Astrophysics MSci

Spectroscopy of Binary Stars

PHAS3332

Abstract

The aim of this project is to determine radial-velocities curves for the spectroscopic binary stars Lambda Tauri and Alpha Aurigae.

A selection of 12 spectroscopic binary stars are observed with the 1.52m telescope at l'Observatoire de Haute Provence. These observations are pooled with those from similar campaigns in 2014 & 2013. With reference to published values of period and epoch of periastron, folded radial-velocity curves are produced. These curves are modeled by least squares fitting to a sinusoid.

For both stars, only the primary component is analyzed. For Alpha Aurigae the amplitude of variation is calculated as (9.6±5.7) km/s and the line-of-sight recession velocity (54.6 ±1.2) km/s. These values are not in agreement with the published results of 25.9611± 0.0044[1] and 29.9387± 0.0032 [1] respectively.

For Lambda Tauri the *amplitude of variation is calculated as* (43.9 ±6.7) km/s which is in slight agreement with the published value of 56.9 ± 0.6 [2] . The line-of-sight recession velocity is calculated as (43.6 ±8.4) km/s, which is in total diagreement with the published value of 17.8 ± 0.9 [3].

Introduction

The aim of this investigation is to produce radial velocity curves for spectroscopic binary stars. This is done by observing a sample of 12 confirmed and suspected binary systems with the 1.52m telescope at l'Observatoire de Haute Provence (OHP), France. This telescope is equipped with the high resolution spectrograph, Aurelie. We shall be observing in the wavelength range 4070-4130 Å, which is centered on the Balmer-delta (H-delta) atomic transition of hydrogen. The H-delta transition occurs when an electron moves from the principal quantum number state n=6 to n=2 and either emits (n=6 $\rightarrow$ n=2) or absorbs (n=2 $\rightarrow$ n=6) a photon of wavelength 4101 Å , which lies in the violet portion of the optical spectrum. A stellar atmosphere is optically thick to H-delta photons, so the line is observed in absorption.

From the high resolution spectra, the Doppler shift, *z*, of absorption lines are calculated by measuring the wavelength at which certain known spectral features occur.

$$z=\frac{\lambda_{obs}-\lambda_{rest}}{\lambda_{rest}}$$

Where λ_{obs} is the observed wavelength of the feature; λ_{rest} is the wavelength of the feature in the rest frame, ie without any Doppler shifting.

From the Doppler shift the line-of-sight velocity of the object can be computed simply beacuse we are considering the non-relativistic regime by :

$V = cz$ where c is the speed of light.

The velocities calculated from spectra taken in 2016 will be combined with velocities determined from spectra taken in previous observing missions using the same equipment at OHP in 2014 and 2013. This way it is hoped that phase coverage is greatly increased, reliable radial velocity curves may be plotted and parameters such as period, amplitude of variation and mass ratio may be computed.

A spectroscopic binary star is a system of two stars orbiting a common centre of mass which display a regular periodic redshift and blueshift in spectral features. This occurs because as the two stars orbit their velocities are changing along the line of sight of the observer.

When the axis connecting the two stars is perpendicular to the line of sight and the primary star (most massive) is moving away from the observer, this is phase=0, as shown in Diagram 1. At phase=0, the velocity vector of each star is directed entirely along the line of sight to the observer, so a maximum red and blue shift is recorded for the primary and secondary stars respectively.

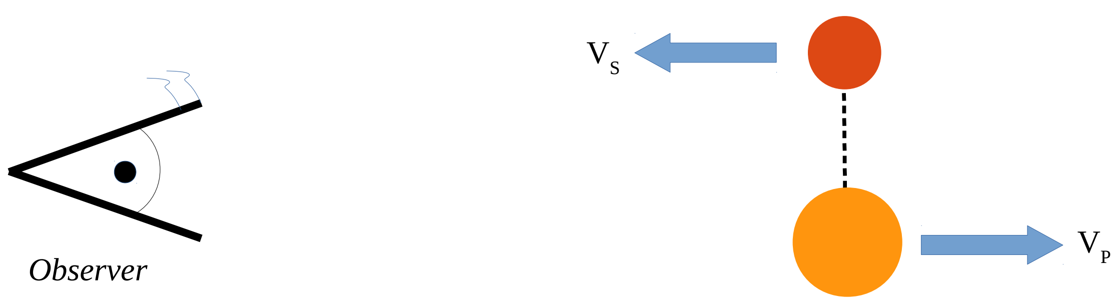

Diagram 1: A view of an edge-on binary system at phase=0. The primary star is orange; the secondary red. The maximum redshift is recorded for the primary star. The maximum blueshift is recorded for the secondary star. The system is rotating counter-clockwise in the plane of the paper.

As the phase increases, the stars move around their common centre of mass and the velocities change direction, so that they have a smaller magnitude directed towards the observer's line-of-sight. At phase= 0.25, both vectors will have no component directed towards the observer, therefore there will be no Doppler shift in spectroscopic features arising from the binary orbit, see Diagram 2.

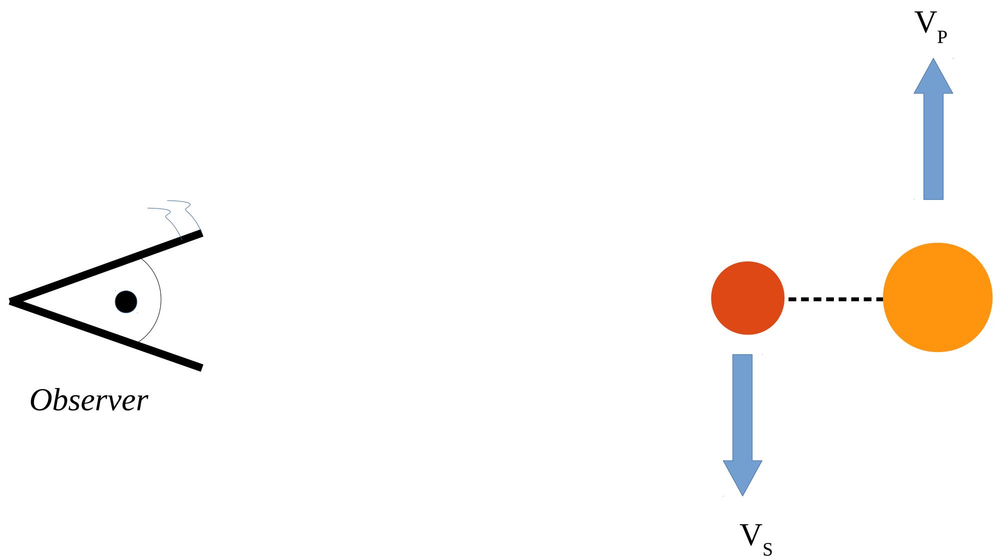

Diagram 2: A view of an edge-on binary system at phase=0.25. The primary star is orange; the secondary red. No Doppler shift is observed for either star. The system is rotating counter-clockwise in the plane of the paper.

At phase=0.5 both stars again have their velocities directed towards the observer, only the velocities are opposite in direction to the case of phase=0. Now it is the primary star's spectrum that is blueshifted and the secondary's that is redshifted. As the stars turn around another quarter turn so that the line connecting them is parallel with the line-of-sight, there is again no Doppler shifting of lines. The system then returns to phase=1, which is the same as phase=0. The phase is a way of describing the position of the stars in their orbit such that from phase going from 0 to 1, they have completed one full rotation. This variation in velocity along the line-of-sight is what produces spectral features to periodically move.

If both stars are of similar luminosities, then a spectrum will show the features of both stars. Some features that arise from both stars will be mirrored because when one star is traveling towards us, the other is traveling away. This is known as a “double lined” spectroscopic binary star. If one star is significantly brighter so as to overpower the signal coming from the other, then the system is a single-lined spectroscopic binary star.

If the system's orbit is inclined by angle i, then the observer will only see a maximum radial velocity of $V = V_{max} \sin(i)$; where V_{max} is the true maximum velocity of a star. Thus it is frequently the case that the system's maximum radial velocity cannot be directly determined from spectroscopy alone. If the system is inclined with i=90 º then it will not be a spectroscopic binary as never will the velocities of each star have a component along the line-of-sight.

If the system can be observed at many points of its phase, this periodic blue and redshifting can be noted and radial velocity curves constructed. If the two stars are sufficiently separated and the orbit circular, one would expect their radial velocities to vary sinusoidally of the form:

$V = A\sin(2\pi\phi + B) + C$ with A, B and C constants and ϕ the phase.

The constant C arises because in general a complete binary system is moving towards or away from us (as most astronomical objects are). This net movement generates its own Doppler shift. The radial velocity of the star is a combination of this net movement and of the orbital motion.

Furthermore binary stars can be studied photometrically. Binary systems which display a periodic variation in brightness are known as eclipsing binary stars. The brightness varies due to the more luminous component being eclipsed or transited by the less luminous. If a binary star can be resolved into two components through a telescope, it is said to be a visible binary. None of the objects discussed here are visible binaries.

The most reliable way to obtain radial-velocities from spectra is by the method of cross-correlation. This involves having a template spectrum that all the others are compared to. This template spectrum may be a synthetic spectrum (ie one generated by model stellar atmospheres), a spectrum of an object with very well known radial velocity (standard star), or the spectrum of the target at a different time. The wavelength shifts relative to the template are determined by overlaying the two spectra. The template spectrum is held still whilst the other is shifted along the x-axis until the features match with those of the template. The shift required to achieve a fit can be used to calculate the relative velocities of the template and spectrum.

Consider that the shift required to give a good it is Δw. The radial velocity of the template spectrum, V_T is given by:

$$V_T = c\left(\frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}}\right)$$

The radial velocity of the spectrum being analyzed,V is :

$$V = c\left(\frac{\lambda_{obs} + \Delta w - \lambda_{rest}}{\lambda_{rest}}\right)$$

Thus:

$$V - V_T = c\left(\frac{\Delta w}{\lambda_{rest}}\right)$$

If V_T is known, then it is simple to recover the radial velocity of the spectrum. If the template spectrum is that of the target at a different time, the radial velocity may be determined by individually measuring the wavelengths of as many lines as possible and computing the radial velocity. Alternatively a radial velocity curve may be plotted with $V- V_T$ on the y-ordinate, as V_T is just a constant.

The binary stars studied in this project are Alpha Aurigae and Lambda Tauri.

<u>Alpha Aurigae</u>

Co-ordinates (J2000) : RA= 05h 16m 41.4s , dec= +45º 59' 52.8"[4]

This target consists of two stars; Aplha Aurigae Aa (primary star) is of K0 III(giant) spectral type, while Ab is of G0 III spectral type [5]. These stars have moved from the main-sequence to become giant stars. The secondary star is believed to be evolving across the Hertzsprung gap. It has completed hydrogen core burning and it beginning to burn hydrogen in a shell around the core. The time spent in this predicament is very short compared to the star's lifetime, hence the Hertzsprung gap is very tenuously populated. Recent models have predicted that the primary star is at the end of core helium burning [1].

Curiously there is a companion to Alpha Aurigae Aa & Ab, named Capella H & L. They are two cool red dwarves (which make up a binary pair themselves) with a predicted orbit of 400 years.

Alpha Aurigae is not an eclipsing binary, so spectroscopy is the only tool available to determine its orbital characteristics. This system is expected to be a double-lined spectroscopic binary as both stars have similar luminosities.

The published period is 104 days [6], therefore the data obtained during previous field trips will be crucial in attempting to construct a radial velocity curve. An orbital eccentricity of 0.00089[1] means that the radial velocity curve is expected to take a sinusoidal form.

<u>Lambda Tauri</u>

Co-ordinates (J2000) : RA=04h 00m 40.82s, dec= +12 º 29 ' 25.2 " [4]

Lambda Tauri was one of the first binary stars to be discovered in 1848 by Joseph Baxendell. The system comprises of a B3 V primary star and an A4 IV [7]. The primary is a hot, main-sequence star that is rotating very rapidly, at 85 km/s [8]. As a result of this rotation, spectral line broadening is very pronounced. The primary star is chemically peculiar as it displays an under-abundance of carbon compared to stars of the same spectral class. Possible explanations for this are that the star has undergone convective mixing which dredged up carbon-depleted material to the photosphere or that the star has experienced mass loss in the past.
The secondary star is a sub-giant as it has almost completed hydrogen core burning. Similarly to the primary it displays a large rotational velocity.

Lambda Tauri is a single-lined spectroscopic binary as the primary star is more luminous than the secondary by a factor of 5000 [7]. However information can be gained about the secondary as the system is inclined by 76 º , making it also an eclipsing binary.

The period is 3.95 days [2] so it is hoped that during our 4 night observing campaign, we can see the target in a range of different phases. The combined data pool with spectra from 2014 and 2013 should offer a reasonable phase coverage. Lambda Tauri is also expected to have a sinusoidal radial-velocity curve because it has an orbital eccentricity of 0.025[2].

Observing Procedure & Data Acquisition

Data acquired in 2016 was taken during three nights from 14-17/02/2016. A total of 12 suspected and confirmed binary stars were observed using the Aurelie spectrograph on the 1.52m telescope at l'Observatoire de Haute Provence (OHP). The spectrograph was in configuration number 1, giving a high resolution of R=45,000 and a dispersion of 2.7 Å/mm. The targets were observed in the spectral region 4070-4130 Å which centres on the hydrogen Balmer-delta (H-delta) absorption line.

Before embarking upon the observing campaign, each member of the group was given a star to research. I was tasked with Alpha Aurigae. For each star it was necessary to determine the times that the star would be easily observed; this is the point when the star crosses the local meridian, where it is highest in the sky. This time occurs when the local sidereal time (LST) equals the right ascension of the object. Figure 1 shows how the altitude of Alpha Aurigae will vary throughout the night 15/02/2016. It can be seen that Alpha Aurigae is best observed before local midnight. The period of this object is 104[6] days, therefore it cannot be expected that we will view the system at a range of phases. To combat this it is suggested that Alpha Aurigae is observed with the greatest possible times between observations (ie observing on the first and last nights). This way we will see as much as possible of the system's period and telescope time may be better devoted to binary systems with shorter periods.

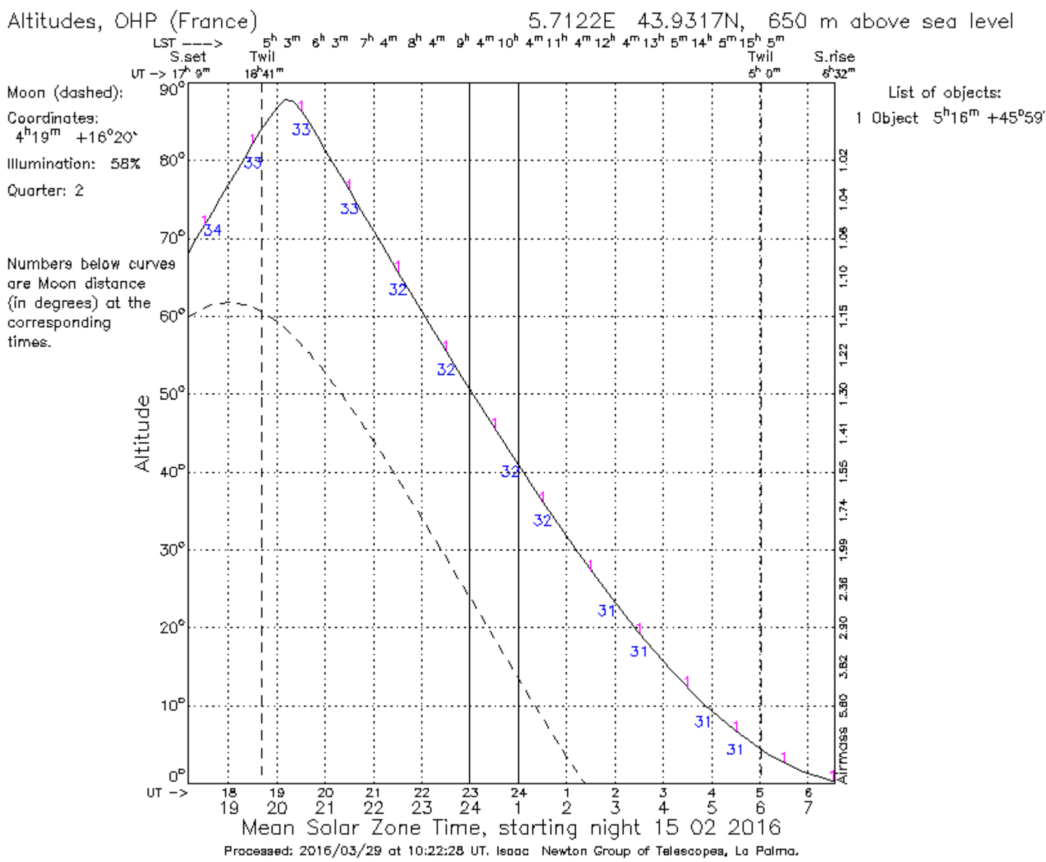

Figure 1 : A plot of the altitude of Alpha Aurigae at OHP on 15/02/2016. The dashed line shows the altitude of the moon, with the blue numbers being the angle (in degrees) of separation between the moon and the target. The lower timescale is local time and the upper scale is UT.

It is noted that throughout our stay at OHP the moon was between ¾ and full and stayed in the sky for much of the night (until 0100 UT). This may present a problem with contamination from telluric lines (spectral features introduced by the Earth's atmosphere) or adding an additional source of noise to our spectra. Figure 2 Shows that this would certainly affect Lambda Tauri, as the moon is only 3-4 º away when the target is observable. As Lambda

Tauri is a short period system (P=3.95 days [2]) it is possible to get good phase coverage over the 4 nights telescope time available. The best practice would be to observe Lambda Tauri at the start of the night (when it is on the meridian), then a few hours later, before it sets too low in the sky.

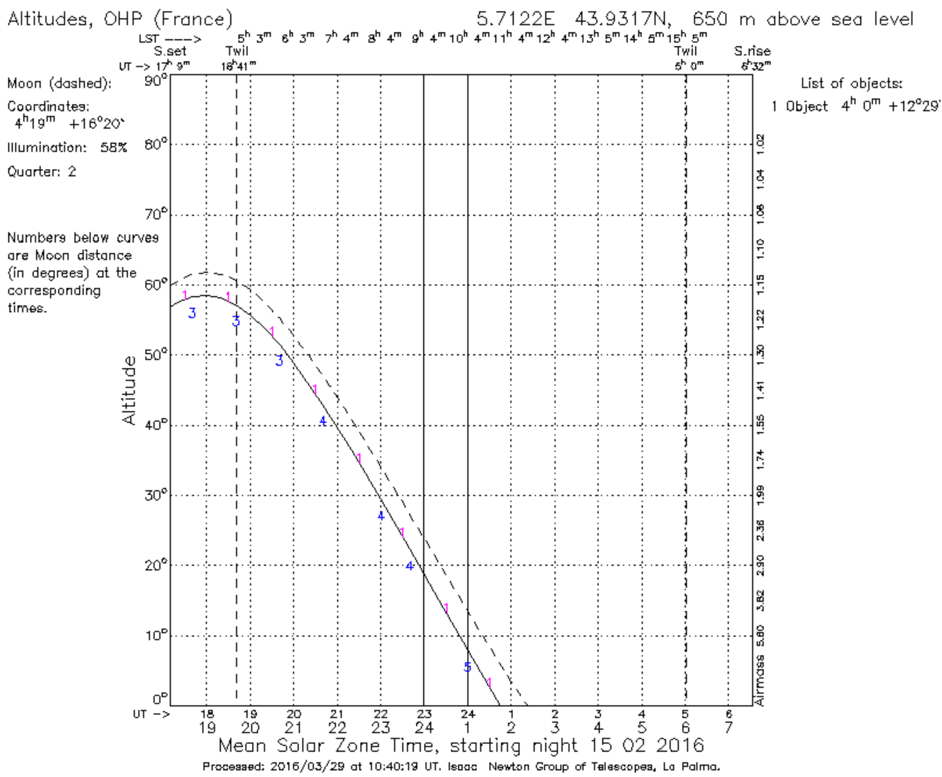

Figure 2 : A plot of the altitude of Lambda Tauri at OHP on 15/02/2016. The dashed line shows the altitude of the moon, with the blue numbers being the angle (in degrees) of separation between the moon and the target. The lower timescale is local time and the upper scale is UT. The target is observable from twilight to 2300 UT.

The observing run enjoyed good conditions with 3.2 clear nights. The evening session of 17/02/2016 was lost due to cloud. Erin Flowers and I participated in one observing session in the morning of 16/02/2016. Six exposures were made during this session.

Erin Flowers and I took over from Vanessa Lam and Anusha Gupta at around midnight UT on the morning of 16/02/2016. We did not observe either Lambda Tau or Alpha Aurigae. The observing procedure was fairly relaxed as exposures were typically 30-60 minutes long. Once the telescope is slewed to the co-ordinates of the target using the controls in the telescope dome and the dome moved into position, one looks through a finder telescope and uses slow-motion controls to move the star onto the centre of the field of view. This is so that the maximum of star-light may pass cleanly into the spectrometer.

To be certain of correct pointing a short test exposure of 60s is made. Once an exposure is complete, a computer in the telescope control room can show a plot of the spectrum trace. This trace is examined for the H-Delta feature that all the target stars exhibit. If the H-Delta absorption line is present, the telescope is deemed to be well aligned.

The exposure time required is calculated by knowing the magnitudes of the targets (which are mostly 5-6) and comparing this to the signal achieved for previous exposures, which are written in the telescope log. The exposure times for Lambda Tau and Alpha Aurgiae were typically 1800s and 600s respectively. During the exposure it is necessary to move the dome to follow telescope guiding system every 15 minutes. Otherwise the telescope aperture will be obscured by the dome, as the dome does not move automatically with the telescope. Periodic checks are made of the weather and the conditions are noted down.

The auto-guider system which keeps the telescope aligned on target consists of motors which move a mirror within the optical assembly to keep a guide star in a fixed position. The guide star is imaged with a CCD camera, and projected onto a computer monitor. When the star moves on this CCD camera, the system automatically moves the mirror so as to correct this movement. This ensures that the telescope tracks the stars apparent motion across the sky. Occasionally the mirror reaches the limit of its movement. When this happens an alarm sounds and one has to move the telescope slightly, so as to re-centre the guide star in the guiding camera's field of view. This is done by using a joystick and viewing the monitor of the guiding system until the star co-insides with a pair of cross hairs. The mirror is then reset to the centre of its limits and auto-guiding resumes. Typically the auto-guider failed every hour or two.

After the exposure, the spectrum trace is viewed and the signal level (in analogue-to-digital-units; ADU) is estimated by reading off the level of the continuum on the computer screen. Any other relevant notes are made such as cosmic ray hits (to be dealt with during data reduction). This information is inputted into the telescope log, along with the filename that the exposure is saved in, the target, exposure time and the UT that the exposure began.

Overall the observations went well and many spectra were taken. All spectra show a signal level greater than 100 ADU. Three spectra of Alpha Aurigae were taken and four spectra of Lambda Tauri were taken. These exposures are summarized in Tables 1 and 2.

Date of Observation (YYYY-MM-DD hh:mm UT)	Exposure Time (s)	ADU
2016-02-16 21:14	600	3000
2016-02-14 23:24	300	1200
2016-02-14 23:29	300	1100

Table 1: A Summary of the observations of Alpha Aurigae

Date of Observation (YYYY-MM-DD hh:mm UT)	Exposure Time (s)	ADU
2016-02-16 19:14	1800	580
2016-02-15 20:52	3600	900
2016-02-14 19:45	900	440
2016-02-14 20:01	900	420

Table 2: A Summary of the observations of Lambda Tauri

Given that the evening of 17/02/2016 perished because of cloud, the observations of Alpha Aurigae are as well spaced as possible. The two exposures taken after one another may prove useful in estimating errors on radial velocities.

We obtained spectra for Lambda Tauri during every evening that was possible. Regretfully we did not obtain spectra during different times of the same evening (when the target is accessible). However there were many targets competing for telescope time, so compromises must be made.

Data Reduction

The first stage of data reduction was to sort the exposures into science frames, bias frames, flat fields and calibration arcs by inspecting the FITS headers. All of the .fits files produced by the CCD camera were converted to .sdf (Starlink data format) files using the Starlink Figaro command "rdfits" (with swap and float set to true).

On the 1.52m telescope at OHP, bias frames are produced by exposing the CCD sensor to a Tungsten lamp which is a continuum source. For each night individually master bias frames were created by summing all of the bias frames taken in one night (using Figaro command iadd) and dividing that sum by the number of frames added (using Figaro command icdiv). This produced a mean of all the bias frames for each night of observations.

The bias is a signal across the CCD chip present in all exposures, irrelevant of the exposure length. It represents the “zero level” of the CCD camera. As the bias signal does not change significantly during one night, it is easy to remove the signal by subtraction. The bias frames contain approximately 120 counts across the CCD array with small variations introduced by the readout process. Producing a mean of several bias frames helps to eliminate this readout noise because it is randomly distributed across the array. 10 bias frames were averaged for each night. This master bias was then subtracted away from all science, calibration arcs and flat field frames.

It was not necessary to consider the effects of dark current because the detector of the Aurelie spectrograph is cooled to -110 ºC by liquid nitrogen.

Secondly a mean flat field frame was produced.This again was done with Figaro iadd and icdiv commands. In 2016 four flat-fields were taken for each night. This mean flat field was divided into every science frame with the Figaro idiv command. It was noted that for observations carried out in 2014, the flat-field frames were poorly exposed. In 2014 the typical counts for thorium-argon arcs were 140 ADU (analogue to digital units) while typical counts in the spectra of Lambda Tauri were 250 ADU and for Alpha Aurgiae 100 ADU. Dividing by a poorly exposed flat-field introduces a lot of noise into the spectrum. To solve this problem, all flat-field frames from 2014 were summed into one frame, which was then divided into the spectra taken in 2014.

Each spectrum had to be collapsed into a single vector so that one may plot flux as a function of wavelength. On the CCD detector, the light of one wavelength is spread out along the short edge of the array (the y-axis). The Figaro command “extract” sums up the counts along the array's columns to produce a 1 pixel high image where each pixel contains the total flux from a particular wavelength interval (as determined by the wavelength bin per pixel of the spectrograph). By inspection in Gaia it was found that the spectra lay on the array in the region y=12 to y=88. Therefore the extract command was used with the parameters 12 and 88.

Next was to wavelength calibrate the spectra. This process begins by creating a mean thorium-argon calibration arc frame from bias-corrected arc frames using the iadd and icdiv commands in Figaro. For each night, two thorium-argon arcs were taken at the start and two at the end of the night. This mean calibration arc was loaded into the Figaro arc routine. Using a list of thorium and argon emission lines and a plot of the wavelength calibrated emission arc provided by Stephen Boyle, each emission line was assigned its wavelength (in Angstroms). For this process a 3rd order polynomial was used to fit the emission lines and a line half-width of 1.4 pixels was used. This resulted in having a wavelength calibrated thorium-argon emission spectrum from which the stellar spectra can be wavelength calibrated. This wavelength scale was copied to every stellar spectra with the Figaro “xcopy” command. We now have a complete spectra; a plot of flux against wavelength which is displayed by the Starlink program Dipso.

Finally the spectra need to be trimmed and normalized. The star-light does not illuminate the whole of the array, but a rectangle upon the array. At the extremes of the wavelength range there will be pixels that received no stellar signal (unilluminated pixels on the other axis of the CCD array were removed during the extraction process). The signal from these pixels therefore needs to be removed. The Dipso command “snip” was used to achieve this. The stellar signal occupied the region of 4063.8- 4138.4 Å. These values were used at the limits of the snip. Snip was also used to remove the signal from a row of dead pixels on the array which affect the wavelength range 4090.50-4090.65 Å. Occasionally some spectra were victims of cosmic rays (evident by a very large spike in flux at a particular wavelength). When this occurred the cosmic ray signal was snipped out.

Within Dipso a continuum was fitted to the spectrum by eye with the “cdraw” command. This drew a straight line between the continuum at the start and end of the spectrum. The spectrum was divided by this simple approximation to the continuum so as to normalize it. Sample spectra of Lambda Tauri and Alpha Aurigae are given in Figures 3 and 5.

The spectra of Lambda Tauri show a clear H-delta absorption line, along with some unknown absorption lines further into the red part of the spectrum. The lines protruding up from the continuum are believed mostly to be either noise or cosmic ray hits. However some of these features redwards of the H-delta absorption line are consistent across the exposures taken on 15 and 16/02/2016 which would suggest that they are telluric lines.

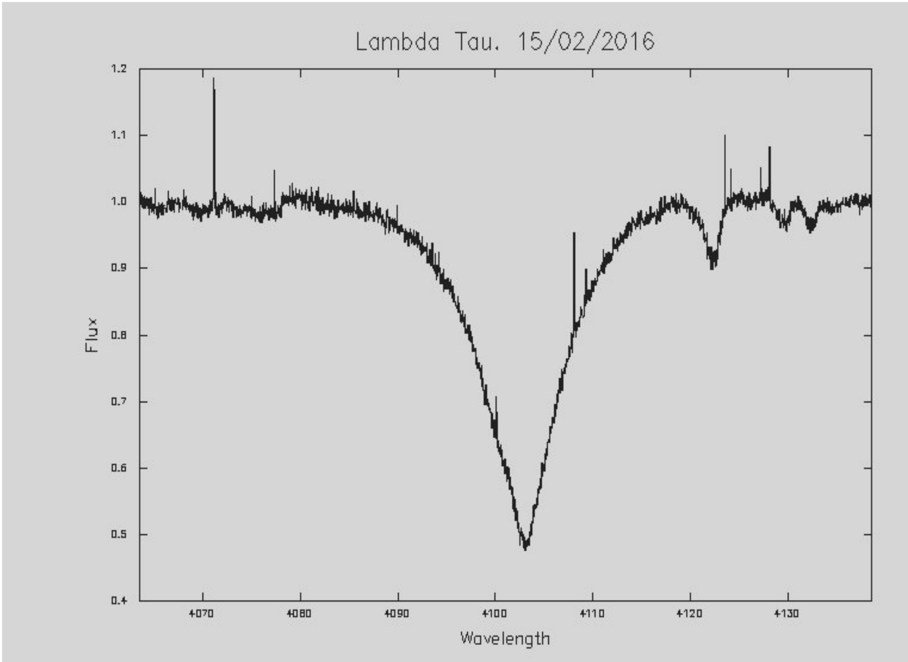

Figure 3 : A reduced spectrum of Lambda Tauri from a 3600s exposure taken on 15/02/2016. The Balmer Delta line can be clearly seen in the centre of the spectrum.

Figure 4 shows the two Lambda Tauri spectra of 15 and 16/02/2016. The spectra have been corrected for the redshift of the H-delta line by the Dipso command “vcorr”. Both spectra are therefore in the rest frame. It can be seen clearly that several emission features are common on both spectra. Both components of the Lambda Tauri system are main sequence stars, so are not expected to display emission lines. One explanation is that given the phase and proximity of the moon to the target during the observing run, these features are telluric (although telluric features are more prominent in the infrared, while these spectra are in the blue region). Bizarrely these features are not prominent in the spectra taken on 14/02/2016. The two features on the blue wing in Figure 4 were snipped out so that they did not interfere with any line profile fitting.

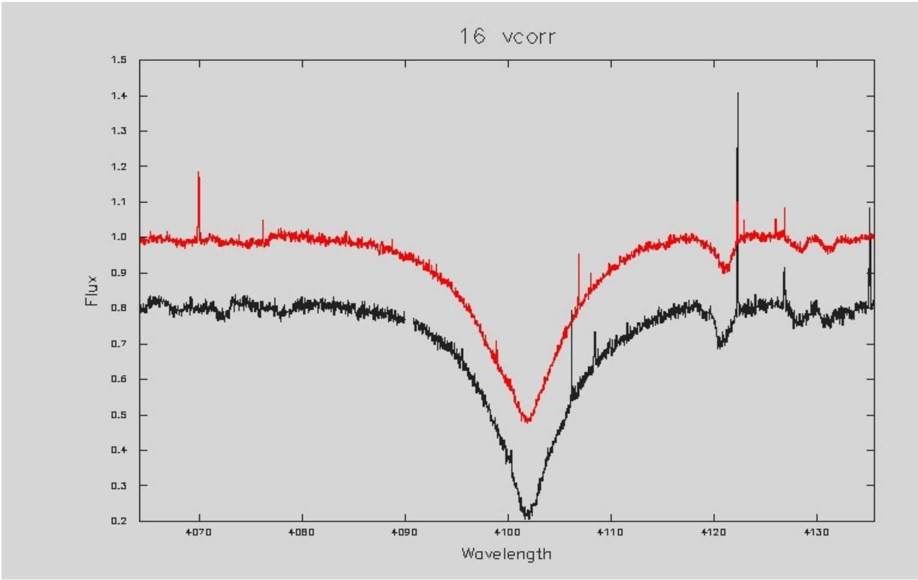

Figure 4 : A comparison between spectra of Lambda Tauri. The red spectra was taken on 15/02/2016. The black on 16/02/2016, which has had 0.2 subtracted from its flux so as to compare features of both spectra. Both spectra have been corrected for redshift of the H-delta line and are viewed in their "rest frames"

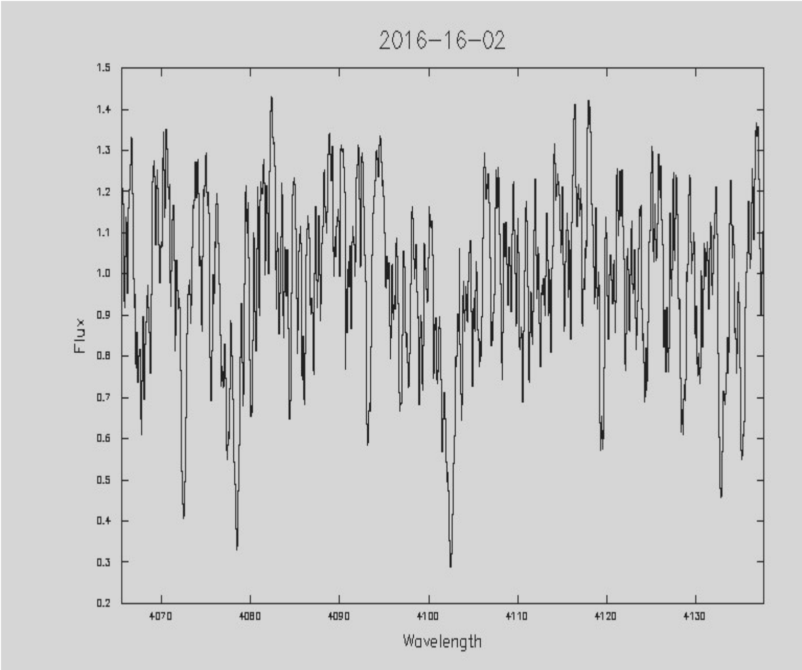

Figure 5 : A reduced spectrum of Alpha Aurigae from a 600s exposure taken on 16/02/2016. The H-delta line can be picked out in the centre of the spectrum, extending down to approximately -0.3 flux.

The spectrum of Alpha Aurigae, shown in Figure 5, is very chaotic with many features. The H-delta absorption feature can be seen just after 4100 Å . Both stars in this system are very evolved, so one may expect many features arising from a complex concoction of various metals and metal compounds. The fact that no continuum can be picked out made it very difficult to judge how to normalize spectra of Alpha Aurigae. Therefore the normalization is not reliable, but for our purposes of measuring radial velocities this is insignificant.

The signal-to-noise-ratio (SNR) of the Aurelie spectrograph on the 1.52m telescope at OHP is given by Gillet et al (1994)[9] as :

$$SNR=\frac{ST}{\sqrt{ST+R_{noise}+DT}}$$

where T is the integration time in s; R_{noise} is the readout noise ;D is the dark current (effectively 0) ; S is the signal in electrons/s/pixel.

The readout noise is given by $R\sqrt{(3+n)/n}$ where R is a constant of 300 electrons and n is the number of flat-field exposures used (n=4 in this case).

Gillet et al (1994) gives the signal S as being :

$$S=F\,T_{at}\,S_t\,T_t\,T_s\,T_c\,\eta\,\delta$$

where:
F= photon flux (photons/s/sq.cm/ Å)
T_{at} = atmospheric transmission
S_t = Surface of telescope=16583 sq.cm
T_t =telescope transmission =0.5
T_s = spectrometer transmission. 0.06< T_s <0.4 depending on configuration
T_c =window cryostat transmission=0.93
η= quantum efficiency of detector=0.859 at 4000 Å
δ= reciprocal linear dispersion (Å /pixel) =2.5 for configuration No 1

Finally the approximations that $F=1000\times10^{-0.4m}$ with m being the magnitude of our target and that $T_{at}=10^{-0.4\,k\,secZ}\approx10^{-0.4\times0.2\times1.5}$ as recommended by Steve Fossey[10].

Plugging all this in an estimate for the SNR for our spectra of Alpha Aurigae(m=0.88) is 1400. For Lambda Tauri(m=3.4) the estimate is 5000. These are very high SNR, indicative that very bright stars were being observed over long exposure times.

The reduced spectra for observations taken in 2013 seem to be very noisy. The exact source of this is unknown, however it may be that the flat fields were poorly exposed (as they were in 2014). In the observing logs, there is no note of the counts recorded on flat fields. An example of one of these spectra is given in Figure 6

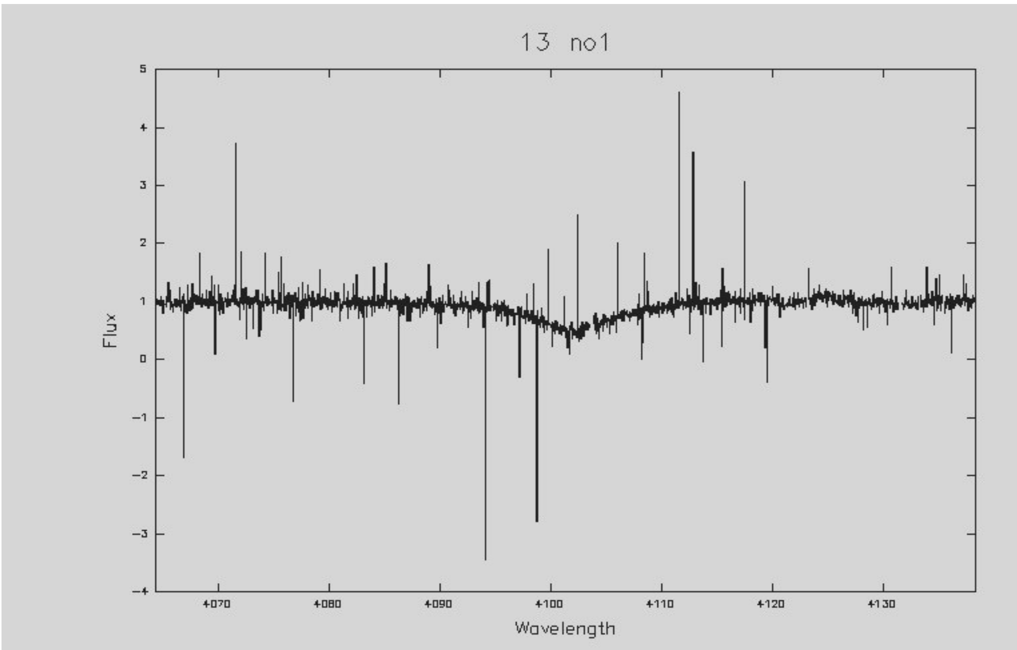

Figure 6 : A reduced spectra of Lambda Tauri taken on 13/02/2013. The spectrum is extremely noisy.

It is noticed that the H-delta profile looks very different in the spectra of the two targets. The profile of Lambda Tauri is very broad, with a Lorentzian shaped peak and Gaussian wings. The profile of Alpha Aurigae is comparatively narrower and best described by a Voight function. From this we may ascertain that the primary component of Lambda Tauri has a rotational velocity much greater than the primary component of Alpha Aurigae (because of the line widths caused by Doppler broadening).

Data Analysis

Lambda Tauri

The spectrum of Lambda Tauri shows a very clear and wide hydrogen Balmer delta line (H delta) therefore the radial velocity of the primary star is calculated by measuring the Doppler shift of the H Del line. Lambda Tauri is not a double spectroscopic binary star because its spectrum does not show mirrored features and when the H delta line is redshifted, there is no corresponding blueshifted feature to be found. Therefore it is only possible to ascertain qualities about the primary star.

Contamination from telluric lines was suppressed by snipping out the emission feature on the red wing of the H delta profile.

The wavelength of this line is calculated by using the ELF(emission line fitting) routine within Dipso. Even though absorption lines are considered here, ELF treats them as emission lines with negative flux, so analysis is still possible. The ELF routine demands that the data is restricted to approximately 30 Å. This is achieved with the "rxr" command, so that the absorption line is isolated. Then the parameters for the fit are guessed, the line centre is guessed as being at 4101 Å and the line width 10 Å in every case. ELF attempts to model the line to a Gaussian fit, with continuum regions modeled by a 2nd order polynomial. A sample fit is given in Figure 7.

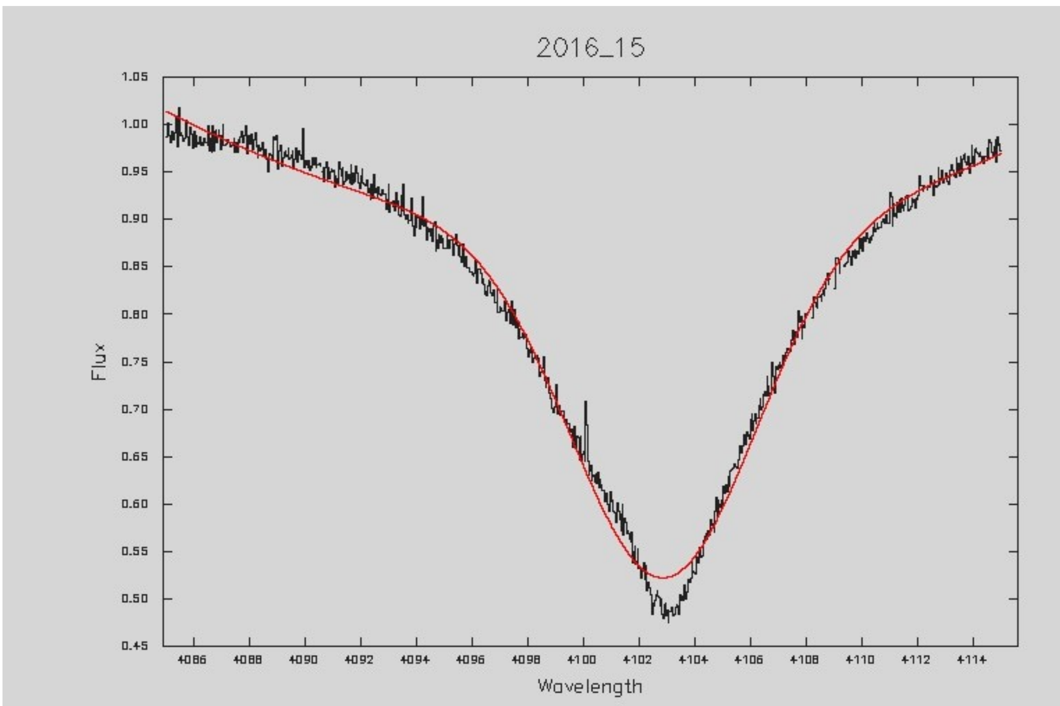

Figure 7 : A Gaussian fitted to the H del absorption line of Lambda Tauri. The exposure was 3600s taken on 15/02/2016. Possible telluric features have been removed from the red edge of the profile.

ELF does not do a fantastic job at modeling the whole shape of the absorption line. However it does find the line centre fairly accurately. The line shape is fairly complex with a Lorentzian peak and Gaussian wings, so is very difficult to model completely. ELF also produces an uncertainty value of the line centre.

Once the wavelength of the line centre is estimated, the radial velocity maybe calculated by considering the Doppler shift of the line, resulting in :

$$V[kms^{-1}]=\frac{\lambda_{obs}-\lambda_0}{\lambda_0}\times 3\times 10^5$$

where λ_{obs} is the observed wavelength and λ_0 is the rest wavelength ;taken as 4101.7370 Å [11]

The date and time of each observation is converted to Julian Date and the Julian Date of the mid-point of each exposure is calculated. This conversion was performed within the astropy library of the Python programming language.

From these observations it is very difficult to estimate the period of the system because there are very few data-points separated by years and no clear maximum or minimum in radial velocity is observed. Therefore a radial velocity curve is plotted using the period and epoch of periastron (the point at which both stars are closest, hence moving quickest and radial velocity is greatest) of 3.9529 days and 2444658.4 respectively [2].

Radial velocity curves were produced by converting the Juilan Date of each observation into phase by the following equation:

$$\phi=(t-T)/P-fl\{(t-T)/P\}$$

where t the Juilan Date of a data point, T is the epoch of periastron and fl{x} is the floor function which returns the smallest integer less than or equal to x, eg fl{5.87}=5. fl{-5.69}=-6 .

The radial velocity curves are modeled by a sinusoid of the form:

$$Asin(2\pi\phi+B)+C$$

where A, B and C are constants to be determined by the fit. The fit was performed by the “LevMarLSQFitter” function of the astropy Python module. This uses the Levenberg-Marquardt algorithm to calculate the least square statistic. The fit is calculated by determining the curve for which the sum of the residuals squared is least. The residual is the difference in y values (radial velocity) and the y-values given by the curve. This process requires initial estimates of the parameters. These estimates were provided by noting that the range of radial velocity values was approximately 100 km/s, with the minimum radial velocity around 0 km/s . From this it is reasonable to suggest that the amplitude of the curve (parameter A) is around 50 km/s and that parameter C also around 50 km/s. The parameter B was estimated to be 0. The fitted radial velocity curve is given in Figure 8.

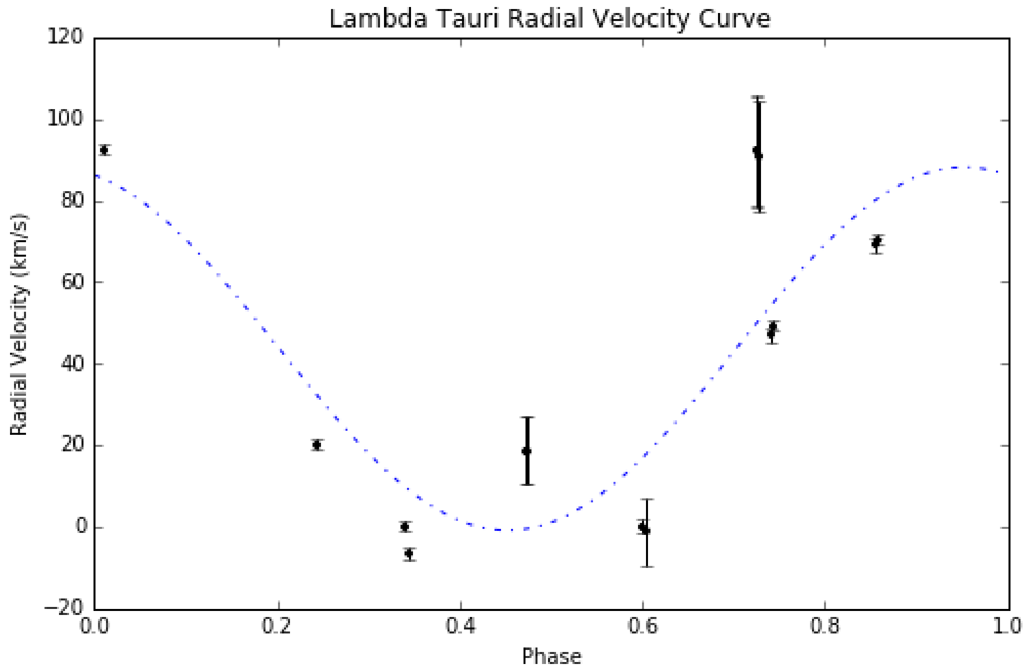

Figure 8 : A radial velocity curve for the primary of Lambda Tauri. The black dots represent data-points with their error bars. The blue dotted line is a sinusoid calculated from least squares fitting.

Alpha Aurigae

The spectrum of Alpha Aurigae seems very chaotic and cluttered, however the H-delta line can be picked out in the centre. A Gaussian fit cannot be performed for this spectrum because there is no continuum. Therefore the wavelengths of features are estimated by use of the "xv" command within Dipso. The absorption feature is isolated as much as possible to give an accurate a result. The wavelengths of the H-delta line and the Sr II (λ=4077.7140 Å) were measured. The Sr II line is the second strongest absorption line (behind the H-delta line). Its identity was confirmed by consulting Wright(1954)[12].

The two lines produce similar radial velocities, so it is assumed that they are produced by the same star. Alpha Aurigae is expected to be a double-lined spectroscopic binary, as both stars are of approximately equal luminosity. However no features can be found that give a radial velocity value opposite in sign to the values produced by the two identified lines. It is known that the rotational velocity of the secondary is 10 times greater than the primary's [1]. This means that features arising from the secondary will be greatly broadened, while those from the primary remain sharp. Therefore the primary features will be superimposed onto the broadened secondary features, making it very difficult to pick out the broad features.

The radial velocity was calculated using the same equation as before. A folded radial velocity curve was plotted using a period of 104.02173 days [1] and a time of periastron of 2447528.514 JD[13].

An attempt at fitting a sinusoid was made, however by some cruel misfortune it seems that all of the observations from 2013, 2014 and 2016 were made at only two points of the phase. The phase coverage is extremely poor therefore. The 2014 and 2016 data sets were both obtained when the system was as phase≈0.3. The resulting plot is given in Figure 9.

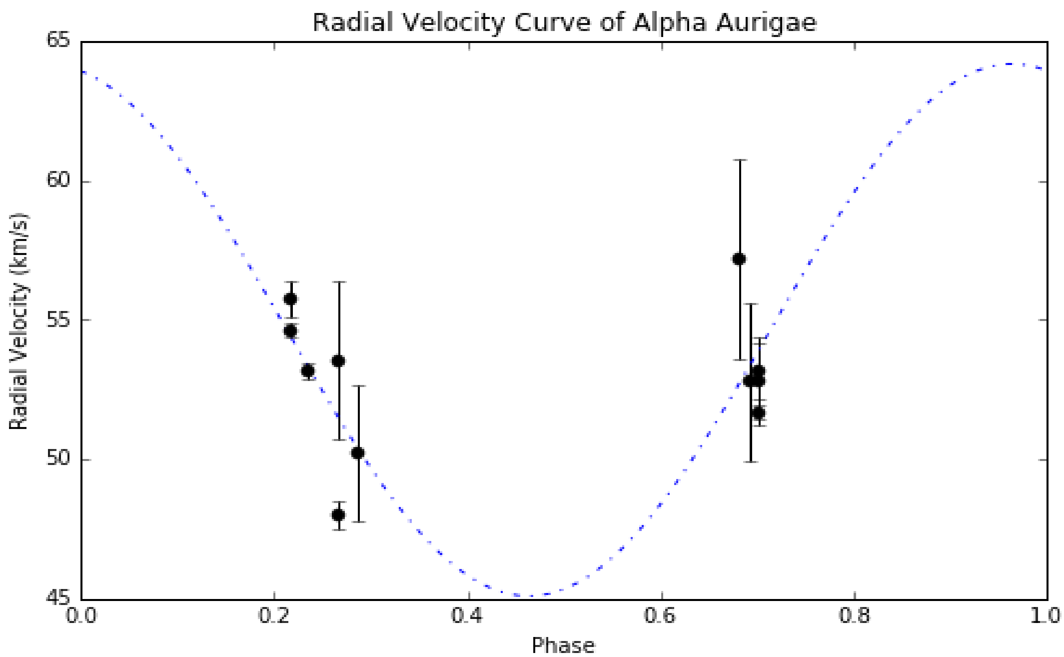

Figure 9 : A radial velocity curve for the primary of Alpha Aurigae. The blue dotted line represents the fitted sinusoid. The black points are individual measurements with their error bars.

Results & Error Analysis

Lambda Tauri

Table 3 shows the results of the ELF analysis. The radial velocity uncertainty is calculated using the variance equation which states that for y being a function of variables x_1 to x_n , the uncertainty on y, Δy is given by:

$$\Delta y(x_1 \ldots x_n) = \sqrt{\left(\frac{\delta y}{\delta x_1}\right)^2 (\Delta x_1)^2 + \ldots + \left(\frac{\delta y}{\delta x_n}\right)^2 (\Delta x_n)^2}$$

By consulting the expression for radial velocity given earlier, the velocity error is thereby:

$$\Delta V = \frac{3 \times 10^5 \times \Delta \lambda_{obs}}{\lambda_0}$$

Date (YYYY-MM-DD)	UT	exposure time (s)	JD(exposure centre)	H-Delta Wavelength (A)	Uncertainty (A)	Radial Velocity (km/s)	Uncertainty (km/s)
2016-02-16	19:14	1800	2457435.3118	4102.013	0.018	20.19	1.32
2016-02-15	20:52	3600	2457434.3903	4103.002	0.018	92.52	1.32
2016-02-14	19:45	900	2457433.3281	4102.380	0.023	47.03	1.68
2016-02-14	20:01	900	2457433.3392	4102.410	0.017	49.22	1.24
2014-02-21	21:05	900	2456710.3837	4102.680	0.021	68.97	1.54
2014-02-21	21:22	900	2456710.3955	4102.700	0.020	70.43	1.46
2014-02-23	19:15	900	2456712.3073	4101.740	0.019	0.22	1.39
2014-02-23	19:31	900	2456712.3184	4101.650	0.020	-6.36	1.46
2014-02-24	19:46	1200	2456713.3306	4101.740	0.022	0.22	1.61
2014-02-24	20:07	1200	2456713.3451	4101.720	0.113	-1.24	8.26
2013-02-13	19:09	300	2456337.2997	4101.992	0.113	18.65	8.26
2013-02-13	19:16	300	2456337.3045	4101.992	0.113	18.65	8.26
2013-02-14	18:58	300	2456338.2920	4102.996	0.184	92.08	13.46
2013-02-14	19:04	300	2456338.2962	4102.997	0.190	92.16	13.90
2013-02-14	19:11	300	2456338.3010	4102.977	0.184	90.69	13.46

Table 3: The results of the wavelength measurements of Lambda Tauri and resulting radial velocity.

It is evident that the uncertainties in radial velocities for observations taken in 2013 are very large. This is most likely due to these spectra being very noisy as mentioned earlier.

The values of the radial velocity curve fitting are given in Table 4 . The uncertainties are calculated from the matrix of covariance which is outputted by the astropy fitting function. The errors on each parameter are given by the square root of the diagonals of the covariance matrix.

Parameter	Value	Uncertainty
A	-43.6	8.4
B	-0.20	0.04
C	43.9	6.7

Table 4: The results of the radial velocity curve fitting for Lambda Tauri

The uncertainties represent rather large fractions of the values. This is a reflection upon the fact that few data-points are considered, and that large regions of the radial-velocity curve have no data-points.

The parameter A tells us the amplitude of variation in the radial velocity. Thus Lambda Tauri has a maximum radial velocity of (43.6 ±8.4) km/s. We can deduce the speed at which this binary system is receding from Earth. If the system were not receding from us, we would observe a radial velocity curve symmetric about the velocity=0 axis. Instead we observe a radial velocity curve that is symmetric about the line y= (43.6 ±8.4) km/s We are observing the results of two Doppler shifts; one from the system receding from Earth and the other from the periodic motion of the stars in orbit. Thus the line-of-sight recession velocity of Lambda Tauri is deduced to be (43.9 ±6.7) km/s.

Alpha Aurigae

The results of wavelength measurement and radial velocity calculation are given in Table 5. To calculate the uncertainty on the radial velocity, the standard error on the mean has been adopted. The error on the velocity is given by:

$$\Delta V = \sigma / \sqrt{2}$$

where σ is the standard deviation of the radial velocity values. The denominator is the square root of two because two values (one from measuring the H-delta line and one from the Sr II line) were used to calculate the mean.

Date (YYYY-MM-DD)	UT	exposure time (s)	JD (exposure centre)	H-delta Wavelength (A)	SrII Wavelength (A)	Radial Velocity (km/s) H-delta	Radial Velocity(km/s) SrII	Mean Radial Velocity (km/s)	Uncertainty (km/s)
2016-02-16	21:14	600	2457435.3882	4102.46	4078.44	52.88	53.41	53.15	0.27
2016-02-14	23:24	300	2457433.4767	4102.49	4078.48	55.07	56.36	55.71	0.64
2016-02-14	23:29	300	2457433.4802	4102.48	4078.46	54.34	54.88	54.61	0.27
2014-02-21	23:02	300	2456710.4615	4102.43	4078.48	50.69	56.36	53.52	2.83
2014-02-21	23:09	300	2456710.4663	4102.40	4078.36	48.49	47.53	48.01	0.48
2014-02-23	22:55	240	2456712.4563	4102.39	4078.43	47.76	52.68	50.22	2.46
2013-02-15	21:06	60	2456339.3795	4102.45	4078.45	52.15	54.15	53.15	1.00
2013-02-15	21:08	60	2456339.3809	4102.44	4078.42	51.42	51.94	51.68	0.26
2013-02-15	21:09	60	2456339.3816	4102.48	4078.41	54.34	51.21	52.77	1.57
2013-02-14	22:42	15	2456338.4459	4102.42	4078.47	49.95	55.62	52.79	2.83
2013-02-13	21:14	60	2456337.3851	4102.47	4078.54	53.61	60.77	57.19	3.58

Table 5: Results of wavelength measurements and resulting radial velocities for Alpha Aurigae.

Again a sinusoid was fitted to the measurements of radial velocities, but without many points to define either a maximum or a minimum radial velocity, the fit is very uncertain. The vales of this fit are given in Table 6.

Parameter	Value	Uncertainty
A	9.6	5.7
B	-0.71	0.01
C	54.6	1.2

Table 6: The results of the radial velocity curve fitting for Alpha Aurigae

Here the fractional uncertainties are not so great as they are for Lambda Tauri. However it can be seen from Figure 9 that a wide range of sinusoids could fit the data, and that perhaps the least squares method has not chosen the correct physical model of the binary system.

Again it is deduced that the calculated line-of-sight recession velocity of the system is (54.6 ±1.2) km/s and that the amplitude of radial velocity variation is (9.6±5.7) km/s.

Conclusions

Lambda Tauri

Table 7 gives a comparison between the values calculated in this project and the published values. There is no agreement in either the amplitude of variation of radial velocity, or the recession velocity. Although the amplitude of variation values do agree to 1 significant figure if the uncertainties are taken into account. This disagreement is most likely a result of the poor phase coverage and relatively few data-points used in calculating the sinusoidal fit to the data.

Parameter of Lambda Tauri	Value	Published Value
Amplitude of Radial Velocity variation (km/s)	43.6 ±8.4	56.9 ± 0.6 [2]
Recession Velocity (km/s)	43.9 ±6.7	17.8 ± 0.9 [3]

Table 7: A comparison of the results of this work with published results relating to Lambda Tauri

Alpha Aurigae

Table 8 shows that the calculated values do not agree well with published values. This discrepancy may be accounted for by the fact that comparatively few data-points were used to model the radial velocity curve and that these data points were very concentrated at two points in the phase of the orbit (phase ≈0.3 and phase ≈0.7).

Parameter of Alpha Aurigae	Value	Published Value
Amplitude of Radial Velocity variation (km/s)	9.6 ±5.7	25.9611± 0.0044[1]
Recession Velocity (km/s)	54.6 ±1.2	29.9387± 0.0032 [1]

Table 8: A comparison of the results of this work with published results relating to Alpha Aurigae

Overall I feel that the project has achieved its aims, although not very successfully. There are many improvements to be made.

If I were to undertake a similar project in the future, I would reduce and analyze the legacy data beforehand. An idea of the phase coverage of the legacy data would be very useful in planning the observations. This way for the long period targets, like Alpha Aurigae, the state of the system when the observations are scheduled can be predicted. Had this have been done, it would be found that observing Alpha Aurigae would not significantly add to the phase coverage of this target. Thus other targets, which are in a previously unobserved phase during our observations, could be observed with higher priority.

An improvement could be made on measuring the wavelength off-set of each spectrum. In the case of Lambda Tauri, the Gaussian profile used did not accurately represent the whole H-delta profile. Because of the width of the H-delta line, Dipso was unable to fit the continuum regions either side of the absorption line into its arrays. If a more sophisticated line profile were used (one with a Lorentzian peak and Gaussian wings) and the continuum included in the model, this would provide a more accurate and reliable wavelength offset. To improve the accuracy of radial velocity measurements, one could identify more spectral features from which to measure the wavelength offset. For both cases, an improvement would be made if the technique of cross-correlation were used, as this considers the whole spectrum, not just a few features.

One problem was the quality of reduced spectra from the 2013 data-set. This is most likely caused by division of a poorly exposed flat-field. To rectify this, all flat-fields from 2013 could be summed into one, and this be divided into each spectrum. This was done with data from 2014 owing to the poorly exposed flat-fields.

Clearly a vast improvement could be made by taking more spectra over a greater range of phases for both systems. It would be beneficial in include legacy data from previous observing campaigns other than just 2014 and 2013.

The data acquired during the 2016 observing mission is of good quality and will provide a good addition to data-sets of future missions, which hopefully can achieve more reliable and accurate results.

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