Astrophysics MSci

CCD imaging photometry of RR Lyrae Stars with the 1.20-m telescope at l'Observatoire de Haute-Provence

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Abstract

Two RR Lyrae variable stars, XY CVn and RR Gem are observed using the 1.20m telescope at l'Observatoire de Haute Provence (OHP) from 14- 18/02/2016. Observations were carried out in V and B Cousins filters. These observations were analyzed photometrically along with observations carried out in 2014 and 2013 to probe trends in the stars' magnitude over time. The aim is to determine the period of variation for each star and thus plot a folded light-curve. The periods of variation in each filter were determined by a novel "string-length" method.

The period of RR Gem is measured as (0.39731 ± 0.00003) days in the V filter and (0.39731 ± 0.00007) days in the B filter. These values both agree with the published value of (0.39728930 ±2.4E-7) days [5].

The period of XY CVn is found to be (0.35728 ±0.00081) days in the V filter and (0.35763± 0.00245) days in the B filter. The V filter value agrees with the AAVSO published period of 0.357279 days [9].

Introduction

The main aim of this exercise is to determine the periods of variation for the RR Lyrae variable stars RR Gem and XY CVn. This will be done by analyzing the light-curves produced for both the stars. Other properties of the stars will also be explored such as the type, presence of overtone modulations and the amplitude of variation in V and B filters.

The aims will be achieved by performing time-series photometry on both targets using the 1.20m telescope at l'Observatoire d'Haute Provence (OHP). Over several nights, the targets will be imaged multiple times throughout the night (producing as many frames as possible) and then differential photometry will be performed for the target star and a comparison star in each frame. This will result in a differential magnitude for the target for each frame (which represents a point in time), therefore it will be possible to plot the variation of the variable star's magnitude with time and thus analyze the period.

RR Lyrae stars are short period (less than 24 hours) variable stars. Due to their short period they are easily discovered and many are known within the Milky Way and its globular clusters. They lie on the "instability strip" and horizontal branch of the Hertzsprung-Russel diagram(see Figure 1).These stars have exhausted the hydrogen supply in their core and they burn helium (by the triple-alpha process) in the core and hydrogen in a shell surrounding the core. They are metal-poor Population II stars of spectral class A to F. They are thought to have had an initial mass of $0.8M_{\odot}$.

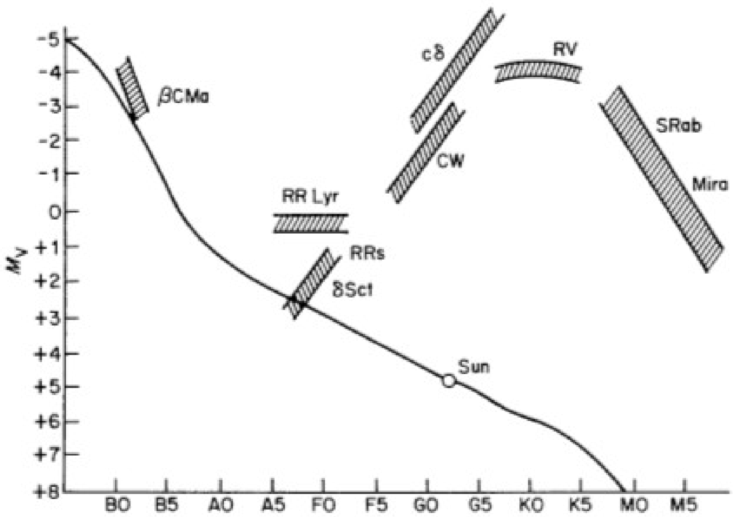

Figure 1 : A Hertzsprung-Russel diagram showing the regions occupied by various variable stars. The portion home to RR Lyrae stars is a horizontal strip; demonstrating that all RR Lyrae stars have equal luminosities. The main sequence branch is shown by a black line. Taken from Variable Stars, M. Petit (1987).

The mechanism by which RR Lyrae stars vary is due to a physical pulsation of the star (just like Cepheid variables). The star is not in hydrodynamic equilibrium, therefore the forces of pressure within the star (acting radially outwards) and gravity (acting radially inwards) are not balanced.

The cycle starts when a star has its minimum radius, the pressure is greatest at this point and gravitational potential energy (GPE) is least. The pressure is high because when the star is small, the number density of particles in the stellar atmosphere is high. This results in a large optical density. When contracted, the star has its maximum luminosity because the temperature is greatest and the luminosity is very sensitive to the temperature ($L \alpha T^4$). The optically thick atmosphere absorbs photons from the star and this heating increases the pressure. Because the pressure force is greater than the gravity force, the star expands. During the expansion, the number density of particles decreases, and the stellar atmosphere becomes optically thin, hence photons can escape from the atmosphere and the gas cools down and decreases in pressure. Whilst the expansion occurs the stellar envelope gains GPE until the force of gravity can overcome the pressure force and the star starts to contract. When the radius is at maximum, the luminosity is least, because the star is coolest.

Pulsations of this manner would decay after about 8000 years without an input of energy [1]. This energy comes from energy stored in ionized helium, known as the kappa-mechanism.

When the star is contracting, the energy released is used to ionize He II to He III. When the star is expanding the He III returns to He II, giving off energy to drive the pulsations.

RR Lyrae stars are useful as distance indicators because they obey a period-luminosity law of sorts. This was noticed from early observations of RR Lyrae stars in globular clusters. It is assumed that every star in the cluster is an equal distance from Earth and using this fact it is determined that all RR Lyrae stars have the same luminosity, independent of their period[2]. Once the luminosity is known, we may measure the flux received on Earth to calculate the distance to the RR Lyrae star by an inverse square law. The period-luminosity relationship can be fine tuned using distances calculated from parallaxes of RR Lyrae stars[3]. RR Lyrae stars have essentially the same luminosity because they lie in a very specific region of the HR-diagram; this region is a horizontal strip (where the horizontal branch meets the instability strip, see Figure 1), so for any spectral class, they have the same absolute magnitude. If a star were to be outside of this region then the layer of ionized helium inside the star would be at the incorrect depth to maintain the kappa-mechanism.

Types of RR Lyrae

RR Lyrae stars have been initially classified into three sub-types:

1) RRa- displaying an asymmetric “sawtooth” lightcurve with an amplitude of approximately 1 magnitude and a period of of around 0.5 days. The star brightens very rapidly, then dims in a slower fashion.

2) RRb- An amplitude of 0.5-0.8 magnitudes, a period of around 0.7 days and a more rounded lightcurve, but still sawtooth shaped.

3) RRc- A symmetric sinusoidal lightcurve with an amplitude of approximately 0.5 magnitudes and a period typically of 0.3 days.

As it is very difficult to separate sub-types a and b and that there is no distinct boundary between the two, they have been collapsed into a single sub-type RRab. It is believed that the types RRc and RRab are physically separated by RRab stars pulsating in the fundamental mode and RRc stars pulsating in the first harmonic[4]. Figure 2 shows examples of typical light-curves for each subtype; it is easy to see the differences between the two types and to contrast their periods.

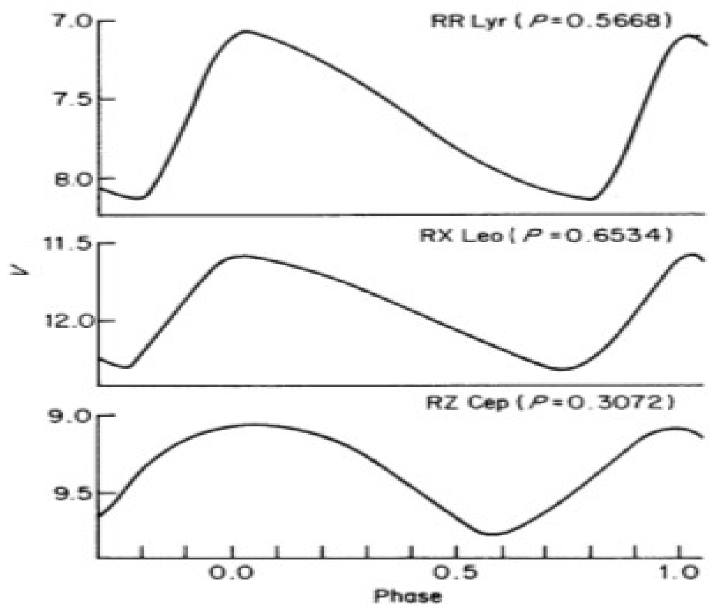

Figure 2 : Three example light-curves of RR Lyr (the prototype star), RX Leo (type RRab) and RZ Cep (type RRc). The curves are plotted as a function of phase against visual magnitude. The period in days is given above each curve. Taken from Variable Stars, M. Petit (1987).

<u>Target Stars</u>

The stars studied here are XY CVn and RR Gem. These stars are not members of globular clusters but are in our own galaxy.

RR Gem lies at co-ordinates (J2000) RA= 07h 21m 33.5s , dec= +30º 52' 59''. It is of type RRab. It is known to exhibit the Blazhko effect (where regular modulations in the amplitude and times of minima and maxima are present with long periods) with a period of 7.21 days and that over 70 years' time the amplitude of the Blazhko modulations varied from being undetectable to 0.25 magnitudes in the B passband [5]. It has a period of variation of 0.3973 days [5].

XY CVn lies at co-ordinates (J2000) : RA= 13h 48m 01.9s, dec= +29º 11' 47''. It is of type RRc. This sub-type does not exhibit the Blazhko effect, however XY CVn does offer a chance to study a low mass star in a very specific point in its evolution.

Observing Procedure and Data Acquisition

The two targets endured 4.2 nights of observations from 14/02/2016 to 18/02/2016 using the 1.20m telescope at l'Observatoire d'Haute Provence. The evening session of 17/02/2016 perished due to total cloud cover. Erin Flowers and I took part in four sessions, totaling 20 hours of telescope time. A large amount of data was acquired for both targets in each filter. Slightly more data is present for XY CVn beacuse the evening session of 17/02/2016(when RR Gem is observable) was lost to cloud.

Before the observing took place, rigorous preparations were carried out. Finding charts were produced and candidate comparison stars were checked, see Figures 3 and 4. For RR Gem the star NOMAD1 1209-0151214 was found to be a good comparison star. It has a magnitude in the V band of 10.336[6]. RR Gem has a V band magnitude between 10.62 and 11.99 [7]. Therefore so long as care is taken to never overexpose the comparison star, the target shall be well exposed because the comparison is slightly brighter than RR Gem at maximum light.

For XY CVn a good comparison star was determined to be NOMAD1 1191-0218907, with a V magnitude of 14.280 [6]. XY CVn has a visual magnitude range of 13.5 to 14.5[7]. Thus if XY CVn is not approaching saturation, the comparison star will also be safely exposed.

It was also found that RR Gem can be observed until 0300 CET while XY CVn is only easily observable after local midnight (see Orientation Report, Ben Hastings 2016 for further details). Thus it was decided to observe RR Gem during evening sessions (spanning from 1900 to 0000 CET) and to observe XY CVn during morning sessions (0000 to 0500 CET).

I engaged in four observing sessions for this project. All sessions ran smoothly and enjoyed fair, clear weather and gathered good data. The CCD sensor on the telescope behaves non-linearly above 60,000 counts and care was taken to ensure that the target star and selected comparison stars were not above this limit. Periodically the counts were noted in the telescope logs and exposure times adjusted if necessary.

The only problem that arose was that the telescope drive stopped after the drive mechanism was not reset. This affected frames 451-459 taken in the B filter for RR Gem on the night 16-17 February. These exposures feature significant star-trails and must be disregarded.

Throughout observations attention was paid to suffix the file names of exposure checks and field checks with “EC” and “FC” respectively. This way it is very easy to sift science frames from exposure and field checks when reducing the data.

Each session would begin with slewing the telescope to either XY Cvn or RR Gem and taking short exposures to check that the target is in the field of view using finder chars (Figs 3 and 4). Nextly, Erin Flowers and I determined the exposure times necessary to obtain approximately 20,000 to 30,000 counts on the target star and ensuring that the comparison star was not overexposed. This was done by trial and error, however after exposure times had been determined in previous nights, these were used as initial estimates. Once field and exposure checks were complete and the telescope's auto-guider system was turned on, we were ready to take science frames.

For observations of RR Gem exposure times were around 2 and 8 seconds in V and B filters respectively (depending on the weather conditions and altitude of the target). It was decided to expose 20 frames in one filter before changing to the other. This was done to minimize the number of filter changes, as a change takes around 20s, so by changing the filter less often we improve the duty cycle of the telescope.

For observations of XY CVn exposure times were around 100 and 300 in V and B filters respectively. We chose to do 3 exposures in each filter before changing to the other because the exposure times were long compared to the time taken to change filters, increasing the number of filter changes does not affect the duty cycle. Also if there is too long a time between successive observations in one filter, the data points will be very clumped together with large regions of the light-curve without any data-points.

The nights continued observing the target in the two filters, periodically moving the telescope dome (which had to be done manually), checking exposures for saturation, and occasionally resetting the telescope drive mechanism.

At the end of a night it was necessary to make bias frames, dark frames and flat fields (if they weren't done by the technician at the start of the evening). Firstly the dome is closed and flat fields are exposed. The telescope is pointed at a white board which is evenly illuminated by a lamp inside the dome. Exposures are made in each filter so that the flat fields are well exposed to a count value well above the science frames, but below saturation.10 flat fields were made in each filter. When the flat fields were made by the technician, the evenly illuminated twilight sky was imaged. Next, the diaphragm over the telescope mirror is closed to prevent any stray light entering the CCD camera. 10 bias frames were taken, which are exposures of 0 seconds, to determine the “zero level” of the camera. As dark current is proportional to exposure time, it is important to consider the different exposure times. For example, if we have exposures of 2s, 8s and 7s then dark frames of 7s and 2s should be taken. The dark frames for 8s long exposures can be produced by multiplying the 2s dark frames by 4. 10 dark frames of each required exposure time were taken.

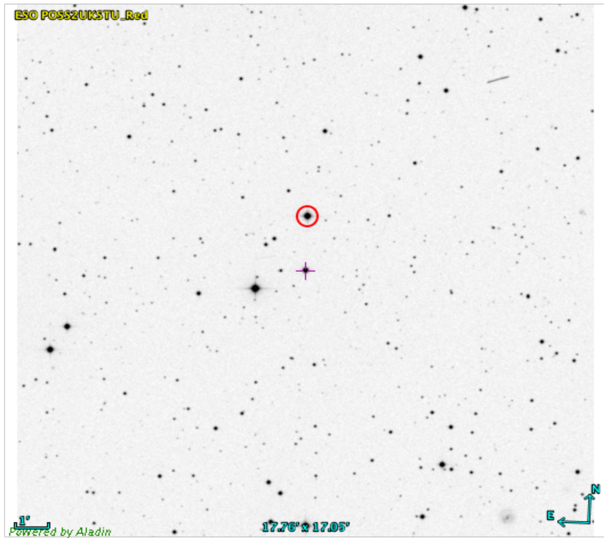

Figure 3 : A finder chart for RR Gem (noted by the purple crosshair in the image centre). The field shown is 17 sq arcmin (11 sq. arcmin is the field on the telescope used). North is up, East to the left. Supplied by Digitized Sky Survey 2(SDSS2) in the red passband. The comparison star NOMAD1 1209-0151214 is highlighted with a red circle.

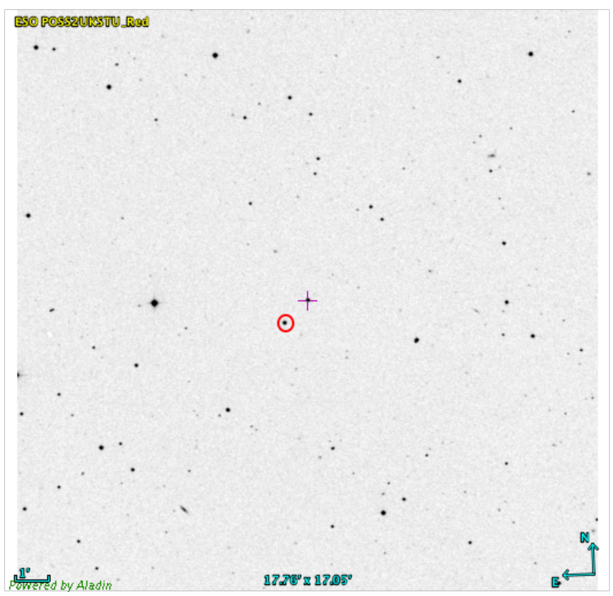

Figure 4 : A finder chart for XY CVn (noted by the purple crosshair in the image centre). The field shown is 17 sq arcmin(11 sq. arcmin is the field on the telescope used). North is up, East to the left. Supplied by Digitized Sky Survey 2(SDSS2) in the red passband. The comparison star NOMAD1 1191-0218907 is shown by a red circle.

Data Reduction

The first stage of data reduction was to sort the exposures into science frames, bias frames, dark frames and flat fields. 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). 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. The bias is a signal across the CCD chip present in all exposures, irrelevant of the exposure length. 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 300 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. 10 bias frames were averaged. This master bias was then subtracted away from all science, dark and flat field frames.

Secondly a master dark frame was produced for each night and for each given exposure time used during that night using the same procedure in Figaro. It was noticed that when the master bias frame was subtracted from the dark frames, many negative values resulted. It would be inappropriate to subtract these bias-subtracted dark frames from the data because by subtracting we would be adding noise (subtracting a negative number is equivalent to adding) to the data. Typically a bias-subtracted dark frame would range between -90 and 30 counts, while the mean bias frame is very consistent at around 300 counts. It is surmised that the many negative values are the result of the readout noise exceeding the actual dark current signal. This is reasonable as the CCD camera on the telescope was upgraded to a new model in 2014, is cooled by peltier plates to -80 ºC and our exposure times were short. The dark current is therefore negligible.

Thirdly a mean flat field frame was produced for each filter V and B respectively. This again was done with Figaro iadd and icdiv commands. This mean flat field was divided by that mean of its own count so as to normalise it. The mean count in the frame was given by the Figaro command “istat” where Figaro was instructed to use the pixels from x=10 to x=1000 and y=10 to y=1000. The whole frame was not used because on one edge of the flat field images there is a row of “hot pixels” see Figure 5, and we are concerned mostly with the stars in the centre of the frame, so we can ignore the image edge where vignetting effects are strongest. This normalized mean flat field frame was then divided into every science frame with the Figaro command “idiv”. Observations taken through the V filter, were divided by a normalized mean flat frame taken in the V filter, similarly for the B filter as well. This completes the reducing process.

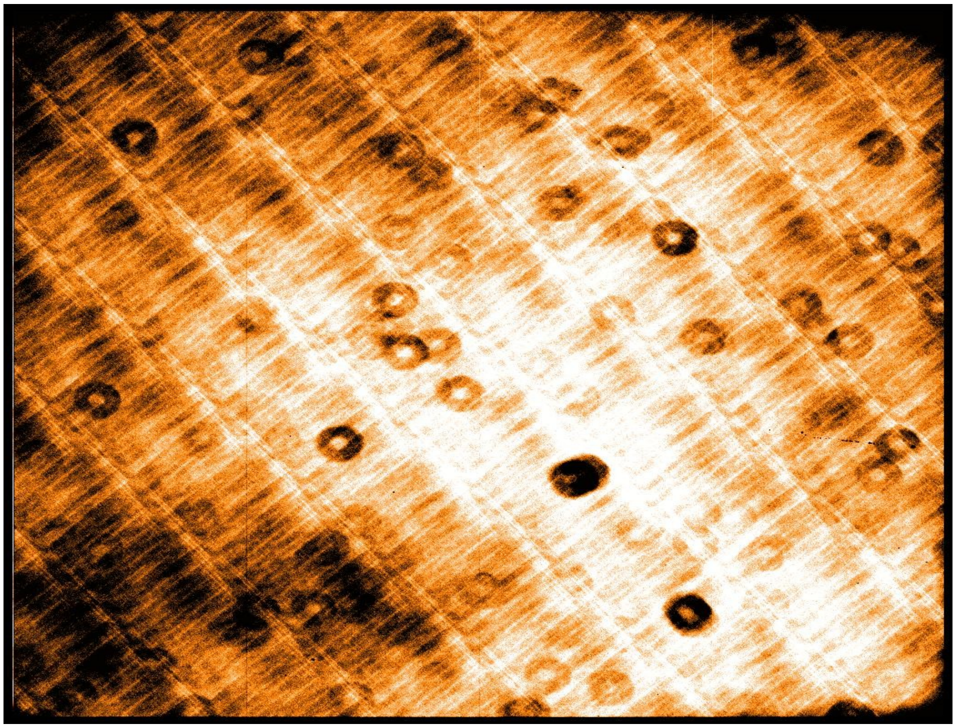

Figure 5 : A mean flat field taken in the B filter on 16/02/2016. Careful inspection shows a row of "hot pixels" on the left of this image. The contrast has been stretched to 90% in Gaia.

The photometry was performed upon the reduced science frames by the Starlink package Photom. The command "autophotom" will perform aperture photometry on one image. It is given an input file containing the x,y co-ordinates of where the apertures should be placed, the radius of the apertures and values describing the sky annuli. The results are written to a text file containing the magnitude, an error estimate on the magnitude, the aperture positions after centroiding and the sky values (in exactly the same format that Gaia would produce when performing aperture photometry). A C-shell script was written to use the autophotom maneuver on every useable science frame. Any frames which showed trailing stars, such as those mentioned previously on 16/02/2016 were disregarded.

After inspection in Gaia, the full-width-at-half-maximum (FWHM) of the stellar point spread function was determined to be approximately 4 pixels throughout all of the observations in 2016. Therefore an aperture radius of 10 pixels was chosen for all photometry (a good aperture size is 2-3 times the FWHM). Circular apertures were also always used. The sky annuli values were set to 1.5 times the aperture radius for the inner scale and 2.5 for the outer scale. An example of this aperture is shown in Figure 6.

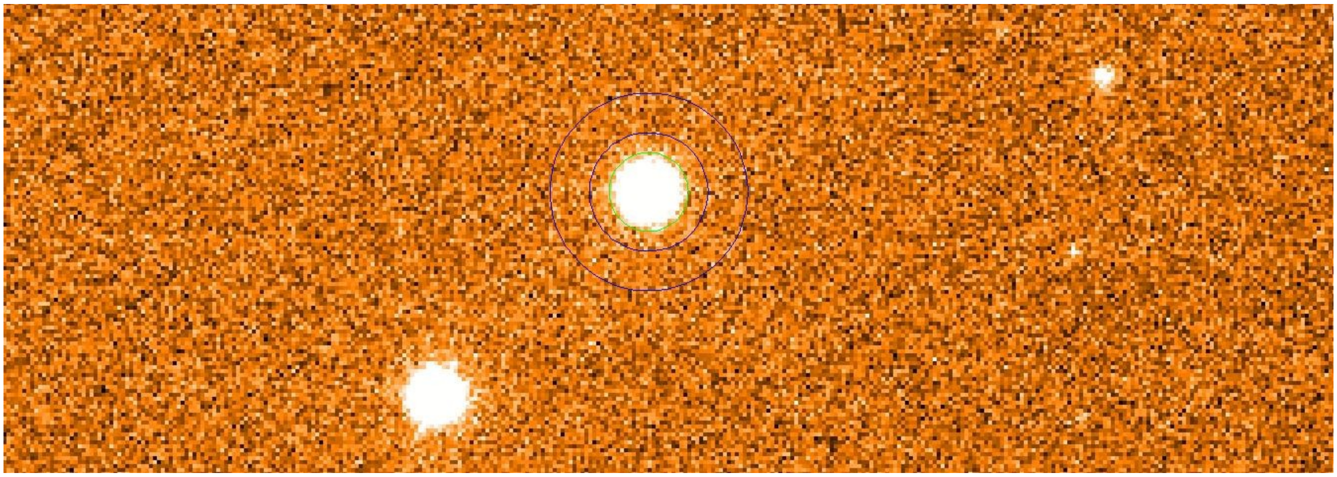

Figure 6 : A view of the aperture and sky annulus used for the photometry. This is a view from a frame of XY CVn. The aperture is defined around XY CVn

Aperture photometry was performed on the target, the comparison stars described previously and a second comparison star which varied from night to night. Measurements were made of this second comparison star so as to ensure that the first comparison star is not varying in its magnitude. This is done by plotting the differential magnitude (magnitude of one star subtracted from the other) against time; if this plot shows no variation, then the two stars are good comparison stars. Before starting photometry frames for each night were checked randomly to ensure that neither the target, nor any comparison stars were saturated (counts greater than 60,000).

This whole process was repeated for data taken on previous field trips in 2013 and 2014. This produced a large data set to draw conclusions from.

The magnitude estimates are believed to be good. The results of the photometry give consistent magnitude errors of around 0.00300 for RR Gem and around 0.00200 for XY CVn. An estimate of the signal to noise ratio (SNR) is given by the calculator hosted online by The Amateur Sky Survey (TASS) is given in Table 1 .The SNR is very favourable, therefore it is concluded that the magnitude estimates are good. The parameters used were those listed on the OHP website regarding the CCD camera on the 1.20m telescope and are given in Table 2.

XY CVn (B/V)	RR Gem(B/V)
720 / 100	420 /590

Table 1: Estimates of signal noise ratio(SNR) for XY CVn and RR Gem in each filter. The number leading the slash is V filter SNR, the one trailing is B filter SNR.

Quantum Efficiency	0.9
Pixel Size (arcsec/pixel)	0.385
Readout noise (electrons)	6.43
Sky magnitude (mag/sq. Arcsecond)	21
Airmass	1.2
FWHM (pixels)	2
Aperture Radius (pixels)	4

Table 2: The values used to estimate the SNR

Data Analysis

XY CVn

Light curves for XY CVn in each filter are given in Figures 8 ,9 ,10, 7. In the V filter we have observed one maximum and in the B filter we were lucky enough to observe two, see Figures 9 and 8. From Figure 10 it can be seen that both comparison stars were well behaved in the V filter. Unfortunately in the B filter, on 16/02/2016 there is a differing magnitude difference between the comparison stars. The source of this is unknown, as neither comparison star is approaching saturation. This is especially unlucky as on this night we observed a maximum light of the target. Therefore the night of 16/02/2016 will not be used to estimate the epoch of maximum light. Instead 15/02/2016 shall be relied upon for the B filter.

The epochs of maximum light are estimated by fitting a polynomial to the data that exhibits a maximum. Once a polynomial is fitted, its turning point can easily be calculated as the estimate of the epoch of maximum light. This was done using the numpy polyfit and scipy optimize.minimize facilities within the Python computer programming language. In the V filter data from 16/02/2016 was used and a 3rd order polynomial was fitted, see Figure 11. In the B filter data from 15/02/2016 was used and a 4th order polynomial was fitted because this better modeled the data, see Figure 12.

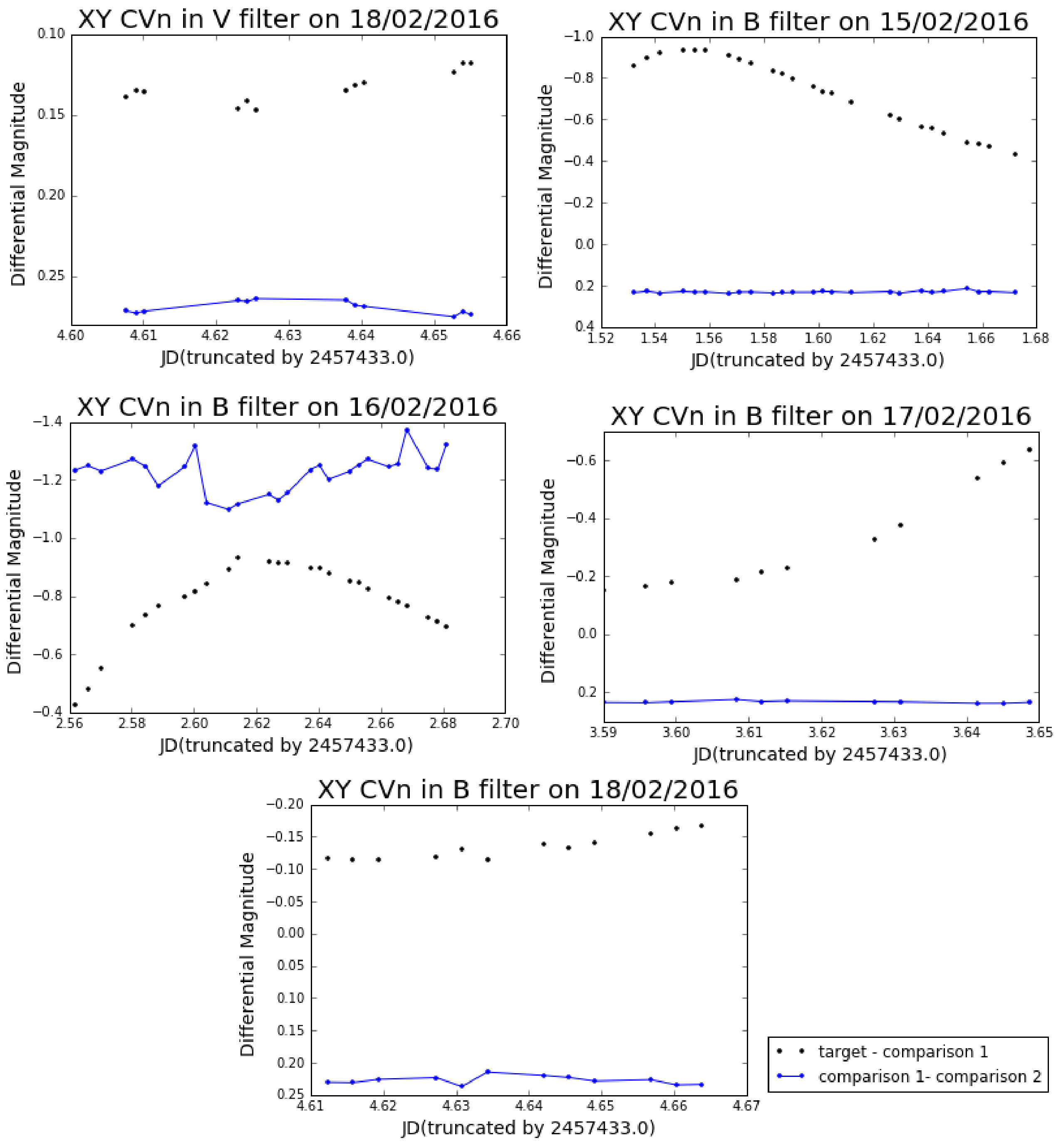

Figure 7 : Plots of data for individual nights for XY CVn in the B filter. The blue lines and dots represent the differential magnitude of comparison star 1 and comparison star 2. They are all flat, except for the night of 16/02/2016. Therefore both stars are deemed good comparison stars.

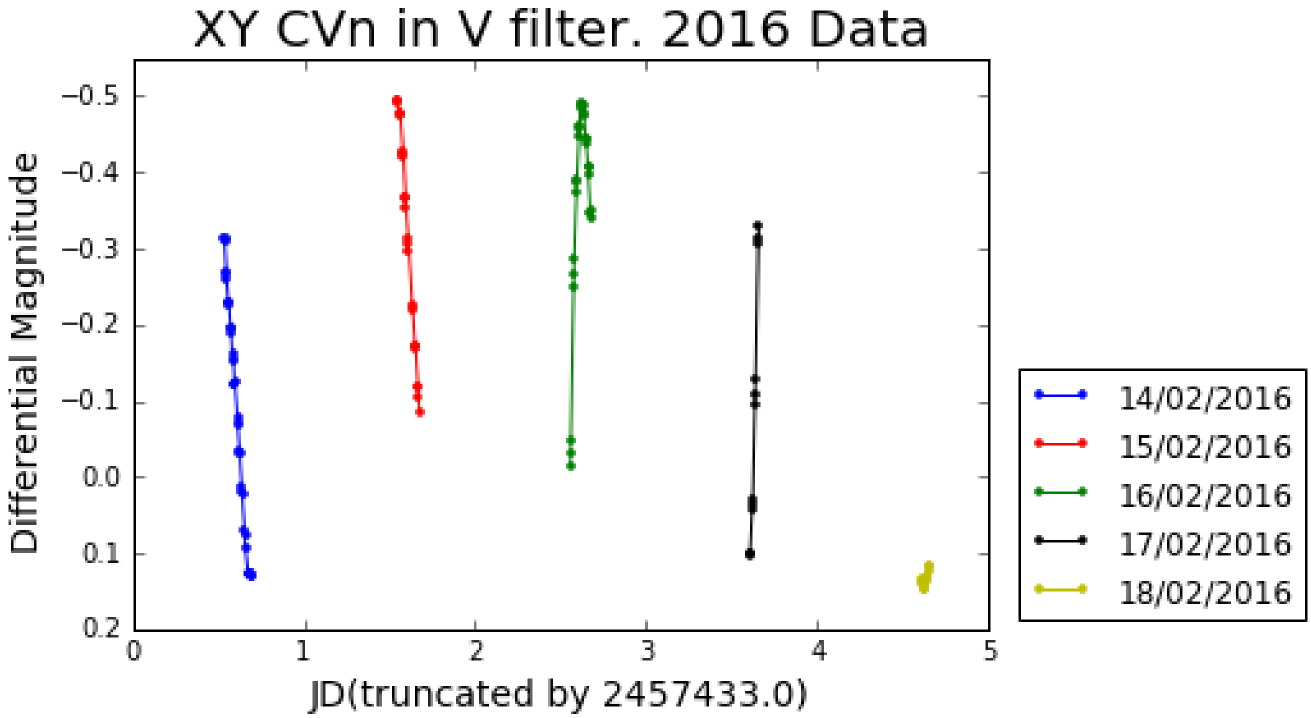

Figure 8: A plot of differential magnitude against Julian Date (JD) for XY CVn in the V filter from the data acquired in 2016. The target reaching maximum can be seen on 16/02/2016.

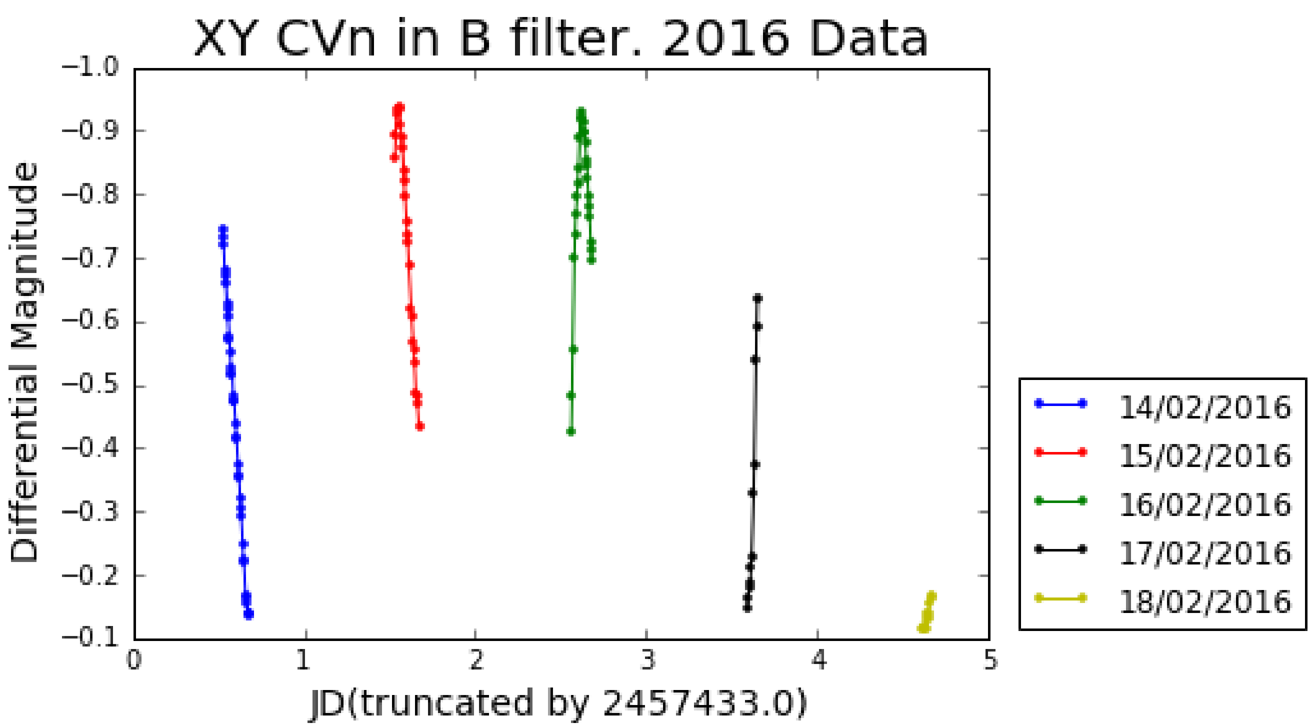

Figure 9 A plot of differential magnitude against Julian Date (JD) for XY CVn in the B filter from the data acquired in 2016. The target reaching maximum can be seen on 16/02/2016 and 15/02/2016.

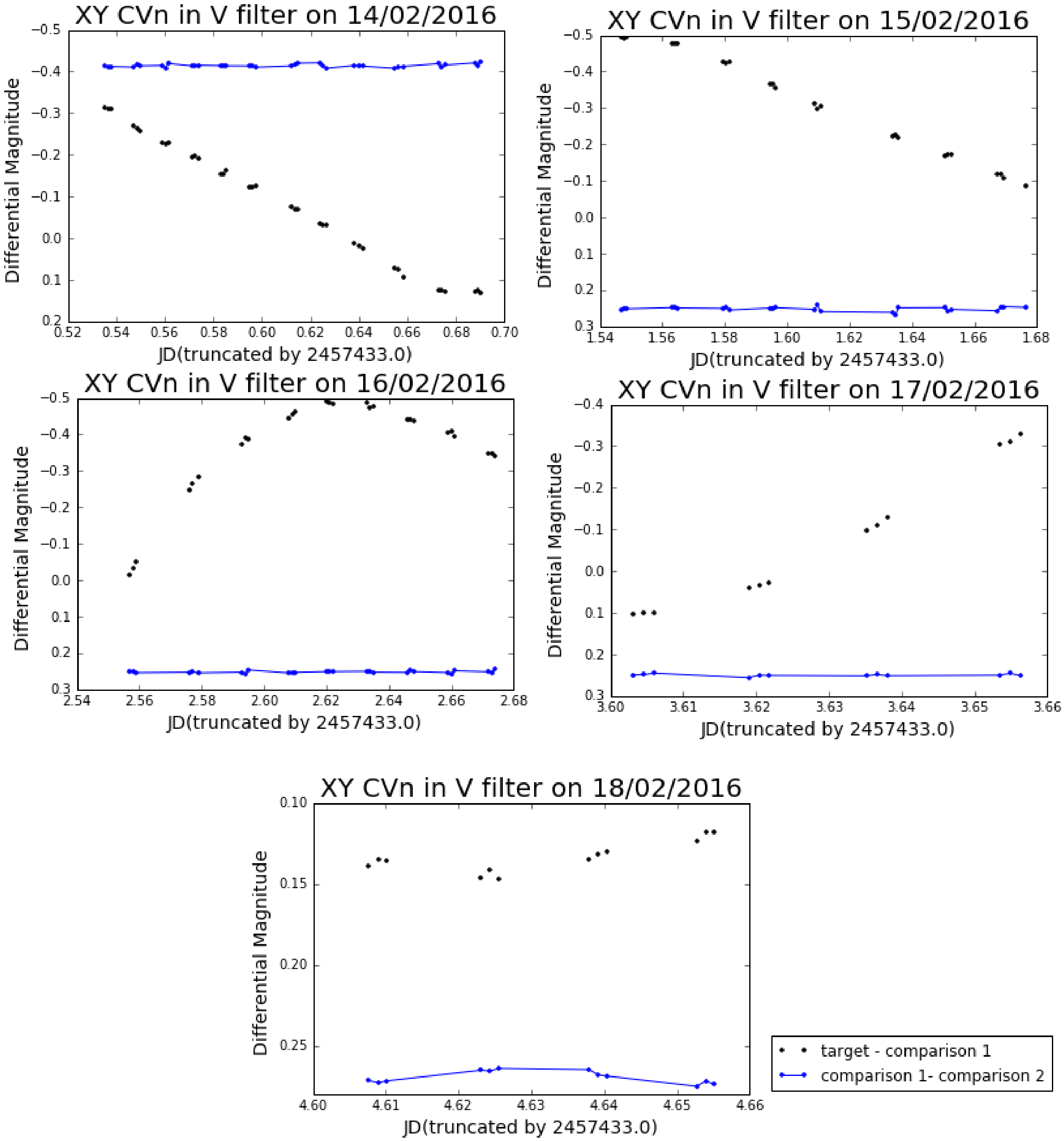

Figure 10 : Plots of data for individual nights for XY CVn in the V filter. The blue lines and dots represent the differential magnitude of comparison star 1 and comparison star 2. They are all flat, except for very small deviations. Therefore both stars are good comparison stars.

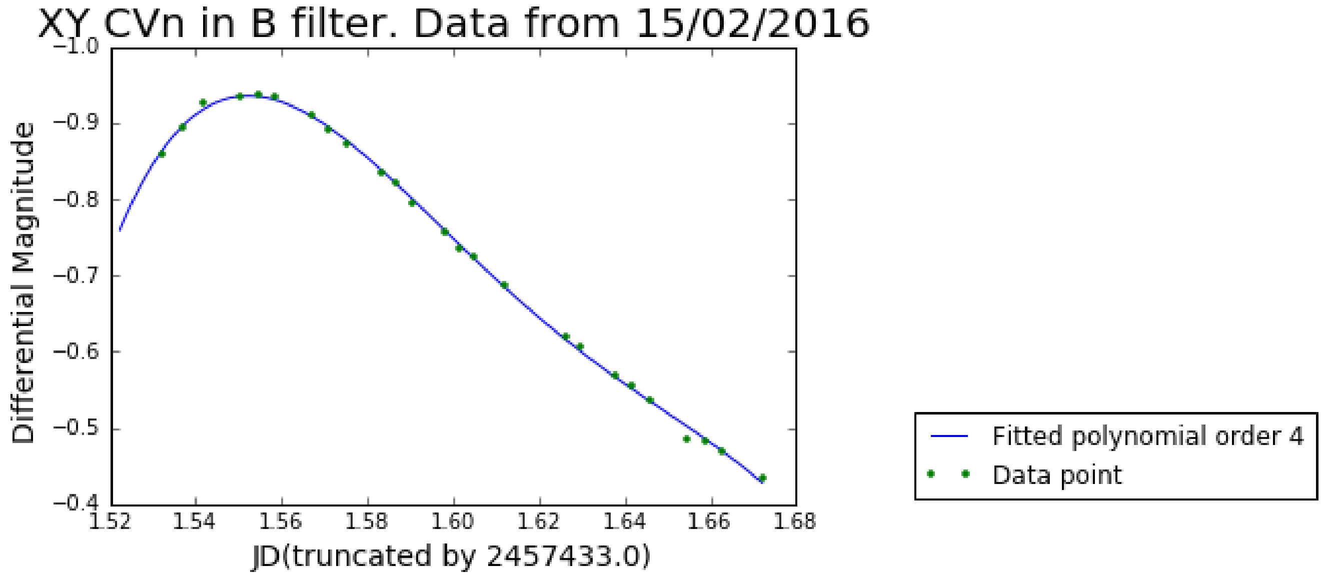

Figure 12 :A lightcurve at maximum fitted with a polynomial used to determine the epoch of maximum light of XY CVn in the B filter

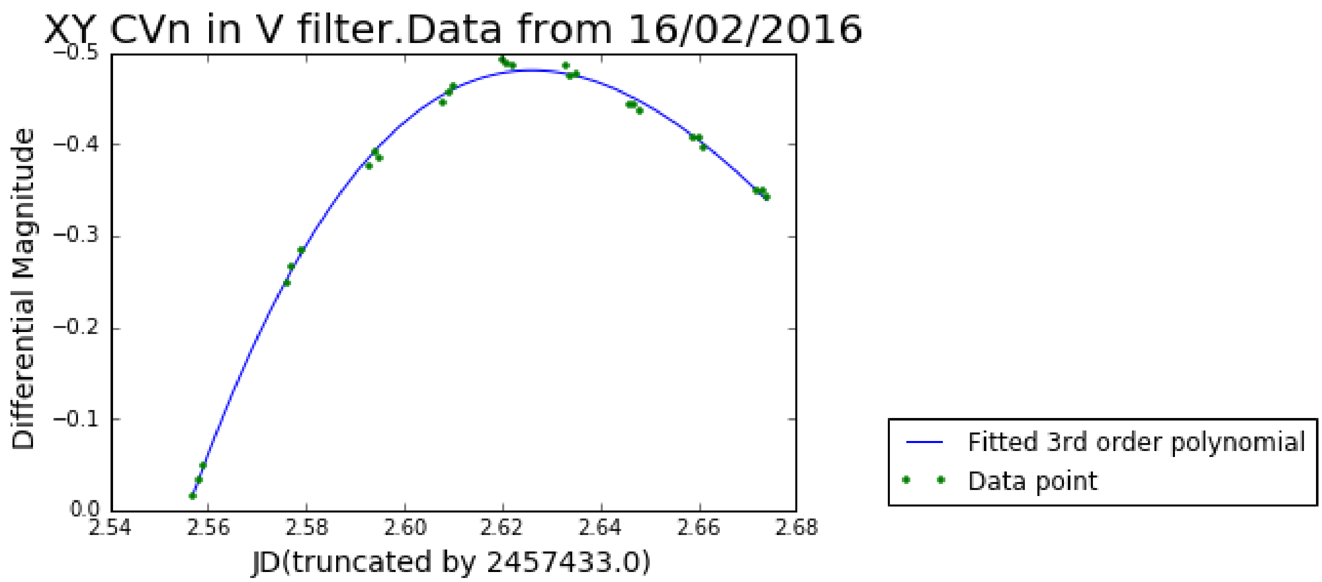

Figure 11 : A lightcurve at maximum fitted with a polynomial used to determine the epoch of maximum light of XY CVn in the V filter.

The value of the period in each filter was estimated by the "string length" method devised by Burke, Rolland & Boy (1970)[8]. The idea is that a folded lightcurve is plotted using an estimate for the period. The length of a "string" connecting each point with its nearest neighbor in phase is calculated and the lengths are summed to give a total "string length". This process is repeated for different estimates of the period and the best estimate is the period which yields the shortest "string length". The equation for the total string length of N data-points is :

$$\sum_{i=1}^{i=N-2}[(m_i-m_{(i+1)})^2+(\phi_i-\phi_{(i+1)})^2]^{0.5}+[(m_1-m_N)^2+(\phi_1-\phi_N)^2]^{0.5}$$

where m represents the magnitude, ϕ the phase. The second term in the summation ensures that the light-curve has a smooth transition from phase=0 to phase=1.

The initial estimates for the period can be bound by knowing that as we have not observed one complete cycle of the star, the period must be greater than the time span of the data for one night (approximately 0.1 days). As we have witnessed two maxima in the B filter, we know that the period of XY CVn cannot be shorter than the time between these two maxima, which is around 1.07 days. An integer number of periods must have passed between these two observed maxima. Folded light-curves with trial periods of 1.07/n (n an integer from 1 to 10) were plotted. The only value of n that did not produce a discontinuous, multi-valued curve or one that produced more than one cycle from phase=0 to 1 was n=3. Therefore a crude estimate of the period is 1.07/3=0.36 days.

Period estimates from 0.34 to 0.38 in steps of 0.00001 were fed computationally into the "string length" method, with the period giving the shortest string length being the best estimate. The period estimates were increased by 10E-5 because our exposure times are measured to a precision of seconds, which is 10E-5 days, thus it seems unreasonable to use a more precise estimate than could be accounted for by the times of exposure.

Folded light-curves were produced by converting the Juilan Date 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 maximum light and fl{x} is the floor function which disregards the part of the number after the decimal place, eg fl{5.87}=5. The period and epoch of maximum light were determined by the methods described above.

The amplitude of variation was given by calculating the difference between the brightest data-point and dimmest data-point.

RR Gem

The light curves for RR Gem are given in Figures 14 ,15. They show that we observed two maxima on 14/02/2016 and 16/02/2016 in each filter and that the two comparison stars chosen are fairly well behaved on most night. On the nights of 15/02/2016 and 16/02/2016 there are slight discrepancies between the two comparison stars that are more evident in the B filter.

To determine the epoch of maximum light, the data-set of 14/02/2016 was used because here the comparison stars showed the least variation. As this data shows a more complicated shape it proved very difficult to satisfactorily fit a polynomial of any degree. Therefore the epoch of maximum is given by reading off the maximum value from a plot.This gives an accurate result because for RR Gem there are many data points which are very close together, acting almost as a continuous line. The estimates of the period were determined by seeing that we observed two maxima on 14/02/2016 and 16/02/2016 in each filter, thus the maximum period possible is 1.98 days as measured from Figures 12 ,13. Likewise, the only folded lightcurve that was not multi-valued, discontinuous or completed multiple cycles from phase=0 to 1 was produced by a period of 1.98/5= 0.39 days. This is the initial period estimate.

Period estimates from 0.37 to 0.41 days in steps of 0.00001 were fed computationally into the “string length” method, with the period giving the shortest string length being the best estimate. The period estimates were increased by 10E-5 because our exposure times are measured to a precision of seconds, which is 10E-5 days, thus it seems unreasonable to use a more precise estimate than could be accounted for by the times of exposure.

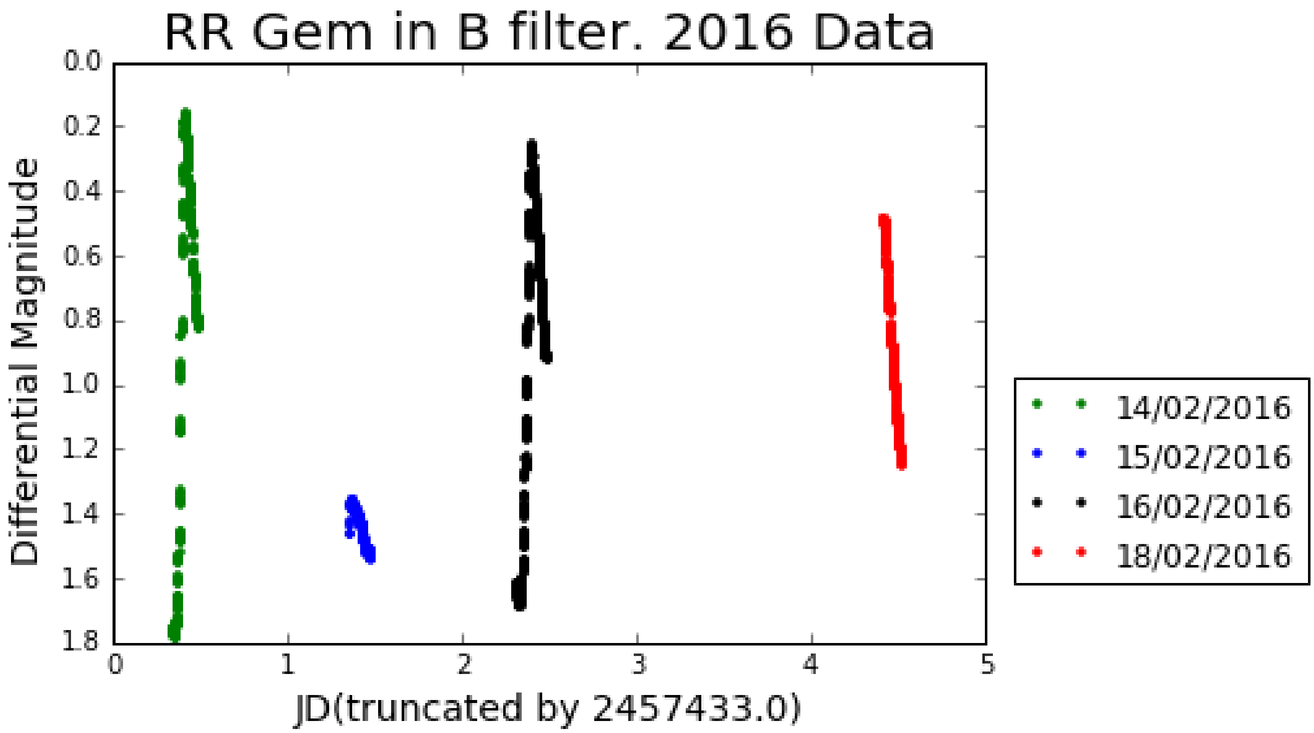

Figure 12 : A plot of differential magnitude against Julian Date (JD) for RR Gem in the B filter from the data acquired in 2016. The target reaching maximum can be seen on 14/02/2016 and 16/02/2016.

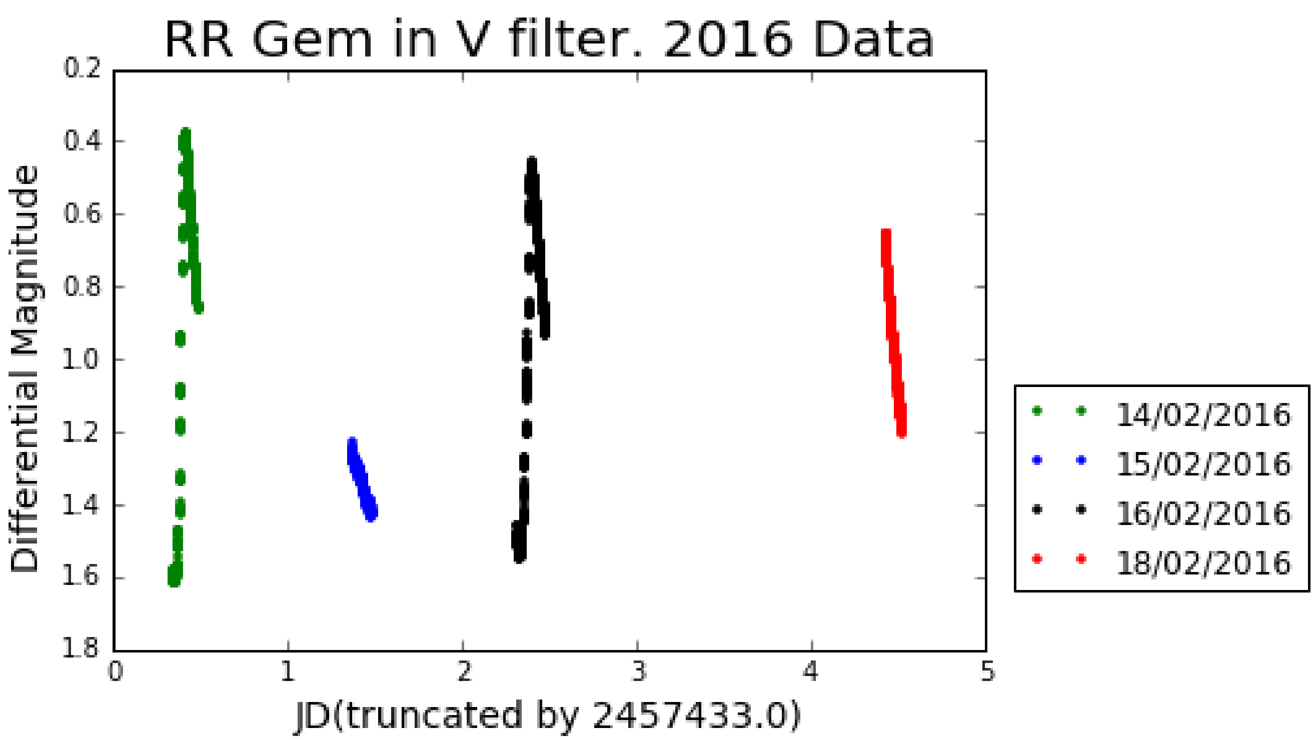

Figure 13 : A plot of differential magnitude against Julian Date (JD) for RR Gem in the V filter from the data acquired in 2016. The target reaching maximum can be seen on 14/02/2016 and 16/02/2016.

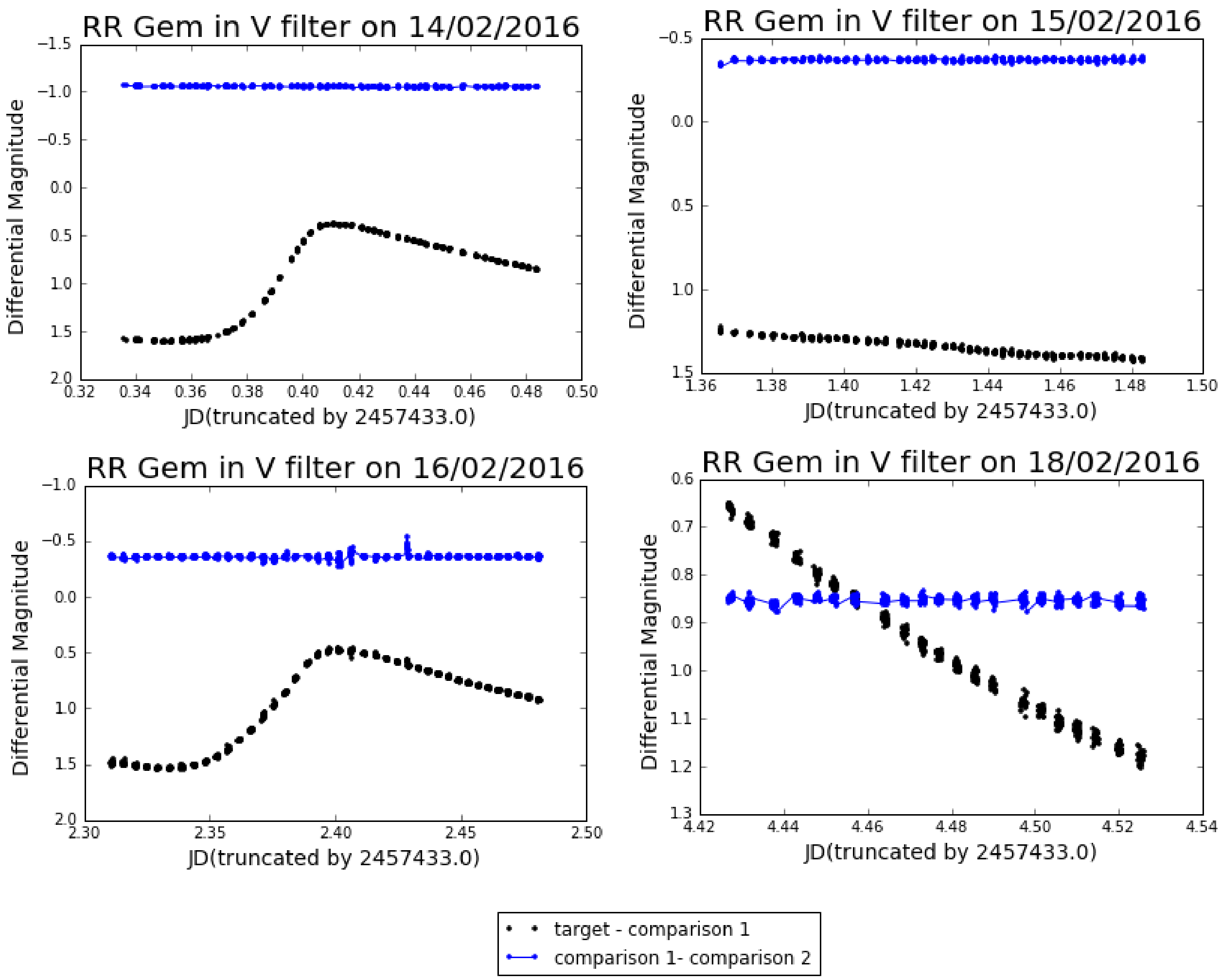

Figure 15 : Plots of data for individual nights for RR Gem in the V filter. The blue lines and dots represent the differential magnitude of comparison star 1 and comparison star 2. The black dots represent the differential magnitude of RR Gem and comparison star 1 .The differential magnitude of both comparison stars shows no general trend. Thus they are both deemed good comparison stars.

Once the analysis had been carried out on the data from 2016, further data sets acquired on field trips in 2014 and 2013 were added and the string-length method was run again to determine the period with more accuracy. For RR Gem Plots of the folded light-curves in each filter are given in Figures 15,16. The data sets from 2014 and 2013 had been reduced in the way described earlier. Table 2 describes the number of exposures used. It can be seen that adding the data from previous years significantly increased the number of frames for XY CVn.

XY CVn (B/V)		RR Gem(B/V)	
2013 & 2014	2016	2013 & 2014	2016
87/94	110/112	161/163	2417/2402

Table 3: The number of exposures used in this investigation. The numbers before the slash denote the exposures taken in the B filter, the numbers after give data for the V filter.

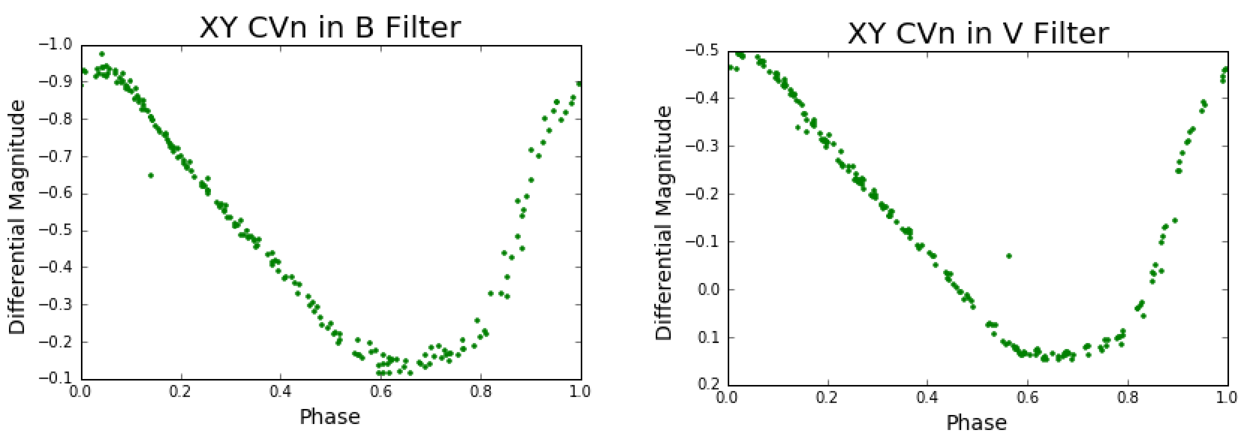

Figure 15 : Plots of folded light-curves for XY CVn in the B filter (left) and V filter (right). The periods used were those described in the Results and Error Analysis section of this report. These plots show data from 2016, 2014 and 2013.

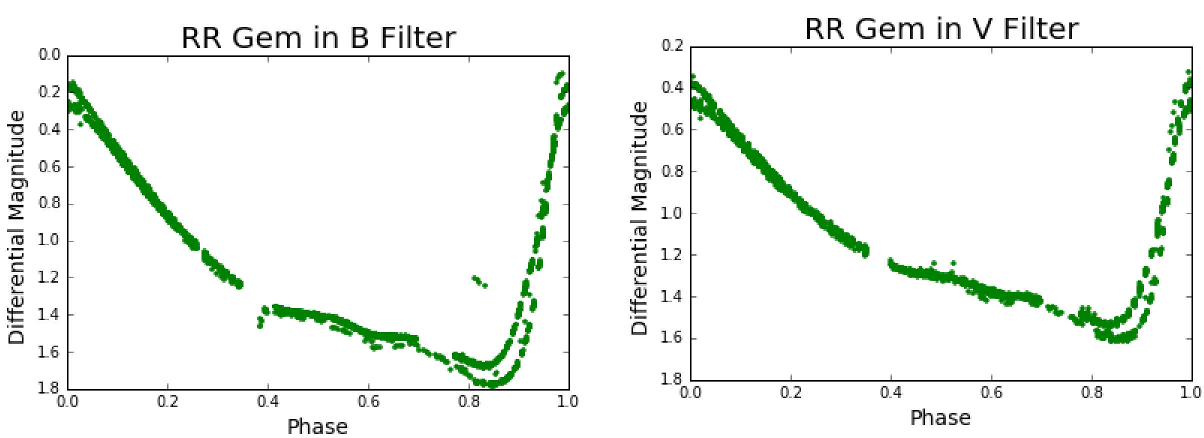

Figure 16 : Plots of folded light-curves for RR Gem in the B filter (left) and V filter (right). The periods used were those described in the Results and Error Analysis section of this report. These plots show data from 2016, 2014 and 2013.

B-V Colour Variation

To investigate the B-V colour variation of the two stars, polynomials were fitted to each folded light-curve. Polynomials have to be fitted because the data-points in each filter do not lie at the same phase values, therefore one cannot subtract one data set from the other without introducing a large uncertainty. For XY CVn, a 10^{th} order polynomial was used. For RR Gem a 20^{th} order polynomial was used as a simpler polynomial did not give a good fit. The results of the fitting are given in Figure 17.

The polynomials in each filter were then subtracted from each other (B filter – V filter) to produce the curves of colour variation shown in Figure 18.

Results and Error Analysis

XY CVn

The numerical results of the methods described are given in Table 4.

Value	V Filter	B Filter
Epoch of Maximum Light (JD,truncated by 2457433)	2.62606 ± 0.00057	1.55224 ± 0.00173
Period (days)	0.35728 ±0.00081	0.35763± 0.00245
Amplitude of Variation	0.64277± 0.00398	0.85869 ± 0.00398

Table 4: Numerical results in each filter for XY CVn using data from 2016, 2014 and 2013.

The error in the epoch of maximum light is given by the error on the timing of each data point.

The exposure times (100s in V filter and 300s in B filter) used give rise to a timing error as we only know that within that exposure time the star was at a certain magnitude. Therefore the error is given by half of the exposure time converted to Julian Date.

The error on the period is estimated by using the fact that during our two observed maxima, an integer number of periods must have passed so that;

$P=\frac{T_1-T_2}{n}$ where P is the period, n an integer and T_1 , T_2 represent the times the maxima occurred.

Assuming that the errors add in quadrature then the error on the period becomes:

$$\Delta P=\sqrt{(\Delta T_1)^2+(\Delta T_2)^2}$$

The errors of the times of the maxima have been discussed just above.

The error in the amplitude of variation was calculated by noting that as differential magnitudes are involved, this value is the sum of four magnitudes:

$$A=M_{max}-M_{min}=[m_{max}(T)-m_{max}(C)]-[m_{min}(T)-m_{min}(C)]$$

where $m_{max}(T)$ denotes the magnitude at maximum brightness of the target;
$m_{min}(C)$ denotes the magnitude of the comparison star when the target is least bright.

Thus the error on the amplitude is given by:

$$\Delta A=\sqrt{\Delta m_{max}(T)^2+\Delta m_{max}(C)^2+\Delta m_{min}(T)^2+m_{min}(C)^2}$$

In the case of XY CVn all the magnitude errors are approximately 0.00200 as given by the results of the Starlink Photom package.

RR Gem

The exposure times used in the data that determined the epoch of maximum light were 3s and 8s in the V and B filters respectively. Thus it is half these values converted to Julian Date that gives the error on the epoch of maximum light.

The period error and amplitude of variation error is estimated in the same way as for XY CVn. For RR Gem the error on magnitude values is approximately 0.00300 as given by the results of the photometry.

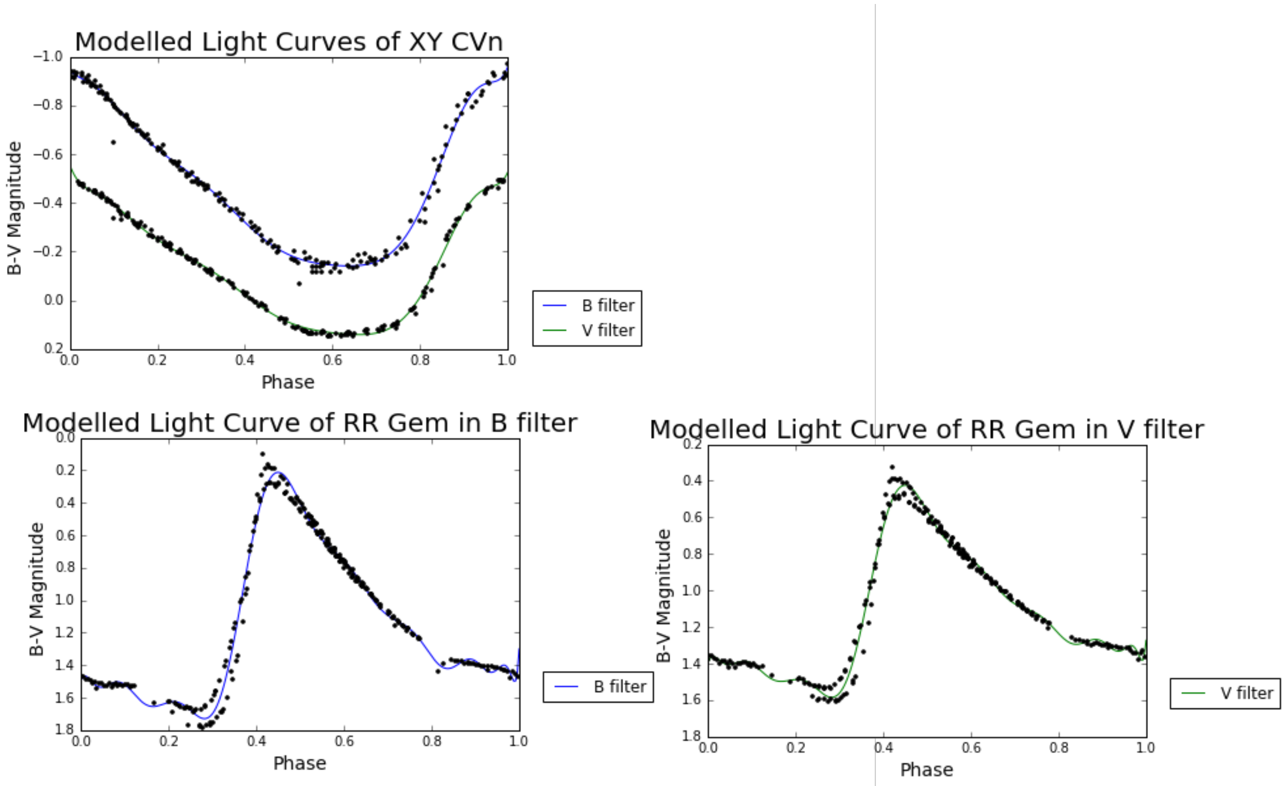

Figure 17 : Folded light curves of XY CVn (top left) and RR Gem (bottom two). The black dots represent actual data-points and the lines the fitted polynomials. For the RR Gem plots only every 10^{th} data point is shown.

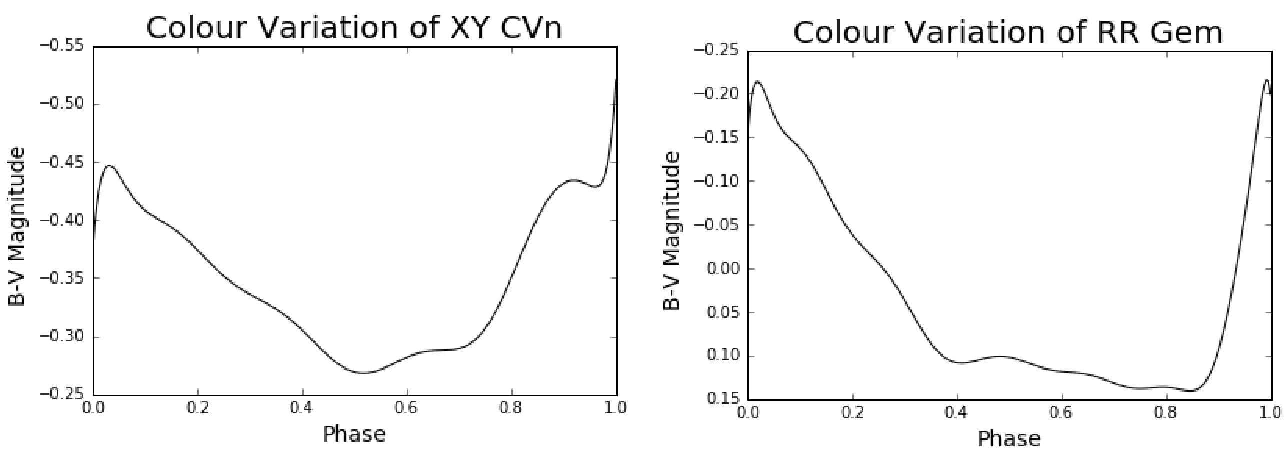

Figure 18 : Plots of the B-V colour variation of the two stars.

The numerical results are given in Table 5

Value	V Filter	B Filter
Epoch of Maximum Light (JD,truncated by 2457433)	0.41109± 0.00002	0.41208 ± 0.00005
Period (days)	0.39731 ± 0.00003	0.39731 ± 0.00007
Amplitude of Variation	1.29202± 0.00600	1.68475± 0.00600

Table 5: Numerical results in each filter for RR Gem using data from 2016, 2014 and 2013.

Physical Interpretation

The mechanisms by which RR Lyrae stars vary their luminosity are discussed in the introduction. The sinusoidal shape of XY CVn's light-curve suggests that this star is contracting and expanding at the same rates. However the asymmetrical, sawtooth shaped curve of RR Gem would suggest that this star is contracting very quickly to its minimum radius (where the star is brightest) then expanding more slowly to the maximum radius.

The amplitude of variation is greatest in the B filter for both stars. The B-V light-curves show that both stars become bluest at maximum light (increasing B-V magnitude means a bluer colour) and then they are least blue at minimum light. This must be related to the frequency dependance on the optical depth of the stellar atmosphere. The kappa-mechanism, as described previously would suggest that at maximum light, He III (doubly ionized helium) recombines to give He II, producing a photon, which we would expect to be blue in colour. At minimum light the He II is mopping up blue photons in become He III. One might expect that these transitions occur at approximately 4000 Angstroms.

Conclusion

XY CVn

The published value of the period of XY CVn is 0.357279 days[9]. The values presented here of (0.35728 ±0.00081) and (0.35763± 0.00245) days, in V and B bands respectively agree with each other as the uncertainties enclose the two values. The V band period agrees very well with the published value, however the B band period does not agree. It is unknown from the source (AAVSO) which wavelengths the period was observed in and an error is not quoted.

It is clear from comparing Figures 2 and 15 that XY CVn is an RRc type. The light-curve is nearly symmetrical and exhibits a sinusoidal- like variation. We have coverage for XY CVn throughout the whole of its phase. The results are believed to be reliable.

RR Gem

The published RR Gem period value is (0.39728930 ±2.4E-7) days[5] in the B passband. This value agrees well with the 0.39731 ±0.00007 days presented here as the uncertainty surrounds the published value. There is excellent agreement in the period of RR Gem in each filter, with both periods being equal.

By inspection of Figures 2 and 16 RR Gem is determined to be an RRab type RR Lyrae star. The light-curve is very asymmetrical and shows a sharp peak at maximum light and a slow decrease in magnitude to minimum light.

Despite having a lot of data-points, we do not have full phase coverage of the star. Also, the two maxima and minima that we observed do not agree with eachother, with observations from one night being slightly brighter than observations from the other. There is a discrepancy of 0.1 magnitudes between observations carried out on 16/02/2014 and 14/02/2014. This may be explained by Blazhko modulations, which are known to occur in the target. This is reasonable as A. Sodor [5] shows the amplitude of Blazhko modulations is 0.11 magnitudes and the period of these overtone modulations is 7.21 days. Our maxima were observed 2 days apart, so the variation in RR Gem seen here agrees with the analysis of A. Sodor. Alternatively the modulation could be explained by the comparison stars not being constant in brightness. In Figure 14,15 there are small variations in the differential magnitudes of the two comparison stars.

Furthermore this possible Blazhko modulation serves to hamper the string length method used to determine the period, as clearly the string lengths will become greatly increased by the relatively large discrepancy. A more accurate period may be calculated by removing one of the evenings from the data in order to plot a smoother folded light-curve. Another approach would be to use a different method to calculate the period such as Fourier analysis.

Reflections and Improvements

I feel that this project has achieved its aims. The periods for RR Gem and XY CVn in the B and V band filters agree with the published values, so are deemed accurate. Overall the data-sets were very good and gave good phase coverage (especially for XY CVn).

One improvement that could be made would be to perform photometry on more comparison stars. This way we may produce a more accurate differential magnitude. From the plots of differential magnitudes of the two comparison stars used here, it is seen that there is some deviation from a flat line. If magnitudes for other stars in the field were calculated, the source of these deviations could be further investigated. Another way of determining a comparison star's variability is to plot the magnitude of the star against the airmass it is being viewed through. If this plot is linear, then the star is not variable.

The method used for determining the period is quite a novel one and is liable to give a “false period”. It is also very difficult to estimate the uncertainty on periods produced using this method. A simple estimate considering the number of periods between the two observed maxima is certainly an over-estimate of the error. It would be better to employ a method such as Fourier analysis. Fourier analysis is more mathematically rigorous and can provide accurate uncertainties.

Whilst conducting the analysis, the presence of overtone modulations has been ignored. This is especially relevant to RR Gem, where some amplitude modulation has been detected. To produce a smoother light curve it would be possible to attempt to normalize the light curve at its maximum. This was the data points would lie closer to eachother and the string-length method would give a more accurate period.

Otherwise it would be better to observe a complete cycle by continuously analyzing the data from the telescope and planning the observing sessions as required to observe as much of a full phase cycle as possible.

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