Measuring the dimming of Betelgeuse from Durham

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The recent unprecedented dimming of the red supergiant Betelgeuse is measured in Durham using CCD cameras over five weeks. The trend of the measured magnitudes is in reasonable agreement with that of AAVSO observers however individual magnitudes are generally in disagreement. The star is measured in the V, B and R bands to help indicate the cause of the dimming and it is shown that there is approximately equal dimming in the V and B bands which supports the recent claim that large dust grains are responsible for the dimming. A sinusoidal model is applied to the data to determine its lowest magnitude and date to return to regular magnitude. This model initially appears to follow the pattern but is ultimately rejected due to a poor fit. The applicability of CCDs for measuring the magnitude of a bright star like Betelgeuse in Durham conditions is discussed.

1. Introduction

Betelgeuse (α Orionis) is a red supergiant and is one of the brightest, reddest stars in the sky. It is predicted to go super-nova in less than 100,000 yrs and like many highly evolved stars it shows semi-regular light variations [1]. Its V band magnitude varies between 0.3-1.0 magnitudes and its cycle has a short period of $\sim$ 400 days and a longer period of $\sim$ 2100 days with possibly other shorter periods [2]. Since Oct 2019 it has undergone a dramatic decrease in all bands reaching its lowest magnitude since records began of 1.614 ± 0.008 in mid Feb 2020 [3]. An image of Betegeuse illustrating its dimming is shown in Fig.1.

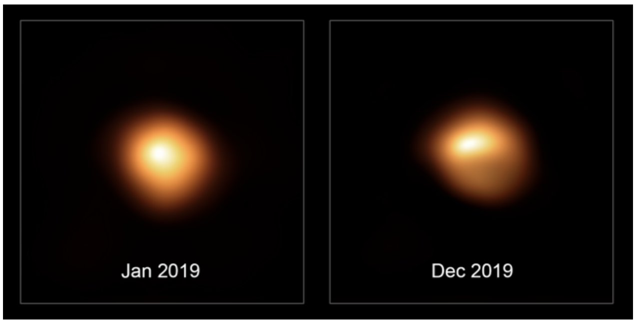

FIG. 1: A visible light image showing the change in Betelgeuse's surface structure taken by the SPHERE instrument on the VLT. The southern hemisphere of the star is visibly darker [4].

The cause of Betelgeuse's unprecedented dimming is unclear. Its semi-regular variations are normally attributed to bright spots caused by huge convection cells rather than radial pulsations [2] [5]. Variations of these convective cells could lead to a decrease in the effective temperature as more radiation is emitted in the longer wavelengths. Betelgeuse reached a minimum magnitude in mid-Feb 2020, 424 ± 4 days after its previous low in Dec 2018 which supports this episode being caused by its periodic, convective cell activity [3]. However, other investigations have calculated the surface temperature by measuring the strength of TiO bands and have shown that the decrease in effective temperature was not sufficient to explain its dimming [6].

In this work, CCD cameras are used to measure Betelgeuse during its minimum brightness. Measurements are made in the V, B and R bands to help determine the cause of its dimming and are compared to AAVSO (American Association of Variable Star Observers) data. A basic model is proposed to describe the variation of its magnitude and the suitability of CCDs to measure Betelgeuse's dimming is tested.

The magnitude of the star is determined by modifying the magnitude equation to compare the relative intensity of Betelgeuse to background stars of known magnitude. Explicitly the apparent magnitude of Betelgeuse, m is:

$$m = m_{zpt} - 2.5log_{10}(I) \quad (1)$$

where m_{zpt} is the magnitude of one count in the calibration image and I is the total number of counts for Betelgeuse.

2. Observations

The magnitude of Betelgeuse was measured during the period of minimum brightness from 28/01/20 to 10/03/20. A 14" Meade telescope was attached to a QSI 683 WS camera to make observations. Calibration images were taken before and after Betelgeuse images to estimate the degree of atmospheric turbulence and determine the zero point magnitude. These were calculated using Gaia software. On each observation eight repeats at fifteen seconds were used to reach sufficient counts and signal to noise ratios. Images of Betelgeuse had to be taken severely out of focus to prevent saturation and remain in the linear domain of the cameras. This was achieved by increasing the distance between the camera and the telescope. On each occasion 16 images at 0.03s exposures were taken to allow for a mean number of counts to be calculated.

Before performing analysis of the data, the images were corrected in two ways. The bias and dark current noise were removed by taking exposures for the same period of time as the star images with the shutter closed. These images were subtracted from the star images. Flat field images were made by taking long exposures of a twilight sky and master flats were created by dark subtracting these. The star images were then divided by the master flats after being bias and dark subtracted. This gave the calibrated images which were used for calculations. The zero point magnitudes were adjusted for the difference in exposure time between the calibration and star images and were shifted by 0.1 magnitudes to correct for the difference in filter absorption.

The mean zero points magnitude and number of counts on a given day were inserted into Eq.(1) to give the magnitude of Betelgeuse. This was automated using Python code. The error in the final magnitude value was propagated from the standard deviation of the zero points and the Poisson error from the counts and is detailed in the Appendix.

The linearity of the CCDs was measured by taking out of focus images of the dome wall for increasing exposure times and measuring the number of counts. Eight repeats between 0.03s and 60s were taken from which a mean was calculated. The effect of temperature on dark current was gauged by measuring the number of counts between -7.5°C and -15°C in intervals of 2.5°C from 0.03s to 1s.

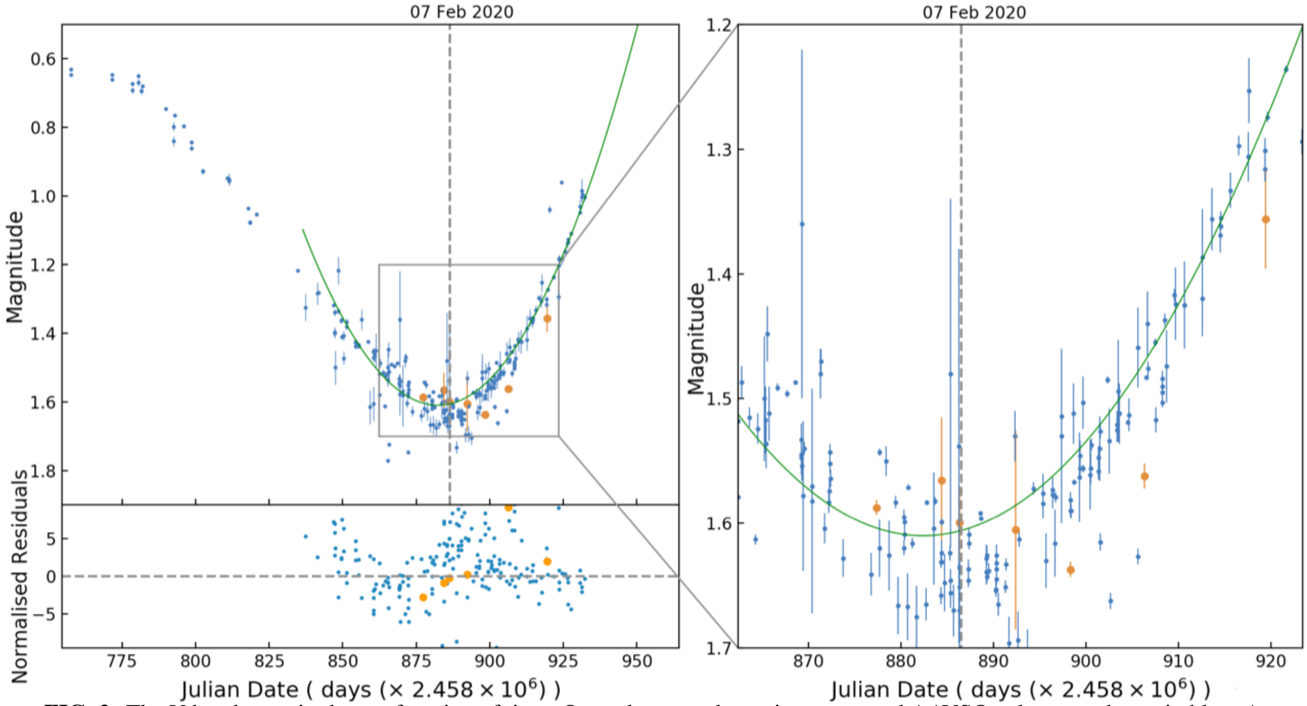

FIG. 2: The V band magnitude as a function of time. Our values are shown in orange and AAVSO values are shown in blue. A sinusoidal trend line has been added in green, as well as error bars. The normalised residuals to the trend line are graphed below and a zoom plot showing the lowest magnitude amongst our values is included.

3. Results and Discussion

3.1. Measurements from Durham

Table I shows the measured magnitudes of Betelgeuse during the period of minimum brightness. These were calculated using Eq.(1) comparing the stellar counts with the zero point magnitudes of background stars. The variation of the V band magnitudes with time are displayed alongside AAVSO data in Fig.(2) and upon initial inspection appear to fit the trend.

TABLE I: The measured magnitudes in the V, B and R bands with their associated uncertainties.

Date	V band	B band	R band
28/01/20	1.587 ± 0.006	N/A	N/A
04/02/20	1.57 ± 0.05	N/A	N/A
06/02/20	1.60 ± 0.03	N/A	N/A
12/02/20	1.61 ± 0.08	3.28 ± 0.02	0.41 ± 0.07
18/02/20	1.637 ± 0.006	3.27 ± 0.01	0.408 ± 0.004
26/02/20	1.56 ± 0.01	3.15 ± 0.04	0.363 ± 0.009
10/03/20	1.36 ± 0.04	3.0 ± 0.1	N/A

Our results in Fig.(2) show a clear decrease compared to Betelgeuse's normal magnitude but are not in good agreement with AAVSO data [7]. Within a half a day of a measurement, only 20% of Durham data agreed with AAVSO values to within one standard error and 68% within two standard errors. This is because the measurements have very small errors, similar to the AAVSO data whose values, on many days, show very little if no agreement. Only 20% of comparisons made between the seven AAVSO values made on the 10/02/20 agree to one standard error.

A trend in the Durham data itself is also not clear, although with more measurements this may not have been the case. The trough is not clear from 28/01/20 to 18/02/20. Our value from 06/02/20 was higher than 82% of values four days before it even though most estimates placed the lowest magnitude as after it, between 07-13 Feb [3].

An improvement to this experiment would have been to take images more regularly which would have made a trend more visible and required less reliance on external data. However this would have been restricted by weather conditions.

The dominant source of error in magnitudes came from sky noise caused by the turbulent atmosphere. This gave an average percentage error of 2.5% in the V band, 1.4% in the B band and 5.1% in the R band, although these are skewed by the logarithmic magnitude system. A typical night of observing such as 04/02/20 in the V band had a zero point of 17.02 with a zero point propagated error of ± 0.05. The error propagated from the Poisson error in counts was 0.0009 which was much smaller. The standard deviation in the counts for such a night was 70,000 with an average count number of 1,520,000 whilst the Poisson error was the square root of this mean giving 1200 counts. Even between consecutive images with an interval of two seconds the count difference could be over 100,000 counts, ten times larger than the estimated Poisson error. This indicated the dominant error was from sky noise. Images taken tens of seconds between each other feature even larger differences up to 200,000.

The standard deviation was used as the error in the zero points because this was a systematic error. The refraction and transmission of light changes every few second due to the density and temperature fluctuations in the atmosphere. Taking a higher number of measurements over a longer period of time would not lead to higher accuracy in the zero point at the time of the star images. This was the reason the error in the zero point magnitudes was so high.

The methods of calculating uncertainties by AAVSO observers were not generally provided and therefore it is difficult to compare our findings.

The error caused by the fluctuations in the atmosphere could have been mitigated by taking shorter exposure time images in quick succession. Although our exposure times were short (0.03s) there were two seconds between images in which the atmosphere would have changed, as shown before. The 'Lucky imaging' cameras could have been considered for this.

3.2. Modelling the dimming

A model of Betelgeuse's dimming was created to see how well it could be described by simple models and to quantitatively determine when Betelgeuse reached minimum brightness and when it could be expected to return to its previous magnitude. It was also hoped that it would be possible to calculate the extent to which values taken in Durham agreed with those by other observers. As can be seen in Fig.(2) the trend appears sinusoidal and therefore a model of the following form was sought:

$$m = A + B\sin(2\pi Ct) \tag{2}$$

where m was the magnitude and A and B were dimensionless constants to be determined. C, also to be determined, had dimensions of inverse time to give a dimensionless argument when multiplied by t, the time in Julian days.
A χ^2 fitting was used to find the optimised parameters and errors, whose derivation can be seen in the Appendix. The model was only applied to the portion of the data which appeared periodic as shown in Fig.(2). A χ^2_{min} value of 737.3 was obtained for this model, 26.1 σ higher than the number of degrees of freedom 207. This gave a χ^2_ν of 3.5, which indicates a poor fit. More importantly the probability of obtaining this value, or higher, $P(\chi^2_{min};\nu)$ was calculated as 1×10^{-60} which indicates a very poor match between the sample and parent distributions.
It was initially thought that the fit was poor because it neglects the fact that magnitude is a logarithmic scale. Although the decrease in flux may have been sinusoidal, as are many periodic phenomena, the magnitude would have distorted this periodic relationship. However a logarithmic sin model of the form $m = A + Blog_{10}(\sin(2\pi Ct + D))$ was attempted and revealed very similar results for χ^2 and $P(\chi^2_{min};\nu)$ with percentage uncertainties in the parameters as high as 5%.
There is also the possibility that the decrease in flux was not sinusoidal at all. The normalised residuals in Fig.1 show portions of the data where the normalised residuals are almost entirely above or below the zero axis. This is a fault in the model itself. However, any model which would have attempted to fit the data with a continuous trend line would have had difficulty even if it was correctly describing the physical phenomena because of the mass disagreement amongst the AAVSO values themselves. This is why the model has been included in Fig.1, even though the model is rejected given the poor fit.
The model predicts that the minimum magnitude reached was 1.61 ± 0.06 on 02 ± 1 Feb. These results are difficult to compare to the literature because Betelgeuse's dimming is a such a recent event. The magnitude value is within one standard error of 1.614 ± 0.008 as measured by Ref.[3] but five away from the same source's estimate of a dimming peak between 07-13 Feb. However, simply observing the light curve in Fig.1 shows that some of the lowest magnitudes are as early as 04 Feb. The model also gave a prediction for a return to normal magnitude on the 06 ± 2 April which appears reasonable, however may be early considering the model generates poor approximations for the early stages of the dimming which is clearly not sinusoidal. Assuming the return to normal magnitude is similarly not sinusoidal, it may return later than anticipated.

3.3. Cause of Dimming

The B and R band magnitude values are plotted together in Fig.(3) to compare the dimming severity. Measuring the decrease in magnitude over several bands allowed us to determine the decrease in flux at different wavelengths. One theory is that there has been episodic mass loss from Betelgeuse which has settled as circumstellar dust in our line of sight [6]. Considering the preferential absorption of bluer light by dust, this theory could be tested by measuring the decrease in flux in different bands. However, as Ref.[6] points out, recent observations of Betelgeuse and those of other RSGs indicate that dust produced in these stars have larger average grain sizes of the order of $\sim 0.3\mu m$ [8]. This dust absorbs light across the optical spectrum and we would not expect to see the blue band decrease more.

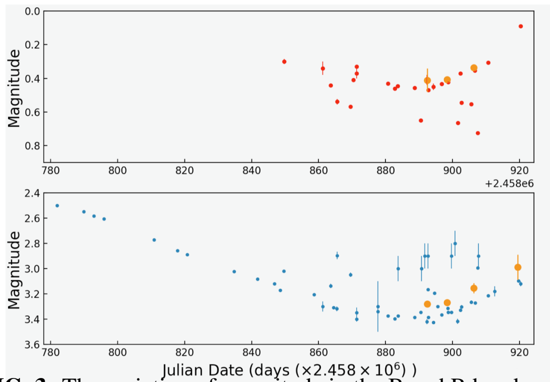

FIG. 3: The variation of magnitude in the B and R bands with time. The top plot shows the R band with our values in orange and AAVSO values in red. The bottom plot shows the B band with our values in orange and AAVSO values in blue.

It is difficult to compare the magnitudes in the B and R bands. The R band is incomplete with AAVSO data and both sets of data have values at very similar times in strong disagreement. The decrease in magnitudes were calculated in the V and B band between 02/11/19, the earliest B band measurement, and 12/02/20 where most estimates place as around the minimum [3]. Our values were used as the minimum as these are in good agreement with other estimates and AAVSO values are in disagreement meaning a weighted mean could not be used. This yielded a difference of 0.86 ± 0.03 mag in the V band and a difference of 0.73 ± 0.02 mag in the B band. Although these do not cover the whole range of Betelgeuse's dimming this would suggest an approximately equal decrease at these wavelengths, possibly more at longer wavelengths. This would support the theory of large grain dust particle ejection, however a decrease in the effective temperature of Betelgeuse would also lead to a decrease in both these bands considering Betelgeuse's peak flux occurs at longer wavelengths (even than R).

3.4. CCD Efficacy

The suitability of the CCDs also had to be considered when making Betelgeuse measurements. The linearity of the

CCDs was investigated because Betelgeuse is an intense star and saturated the detectors quickly. At higher counts the number of counts is not directly proportional to the number of photons received and the counts plateau for higher flux. This was tested by measuring the mean number of counts for one pixel at increasing exposure times. The results of this can be visualised in Fig.(4).

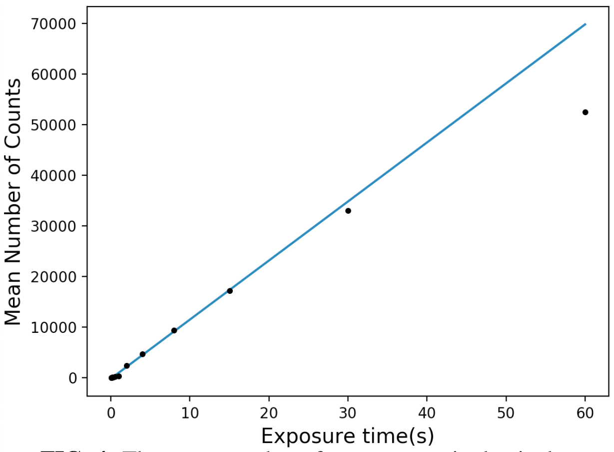

FIG. 4: The mean number of counts on a single pixel as a function of exposure time. A linear trend line has been added, calculated from all the points excluding the last two. The error bars are too small to be seen.

There is clear deviation from linearity above 30,000 counts, however there were limitations in gauging the point of inflection. The regularly changing light intensity upon the dome wall (from outside) and inability to change exposure times made it difficult to see a trend. Taking more repeats or pointing at a variable light source might have resolved these issues. Images were taken heavily out of focus and at short exposure times to lower the highest pixel counts. Any images which contained pixels with counts higher than 45,000 were removed to mitigate these problems, although in practice no images over 25,000 were created for the same reason.

Conversely, the effects of CCD temperature on the dark current were found to be negligible at lower exposure times. Fig.5 shows how temperature affected the bias and dark currents.

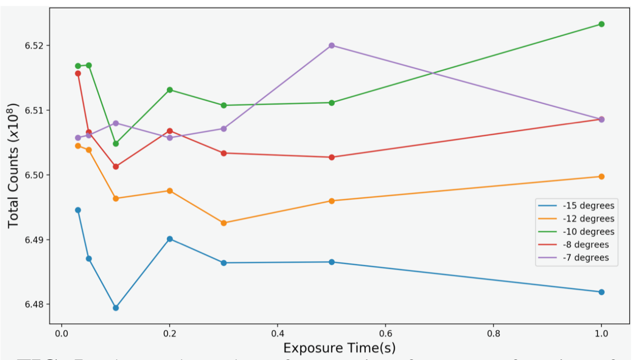

FIG. 5: The total number of counts in a frame as a function of time at different temperatures. The error bars are too small to be seen.

As expected, the higher temperatures generally produce higher counts as dark current is a result of thermally excited electrons. However $-10°$C, at which all measurements were taken had the highest total counts at one second exposure. This was likely because dark current is negligible at short exposure times and the readout noise which was the dominant cause of difference is not significantly affected by temperature. The relatively constant count number at increasing exposure times at all temperatures shows the bias current is dominant. Therefore at least for our short exposure times -10°C was a sufficient temperature to use. It would have been more useful to measure how temperature affected the dark current at longer exposure times such as those taken in the calibration field for 15 seconds.

The signal to noise ratios of the measurements of Betelgeuse were also read-out noise dominated as the images were taken at such short exposures. Assuming a gain of one, typical values such as that for 12/02/20 were 1,000,000 for the mean total star counts, 47,000 for the total background counts and 4,000,000 equivalent counts for the readout noise total counts giving an SNR of 440. This is very high because Betelgeuse is such an intense star. The signal to noise for calibration images would have been much lower and these should have also been investigated.

4. Conclusions

In conclusion, the dimming of Betelgeuse has been measured to a reasonable accuracy. Although measured values appear to fit the trend, an accurate trend in itself is not visible in our data and there is poor agreement with AAVSO observations. More measurements made in Durham might have revealed this trend but this was limited by the weather conditions. It has been shown there was equivalent dimming in the V and B bands over a portion of the decrease supporting previous theories that the cause of Betelgeuse's dimming was the ejection of large grain dust from episodic mass loss in our line of sight [6]. A sinusoidal model which made some good predictions from the data and followed the trend was ultimately rejected as it was a poor fit and led us to believe the dimming was a more complicated phenomenon. The suitability of CCDs to measure the variation in such a bright star was discussed. The dominant source of error in the experiment came from the constantly changing atmosphere and was limited by the rate at which the CCDs could take images. However, images could be easily taken in the linear domain of the camera and high signal to noise ratios were maintained thanks to Betelgeuse's high intensity.

References

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5. Appendix

The sources of error in our magnitude values were the star counts and zero point magnitude.

The error in the star counts was the square root of the mean of the star counts because it is described by a Poisson distribution. The standard deviation of the zero points was used instead of the standard error since the atmosphere constantly changes the mean of measured values. Taking measurements over a longer period of time and therefore increasing the number of measurements would not have improved the precision or accuracy.

A combination of the functional approach and calculus approach was used to propagate these errors in the magnitude equation (Eq. 1). The error in the magnitude α_m was therefore explicitly:

$$\alpha_m = \sqrt{(\alpha_{zpt})^2 + 2.5^2 \left(\frac{\alpha_I}{ln(10)I} \right)} \tag{3}$$

where α_{zpt} was the standard deviation in the zero point and α_I was the square root of the star counts.

A purely functional approach was also used and yielded almost exactly the same values.

The error in the time of the measurements in Julian days was small enough to be neglected.

The errors in the V and B band magnitude difference before and during dimming were calculated by adding each of the starting and ending magnitudes' error in quadrature.

A χ^2 analysis was used to find the optimal parameters in the sinusoidal fitting. This was used as the errors were heteroscedastic and therefore points with lower error were given more credence. This was done by first minimising the χ^2 statistic giving the best-fit parameters (constant, coefficient, argument constant for the sin curve). The error of each parameter was then calculated by finding the extremal difference between the best-fit values and their values at the $\Delta\chi^2 + 1$ contour. Practically, this can be done by increasing one parameter whilst keeping the other constant until it reaches the $\Delta\chi^2 + 1$ contour. Then, the χ^2 is re-minimised and this is repeated until there is no discernible difference in the$\chi^2 + 1$ calculated. This looks like a series of orthogonal steps between the best-fit parameters to the $\Delta\chi^2 + 1$ contour, touching said contour between the re-minimisation steps. Fig.6 illustrates this process.

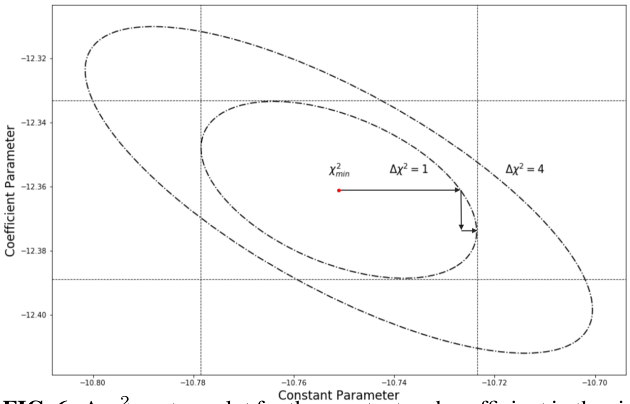

FIG. 6: A χ^2 contour plot for the constant and coefficient in the sinusoidal model. This is the two dimensional version, omitting the argument constant which would create a three dimensional ellipse. The best-fit parameters are shown as the red dot in the centre. The $\Delta\chi^2$ contours for one and two standard deviations are included to show the sensitivity of each parameter. The arrows orthogonal to each other show the first few steps for finding the errors in the constant parameter.

Errors in the values of lowest magnitude, its date, and the date for Betelgeuse to return to its normal magnitude were calculated using a functional approach on the sinusoidal model. This was done by considering the effect of the error in each parameter using the functional approach and then using Pythagoras' theorem to combine these errors. The effect of the error from the constant C on the magnitude for example was

$$\alpha_m^C = |A + Bsin(2\pi(C + \alpha_C)) - (A + Bsin(2\pi C))| \tag{4}$$

where A and B are the unchanged constants and C has its error propagated through α_C giving an error from C of α_m^C. The equation is unsimplified for clarity.

The errors from A, B and C are combined in quadrature giving the final error in the lowest magnitude estimate:

$$(\alpha_m)^2 = \left(\alpha_m^A\right)^2 + \left(\alpha_m^B\right)^2 + \left(\alpha_m^C\right)^2 \tag{5}$$