Measuring the Dimming of Betelgeuse

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The recent unprecedented dimming of the red supergiant Betelgeuse is measured from Durham University. The data is found to follow the general trend of getting brighter over the weeks however is it not in agreement with AAVSO data. Simple polynomial and sinusoidal fits are rejected as possible models for the light curve. The cause of the dimming is investigated by comparing the relative magnitude changes between Betelgeuse's light curves in bands B, V and R. It is found that the R band experienced more dimming than the V and B bands which supports the hypothesis that a superposition of Betelgeuse's different periods has triggered the release of large-grain atmospheric dust and caused the extinction of its light. The CCD is also confirmed to be linear.

I Introduction

Betelgeuse is the brightest star in the Orion constellation, making it one of the largest and most luminous stars visible to the naked eye (the tenth brightest in the night sky). It is a red supergiant, a rare class of massive and very luminous stars that are reaching the end of their lives. Their large radius means that their outer atmospheres are often cool enough for relatively large molecules to form (such as TiO) which can make their spectra complex. The combination of this complexity and rarity means that red supergiant atmospheres are an active area of research. Betelgeuse's apparent magnitude changes over time, approximately between 0.0 and 1.0, making it often the second brightest star in Orion after its blue neighbour Rigel. Magnitude can be calculated by comparing the ratio of fluxes of two stars where one star's magnitude is already known:

$$m_1 - m_2 = -2.5\log_{10}(\frac{I_1}{I_2}), \tag{1}$$

where m is apparent magnitude, I is the intensity or flux and subscripts 1 and 2 denote the two stars. While many variable stars have well defined regular periods, Betelgeuse is a semiregular variable star (its period and magnitude can vary between oscillations). However, in late 2019 Betelgeuse exhibited unprecendented levels of dimming and by early 2020 had become dimmer than ever previously observed (briefly becoming the twenty third brightest star in the sky and the third brightest in Orion). The complicated nature of Betelgeuse's atmosphere and variability mean that there are many possible explainations for this dimming. One possible explaination is that the star itself is getting cooler and has become less luminous. However measurements have shown that, although Betelgeuse has cooled, it has not cooled suffieciently to fully explain the recent dimming [1]. This suggests that the cause of the dimming is mainly due to a change in extinction (the amount of light absorbed by dust and gas) as opposed to an intrinsic change of the star. A candidate for causing the extinction is the interstellar medium (ISM). If the ISM is causing the extinction then we expect Betelgeuse to appear more red because the primary constituent of the ISM is hydrogen gas which scatters blue light and lets red light through. Another candidate is dust emitted by the star. The low surface gravity and high luminosity of red supergiants mean that they lose large fractions of their mass over the course of their lives which accumulates around the star [2]. This atmospheric dust is comprised of molecules 50 times larger than the hydrogen in the ISM [3] and so will block red light and make Betelgeuse appear more blue. Betelgeuse's strange variability may also be a factor. Some models propose that Betelgeuse has 2 periods ((388 ± 30) days and (2050 ± 460) days [4]) and that a superposition of these waves within the star could produce an unusually low minimum luminosity at some point between 14th and 28th February 2020 [1].

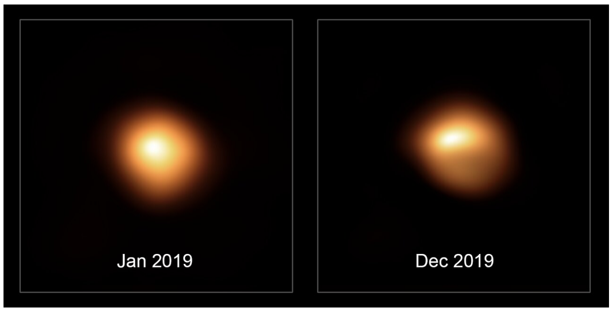

FIG. 1: Betelgeuse before (Jan 2019) and during (Dec 2019) the unusual dimming, its lower luminosity and change in shape can clearly be seen. Image taken by ESO using the SPHERE instrument on the VLT [5]

Measuring and understanding this unusual dimming is of scientific importance as it will help us to understand semiregular variable stars and supergiant atmospheres. In the following sections we present observations of Betelgeuse, compare them to existing light curves and determine how well the dimming can be measured from Durham University. Using these observations we discuss whether they can be used to determine the cause of the dimming by comparing them to the theoretical predictions made by the hypotheses outlined above. Finally we check the validity of the observations by presenting the linearity of the CCD used.

II Observations & Methods

In order to measure the dimming we needed to measure the magnitude of Betelgeuse over multiple weeks. Betelgeuse is extremely bright so measuring it directly would saturate the CCD i.e. the pixel will be full of photo-electrons and unable to absorb any more during that exposure. Saturated images cannot be used because CCDs are not linear when they are close to saturation and the true number of photon counts in the image will be much higher than recorded by a saturated image. This is solved by de-focusing the telescope which causes the image of Betelgeuse to spread over multiple pixels so that no one pixel becomes saturated, while still accurately recording the total photon counts. Exposure times for Betelgeuse were set to the minimum possible value of 0.03 s to ensure there was no saturation. At least 16 images images of Betelgeuse were taken per night in order to reduce the effects of random errors such as the changing

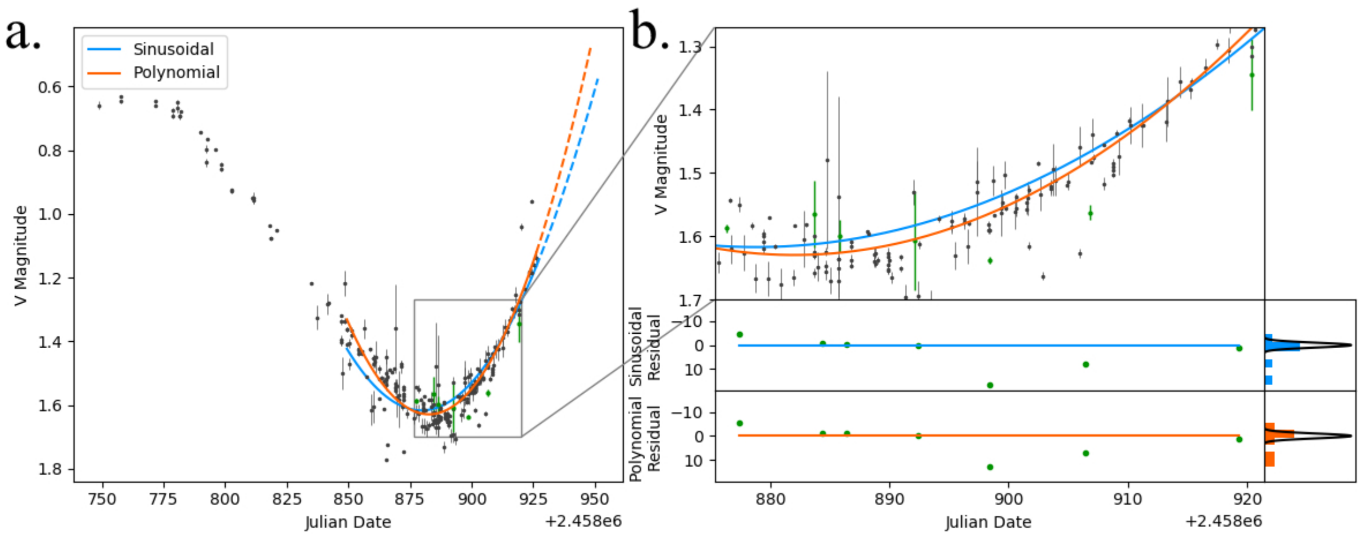

FIG. 2: In figure a. the Johnson V band magnitude of Betelgeuse is plotted over time from 21/9/2019 until 17/3/2020 (as Julian days). Our data from Durham (green) is plotted together with AAVSO data (black). The curves of best fit become dashed once they are extrapolated beyond the end of the data to estimate when Betelgeuse will return to its usual magnitude. In figure b. the region of figure a. containing our data from Durham is magnified and its normalised residuals are produced for each curve of best fit.

conditions in the sky and weather.

In equation 1, a star of known magnitude is needed to calculate the magnitude of the target star. The stars of known magnitude were chosen from an arbitrary starfield 1° dec above Betelgeuse. Images of this starfield (or calibration field) will be called calibration images throughout. Using the GAIA software, aperture photometry was used to compare the photon count from each star in the calibration image to its magnitude from existing star catalogues and calculate the average zeropoint magnitude (the magnitude of one photon in that image). Equation 1 can then be simplified significantly since $I_2 = 1$:

$$m_B = m_Z - 2.5\log_{10}(I_B), \tag{2}$$

where B represents Betelgeuse and Z represents zeropoint, the other symbols retain their previous definition. We assume that the conditions of the sky do not change significantly between images and that they are the same for Betelgeuse and the calibration images; this is why the calibration field was selected to be as close to Betelgeuse as possible so the conditions are broadly the same across the same small area of sky. Additionally, having a closer calibration field means that the telescope can move quickly between it and Betelgeuse so the sky conditions are less likely to have changed in the time elapsed. In order to minimise the change in sky conditions, the calibration images were split either side of the Betelgeuse observations. A typical observation would consist of 8 calibration images, then 16 Betelgeuse images, then 8 more calibration images per band. As the stars in the calibration field are much less luminous than Betelgeuse, they can be imaged in focus and at long exposure times without saturating the CCD. Longer exposure times are good as they increase the signal to noise ratio (SNR) however they increase the time between images so the sky conditions can change and this increases the random error between zeropoints. An intermediate exposure time of 15s was chosen for each calibration image.

Date	Telescope	Bands	Betelgeuse Images	Calibration Images
28/1/20	West-14	V	8	7
04/2/20	West-14	V	17	23
06/2/20	West-14	V	42	32
12/2/20	West-14	B,V,R	16	16
18/2/20	West-14	B,V,R	16	16
26/2/20	West-14	B,V,R	16	16
20/3/20	Far-East-16	V	16	16

TABLE I: Summary of the observations.

III Results and Discussion

To determine the accuracy of our data from Durham, we plotted it alongside data from the American Association of Variable Star Observers (AAVSO) [6] in figure 1. As the exact nature of Betelgeuse's oscillation is unknown, there is no precise model that predicts its behaviour to fit the data to. As such, we present two relatively reasonable forms for curves of best fit. We chose a sinusoidal curve of the form:

$$m = a + b\sin(ct + d), \tag{3}$$

where m is magnitude, t is time (in Julian days) and a,b,c and d are parameters to be optimsed. As all periodic functions are approximated by linear combinations of sines and cosines, it seems reasonable that if the dimming is casued by a superposition of Betelgeuse's oscillations, then the data would fit well to a sinusoidal curve. We chose not to include more terms as this over-fitted the data i.e. the curve went through every data point rather than following the general trend, with the data points randomly distributed around it as we expect. We also chose a 10th order polynomial of the form:

$$m = \sum_{i=1}^{10} n_i t^i, \tag{4}$$

where n_i are the polynomial coefficients to be optimised and m and t have their previous definitions. As many functions

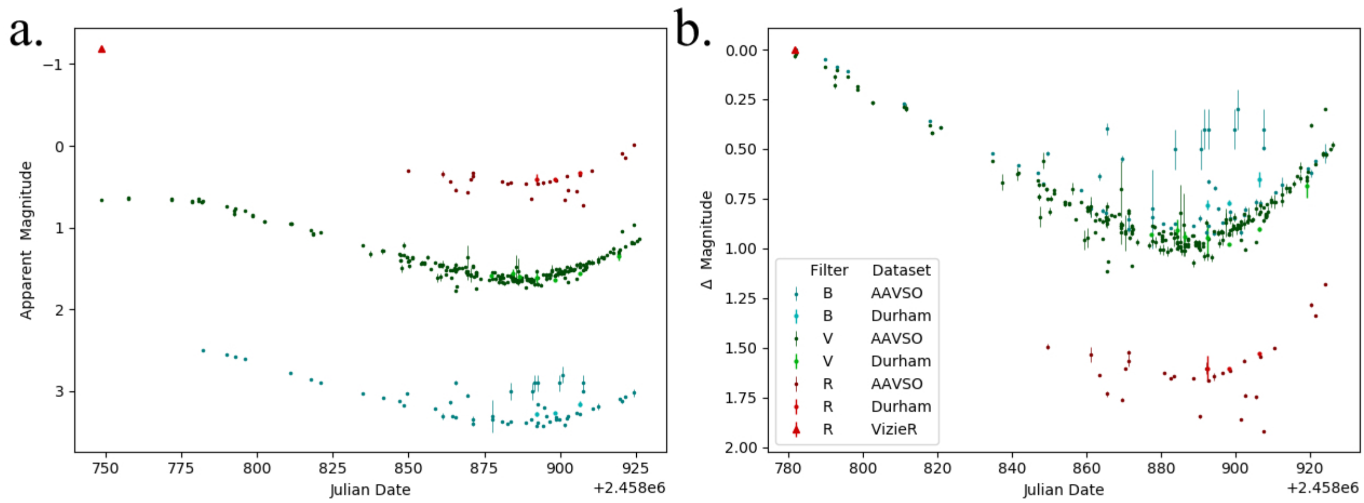

FIG. 3: In figure a. the apparent magnitude of Betelgeuse is plotted over time from 21/9/2019 until 17/3/2020 (as Julian days) in 3 seperate filters: Johnson B, V and R. Our data from Durham is plotted alongside the AAVSO data. In figure b. the data has been translated such that the original pre-dimming magnitude of Betelgeuse is zero so the relative change in magnitude can be compared between different bands.

are approximated by sums of polynomials, it seems reasonable that this polynomial might closely resemble Betelgeuse's oscillation. We chose a 10th order polynomial as this is enough terms to follow the data but not so many terms that it over-fits it.

We calculated the optimised parameters using chi squared minimisation and plotted both curves in figure 1. We then calculated the reduced chi squared values for each data set against each curve.

Curve	Durham χ^2_{red}	AAVSO χ^2_{red}	Combined χ^2_{red}
Sinusoidal	356.2	182.4	177.7
Polynomial	245.0	162.5	157.8

TABLE II: Chi-squared values for each model and dataset.

A reduced chi-squared value of one suggests that it is a good fit, a value of much less than one suggests that the model over-fits the data and a value much greater than one means the model should be questioned [7]. Therefore, these models must be rejected. This may imply that Betelgeuse's oscillation is modelled by something more complicated than a sine curve or a tenth order polynomial. However, the data is heteroscedastic (non-uniform error bars) and slightly stochastic (random) because much of the data (both Durham and AAVSO) had differing: equipment, locations, people and dates. It is unlikely that data such as this can be well fitted by any model without over-fitting. These models may be appropriate for a more uniform dataset i.e. the same instrument making the same observations every night. The chi-squared values for the AAVSO and Durham data are the same order of magnitude and the chi-squared values for the combined data are lower than either dataset individually. Despite this, it is difficult to say whether the Durham data matches the AAVSO data due to the aforementioned inconsistencies. Perhaps with more observations, a clearer distinction could be made between the datasets. However, given the limited time of the experiment and the often unfavourable weather conditions in Durham, this is rather unrealistic.

The curves can be used to predict the behaviour of Betelgeuse, specifically when it reached its minimum magnitude and (if extrapolated) when it is due to return to its normal magnitude, as seen in Table III. Both curves predict dates that are in disagreement with the measured value as they are over 2 standard errors away. The combined value predicts a date that is 9 days too early, if its prediction for when Betelgeuse returns to normal is equally as early then we would expect it to return to normal on 15/4/20 ± 2 days. The observed minimum point is in reasonable agreement with the predicted minimum point of 14-28 February, this suggests that the cause of the dimming could be due to the superposition of its two periods.

Curve	Minimum	Return to Normal
Sinusoidal	31/1/20	8/4/20
Polynomial	3/2/20	3/4/20
Combined	1/2/20 ± 1 day	6/4/20 ± 2 days
Reality	10/2/20 ± 3 days	TBC

TABLE III: The predicted dates of Betelgeuse's minimum magnitude and its return to normal for each curve of best fit and their average compared with reality [8].

By plotting the data from each band on the same axis, their relative dimming can be seen. In Figure 3 this is done for the B,V and R data in both apparent magnitude and relative change in magnitude. The greatest magnitude change for each band are shown in table IV.

Band	ΔMagnitude
B	0.926 ± 0.007
V	1.113 ± 0.003
R	1.917 ± 0.006

TABLE IV: The greatest change in magnitudes for each band.

The R band experienced much more dimming than the V and B bands, this supports the theory that the star ejected large-grain dust from its upper atmosphere which blocks light at redder wavelengths. As the AAVSO data did not include any R band observations before the dimming, the initial R magnitude of Betelgeuse is an average of 3 earlier measurements from the VizieR catalogue [9].

IV Linearity of the CCD

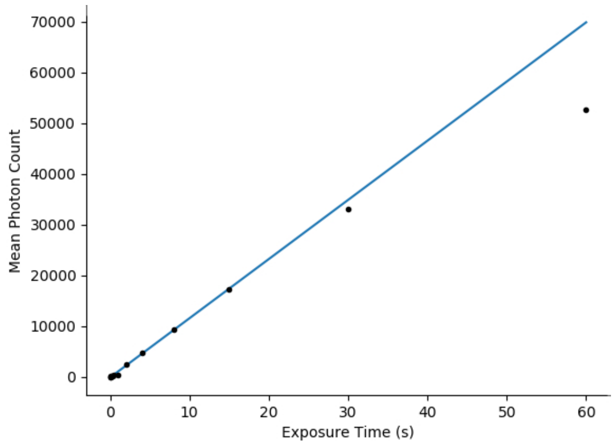

FIG. 4: The relationship between exposure time of the image and the photons recorded by the CCD.

The linearity of the CCD was measured by taking images of the inside of the telescope dome at varying exposure times and measuring the photon count of an arbitrary pixel at position (100,100). The room was kept dark and isolated to minimise the impact of wind and sunlight. 8 images were taken at each exposure time to limit the effect of changing conditions between images. The temperature of the CCD was kept constant at -10°C as it can affect the dark current. This data is plotted in figure 4. The CCD is clearly linear at small photon counts but this relationship breaks down at higher photon counts, this is expected because when pixels accumulate photo-electrons they are less likely to accept new photons. The CCD is 16 bit, meaning that each pixel can count 65,536 photons. We expected the CCD to remain linear up until 30,000 counts, however the telescope had no exposure time setting between 15s and 30s so this data couldnt be gathered and the conclusion is that the CCD goes non-linear somewhere between 17,000 and 33,000 counts. By de-focusing the telescope when measuring Betelgeuse, we ensured that our images were all taken in the linear regime of the CCD and that this error was not present in our results.

V Conclusions

To conclude, the dimming of Betelgeuse can be measured from Durham to a limited degree of success. The general trend of Betelgeuse getting brighter after its dimming can be seen in the Durham data, however it does not agree with the AAVSO data. It is difficult to say whether the two datasets are in disagreement due to their slightly stochastic characteristics. More uniform data taken by the same instrument under the same conditions over multiple nights would provide a better reference dataset. This is unrealistic in Durham due to time and weather constraints. The polynomial and sinusoidal curves of best fit do not fit the data and should be rejected, although they may fit a more consistent dataset. From this data, Betelgeuse's oscillations appear to be modelled by something more complicated than either of these simple models.

The R band was dimmed more than the V and B bands which suggests that the red light has been scattered by large-grain atmospheric dust recently ejected by Betelgeuse. The date of the minimum magnitude was in reasonable agreement with the prediction made by the theory that the dimming is casued by a superposition of Betelgeuse's two periods. One possible theory is that the superposition of Betelgeuse's periods has caused a rapid change in its atmosphere which released the large-grain atmospheric dust. This is in agreement with recent literature which reports that "the recent dramatic fading observed at visual wavelengths is due mostly to local surface phenomena, such as changes in dust extinction" [10].

VI Acknowledgements

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VII Error Appendix

Between images there are 3 main sources of error. One source is the random error (α_Z) between zeropoint values (Z) of different images:

$$\alpha_Z = \sigma_Z, \tag{5}$$

where (σ_Z) is the standard deviation of the zeropoints. The standard deviation is used here instead of standard error since we do not expect taking more measurements to reduce this error (due to the randomly changing atmosphere sky conditions between images). Another error is the random error (α_{I_B}) between Betelgeuse counts (I_B):

$$\alpha_{I_B} = \sigma_{I_B}. \tag{6}$$

Standard deviation instead of standard error is used here for the same reasons as before. This was propagated into the magnitude via the functional approach:

$$\alpha_m = m_Z - 2.5\log_{10}(I_B) - (m_Z - 2.5\log_{10}(I_B + \sigma_{I_B})) \tag{7}$$

The final source of error (α_{I_B}) is dominated by the poisson error of the individual Betelgeuse counts (I_B):

$$\alpha_{I_B} = \sqrt{I_B}. \tag{8}$$

This was propagated into the magnitude via the functional approach:

$$\alpha_m = m_Z - 2.5\log_{10}(I_B) - (m_Z - 2.5\log_{10}(I_B + \sqrt{I_B})) \tag{9}$$

Of these 3 errors, the zeropoint scatter was dominant and so this was the error used for the graphs and chi-squared, this means the observations were sky noise limited as the changing sky conditions between images were the main causesof error.