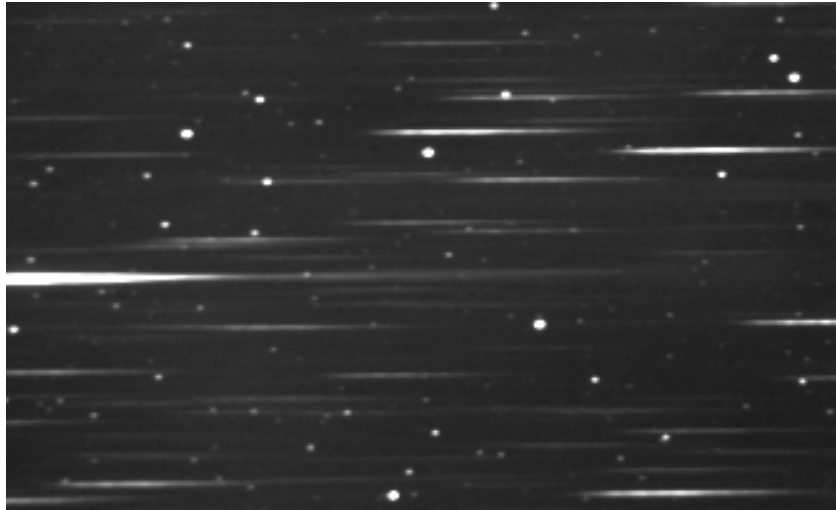


INTRODUCTION TO PHYSICS RESEARCH
University of Adelaide

Final Report:
Astronomical Spectroscopy

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in semester two 2003, Adelaide

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Region of Markarian 509

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1. Introduction

1.1. Abstract

In this project, we took exposures during two observation nights from five stars, three nebulae, Mars and one quasar Markarian 509 in total. We used the nebulae to identify some spectral lines for wavelength calibration and the stars to correct the spectra for instrumental response. For this we needed some theoretical background about cosmology, spectra and astronomical instruments. We measured a redshift from Markarian 509 of about (0.036 ± 0.005) and a distance of about (144 ± 15) Mpc. These results were in good agreement with official values. I took this project together with Ronak F. Kalhor and Victor Stamatescu.

1.2. Aim of the experiment

The aim of this project is to take exposures from different kinds of objects like stars, nebulae and one quasar. We have to prepare and calibrate this raw images to use these for identifying some absorption and emission lines, especially to measure the redshift and with this its correlated distance of the quasar Markarian 509. To do this we have to learn to work with the telescope and its instruments like the grating and CCD camera and we have also to learn how you use different software (IRIS and VSpec) for preparing raw images.

2. Theoretical background

2.1. Redshift and expansion

With the beginning of the universe for 15 billion years in a singularity, called the Big Bang, the universe is continuously expanding. For this reason there is, in the first approximation, a simple relationship between distance and relative velocity between two objects if they are not mutually influenced by gravity:

$$\text{Hubble's law: } H_0 r = v = c z,$$

with *Hubble constant*: $H_0 = (75 \pm 25) \frac{km}{s \text{ Mpc}}$ and *speed of light*: $c = 299792458 \frac{m}{s}$.

This relative velocity is observed in spectra as redshift z :

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c},$$

with λ_0 = *laboratory wavelength* and λ = *measured wavelength*.

It means an object which is further away from us than another object has a bigger redshift, it moves with a higher speed away from us, and since the speed of light has a defined value we observe how it looks in a younger period of the universe.

2.2. Spectra

The only thing that we get normally from distant objects is electromagnetic radiation. And so it is very important to understand how spectra could be produced. Since we know some processes, we can predict some features in spectra: absorption and emission lines in particular.

The most important element for astronomy is the Hydrogen atom with its emission and absorption lines.

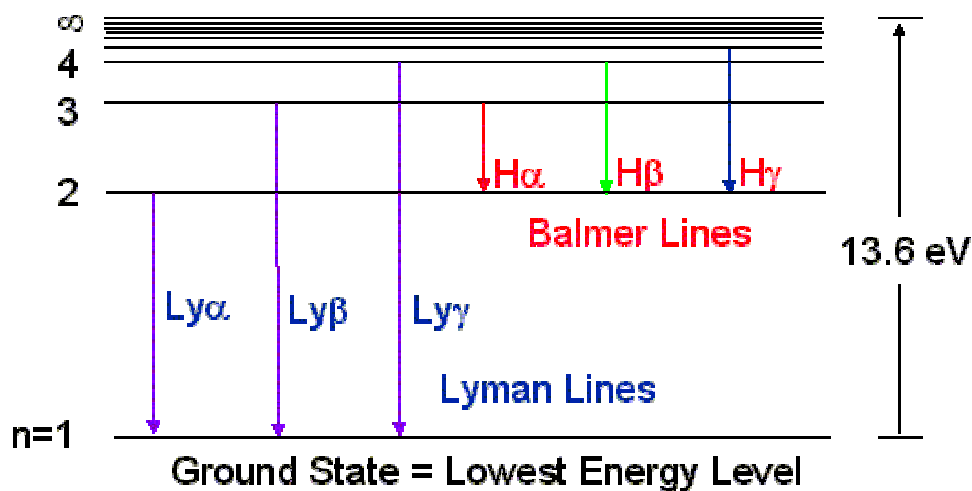


Figure 1: Energy Levels

The Balmer lines (transitions to and from the second energy level to higher levels) are in the visible part of the electromagnetic spectrum. You can get emission or absorption lines depending on the observed object:

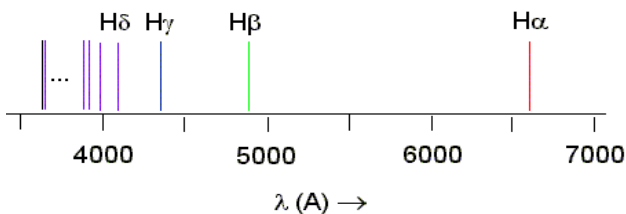


Figure 2: Emission lines

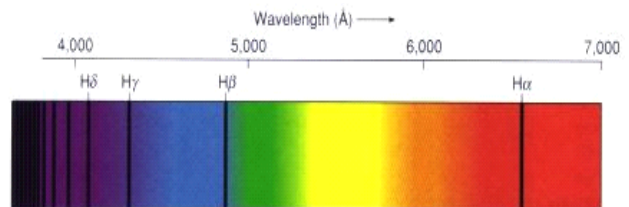


Figure 3: Absorption lines

2.2.1. Stars

The spectral distribution of a star follows normally the Planck law (black body radiation). They can have additionally absorption and emission lines. These lines can be broadened through rotations or some effects from the atmosphere of the star.

$$\text{Planck law : } u(f, T) = \frac{8\pi}{c^3} \frac{hf^3}{e^{\frac{hf}{kT}} - 1}$$

with: f = frequency , h = Planck constant ,
 T = temperature and k = Boltzman constant

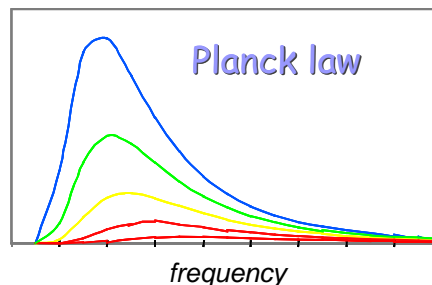


Figure 4: Planck law

It means for hotter stars, the frequency with the maximum intensity is higher than for cooler stars. You can see the translation of the maximum in stellar spectra in Figure 5:

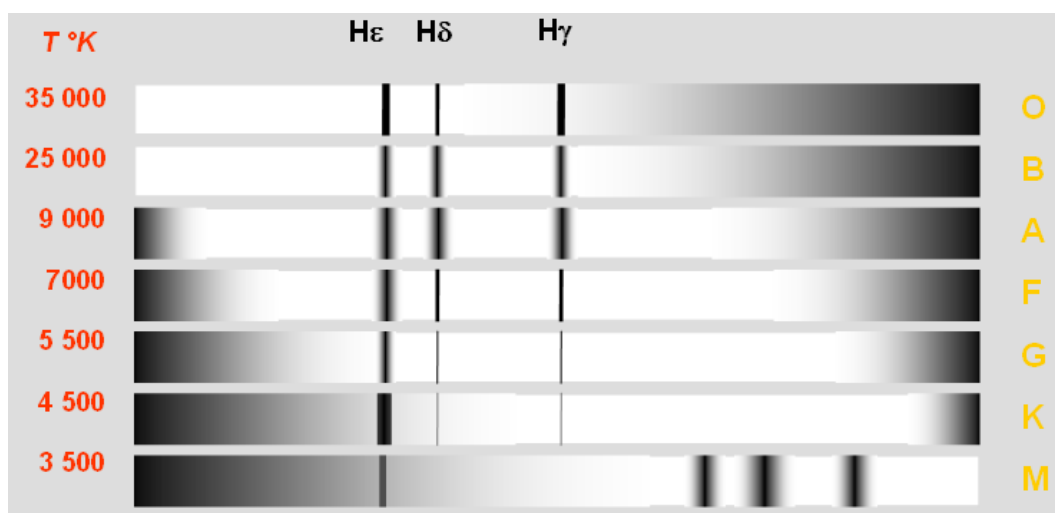


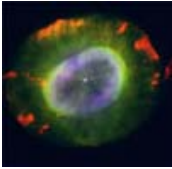
Figure 5: Spectral classes

One may subdivide stars into different spectral classes by correlation of their temperature. These different spectral classes have special properties in their spectra. Hot stars could have emission lines and cool stars have more absorption lines:

Spectral class:	Important spectral lines:
O:	He II, continuous emission
B:	He I
A:	H
F:	metals
G:	Ca II, metals
K:	Ca II, Ca I, molecules
M:	(TiO) S(ZrO) N (C2)

Table 1: Spectral lines

2.2.2. Planetary nebulae



In comparison with stars, typically nebulae have only strong emission lines. Nebulae are clouds of gas and dust within galaxies. Planetary nebulae are remnants from stars. When a star like our sun has used up all its central nuclear fuel, it finally ejects a significant portion of its mass in a gaseous shell which is then visible in the light emitted due to high energy excitation by its extremely hot central star, which previously was the core of the stellar progenitor.

The most intensive lines are the **H**, **He**, **N** and **O** lines. There are also forbidden lines. Useful lines are the H α and the forbidden OIII emission line:

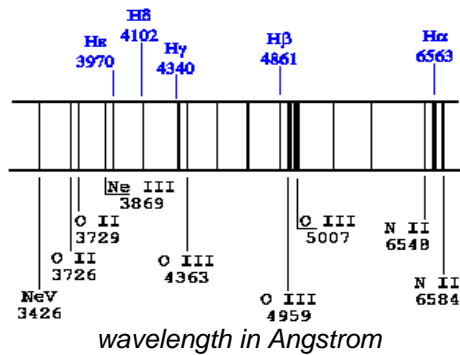


Figure 6: Emission

2.2.3. Quasars

Quasars are very distant objects. A quasar looks like a star because the centre of this galaxy is much brighter than the rest of this galaxy and has a high luminosity. Quasar means “quasi-stellar”. They are generally billion of light years far away from us with redshifts z of about 0.3 to 3.0 and more. In the host galaxy's centre exist a few billion solar mass black hole with an accretion disc and two jets.

The spectrum that we get from a quasar is non-thermal. It has the same intensity over a whole range of wavelengths and some strong broad and narrow emission lines like H lines. They emit in radio, x and γ -ray. A typical spectral distribution looks like this:

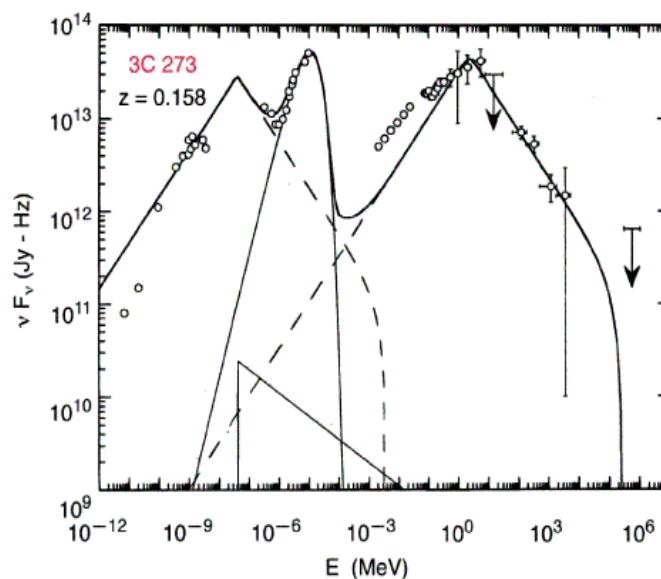


Figure 7: Spectral distribution

3. Experiment

3.1. Equipment

We observed on two nights in total at the dome on the University of Adelaide ($34^{\circ}55' 7''$ south; $138^{\circ} 36' 47''$ east). We used a **8" f/6.3 MEADE LX200 Telescope** for our observations.

At the end of this telescope was fixed a **Diffraction Grating** which disperses the light in its wavelengths and projects the spectrum onto the CCD image plane.

Our cooled (to reduce thermal noise) **ST-6 Charged-Coupled Device (CCD)** has 376 by 242 pixels. Each pixel has a size of 24 by 27 microns. For controlling the CCD we used the computer software CCDOPS.

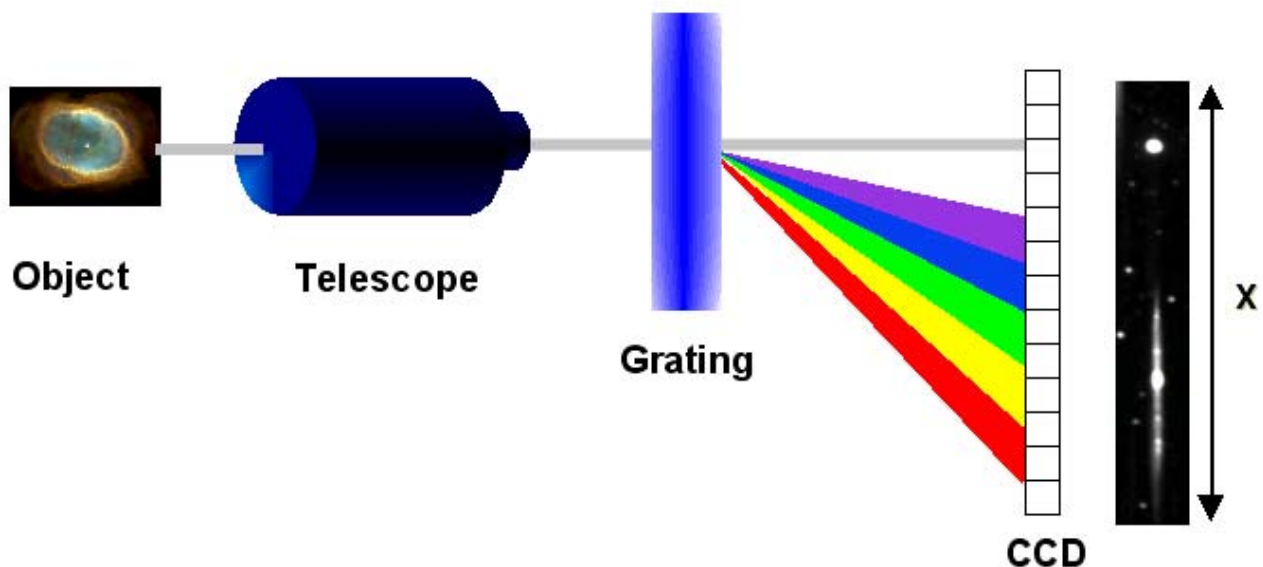


Figure 8: Schematic construction of our telescope, grating and CCD camera

With the distance between the Grating and the CCD plane we could determine the linear dispersion. Dispersion $\Delta\lambda$ means how many Ångstrom are associated with one pixel.

Following the resolution is given by: $R = \frac{\lambda}{\Delta\lambda}$. We have had a low resolution ($R < 1000$).

For preparing our raw images from the CCD camera (extract the spectrum, calibrate for wavelength and instrumental response) we worked with the computer software IRIS and Vspec.

3.2. Measurements

Before we started with our observations we calibrated the telescope itself. It means we set the time, orientated the telescope on the correct coordinates, cooled the CCD and focussed the incoming beam on the spectrum. Important for our exposures were a clear night without moon, because the sky background coming from the city was quite high and a full moon would increase the background; our quasar is also very faint.

In our first observation session (Wednesday, 03.09.2003) we took images from the following objects (temperature of the CCD: -33°C ; dispersion: $22 \text{ \AA}/\text{pixel}$):

Object	Type	Spectral type	Exposure time	Coordinates		Apparent magnitude m_v
				Declination	Right Ascension	
MR 84	star	WC	3 s	$-21^{\circ} 15' 11''$	18h 08m 28s	+ 7.7
Altair	star	A7 V	0.8 s	$+08^{\circ} 52' 05''$	19h 50m 47s	+ 0.78
Antares	star	M .5 Ib	0.8 s	$-26^{\circ} 25' 55''$	16h 29m 24s	+ 0.96
δ Sco	star	B0.5 IV	0.8 s	$-22^{\circ} 37' 17''$	16h 00m 20s	+ 2.32
NGC 5882	nebula	-	60 s	$-45^{\circ} 38' 56''$	15h 16m 50s	+ 10.5
M57	nebula	-	2x 120 s	$+33^{\circ} 02' 00''$	18h 53m 36s	+ 9.4
Mars	planet	-	2x 0.05 s	$-16^{\circ} 12' 59''$	22h 31m 14s	- 2.8

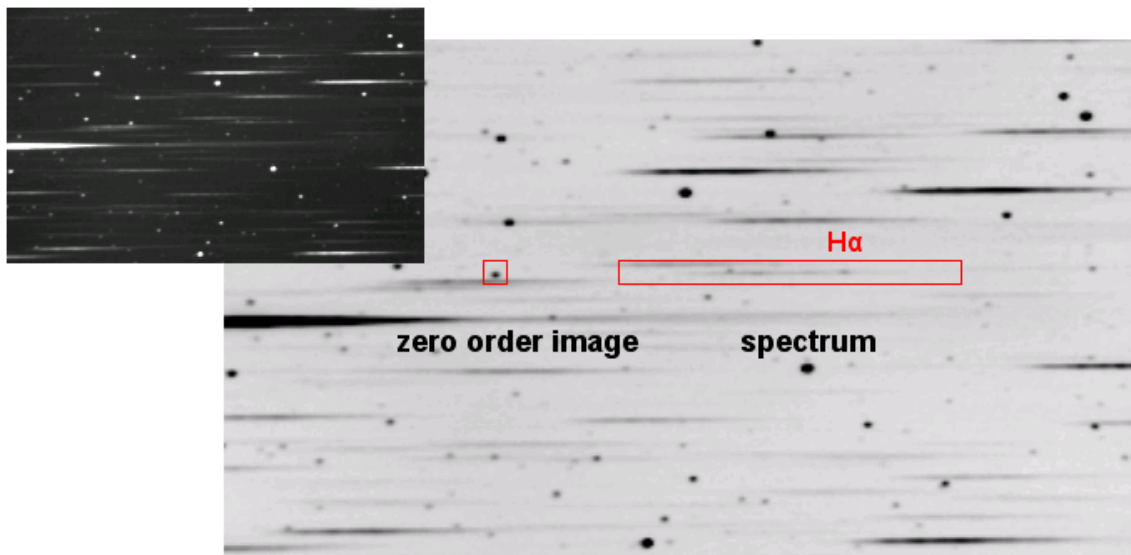
Table 2a: First observation

And in our second observation session (Monday, 13.10.2003; temperature of the CCD: -24°C ; dispersion: $53 \text{ \AA}/\text{pixel}$):

Object	Type	Spectral type	Exposure time	Coordinates		Apparent magnitude m_v
				Declination	Right Ascension	
τ Sco	star	B0 V	1 s	$-28^{\circ} 12' 58''$	16h 35m 53s	+ 2.82
NGC 6572	nebula	-	40 s	$+06^{\circ} 51' 00''$	18h 12m 06s	+ 8.00
Markarian 509	quasar	-	32x 180 s	$-10^{\circ} 43' 22''$	20h 44m 10s	+ 14.5

Table 2b: Second observation

On *Figure 9a* you can see such a raw image. Normally you get a image where the bright pixels are white. If you invert the image you can see for an object the zero order image and its spectrum more easily. These images are stored as fits files. You see on *Figure 9a* in the red square our quasar Markarian 509 and in its spectrum the H α line:



*Figure 9a: Raw image of Markarian 509;
inset: as a positive, main image: as a negative*

The field of view of our images is approximately 20 by 30 arcminutes. These images are already dark current corrected. Our CCD-camera did this automatically.

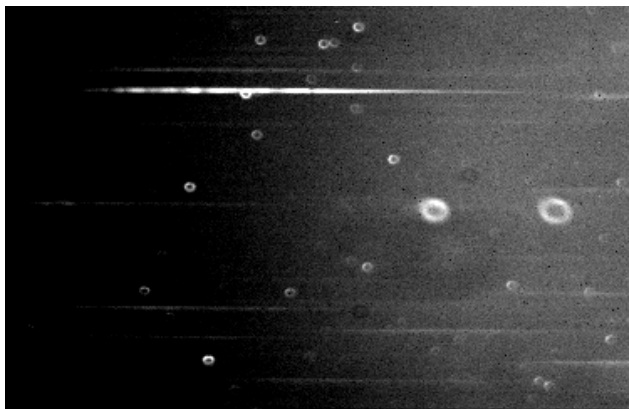


Figure 9b: Raw image of M 57



Figure 9c: Raw image of Altair

On the raw image of M 57 you see only its spectrum because the zero order image is very faint and not visible. You see two emission lines. In contrast Altair and its spectrum is very bright and you do not see any background (short exposure time).

3.3. Extraction and data reduction

After you took these images you have to extract the spectrum from the image. For this you can use the computer software **IRIS**.

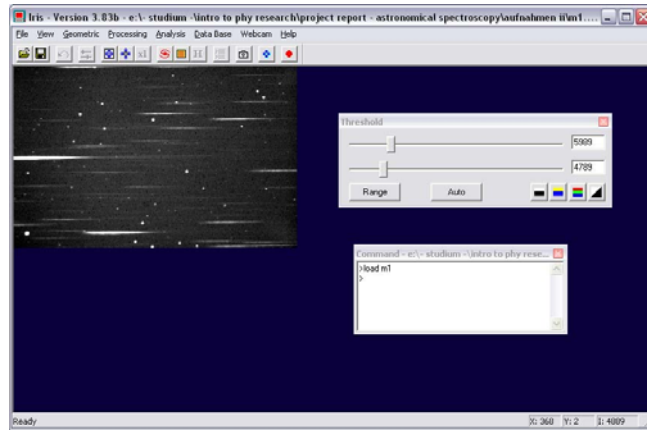


Figure 10: IRIS

At first you correct the images for flatfield effects. It means every pixel has a different sensitivity. For this you need a constant white area in the dome (or a constant bright sky at the horizon) to get a image where you can read the pixel variations. If you divide your raw image by such a normalised flatfield you get a corrected image.

Next you can rotate, translate or add images with IRIS. With this you obtain an image where the spectra are parallel to the edges of the image and the zero order images are all at the same pixel number.

For the quasar you add all 32 single images to one image to get a whole exposure time of 96 minutes. With this long exposure you get a better signal-to-noise ratio for identifying emission lines. We get a $\sqrt{32} = 5.7$ times lower noise in comparison to a 3-minute single exposure.

You split such a long exposure to avoid saturations of pixels. Another reason is to avoid auto-guiding errors. The aim is to maximise signal and minimise background. The noise could consists of the CCD offset, the dark current and the sky background (city, moon).

With this preparations you can now extract the spectrum from the image with IRIS as stripe spectrum:

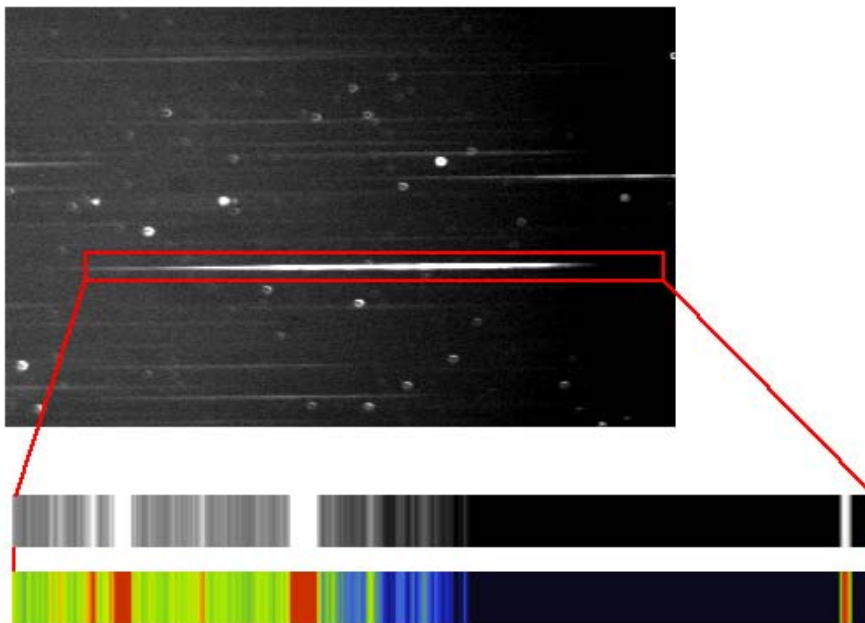


Figure 11: Extraction

One may display the spectrum using a false-colour palette to see the distribution of the intensity in a better way. The following *Table 3* shows all our ten spectra:

Object	Spectrum	Dispersion
MR 84		22 Å/pixel
Altair		22 Å/pixel
Antares		22 Å/pixel
δ Sco		22 Å/pixel
NGC 5882		22 Å/pixel
M57		22 Å/pixel
Mars		22 Å/pixel
τ Sco		53 Å/pixel
NGC 6572		53 Å/pixel
Markarian 509		53 Å/pixel

Table 3: Raw spectra; red lines indicates the H α line in all spectra

On the left-hand side you see the zero order image and on the right-hand side its spectrum. You see also the spectra have different dispersions.

Next you can use **VSpec** to visualise these spectra:

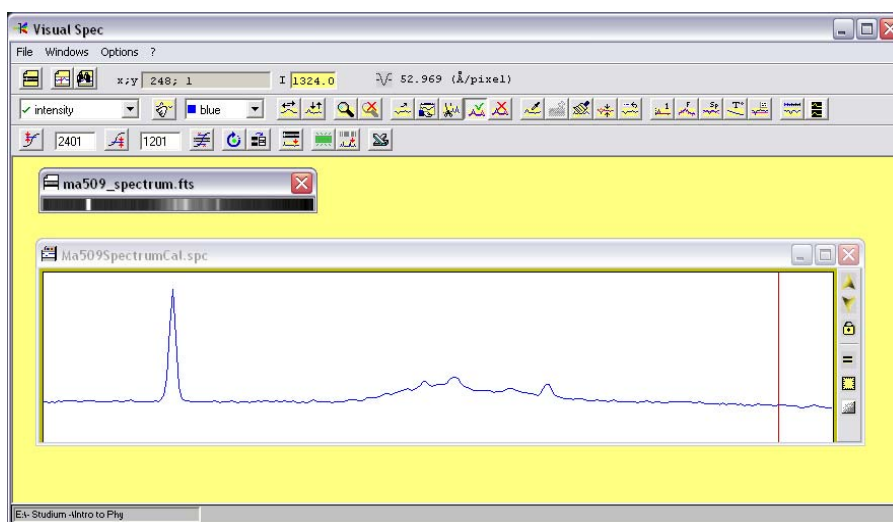


Figure 12: VSpec

Via object binning, you get a diagram from this stripe of spectrum. It shows intensity versus pixel number. The value of the intensity is not important for us. We want only to know which pixel number is associated with which wavelength. For this reason we use the spectrum from the nebula to calibrate all spectra because we know the wavelengths of its emission lines:

OIII: 4982 Å
 Hα: 6563 Å

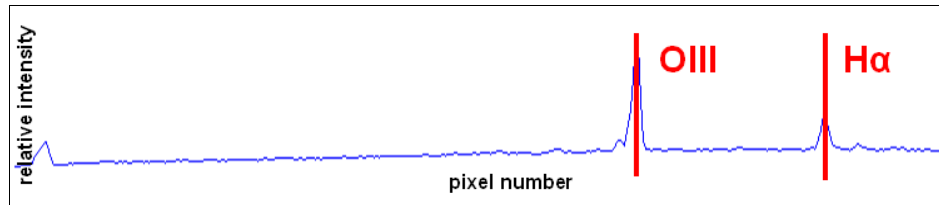


Figure 13: NGC 5882

With VSpec you can also measure the dispersion with this calibration. To calibrate the spectra from our first observation night we used NGC 5882 and for the quasar we used NGC 6572.

The next step is to correct the spectra for instrumental response. You can do this with a star whose spectrum follows approximately a Planck spectrum associated with its temperature. If you divide an observed spectrum by its theoretical Planck spectrum from the library of IRIS you get an instrumental response profile.

We used the δ Sco star (it is a B0V type star) to correct the spectra from the first observation night:

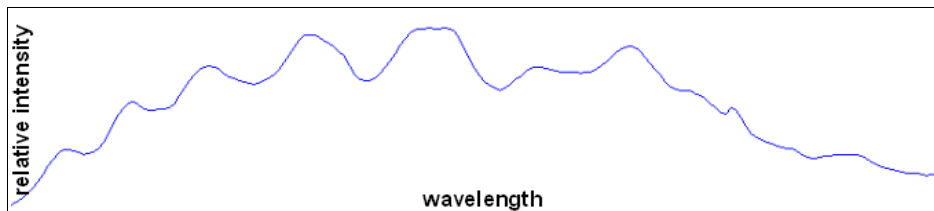


Figure 14: Observed spectrum of δ Sco

divide by

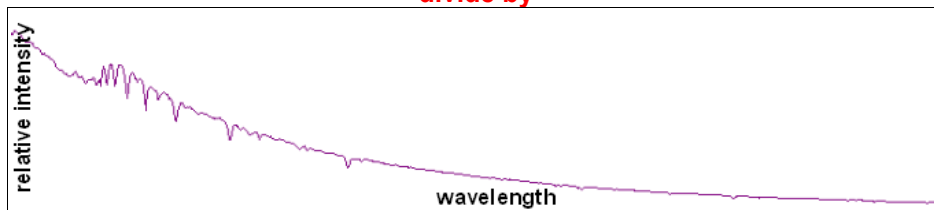


Figure 15: Theoretical spectrum of a B0V star

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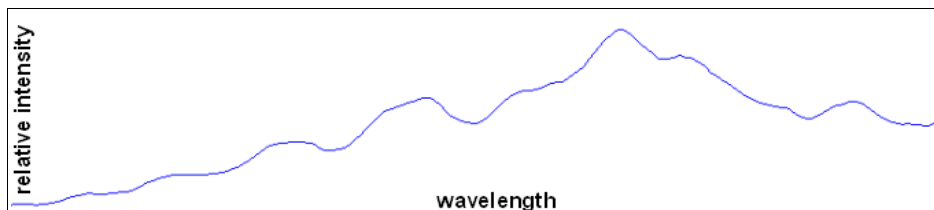


Figure 16: Smoothed instrumental response profile

This is important because our CCD has different sensitivity for different wavelengths. Other influences are from our atmosphere and the used optics. At about 6200 Å our CCD has the best sensitivity (Figure 17):

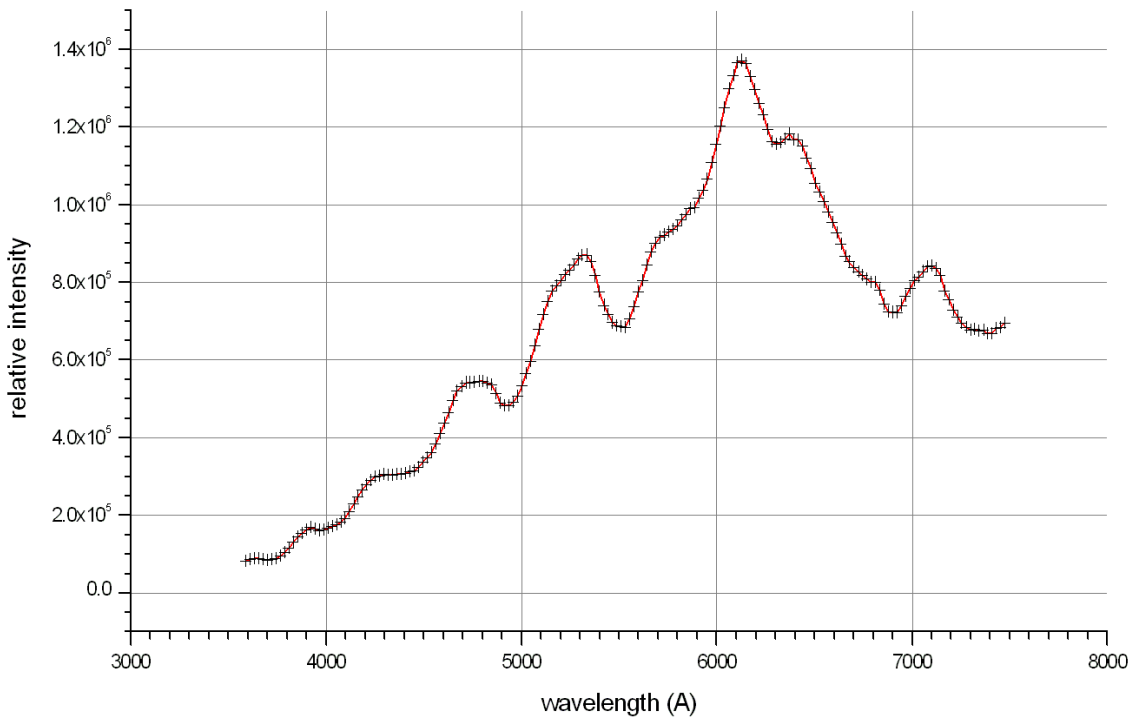


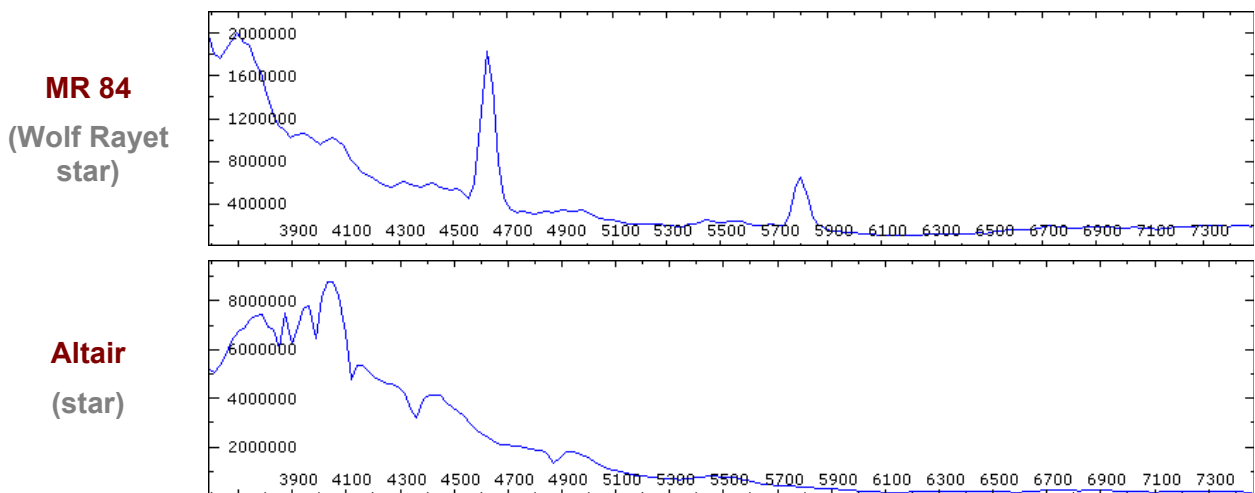
Figure 17: Instrumental response profile with relative intensity versus wavelength in Å

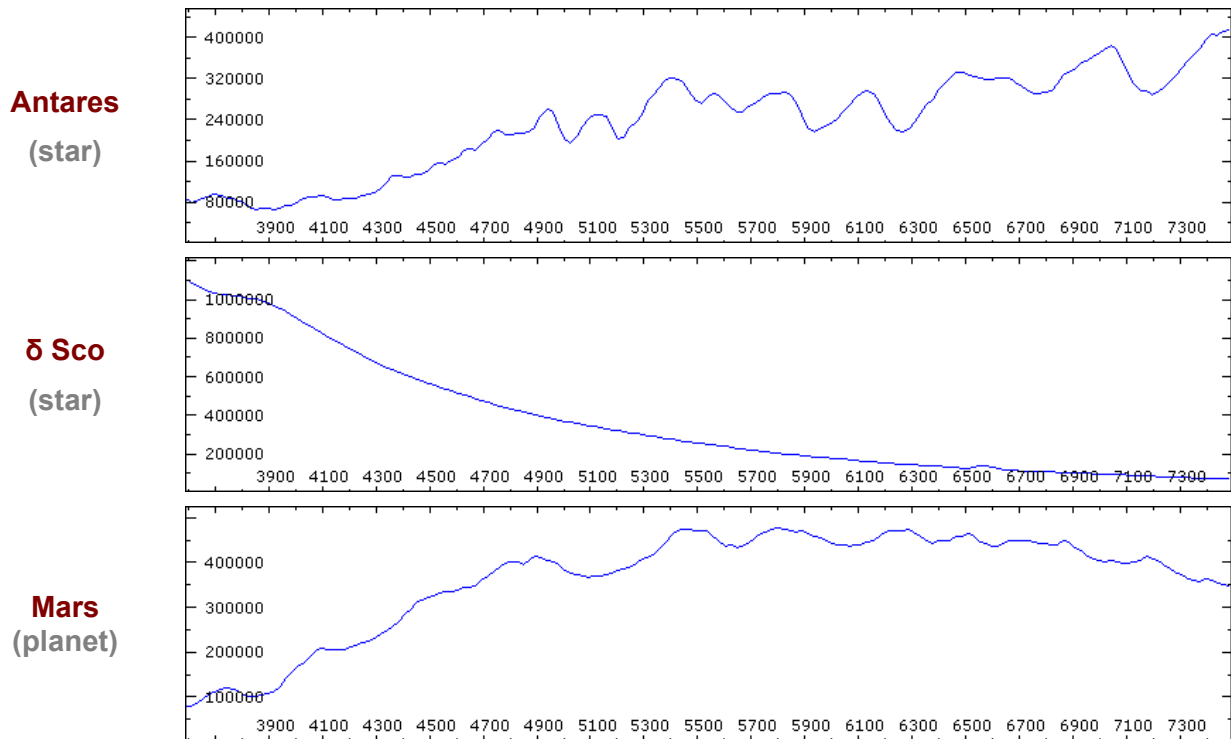
With this profile you can correct all spectra by dividing each spectra by this profile. For the quasar, we have not used an instrumental correction. For some unknown reason, this process did not work successfully for the second night's data. This was not so important for us because we were only interested of the redshift and not of its energy distribution.

3.4. Interpretation of star and nebula spectra

As result, we get all these spectra:

Wavelength-calibrated and instrumental-response-corrected spectra from the first observation night:





Wavelength-calibrated spectra from the first observation night:

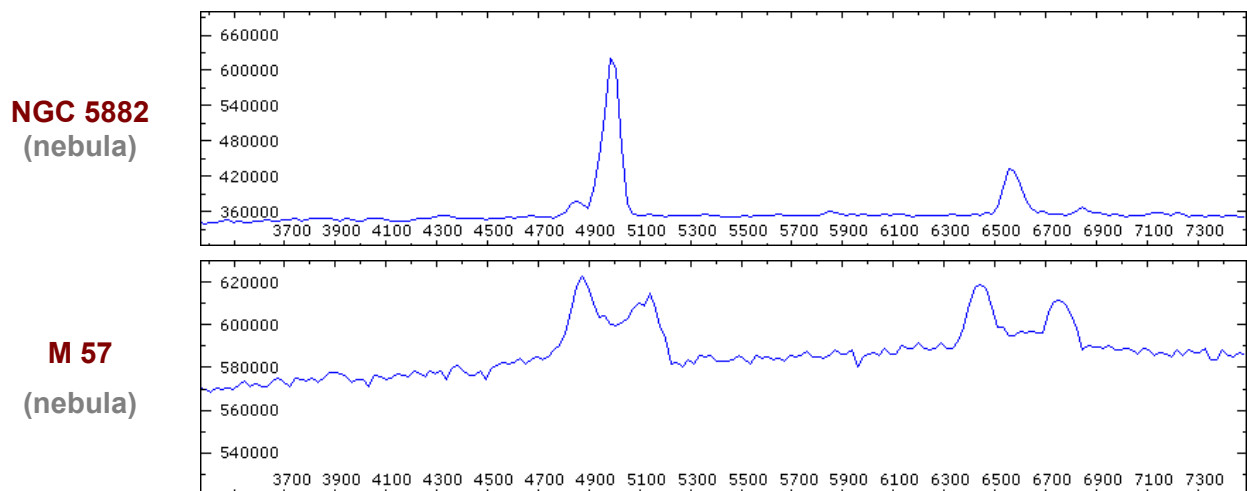


Table 4a: Final spectra (relative intensity versus wavelength in Å)

In all star spectra you see absorption lines except MR 84. MR 84 is a special kind of star. This Wolf-Rayet star has emission lines. The other stars following approximately a Planck spectrum with Hydrogen, Oxygen and Nitrogen absorption lines. At Altair you see a lot of the Balmer absorption lines.

The maximum intensities are all on the left hand side to lower wavelengths except Antares. These stars are very hot stars with spectral types around B. Antares is a cooler M type star with the maximum more to the right-hand side. This red giant has molecular absorption bands.

The nebulae have strong emission lines (OIII and H α). There are displayed only with the wavelength calibration to see the emission lines more easily. On the spectrum of M57 you see two peaks for each emission line because you see M57 as a two dimensional object (you see two spectra in one; compare Figure 9b).

Mars reflected only the spectrum from our sun but you can determine that our sun is not a very hot star in comparison to the other stars because the wavelength with the maximum intensity is higher. The sun is just a G2 type.

Wavelength-calibrated spectra from the second observation night:

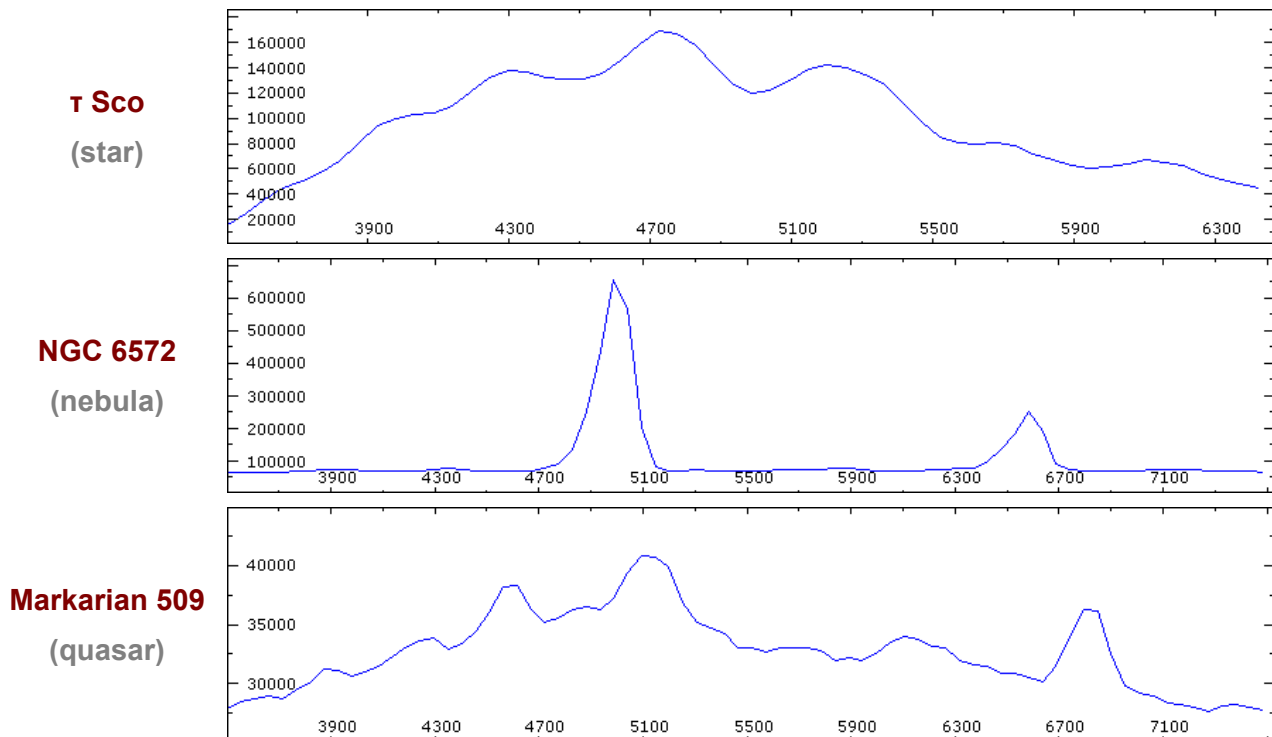


Table 4b: Final spectra (relative intensity versus wavelength in Å)

For our second observation night, we have only wavelength-calibrated spectra. On the broadened lines you can see we used another dispersion (and resolution). We used a lower dispersion for the fainter quasar to get a larger signal-to-noise ratio. The disadvantage is the lines are broadened (and the peaks are closer together on the raw images).

At the spectrum of the quasar Markarian 509 you can estimate that the OIII and H α spectral line are redshifted (shifted to higher wavelengths) if you compare with the nebula NGC 6572 spectrum.

3.5. Redshift of the quasar Markarian 509

With VSpec you can calculate the wavelength of the peak. In *Figure 18* you can see a histogram plot of the spectrum for Markarian 509.

This spectrum is not instrumental-response-corrected. This could be a problem if you want to identify faint emission lines. On this histogram you can also make out how big a dispersion of 53 Å/pixel is.

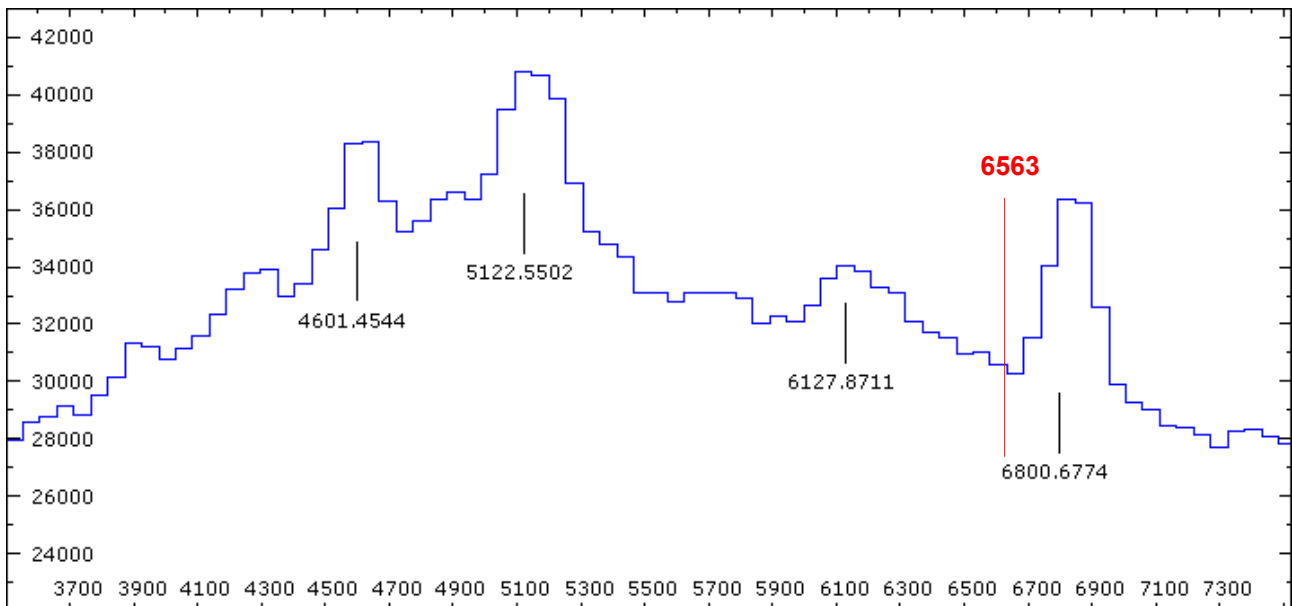


Figure 18: Spectrum of Markarian 509 with labelled emission lines (intensity versus wavelength)

You can identify some redshifted emission lines. Shifted lines are labelled black and the laboratory wavelength of H α is labelled red. In Table 5 is the laboratory and our measured wavelength listed with some other lines.

	Laboratory wavelength	Measured wavelength
Hα	6563 Å	(6801 \pm 30) Å
OIII/Hβ	4959/4861 Å	(5123 \pm 30) Å

Table 5: Redshift

The error can you estimate if you presume you could have a variation of a half pixel. It gives a redshift calculated with the important H α line of:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{6801 \text{ \AA} - 6563 \text{ \AA}}{6563 \text{ \AA}} = 0.036 \pm 0.005 ;$$

then the recessional velocity is:

$$v = cz = (10800 \pm 1500) \frac{\text{km}}{\text{s}} ;$$

with Hubble's law you get a distance of about:

$$r = \frac{v}{H_0} = (144 \pm 15) \text{ Mpc} ; H_0 = (75 \pm 25) \frac{\text{km}}{\text{s Mpc}}$$

The error in distance is mainly caused by the imprecise value of H $_0$.

The published value of **z** is **0.0344**. Our measured value is close to this value and our error is big enough that the published value could be possible. Markarian 509 is not a normal quasar. It is relatively close to us. Our quasar is a Seyfert 1 galaxy with an active nucleus.

4. Final discussion

4.1. Conclusion

To work with the telescope and its controlling instruments was very easy. It works well to take and process the images. Our final spectra could be better but you can see the things how we wanted. To improve these results you could use another CCD with more pixels to get a better dispersion and resolution. With this, the wavelength calibration would be more exact. A telescope outside of the town would reduce the sky background.

Our measured value of the redshift for quasar Markarian 509 of $z=0.036$ with its error is very close to the accepted value of 0.034. This result shows what good accuracy may be achieved with our instruments.

4.2. Acknowledgement

I would like to thank Paddy McGee for his big support during this physics research project. His help during this project was fantastic. I would also like to thank Bruce Dawson for his support for our oral presentations.

4.3. References

Software:

IRIS:	www.astrosurf.com/buil/us/iris/iris.htm
VSpec:	valerie.desnoux.free.fr/vspec/download.html
Cartes du Ciel:	astrosurf.com/astropc/index.html

Spectroscopy:

www.physics.adelaide.edu.au/~pmcgee/
astrosurf.com/buil/us/spe6/planet.htm
www.astroman.fsnet.co.uk/quasars.htm
www.astrosurf.com/buil/index.htm

Star catalogues:

www.alcyone.de
simbad.u-strasbg.fr/Simbad