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

By Daniel Underwood
PHAS3332
Msci Astronomy

26th March 2010
Abstract

Between the 11th and 19th of February 2010, observations of two RR Lyrae type variables were made at l’Observatoire de Haute-Provence in the south of France, using a 1.20-m reflecting telescope and Cousins filters of the B- and V-bands. Through compiling the data obtained in 2010, along with data from observations made in 2006 of the same targets, it was possible to create composite folded light curves of each target.

The period of RR Gem was estimated from the analysis of all curves through the B- and V-bands for both years; 2006 data showed P=0.39732 ± 0.00008 in the B-band and 0.39733 ± 0.00007 in the V-band, and 2010 data showed P=0.39721± 0.00018 and 0.39749± 0.00006 in the B- and V-bands respectively. These all compliment the accepted value of P=0.397 [1].

The period of XY CVn were only estimated from two sets of data; 2006 data showed P=0.35543 ± 0.00347 for the V-band, and 2010 showed that P=0.35473 ± 0.00250 for the B-band, where both values deviate from the published result of 0.36 [8], but within their calculated error margins.

It was also calculated that the magnitude variation for RR Gem was 1.686 ± 0.003 and 1.265 ± 0.004 in the B- and V-bands, respectively, where the variation for XY CVn was 0.8145 ± 0.0076 and 0.6321 ± 0.0057 in the B- and V-bands, respectively, both suggesting a larger differential in shorter wavelength emissions across each cycle, and a colour index shifting towards the blue.

Introduction

The purpose of this project was to determine the properties of two particular types of variable stars, which are known as RR Lyrae variables. The experiment ultimately sought out to produce light curves for the varying magnitudes of these two stars, RR Gem and XY CVn.

The period of variation for a RR Lyrae type star is typically ranges from 0.2 – 1.2 days [1], making them quite easy to analyse. Over these cycles the magnitudes of these objects vary due to dynamical processes happening within the star.

The dynamics of their pulsations are thought to be the same as those for Cepheid variables, where there is a constant battle between the pressure gradients and the gravitational forces in the star as it attempts to maintain hydrostatic equilibrium. The mechanism also depends greatly on the opacity properties of ionized Helium; He$^{2+}$ has a higher opacity than He$^{+}$, and both are present in the atmospheres of the stars during the cycle.

The expansion begins at the dimmest part of the cycle. This dimness is attributed to the presence of the opaque He$^{2+}$, and the increasing heat is the cause for the expansion. As the expansion occurs the star begins to cool, at which point the doubly-ionized Helium is converted back to He$^{+}$ (of lesser opacity), until the expansion reaches its limit. This is where the peak brightness is observed as the increased transparency allows great amounts of radiation to be released. This continues to the point where the pressure forces cannot overcome the gravitational force acting inwards. Consequently the star begins to contract, and as it does its temperature increases. The opacity increases once again as the He$^{+}$ has become doubly-ionized. The star then reaches the state it was at initially, where the process repeats again.
Light curves can be obtained from making observations of these types of targets. Each individual exposure would be attributed to a specific point on a graph of Time vs. Magnitude. Making several exposures over a long period of time will contribute towards a curve where the variation can be graphically observed, and the period of the variation can be deduced.

The main distinguishing feature of these period-luminosity properties is that the more luminous the object, the larger the period. Many pulsating objects that behave in this way tend to have incredibly precise relationships between their periods and luminosities, which make them good targets for standard candles.

RR Lyrae stars are situated on the H-R diagram, in a section known as the ‘Instability Strip’, alongside the stars classified as Cepheid variables (the instability being the cause for the fluctuation phenomena). The main difference that distinguishes RR Lyrae variables from Cepheid variables lies in the fact that RR Lyraes are smaller compared to Cepheid variables, which gives rise to their shorter periods, and lower luminosities.

The spectral types of RR Lyrae variables fall around A and F and they lie on the “Horizontal Branch” of the Hertzprung-Russell diagram [1]. Their poor metal content classes them as Population II stars.

Being on the horizontal branch places them on the evolutionary track that immediately follows the Red Giant Branch for stars with masses close to the solar mass. At this point they are at the helium burning phase of their lives. This means that they all essentially have same intrinsic luminosities.

This is what makes them fairly good standard candles, and this can be reinforced by their period-luminosity dynamics, given that there is an adequate calibration.

**RR Lyrae**, which is the prototype for this class of variable star, is the probably the closest we have to a calibration. Its distance is fairly uncertain however, as parallaxes measured have yielded different distance values, however, observations using Hubble have produced a distance calculation of about 854 light years (262 pc) [2]. Refining this measurement is necessary to establish a firm standard candle model for RR Lyrae variables.

Because of their intrinsic dimness, RR Lyrae variables are typically only used for measuring distances within the galaxy and nearby globular clusters, contrasting with the ability to view Cepheid variables in other local galaxies.

Despite the roughly identical properties that make these variable stars good distance indicators, RR Lyrae type stars can be divided into separate categories, depending on the dynamics of their fluctuations.

Solon Bailey devised a classification system which grouped every RR Lyrae variable into groups according to the shape of their light curve. The subclasses, a, b, and c are attributed to the following descriptions [1]:

a – The light curve has a steep increase towards the maximum, followed by a more gradual decrease towards the minimum. The minimum is maintained roughly constant for about half of the entire period, with small gradients.
b – The increase of the light curve is less steep than that of subclass “a”, and the decrease is fairly slow. The decrease is also typically continuous towards the beginning of the next increase. The periods of this subclass tend to be longer than those of subclass “a”.

c – The light curves of these types seem to show little or no variation between the steepness of the increase and decrease, with a constant change in values. In other words they roughly present a more sinusoidal variation. This subclass also presents periods that are less than both the “a” and “b” subclasses.

However, due to their similarities, the subclasses “a” and “b” are usually seen as a single class “ab”, due to the fact that the “b” subclass appears to be a modified version of “a”, thus giving the classes RRab and RRc.

The differences in the curves for the different RR Lyrae types are described as being due to differences in the pulsation mechanisms, based on harmonics. The pulsation of RRab types are thought to be based on the ‘fundamental radial mode’, whereas the pulsation of an RRc type is described by a pulsation about the first overtone, due to a physical phenomena inside the star itself.

A curious phenomena observed in a number of RR Lyrae type stars involves a long-term modulation of amplitude and phase over the course of tens to hundreds of days [9], known as the Blazhko effect. What is observed is a shift in amplitude, or period, of the light curve of the target star over the course of many observations.

The cause for the effect is still debated, but there are two hypotheses that appear to be the most plausible. The first is that the modulation is due to a “non linear” resonance inside the star, between the fundamental mode described in the mechanism, and another non-radial mode.

The second theory suggests that the magnetic field of the star causes the radial mode to be distorted, so as the star rotates our view of the pulsation changes over time.

Signatures of the Blazhko effect can be indentified provided that there is a substantial amount of data available to form light curves for at least two distinct phases.

The two stars being observed in this project are RR Gem and XY CVn. RR Gem is found in the Gemini constellation, and has the class of RRab. It has a period of 0.397 days [1].

It has a Right Ascension of 07h 21m 33.5s and a Declination of +30d 52’ 59” according to the 2000 epoch.


This target historically presented the amplitude variation properties of the Blazhko effect, however in recent years it has not been observed [1]. Due to the uncertainties in the cause of this effect, it is not clear why this phenomena has ceased to be observed.

The diagram below shows a field of view star chart centred on RR Gem, obtained from the electronic sky-map software Xephem. RR Gem is circled in red, where the calibration star, TYC 2452-1557-1, is circled in black.

Note: the use of calibration stars will be discussed later.
The star XY CVn is found in the constellation of Canes Venatici, at a Right Ascension of 13h 48m 01.9s and Declination of +29d 11’ 47”. It has a period of 0.36 days, where its V-band magnitude varies from 13.5 – 14.5 over each variation [8]. This variable is different from RR Gem in the sense that it is of RRc type, meaning its light curve possesses a sinusoidal variation.

Below is a star chart showing the field of view for XY CVn, circled in red. The calibration star used for the subsequent measurements, USNOA 2 1125-06806334, is circled in black.
The method used to extrapolate a curve which shows the variation properties of a variable star involves analyzing a set of exposures taken over a period of time. The target star is observed alongside a number of comparison stars that can act as a calibration, which should have constant magnitudes. For every exposure, the magnitude of the target star is examined alongside the same comparison stars, which makes it possible to produce a differential magnitude for the target star relative to these comparison stars. Providing that the comparison stars remain at a constant magnitude over the series of exposures, the differential magnitudes can be plotted which should show a variant behaviour in the magnitude of the target star.

The calibration is required as the differential magnitude plot only shows a magnitude variation relative to a comparison. By observing data points through different filters we can examine how the differential magnitude behaves for different wavelength bands. We expect to see similar results in the shape of the light curves, but by taking exposures through B- and V-band filters we can extrapolate further results for a colour index analysis; by plotting a (B-V) colour index as a function of phase we should expect to see some colour variation in the targets over a phase.

**Observing Procedure and Data Acquisition**

The data acquired for this investigation was obtained using the 1.20m telescope at OHP. This Newtonian telescope reflects light from the source onto a CCD, which redirects light counts directly to a computer in a digital format. This digital image can then be manipulated in our reduction and analysis.

The light falls onto the 1024 x 1024 pixel CCD array, where the size of a pixel is 24 microns. For the 1.120m telescope the corresponding portion of sky observed per pixel is 0.69", giving a field of view of 11.8 x 11.8’ [10].

Once an exposure is fed from the CCD and downloaded to the computer, it is saved as a FITS file type, where x,y coordinates, as well as other properties can be attributed to the image for further analysis. Saturation levels of the CCD chip lie roughly around the 60,000 count region. The CCDs maintains linearity up until this point. [10].

The objective of this project was to make use of the six available nights of our stay at the OHP by observing both targets in each observing session. Given That RR Lyrae variables have short periods, typically of less than one day, obtaining data for each object on each night would mean that we should accumulate enough data points in order to create a sufficient light curve by gathering data for maxima, minima and slope sections of the variations. This was, of course, provided we were lucky enough to enjoy good observing conditions.

Our team was split up into groups in order to delegate the numerous tasks (our trip involved making observations with another telescope for a different project). Each observing session was scheduled to last for 10 hours each night.

Because the task of acquiring the data was done by a rotation of our groups, it was necessary to plan and corroborate with each other on the specific procedure.
Firstly, the time range in which we would observe each target was arranged according to their altitudes at specific times in the night. Since we would be observing from 19:00 – 05:00 (LT) it was possible to separate the session into two observations by determining when the targets would culminate.

Given the sidereal time, the date and the right ascension of the objects, a time for their meridian transits can be determined so that an appropriate time range for observation can be decided upon.

During the duration of our trip, from the 11\(^{th}\) – 19\(^{th}\) of February 2010, RR Gem, with its RA of 07h 21m 33.5303s [4] has a local upper culmination between the hours of 22:00 and 23:00 hours, where XY CVn, with RA of 13h 48m 01.5s [4] reaches it’s highest point between the hours of 04:00 and 05:00 (local time). Intuitively, it was decided to separate the observation session in half, by observing RR Gem up until midnight, then swapping over to XY CVn afterwards, and observing it until the end of the session at 05:00, as these time ranges would allow us to benefit from the improved clarity of the objects.

This allowed for a fairly comfortable timetabling process. In theory only two slews would be required, one to each object at the beginning of the night and one just after midnight, where automatic tracking would take care of following the target through the sky.

Before our observations had begun we had produced copies of a star chart for each target (using the program Xephem), which was graphically represented field-of-view as viewed through the 1.20-m telescope. These were made to assist with recognising the target through the actual telescope, and making note of possible comparison stars.

However, on our first observation night it was not possible for things to run quite so smoothly.

Slewing to the target involved a rather old-fashioned, physical process involving the turning of wheels inside the dome to make changes in right ascension and declination. These are unfortunately not precise enough to centre on the target straight away, but once a close enough position is reached where the telescope is aimed in roughly the direction of the target, the RA and Dec can be fine-tuned from the control room.

By taking a short test exposure to observe the field of view, we initially found that the slewing procedure did not correctly centre on the target star. This must have been down to some intrinsic problem with the telescope, where it may require a regular calibration. Nevertheless, by inspecting the field of view presented by the initial exposure, we were able to note specific star arrangements. We used this to our advantage by cross referencing them with a program called Xephem, which we had access to via a laptop computer.

The program allows users to view a digital star map and obtain specifications of each object that is graphically represented. Having centred on our target star on the Xephem map we cross referenced an out-standing feature from the actual field of view of the telescope with the surrounding area on the star chart we had on the computer screen. Once we found a matching feature (and hence a matching object) we queried the program for its RA and Dec.

By knowing this, along with the RA and Dec of our desired target, we were able to calculate the differences in both the RA and Dec between the two, and this would allow us to determine in which way we would have to slew the telescope in order to move from the object that was
presented in the field of view to the target we actually wanted to observe, by changing the RA and Dec on the control console by the same amount.

After this was done we eventually found our target star in the field of view, and eventually centred it over the course of a few short test exposures.

This unfortunately compromised our time for the first night of observation, however having made a note of the necessary RA and Dec to centre on our target it was hoped this problem would no longer occur.

It was still necessary to compromise yet more time in order to agree upon an appropriate duration for each exposure in order to obtain a signal-to-noise ratio that would not cause an over-saturation in any of our count readings. This also involved choosing our comparison stars in the field of view; we wanted to ensure that they were roughly all the same brightness and giving similar counts.

By a trial and error process we obtained counts for a number of stars, including the target, for a number of different exposure times. When over saturation occurred we decreased our exposure times until the exposure produced decent count levels without over saturation, but was still regarded as an optimum exposure time to produce good enough count levels (the saturation levels, as advised by the present technician lay at about 60,000 counts).

This had to be done through both the B- and V-band filters, as count levels for the same objects differed greatly for each of them, and consequently different exposure times were agreed upon for the different filters.

Exposures were taken through the B- and V-band filters in alternating order, i.e. one was taken consecutively after the other. This was in order to ensure that we would obtain the same portion of the curve at roughly the same time through both of the filters.

These procedures had to be carried out for both targets on the first night, which lost us a large amount of time that could have been spent acquiring useful data. However this could not have been overcome beforehand so it was a vital necessity. The important aspect was to make note of what was carried out in order to be able to address the situation immediately on the following nights of observation, as well as to provide the other observing groups with concise steps in order to duplicate the procedures.

Once we started obtaining useful data on our first night things ran smoothly. Moving the dome was the only frequent update required as it did not have a tracking function, so we had to enter the dome every now and then to align the open shutter with the aim of the telescope. It was necessary to do this between exposures; there was a small break between exposures as the image was downloaded to the computer. This was to ensure the exposure was not compromised by any light source we brought into the dome.

Unfortunately during our stay at the OHP our team only enjoyed 2 nights of good observing conditions out of the scheduled 6, which meant we were not able to obtain complete light curves of RR Gem and XY Cvn over the course of the week. Curves were only produced for the 12th and 14th of February.

Due to this, it was decided that in order to analyse the data obtained during this trip, we would make comparisons with a previous year’s data that made observations of the same targets
through the same filters. Upon researching this data from 2006, which made observations of RR Gem and XY CVn over 3 nights, it was apparent that the data sets were comparable to our own, with incomplete curves due to sporadic observations. By reducing both sets of data, from 2010 and 2006, it was hoped that some analysis of both curves may yield some sufficient and respectable conclusions by cross-correlating data sets.

There are however some disadvantages from the combination of data sets. By definition, determining a period and amplitude for a star’s composite light curve must assume that there is no Blazhko effect present in the star that can be observed across the two years’ data sets. Also, as this is the case investigation into the modulation in period and amplitude can not be made, however with already incomplete light curves this would have been an unlikely task anyway.

**Data Reduction**

Before measurement and analysis of our exposures can take place, a calibration procedure must be carried out to remove elements from the CCD images that are unwanted. As with all CCD imaging, correction to raw images must be made in order to remove elements such as a bias offset, and the uneven illumination of the CCD chip (flat-field correction), and it is these corrections that we have to make to our raw images in order to obtain a calibrated set of data.

A bias offset occurs when pixels are read out from the CCD, and can be thought of as a “zero point” for the imaging device. Each CCD device has its own intrinsic bias properties due to the electronics of the apparatus, and as images are read out from the CCD the bias can vary across it (a bias value is added to each individual pixel). But the bias for a particular imaging device is fairly constant from image to image, which means it is possible to subtract it.

This is done by taking a bias frame, which is subtracted from each exposure. The frame is a “zero-length” exposure that is taken with the shutter closed. Here each pixel will have a value that differs slightly from others, and this value is consistent from image to image, which is the cause for the constant bias. Any readout noise that is produced by the electronic components within the device can be suppressed by a combination of a number of bias frames. This master bias frame is then subtracted from every other observation frame.

Flat-fielding is required to correct for the variation in sensitivity across a CCD chip and the irregular illumination that falls onto it. This is done by taking an exposure of an evenly illuminated screen (which may reside somewhere inside the dome) over a certain duration such that the pixel counts reach a certain percentage of the saturation level of the CCD, and this flat-field image then shows a measure of the variation of light hitting and being read on the array. A flat-field frame will have some noise so it is necessary to combine many to get a master flat-field frame whose large signal-to-noise ratio will mean that the image it is applied to will not be largely affected by noise provided the individual frames have the same exposure times.

Flat-field frames must also be bias subtracted as well as the target frames in order to be calibrated correctly; a bias subtracted target frame cannot be flat-fielded to correct for light variation until the master flat-field frame has been bias subtracted also.

Once this master flat field frame has been normalized it can be divided through each of the raw target frames, and the correction is complete.
**Figaro**

Bias frames and flat-field frames were taken at the beginning and end of each of the observing session in order to give us an even and fair spread, and each target frame collected from a particular session was calibrated using the bias and flat-fields taken in that session.

This is a procedure that is done using the *Figaro* program installed on the ULO computer system. A laptop computer was taken to the OHP acting as a server, installed with the main programs that we would require to reduce and analyse our data, as well as containing the data obtained from previous years. Being connected to this computer locally allowed us to access these programs as well as the data. This is all done using a command based terminal interface.

The image data we were obtaining in our observation sessions was saved as a ‘Flexible Image Transport System’ file (.fits), and subsequently transported to the server laptop after the observation session in which they were obtained had finished.

The ‘Flexible Image Transport System’ file format is the most commonly used file format used for astronomy, endorsed by NASA and the IAU [5], and is a standard format used for analysing and manipulating scientific data.

However we convert these file formats in order to be used in our data reduction programs produced by *Starlink*, a UK based astronomy based computing project.

The *Figaro* program allows us to convert from a .fits file format into a ‘*Starlink Data Format*’ (.sdf) file format which we can then continue to manipulate using our reduction programs. The *rdfits* command was used in order to do this, which is a command that reads in the .fits files, which are then subsequently saved as .sdf formats. The command has parameters called *swap* and *float* which are both set to “true”, which is required for converting the particular type of FITS file onto our system.

This is done for each and every .fits file that had been obtained, including the target, bias and flat-field frames from our own observations and those from 2006.

At this point we use the *Figaro* program to start summing our bias frames from each session together in order to get the mean bias. The summation of different bias frames (now in .sdf format) is done using the *iadd* command, and once the frames are added the sum is divided by the number of frames used to create it in order to obtain the mean; this is done with the *icdiv* command.

This mean, master bias is subtracted from all of the target and flat-field frames, using the command *isub*. At this point it is important to rename our bias subtracted frames in such a way that we can differentiate them from the ones that are still raw, so we rename them with an indication of this (e.g. an un-reduced frame f28283 will be renamed f28283_biassub).

Once every frame is bias subtracted there remains only one procedure before the target frames can be properly calibrated – the flat-field frames must be combined into a normalized master frame, which is then divided through each observation frame.
The process of creating the master flat-field starts out by combining to an average much like with the bias frame, by adding together separate flat-field frames and dividing by the total number combined.

This frame is then normalized in accordance to its mean count number; the frame must be divided by this mean count value. The istat command in Figaro allows for the statistics of a data set to be obtained within a certain range of the set, i.e. within a range of pixels (1024 by 1024 for the 1.20-m telescope). By using this command on the mean flat-field file, the mean count value can be obtained for the data within the pixel array, by inputting this number range.

Once this number is obtained it is simply divided through the mean flat-field frame using icdiv, thus preparing the final normalized master flat-field.

It is important to note that flat-fields are taken through each filter that we use (B- and V-band) so when it comes to creating a master flat-field frame for a particular filter, the combination must be made using individual frames that are all taken through the same filter. This ensures that for every observing session there are two normalized master flat-fields, one for each filter.

The master flat-field frames are then divided through each of the bias-corrected observation frames using the icdiv command, remembering that for observation frames obtained through a certain filter is flat-field corrected by a master flat-field frame that corresponds to that particular filter.

The raw target observation frames are now corrected and ready for further reduction processes. It is helpful at this point to re-name each observation frame to indicate its complete correction.

During the flat fielding procedure a problem was encountered with one of the original flat sets for the 2006 data; the frame did not expose a uniform illumination of light, causing the final flat field to have incredibly large variations across the array, contradictory to the purpose of a flat field. This was due to unknown reasons, but can be put down to a human error at the time. However after a few test reductions on certain observation frames it was seen that the variation did not fluctuate greatly in the read outs of the final produced frames, and therefore we decided to use the faulty flat field frame given that it was the only one available for the particular observation session. Below is a picture displaying the frame in the GAIA user interface.
The next step is to interpret counts from every corrected observation frame in order to start accumulating data that can be used to plot differential magnitudes.

This is done using the Starlink Graphical Astronomy and Image Analysis Tool (GAIA), which is a graphical user interface that allows users to analyse and extrapolate information from displayed files that are in SDF format. For example, with the .sdf frame of a calibrated observation is displayed on screen in GAIA, it is possible to measure counts across the image as well as vary the levels and colours in order to change the view, and improve the ability of distinguishing objects where necessary. These can be altered accordingly in order to make it easier to do measurements.
However the main use of which we will exploit with this program is the ability to measure magnitudes of objects in the field of view digitally represented by the .sdf file. Using the Image Analysis function an aperture can be defined to place over the digital image, for which GAIA can use to read out a count value for the pixels confined within the aperture, and give a value in the form of a magnitude reading.

In this case, an aperture will be defined for the brightest of the stars in the field of view (which will either be the target star or a comparison star) where the aperture size will be limited to the size of the star. Using a circular aperture will ensure that the object, being circular, will fall inside the aperture ‘ring’. Within this ring the star count will be measured.

The aperture measurement also includes an annular aperture surrounding the circular target aperture. This annular aperture contains a band of given width which measures the sky count surrounding the star. The distance of this annular band from the object aperture can be increased, as can the width of the band measuring the sky background (see Fig. 5).

Figure 4: The GAIA user interface. Displayed is the field of view for RR Gem in .sdf format (the colour has been inverted where darker regions represent higher counts). The top of the interface displays the various toolbars for image manipulation, as well as showing coordinates and count levels of selected regions.
Once an aperture is defined for the brightest of the stars that we wish to measure, an option in the interface allows us to ‘Calculate Results’, which returns image coordinates and star and sky magnitudes, as well as other results defined by the placing of the aperture. It is these measurements that we are interested in. GAIA automatically attributes a magnitude reading, but they are not true values, only values returned using constant offset reading set up by the program. The value returned by this is incorrect because the image being analysed is not calibrated for this offset that GAIA assumes, but at this point is not a concern. This is because we use these measurements to calculate a differential magnitude from the difference in magnitudes of the target star and the comparison star, so this offset will disappear in this subtraction, and the difference in magnitude between the stars will be correct.

Once the measurements made for a particular star are saved, the aperture must be copied to make the same measurements on the other stars of interest.

The final output for each frame by making these measurements will contain information on the magnitude, sky background, the error on these magnitudes, and object image coordinates for each star that was measured using the aperture method. The values of interest are the star magnitudes along with their uncertainties, as these are values that will be plotted against a time in order to observe a variant behaviour in the target star.

One problem that we encountered using the aperture method was to do with the annular region that measured the sky count around the stars in the XY CVn frames. We had a number of comparison stars, one which had a small background star in the region where the program’s default annular radius was set to, i.e. the outer annuli which were meant to measure the sky background contained another star in its ‘capture’ region. This meant that for each and every one of the frames for this target we had to define the annuli at a larger radius in order to measure a proper sky count. However we kept the width of the ‘capture’ region constant with GAIA’s default settings (see Fig. 6). We kept this constant for all of our measurements for this star.

Having done this for each star through each filter, we can tabulate the saved measurements for each star, remembering to separate the different measurement readings for each of the pass band filters, and obviously for each star!

Before these measurements can be tabulated in some order, it is necessary for the Julian dates that correspond to each frame to be calculated, which will consequently order the individual frame calculations by a timescale.
The Julian date, which is a widely used method for presenting dates in Astronomy, converts days, hours, minutes and seconds into a single number with a decimal fraction.

Because standard time keeping is a cyclical process, scientific measurements require a continuous method for recording epochs such that they can be easily manipulated, i.e. with addition and subtraction to determine time spans between data points etc. Julian days are represented by a number that has 5 decimal places. A Julian day starts at 12 noon, and each second represents a specific fraction of a whole number. When the consecutive day begins at 12 noon the decimal fraction reaches unity, and the process repeats (e.g. 2343534.00000 at noon one day will become 2343535.00000 the next day at noon).

Julian dates are calculated for the corresponding dates and times of which each frame was exposed. For our experiment we took the central point of each exposure to be the time that the exposure was taken, and this exact time was converted to a Julian date for each observation.

Once a Julian date for a particular frame is calculated it can be tabulated alongside the corresponding measurements for that frame (magnitudes and errors). This ultimately gives us enough information to make a plot of Time vs. Brightness, where the time has the units of Julian Date and the brightness is measured in Magnitudes, which for this case will be the differential magnitude of the target star relative to the calibration star. From this we should see a variant behaviour in each of our target stars, for each of the filters.

It is also a good idea to test the consistency of the comparison stars with respect to their magnitudes, which is done by simply subtracting the count levels of one from the other over a period of time. A straight horizontal line on the time graph represents a constant magnitude for both, an example of which can be seen below in Figure 7.

Each data point is grouped into a data set for the appropriate star. This is further divided into data sets corresponding to each filter, and then by the year in which the exposure was taken. This leaves us with 8 separate data sets which we can use to plot the light curves.

![Figure 7: A plot of the differential magnitudes between the target and calibration (red) and two comparisons (blue)](image-url)
Data Analysis

Having tabulated all the data into four separate spreadsheets, containing arrays of differential magnitude readings (with errors) and their corresponding Julian Date measurements, we can begin an analysis.

Below are the light curves for each star, and have been labelled appropriately corresponding to the filter the star was taken through and for what year. The graph titles also indicate a key for the x-values measured off the plots; each x value measured must be added to the number displayed in the “JD - <number>” section of the title. The x-array has had this number subtracted from all the data points for ease of analysis. Adding this number to any x-values obtained will give the full Julian Date value.

The numbers are subtracted from the Julian Date because the analysis program Dipso only allows values to be read off graphs to 6 significant figures, which is not sufficient enough to read out entire Julian date numbers, therefore the number is subtracted such that any x-values read off represent the decimal places of the Julian Date.

RR Gem

2006 Observations

![Graph showing light curves for RR Gem with Julian Date and magnitude values.](image)

Figure 8: B-band Observations
Figure 9: V-band Observations
2010 Observations

Figure 10: B-band Observations

Figure 11: V-band Observations
XY CVn
2006 Observations

Figure 12: B-band Observations
Figure 13: V-band Observations
2010 Observations

Figure 14: B-band Observations

Figure 15: V-band Observations
The estimation for each stars’ period is made by analysing each light curve, and by using some basic mathematics.

For each curve an estimation for the epoch of maximum brightness is made. This epoch is a reference point that complements the subsequent measurements made on the curve.

For a given curve, a measurement of the Julian date corresponding to the maximum brightness is made, which we represent as the epoch of maximum brightness, $\varepsilon_0$. On the same curve, the following peak of the curve is analysed, and again the Julian date corresponding to this brightness peak is extrapolated, represented by $\varepsilon_1$.

The difference between these two epochs, $T$, is where the interest lies; due to the nature of the target stars these peaks represent a specific moment in the variation timescale, and the difference in time between these two maxima will be an integer multiple of the actual period of the stars’ variation:

$$T = \varepsilon_1 - \varepsilon_0 = nP$$  \hspace{1cm} (1)

If observers are lucky enough, this integer, $n$, may be equal to 1 if it was possible to observe two consecutive peaks. However in this case it must be determined what the integer value is by constraining it to a range of possible values.

The value of this integer can be no lower than 1, so a lower limit is already available, however it is necessary to define a maximum limit. This is done by measuring the time span for the largest range of interrupted data, $\tau$, where it must be true that $P > \tau$ (see Fig. 16). Dividing the time between two peaks, $T$, by this number puts an upper limit on the possible amount of cycles between the epochs separated by $T$, as:

$$\frac{T}{\tau} > n.$$  \hspace{1cm} (2)

Therefore,

$$1 \leq n \leq \frac{T}{\tau}.$$  \hspace{1cm} (3)
Having established this theory we can carry out the practical analysis on each set of data, for each of the target stars.

There are 8 sets of data that need this analysis carried out on them, for each star in each filter in each year.

The process can be carried out using the Dipso graphical analysis program. The text files on which the data is stored can be read into an x and y array in Dipso. The x and y arrays can be saved inside a “stack” and titled to indicate which data is stored in it. This stack can be read into dipso immediately at any time in a format that is compatible. In this stack we save the 8 separate x – y arrays for each star in each filter for each year (the x- and y-values in the array represent the corresponding Julian dates and differential magnitude readings, respectively).

A plotting device can then be established, and once this is set up we can plot one of the stack entries using the pm command. This will plot whichever data set from the stack is selected, for example the data set for RR Gem in the B-band, for the year 2006.

This plots the data graphically within a certain x – y range, both of which can be altered using the xr and yr commands, where the command is followed by the desired number range. Dipso will order the y-axis in ascending order of value, but it is necessary to flip this order to observe brightness peaks for the curves, as increasing magnitudes become more negative.

Now for a given data set we should be able to distinguish some of the variant behaviour observable from the differential magnitude as a function of time. If we can establish two peaks then it is possible to apply the above theory in order to estimate possible values for the period of each star from the data sets supplied. 

Dipso further supplies us with analysis tools that can make this possible. The xv command allows users to select a data point on the plot of the data set using the cursor represented by a cross-hair, which will then return an x-value for the point selected. This tool will allow us to measure
the x-value corresponding to the peak of the first light curve, i.e. the Julian date epoch of maximum brightness, $\varepsilon_0$.

However there will be a measure of uncertainty concerning the read out of the x-value. The mark command makes the program plot the data set as a scatter of points, and the poly command can be used to join these points, and thus determine an approximate maximum. Once a peak is observed on the graphical plot the x range can constricted such that only this peak is observed on the screen, which will make the cursor reading more precise.

Once the first epoch, $\varepsilon_0$, has been found, the same method must be used to find the subsequent peak on the curve representing the same set ($\varepsilon_1$). Once this is measured, along with its corresponding uncertainty, Equation (1) can be used to obtain a value for $T$, whose uncertainty will arise out of a propagation of the uncertainties of $\varepsilon_0$ and $\varepsilon_1$. The uncertainty for the value of $T$ will be important for deducing the uncertainty on the final value of the period of variation.

The value of $\tau$ is found in exactly the same way, once it is established where the largest spread of data lies on the graph. The two x-values measured are the start and end points of this data spread, and the difference between the two will give a value for $\tau$ (see Fig. 16)

An upper limit on the n integer can then be found using Equation (2), leaving a range of possible n values that can be substituted into Equation (1). This process must be carried out for all of the data sets, so plots must be made for all of the stack entries.

One problem that we came across in using this method by determining the x-range between two peaks is that there were two sets of data for RR Gem that did not show two separate peaks in the light curves. In an effort to overcome the problem, we attempted to identify two other epochs on the curve that both represented the same point of the magnitude variation. There were substantial amounts of data points around the y=1 region of the graph, i.e. where the differential magnitude is equal to one. Because we could centre the cross-hair cursor on the y=1 line, we could obtain epochs for when the curve crossed this line. This was the only way in which we could provide ourselves with a greater spread of data to analyse.

Other data sets showed no common reference points on their curves at all, so a value of $T$ was impossible to obtain. These sets were both for XY Cvn, and where the 2006 V-band measurements and the 2010 B-band measurements. However this does not render them completely useless, which we become clear later on.

This left us with 6 foldable data sets.

The values of each parameter for each star are listed in the tables below.
## RR Gem

### B-band

<table>
<thead>
<tr>
<th>Year</th>
<th>T</th>
<th>n</th>
<th>P = T/n</th>
<th>Year</th>
<th>T</th>
<th>n</th>
<th>P = T/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1.98661</td>
<td>1</td>
<td>1.98661</td>
<td>2010</td>
<td>1.98603</td>
<td>1</td>
<td>1.98603</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.99331</td>
<td>2</td>
<td>0.99302</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.66220</td>
<td>3</td>
<td>0.66201</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.49665</td>
<td>4</td>
<td>0.49651</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.39732</td>
<td>5</td>
<td>0.39721</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.33110</td>
<td>6</td>
<td>0.33101</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.28380</td>
<td>7</td>
<td>0.28372</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.24833</td>
<td>8</td>
<td>0.24825</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.22073</td>
<td>9</td>
<td>0.22067</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.19866</td>
<td>10</td>
<td>0.19860</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.18060</td>
<td>11</td>
<td>0.18055</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.16555</td>
<td>12</td>
<td>0.16550</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### V-band

<table>
<thead>
<tr>
<th>Year</th>
<th>T</th>
<th>n</th>
<th>P = T/n</th>
<th>Year</th>
<th>T</th>
<th>n</th>
<th>P = T/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1.98663</td>
<td>1</td>
<td>1.98663</td>
<td>2010</td>
<td>1.98745</td>
<td>1</td>
<td>1.98745</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.99332</td>
<td>2</td>
<td>0.99373</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.66221</td>
<td>3</td>
<td>0.66248</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.49666</td>
<td>4</td>
<td>0.49686</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.39733</td>
<td>5</td>
<td>0.39749</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.33111</td>
<td>6</td>
<td>0.33124</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.28380</td>
<td>7</td>
<td>0.28392</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.24833</td>
<td>8</td>
<td>0.24843</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.22074</td>
<td>9</td>
<td>0.22083</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.19866</td>
<td>10</td>
<td>0.19875</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.18060</td>
<td>11</td>
<td>0.18068</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.16555</td>
<td>12</td>
<td>0.16562</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td></td>
<td>13</td>
<td>0.15288</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td></td>
<td></td>
<td>14</td>
<td>0.14196</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td>15</td>
<td>0.13250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
XY Cvn
B-band

<table>
<thead>
<tr>
<th>2006</th>
<th>T</th>
<th>n</th>
<th>P=T/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0642</td>
<td>1</td>
<td></td>
<td>1.06420</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.53210</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>0.35473</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.26605</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>0.21284</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>0.17737</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td>0.15203</td>
</tr>
</tbody>
</table>

V-band

<table>
<thead>
<tr>
<th>2010</th>
<th>T</th>
<th>n</th>
<th>P=T/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.98745</td>
<td>1</td>
<td></td>
<td>2.13256</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>1.06628</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>0.71085</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.53314</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>0.42651</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>0.35543</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td>0.30465</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>0.26657</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td></td>
<td>0.23695</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>0.21326</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td></td>
<td>0.19387</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td></td>
<td>0.17771</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td>2.13256</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td></td>
<td>1.06628</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td>0.71085</td>
</tr>
</tbody>
</table>

The process for estimating the correct period involves “folding” the data from a specific set by reducing it into a single cycle. Because of the repeated periodic behaviour of the curve, the data points across the entire range of data can be mapped all together onto a single phase. An advantage of this is of course that given a sporadic spread of data points across the larger range, folding all the points into a single cycle makes it possible to create a much clearer visualisation of the light curve.

In order to fold a data set it is necessary to have an estimation of the period of variation for the star in question. As well as the Dipso program, the ULO server has another special version which allows the user to use a “fold” command to act on a data set, given an input of period estimation.

The fold command, when performed on a stack entry, takes an estimation for the period of variation (which is entered by the user) and uses it to fold segments of the curve together into one
phase, i.e. the data set is ‘sliced’ evenly into segments whose numerical x-axis length is that of the period value entered by the user.

If the period estimate that is entered is too small then the segments will be folded together incorrectly, such as in Figure 18. The same is true if the segment ‘slices’ are too large. In order for the light curve to be folded correctly the period entered will have to be equal to the actual period of variation for the RR Lyrae star in question, or indeed be fairly close to it.

It is this property of the folding tool that we will take advantage of. By a trial and error process the possible periods calculated from each particular data set will be input into SDipso using the fold command on the particular data entry. The final folded image that yields the best fitting curve will be attributed to the best estimate of the period of the variable star.

![Figure 17: An example of folding - Graphs 1 and 2 show the same light curve of Julian Date vs. Magnitude. Graph 1 is ‘sliced’ into small even segments, which are subsequently reduced to a single phase in the graph underneath. Graph 2 is separated into even segments that are much larger, which are also folded into a single phase. Clearly, the segment sizes of graph 2 are a much closer approximation to the actual period of the variation.](image)

It is the estimations of $P$ using Equation (1) that are entered into SDipso under the fold command.

Each stack entry representing a data set will have its own range of possible $P$ values, which must individually be entered into SDipso. Upon entering a particular value of period the program will then fold the data in the process described above, and this can be plotted using $pm$.

Note: It is important to notice that the fold command has the default setting of combining the data to a single phase, much like a normalisation. It is therefore necessary to have the x-axis ranging from 0 to 1 on the plotting device.

By process of elimination, it is possible to ‘cross off’ some of the period calculations for each of the data sets.
For example, Figure 19 shows a folded light curve for RR Gem through the B-band in 2006, with the estimated period of \( P=0.24832 \) (from \( n=8, \ T=1.98661 \)) included in the fold calculation. The period estimation is clearly wrong as the folding process has ‘sliced’ segments across the original curves that are too small, and subsequently has folded the sections of the original curve out of phase, much like described in Figure 18.

![Figure 18: An example of incorrect folding procedure. The estimated period is not correct and therefore the folding process has misaligned the elements of the curve.](image)

By singling out these misalignments that are a result of the folding process using a false period estimation, it is possible to narrow down the range of the possible periods of each star. We can then concentrate on the period values that produce more believable folded curves, such as in Figure 20, which shows a folded curve for RR Gem through the B-band in 2010, with \( P=0.24832 \) (from \( n=8, \ T=1.98603 \)):
However it is only possible to determine the closest approximation to the period if there is a big enough range of data in the set. For example, the data set obtained for RR Gem through the B-band in 2010 yielded 12 possible values for the period. Figure 21 shows the folded curves for each of these possible periods plotted all together as a function of phase.

From this plot it may be possible to eliminate some of the calculated period values as they cause the folded curve to spread too far across the phase before it can reach minimum again. However the problem lays in the fact that the remaining folded curves are all possible candidates for being correct, but there is insufficient enough data to plot the remainder of the curve, so an approximation for the period of this star cannot be extrapolated from this data set alone as it will never be seen which curve reaches a minimum at the end of the phase.

At this point we take the fact that we have data sets from previous years to our advantage, and attempt to cross-correlate the data, paying particular attention to compare data sets that represent measurements of the same star through the same filter. We can also make use of the light curves which were un-foldable.

By folding all the possible data together and eliminating “bad folds” (see Figure 19) it is possible to compare folded curves taken through the same filter but from different years. The calculated period values can also be used to fold the curves which could not yield n and T values, given that they correspond to the same star through the same filter. However, this makes an assumption that there has been no period modulation between the times that the measurements were made.
The process simply involves plotting two separate curves of the same star through the same filter, but from different years onto the same phase. The data sets that are combined are the folded sets corresponding to the same n values, i.e. the folded curve for 2006 must be combined with the folded 2010 curve whose period input was calculated from the same n value. This ensures that they each represent the same period, though they will not match due to the constraints of measurements, and their subsequent uncertainties.

Plotting the curves of the same star, band and intrinsic n value together in Dipso will cause the curves to be plotted out of phase, therefore it is necessary to account for this (see Figure 22).

This is done by determining the difference between two epochs representing the same point of the variation, then aligning them, using the Dipso program. They can then be plotted alongside each other in phase. Plotting them together should hopefully create a composite folded light curve (see Figure 23).

Figure 20: Folded curves for 12 possible values of period are plotted together in a single phase. It is possible to disregard the curves that reach too far right (as they will not complete a single cycle within one phase).
It was a fairly straightforward process obtaining the best fitting fold for XY CVn, as the range of P values for each year for each filter was easily narrowed down to a single possible value by the process of eliminating the bad folds. This made producing composite light curves much easier.

Doing the same for RR Gem was slightly more problematic, due to the numerous possible folds that can be seen in Figure 21. However the corresponding plots for the 2006 data helped eliminate the problem of ‘several candidates’. If the folds for the corresponding n values in 2006 were incorrect, then it would automatically render the same folds in the 2010 data incorrect also. So
a correct fold found in the 2006 data can complement the corresponding fold in 2010, eliminating the remaining folded curves from the analytical process.

Below are the final composite light curves for both stars through both filters. These can subsequently be used to create a plot for the variation in the B-V colour index.

The curves on the plots are of a different colour, which denotes that they are a combination of the separate years.
RR Gem

B-band

![B-band graph]

Figure 23

V-band

![V-band graph]

Figure 24
XY CVn

B-band

Figure 25

V-band

Figure 26
These plots are composite folded curves for the same star through the same filter, and they appear to show that there is little or no variation in the period. The fact that they fold correctly within the single phase shows that the period value used to create the folds is a correct approximation for the true period.

A B-V colour index curve can be created by ordering the x values in the array to monotonically increase (using the \texttt{sjsort} command), and then subtracting the array for the V-band folded curve from that of the B-band folded curve for each star. This is done in Dipso, however the B-V curves cannot be created wholly; they must be made from a combination of B-V curves for each separate year, much like the combination methods described for the folded light curves.

These curves of B-V as a function of Phase are displayed below for each star, created from the data sets that we had available. Therefore they are not fully complete for the cycle. They both show the same general shape of a rise in colour index value, followed by a decrease as the cycle continues.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{b-v_rr_gem.png}
\caption{B-V RR Gem}
\end{figure}
Figure 28
**Results & Error Analysis**

**Period of Variant Behaviour**

The estimations for the periods of RR Gem and XY CVn are determined by the folding method by analysing the light curves, described in the Data Analysis section; the curves which complete a single cycle within the plotted phase represent the correct period estimation. The equations (1), (2) and (3) from the previous section describe the following calculations, where the value $T$ is the difference between two epochs representing the same point of the cycle for the variable star. The correct $T$, $n$ and hence $P$ values are listed below, derived from the folding process:

### RR Gem

**B-band**

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th></th>
<th>2010</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>1.98661</td>
<td>$n$</td>
<td>5</td>
<td>$P = T/n$</td>
</tr>
<tr>
<td>$T$</td>
<td>1.98603</td>
<td>$n$</td>
<td>5</td>
<td>$P = T/n$</td>
</tr>
</tbody>
</table>

**V-band**

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th></th>
<th>2010</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>1.98663</td>
<td>$n$</td>
<td>5</td>
<td>$P = T/n$</td>
</tr>
<tr>
<td>$T$</td>
<td>1.98745</td>
<td>$n$</td>
<td>5</td>
<td>$P = T/n$</td>
</tr>
</tbody>
</table>

### XY CVn

**B-band**

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th></th>
<th>2010</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>1.0642</td>
<td>$n$</td>
<td>3</td>
<td>$P = T/n$</td>
</tr>
</tbody>
</table>

**V-band**

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th></th>
<th>2010</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>1.98745</td>
<td>$n$</td>
<td>6</td>
<td>$P = T/n$</td>
</tr>
</tbody>
</table>

The calculations for XY CVn in the B- and V-band for 2010 and 2006, respectively, could not be carried out due to the inability to determine two epochs on the curve representing the same magnitude, consequently making it impossible to determine the value $T$. 
It must also be stated that for RR Gem, the T values for the 2006 data set were not determined from epochs of maximum brightness, but from common points laying on the y=1 line, i.e. where the differential magnitude on the plot equals 1.

All of the P values were entered into Dipso for the appropriate light curves in order to obtain a folded curve for each of the data sets. The highlighted values correspond to the final folded curves obtained for each star, and hence are the correct estimates for the period of each star from this method. Errors in reading the graphs transpired to be negligible compared to the errors described below.

The uncertainties of each period value arise from a propagation of uncertainty in the epochs of maximum brightness (or other common epochs) used to determine T.

The Julian dates for each data point were determined by calculating the time of the mid-point of each exposure (for example, if an exposure began at 00:00 and lasted for 120 seconds, the mid-point would be 60 seconds in, making the ‘mid-point time’ 00:01). Therefore the Julian date measurements will lie halfway between a margin of error that is equal to the exposure time for each reading, as it is uncertain at which point during each exposure that a maximum reading is obtained.

\[
\Delta J_D = \pm \frac{\text{Exposure time of measurement}}{2}
\]

By converting the exposure times corresponding to each data point into a Julian date format we can begin to propagate an error for the period values.

This requires some care as exposure times differed between some of the observing sessions (due to insufficient count levels etc.) so the exposure times of each of the reference epochs used to determine the value of T for each light curve must be checked individually.

The tables below show the exposure times for each target star through each filter, for all of the observation sessions in 2006 and 2010, along with the associated errors and their Julian date conversions. From these the uncertainties on each epoch measurement can be found by determining on which date they were obtained.

### RR Gem

<table>
<thead>
<tr>
<th></th>
<th>31/01/06</th>
<th>01/02/06</th>
<th>02/02/06</th>
<th>12/02/10</th>
<th>14/02/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex. time (s)</td>
<td>B</td>
<td>V</td>
<td>B</td>
<td>V</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Error (s)</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Error (JD)</td>
<td>0.00006</td>
<td>0.00005</td>
<td>0.00006</td>
<td>0.00003</td>
<td>0.00006</td>
</tr>
</tbody>
</table>
The columns highlighted in green are for the curves which epochs were determined from peaks in magnitude. Those highlighted in yellow represent the curves where epochs were determined from the y=1 common reference point. The rest are not useful as the T values are not calculated from these dates/filters.

To calculate uncertainties for T, and hence P, it is necessary to propagate these errors by the following formula:

$$\Delta T^2 = \Delta \epsilon_0^2 + \Delta \epsilon_1^2 \quad (4)$$

$$\Delta \epsilon_0$$ and $$\Delta \epsilon_1$$ represent the errors on the two epochs used to calculate T. For whichever value of T calculated, the errors for the epochs must be carefully determined by recognising when the exposures were taken, so that the correct error value is used from the table above.

Because T is directly proportional to P (by the constant n value), the error on T values are also the error on the period values that are derived from them.

Below, the process of calculating the T value uncertainties is shown, for the dates that they could be calculated for:

### RR Gem

**B-band**

<table>
<thead>
<tr>
<th>Year</th>
<th>$\epsilon_0$</th>
<th>$\epsilon_1$</th>
<th>$\Delta \epsilon_0$</th>
<th>$\Delta \epsilon_1$</th>
<th>T</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>2453767.34855</td>
<td>2453769.33513</td>
<td>0.00006</td>
<td>0.00006</td>
<td>1.98661</td>
<td>0.00008</td>
</tr>
<tr>
<td>2010</td>
<td>2455240.39515</td>
<td>2455242.38118</td>
<td>0.00017</td>
<td>0.00006</td>
<td>1.98603</td>
<td>0.00018</td>
</tr>
</tbody>
</table>

**V-band**

<table>
<thead>
<tr>
<th>Year</th>
<th>$\epsilon_0$</th>
<th>$\epsilon_1$</th>
<th>$\Delta \epsilon_0$</th>
<th>$\Delta \epsilon_1$</th>
<th>T</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>2453767.34790</td>
<td>2453769.33453</td>
<td>0.00005</td>
<td>0.00003</td>
<td>1.98663</td>
<td>0.00006</td>
</tr>
<tr>
<td>2010</td>
<td>2455240.39542</td>
<td>2455242.38197</td>
<td>0.00006</td>
<td>0.00003</td>
<td>1.98745</td>
<td>0.00007</td>
</tr>
</tbody>
</table>

### XY CVn

**B-band**

<table>
<thead>
<tr>
<th>Year</th>
<th>$\epsilon_0$</th>
<th>$\epsilon_1$</th>
<th>$\Delta \epsilon_0$</th>
<th>$\Delta \epsilon_1$</th>
<th>T</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2455240.56517</td>
<td>2455242.69773</td>
<td>0.00208</td>
<td>0.00139</td>
<td>2.13256</td>
<td>0.00250</td>
</tr>
</tbody>
</table>
V-band

<table>
<thead>
<tr>
<th>Year</th>
<th>$\varepsilon_0$</th>
<th>$\varepsilon_1$</th>
<th>$\Delta\varepsilon_0$</th>
<th>$\Delta\varepsilon_1$</th>
<th>$T$</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>2453768.60299</td>
<td>2453769.66719</td>
<td>0.00208</td>
<td>0.00278</td>
<td>1.06420</td>
<td>0.00347</td>
</tr>
</tbody>
</table>

Given these calculations, the final results for the periods of each star through each filter for both years can be have uncertainties attributed to them.

For RR Gem, the periods determined from observations through the B- and V-band filters are:

*B-band*

2006: $0.39732 \pm 0.00008$

2010: $0.39721 \pm 0.00018$

*V-band*

2006: $0.39733 \pm 0.00007$

2010: $0.39749 \pm 0.00006$

The curves in Figures 24 and 25 suggest that RR Gem is an RRab type curve, with a steep increase followed by a gradual decrease (towards a minimum that is not observed).

For XY CVn, the periods determined from observations through the B- and V-band filters are:

*B-band*

2010: $0.35473 \pm 0.00250$

*V-band*

2006: $0.35543 \pm 0.00347$

The error margins for all the data have an overlap, and each period value appears to be precise to 3 decimal places.

The curves in Figures 26 and 27 suggest that XY CVn has the class of RRc, showing a sinusoidal variation.

**Magnitude Variations**

The plotted curves that show the variant behaviour through a comparison with some calibration star, i.e. the differential magnitude for the targets relative to their calibration stars is plotted as a function of Julian date.

The change in magnitude of the cycle for each star can be determined by measuring the maximum and minimum points of the differential light curves.

However, because of our insufficient data sets we have had to make use of combining data from both 2006 and 2010. With respect to measuring maxima and minima in the amplitudes of the
magnitude variation this means that we must assume that there has been no Blazhko
effect phenomenon that differentiates the two folded curves.

The values below represent the measured maxima and minima for our data sets for each
star in each band, from combined folded curves. Much like the epochs of maximum brightness were
read off the graphs, the maximum and minimum differential magnitude values are read from Dipso,
by using the \texttt{yv} command.

\begin{tabular}{|l|l|l|}
\hline
\text{RR Gem} & B & V \\
\hline
\text{Minimum (differential mag)} & 1.791 ± 0.003 & 1.6155 ± 0.0032 \\
\text{Maximum (differential mag)} & 0.1052 ± 0.0014 & 0.3505 ± 0.0022 \\
\hline
\end{tabular}

\begin{tabular}{|l|l|l|}
\hline
\text{XY CVn} & B & V \\
\hline
\text{Minimum (differential mag)} & 0.0805 ± 0.0057 & 0.391 ± 0.005 \\
\text{Maximum (differential mag)} & -0.734 ± 0.005 & -0.2411 ± 0.0028 \\
\hline
\end{tabular}

The errors on these differential magnitudes are obtained from a propagation of errors given
by the Gaia program upon carrying out the measurement procedure discussed in the Data Analysis
section.

Because these are differential magnitudes, the errors shown are derived much like the
errors in Julian dates using equation (4):

\[
\Delta Differential \text{ Mag}^2 = \Delta \text{Mag}_{\text{Target}}^2 + \Delta \text{Mag}_{\text{Calibration}}^2
\]  
\hspace{1cm} (5)

The range of magnitude variation across the cycle can further be calculated, along with its
type; the error in this is calculated in the same way, using the form of equation (5), except the error
being calculated is in the magnitude displacement, and is produced from a propagation of the errors
in the differential magnitude results.

RR Gem has a magnitude variation of \textbf{1.686 ± 0.003} in the B-band, and a magnitude variation
of \textbf{1.265 ± 0.004} in the V-band. For this measurement the minimum was taken to be the lowest point
on the curve. The curve presents an apparent minimum however it is not followed by a subsequent
increase, so these measurements may present a discrepancy with published values.

XY CVn has a magnitude variation of \textbf{0.8145 ± 0.0076} in the B-band, and a magnitude
variation of \textbf{0.6321 ± 0.0057} in the V-band.

There is clearly a greater increase in magnitude from minimum to maximum by observing
the stars through the B-band, compared to variations of magnitudes through the V-band. This could
be explained by the opacity variations in the atmosphere of the RR Lyrae stars during their periodic
cycle (this is explained in the introduction of this report).
The brightness of the blue end of the spectrum will vary more than that of the visual section
of the spectrum as the opacity will be wavelength dependent; the opacity will affect shorter
wavelengths more so than longer wavelengths.

The variation of visual magnitude will be less due to the fact that the opacity caused by the
doubly ionized Helium will not affect these wavelengths to the same extent that it will affect
the shorter wavelength photons. So as the opacity goes from a maximum to a minimum during the
cycle, the transmission of bluer wavelengths will increase, whereas the transmission of longer
wavelengths (observed through the V-band) will not depend on the change in opacity as much.

It may also be reasonable to claim that recombinations involving the ionized Helium are the
source of the increase of shorter wavelength photons. As the star becomes cooler during the
expansion and causes the doubly-ionized Helium to be converted back to He$^+$, causing the emission
of short wavelength photons that are subsequently detected through the B-band filter.

The increase of blue photon emissions during the peak of the brightness variation is also
supported by the colour index curves plotted previously in the Data Analysis section (Figures 26 &
27). These graphs show the B – V colour index for both stars as a function of phase, from the
available data. They both show a peak corresponding to the peaks of magnitude of their stars,
preceded by a steep rise and followed by a gradual decrease (although it may seem less clear for XY
CVn due to the sporadic data used).

The colour indices of both stars move towards lower values as the light curves approach a
maximum, which corresponds in a colour shift towards the blue end of the spectrum. After the peak
the colour index value for both stars starts to increase once more, which represents a decrease in
short wavelength detections.

**Conclusion**

From the results obtained in our experiment, concerning the periods of variation for both
our target stars it would be reasonable to state that the folding method used to determine the
periods is a good method regardless of its lack of mathematical rigour. However it is absolutely
necessary to have a complete enough set of data covering a large range of observations in order to
obtain a more accurate and water-tight result.

Having said that, the period approximations calculated for RR Gem and XY CVn through the
different filters give fairly promising results, complementing published results of 0.397 [1] and 0.36
[8] days respectively.

The periods calculated for RR Gem are accurate to 3 decimal places in comparison with the
published result, with all measurement s falling within each others’ error margins; however for XY
CVn the accuracy of the result was only to a single decimal place when compared to the accepted
value, though this published result falls within the catchment of the error margins derived in this
experiment. The reasoning behind this can be attributed to the amount of data points we had
available for each star; our coverage of the RR Gem light curve was much more compact and defined
than our data sets for XY CVn, which could have been improved given more exposures. This affected
our final result as it greatly affects the measurements made of the T value used in the data folding.
A larger set of data for RR Gem would have been required to complete the folded light curve, as it was impossible to build a complete phase for the curve out of the data that we had available; for this reason, though it agrees well with published data, the period value determined for RR Gem is somewhat a speculation, and perhaps its uncertainties may be narrowed down through more observations.

However, the curves for both stars confirm that they are indeed RRab type for RR Gem, and RRc type for XY Cvn.

However where XY CVn observations lacked in data points, the sets made good coverage of phase. This made it slightly easier to determine maxima and minima for the differential magnitudes albeit still with reduced data points.

These were still unsuccessful though in being comparable with published values; magnitude variations were 1.37 and 1 for RR Gem and XY CVn respectively, for the V-band [8]. Results obtained here do not even cross over with these published values from their uncertainties. The readings were also obtained from insufficient data sets, whether they are incomplete or too sporadic.

One major disadvantage of our data analysis method was due to the assumption made that amplitude variation did not occur. If it had occurred then our compound curves would be meaningless when it came to determining an amplitude for a single phase, as the data sets will correspond to completely different points in the long-term modulation. This may explain the discrepancy between the magnitude variations of each star through the V-band. Our bad flat field data from 2006 may have caused slight variations in magnitude readings, due to its lack of even illumination which is required of all flat field frames. This may be one of the single human errors in the observations.

It also transpired that the calibration star we used to make all of our calculations in magnitude for RR Gem was in fact a variable star. Although the differential light curves showed variant behaviour still, due to this fact there may have been a significant difference had we used a star that presented more constant readings, as required.

In summary, there was not enough data coverage to determine any presence of a Blazhko effect between the two years, and given that the period calculations were derived from compiling data of the two separate years, as were magnitude variations, it must be stated that any value we derive must be estimation. This is also due to the fact that there were significant gaps in data sets, particularly for XY CVn, due to the need for longer exposure times.

Preparation for the project may have been improved in order to change these disadvantageous properties for our data. Due to our ‘trial and error’ procedure of determining count levels by taking numerous test exposures much time was wasted during the initial observing sessions, as well as making calculations to correct for the telescope offset. Research into this before our departure may have significantly increased our observation time on these occasions, which turned out to be our only observations for 2010. Certainly I would advise any thorough observation of these targets to be undertaken over a much larger scale of time. Though the 6 days would have been sufficient enough to collect data to compile complete light curves, it does not allow for the poor observing conditions that we experienced in 2010.
References

8) Demande de Temps de Telescope OHP, Septembre 2009 – Fevrier 2010: Program for observations at the Haute-Provence Observatory made available to the UCL students