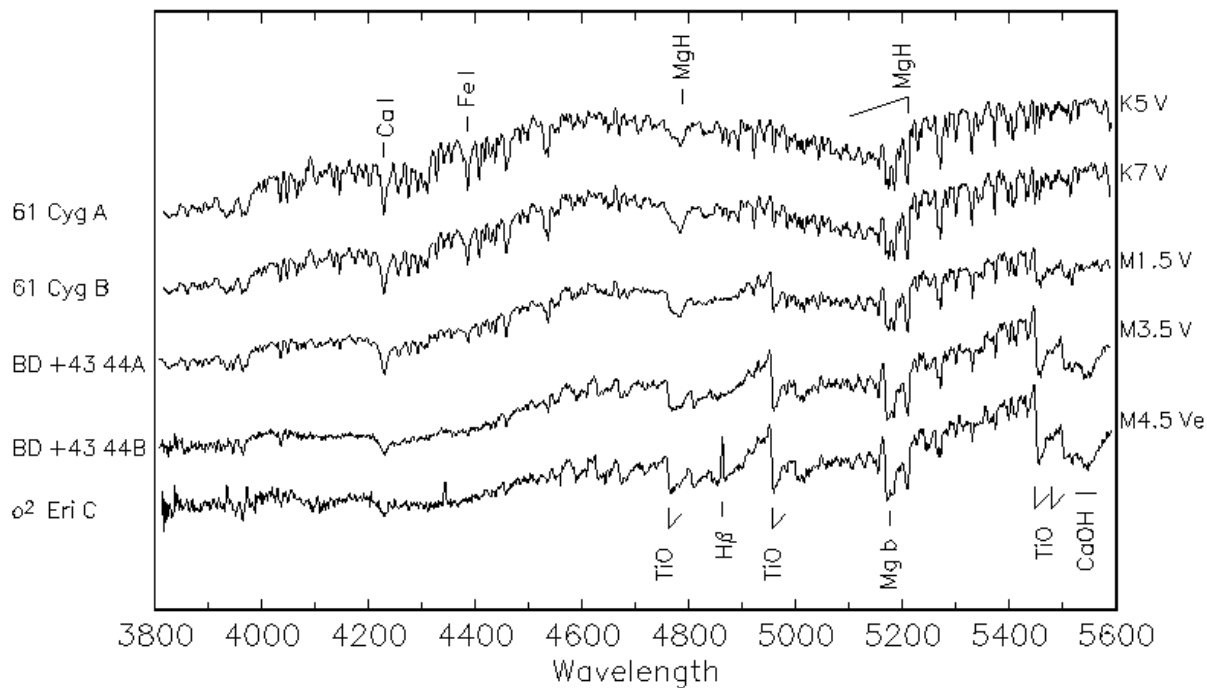
Main Sequence A5 – G0



Main Sequence G0 – K5



Main Sequence K5 – M4.5 Normalized Flux



Luminosity Effects at A0

