Betelgeuse Was Not Fainter Because of Dust

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Earlier this year, Betelgeuse took the media by storm after a record-breaking dimming at visual wavelengths. This surge of public interest was largely fuelled by exaggerated claims of the red supergiant's impending demise, though several experts opined that the dimming was likely not a precursor to an imminent supernova explosion. Regardless of the ultimate fate of Orion's shoulder, the dimming event was obviously worthy of investigation for the potential implications of evolved stellar evolution and the surrounding environment of the massive star. While the dominant narrative in the literature suggested that the dimming was due to a newly formed dust enhancement in the line of sight to the star (Levesque & Massey 2020), new JCMT/SCUBA-2 submillimetre observations also show a dimming, suggesting the change in brightness was not due to dust, but a change in the photosphere of the star, itself.

Betelgeuse is the nearest red supergiant star to the Earth at a distance of only 152 ± 20 pc (van Leeuwen, 2007). With such a close proximity, it acts as a unique laboratory to aid in the understanding of the late stages of red supergiant evolution. Massive stars ($M>8M_{sun}$) are important to study as they are the main drivers of chemical evolution in the universe (Karakas & Lattanzio 2014). Even before the explosive end of their lives, stars like Betelgeuse undergo significant mass loss, enriching their environment with newly formed elements. While the evolution of mass loss during these phases is critically important in understanding the final stages of a star's life and what type of supernova will eventually occur (e.g. Georgy 2012; Groh et al. 2013), the driving forces behind the mass loss episodes are still under active investigation. Radial pulsations with periods of up to a few years, however, clearly play a role in at least some cases (e.g. van Loon et al. 2005; Harper et al. 2009) and their semi-regular variations are tracked by optical and near infrared fluxes.

Beginning in October, 2019, Betelgeuse experienced an unprecedented V band dimming of >1 mag (a factor of ~3 change in brightness; see top panel of Figure 1) during one of its regular pulsation cycles. A variety of explanations were proposed to explain this phenomenon such as: 1. A confluence of the star's short (~ 400 days) and long (~ 5 years) variation periods, 2. Changes in known hot and cold spots on the stellar surface, 3. Photospheric structural changes indicating an imminent supernova (which is now ruled out by the star's return to its original brightness), and 4. A large ejection of newly formed dust along the line of sight. The latter emerged as the most favourable explanation based on optical spectrophotometry.

The dust emission at 450/850 μm wavelengths is optically thin. Therefore, if the dimming of Betelgeuse truly was due to a newly formed dust cloud, we would expect to see either a constant submillimetre flux before and during the event or, perhaps, a slight increase in the flux during the optical dimming. Regardless, an increase in the dust mass cannot decrease the submillimetre flux. We used both archival and newly obtained SCUBA-2 continuum data at 450 and 850 μm in conjunction with Apex/LABOCA (870 μm) data to investigate this hypothesis. At these wavelengths, we avoid the effects of extinction along the line of sight, providing an unbiased probe of the emission of the star and its environment. The LABOCA data was obtained in two epochs between 2007-2011 and 2016-2017 while archival SCUBA-2 data was obtained in 2012-2013. The pre-optical dimming (2012-2013) SCUBA-2 850 μm fluxes are consistent with those derived by O'Gorman et al. (2017) using the ALMA main array at a wavelength of 890 μm. New SCUBA-2 observations were obtained using Director's

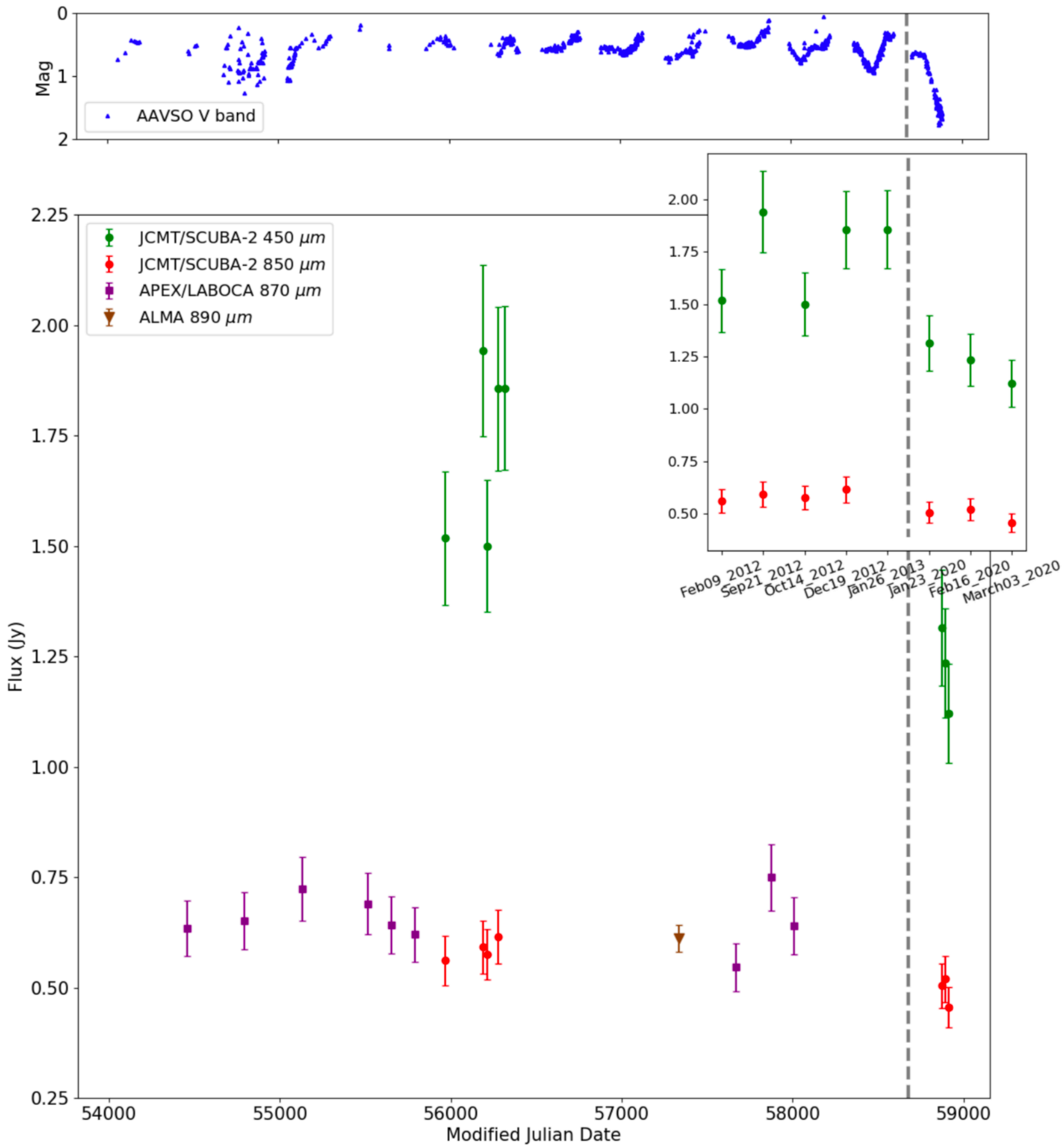

Figure 1: From Dharmawardena et al 2020. Lightcurves of Betelgeuse for the last fifteen years: The top panel shows the AAVSO optical (V band) light curve; The bottom panel shows the JCMT/SCUBA-2 450 μm (green points) and 850 μm (red points) light curve. The APEX/LABOCA 870 μm light curve (purple squares) was obtained from archival data. We also show a single ALMA 890 μm data point (brown triangle) from O'Gorman et al. (2017), to illustrate the consistency. The grey dashed line indicates the beginning of the dimming of the recent pulsation cycle. The inset panel shows a zoomed in version of the JCMT/SCUBA-2 light curve with the corresponding UT date for each observation.

discretionary time and a follow-up urgent queue program resulting in three observations in January, February, and March 2020 (during Betelgeuse's optical dimming). A cursory look suggested the newly obtained submillimetre data appeared to be fainter than the archival data.

To statistically verify whether there was indeed robust evidence of variation at submillimetre wavelengths, Bayesian inference by forward modelling was employed. Three models were constructed: 1. The "Constant flux model", where the 450, 850, and 870 μm data remained constant over the whole light curve, 2. The "two epoch model", where the behaviour is broken into two distinct epochs (pre- and during optical dimming), each with constant, but different flux, and 3. The "linear flux variation model", where fluxes are proportional to $mt+c$, where each wavelength follows the same slope, m, over time, t. The priors on all free parameters were assumed to be flat, drawn from uniform random distributions.

To compute the evidences for each model, the Python package "Dynesty" was used (Skilling 2004, 2006; Higson et al. 2019; Speagle 2020). The most robust model was found by computing Bayes' factor (K) for each pair of models. The Bayes' factor enables the selection of the most appropriate model from a given set by comparing the ratio of evidences (assuming that all models are equally likely, a priori). The Bayesian analysis clearly favoured the "two epoch model" by a wide margin when compared to either of the other two models. This result decisively indicates that the submillimetre flux is variable and that it was fainter during the optical minimum when compared to earlier observations.

Once it was clarified that the decrease in flux was visible over optical through submillimetre wavelengths, we performed dust radiative transfer modelling using the Hyperion Monte Carlo radiative transfer code (Robitaille 2011) to robustly disentangle the effects of the flux from a potential dust shell compared to the flux from the photosphere of Betelgeuse at submillimetre wavelengths. Two models were run assuming a spherically symmetric wind with constant outflow speed and a dust model/mass loss rate that match the optical to mid-infrared photometry. In one of the two models, however, an additional shell of dust was added between 2 and 4 $R_{\star}$, creating an optical dimming of ~1 magnitude. These models indicate that Betelgeuse's emission at submillimetre wavelengths is entirely dominated by the stellar photosphere, with only small contributions from circumstellar dust, as expected (see Figure 2). While we were unable to probe changes in dust mass at the level that would produce the optical dimming, it is clear that only changes in the photosphere can reproduce the observed submillimetre dimming.

The amount of submillimetre dimming implies that the luminosity of Betelgeuse has decreased by nearly 20% (a 3.6σ change) and argues strongly against models in which the optical dimming is caused by the formation of a new cloud of dust along the line of sight to the star. This 20% reduction in luminosity could take the form of a change in radius or temperature. The required change in radius would be small (~10%), while a change in temperature could be explained either through a ~200 K global change, or through the presence of spots ~ 400 K cooler covering ~ 50% of the visible surface or ~300 K cooler covering 70% of the surface. These scenarios all replicate the ~1 magnitude dimming observed at optical wavelengths.

Betelgeuse has since returned to its normal brightness at optical wavelengths and the JCMT's operational hiatus due to the COVID-19 pandemic precluded further submillimetre data from being obtained. Over the next year, Betelgeuse's submillimetre light curve will continue to be monitored monthly with SCUBA-2 to investigate further photospheric changes.

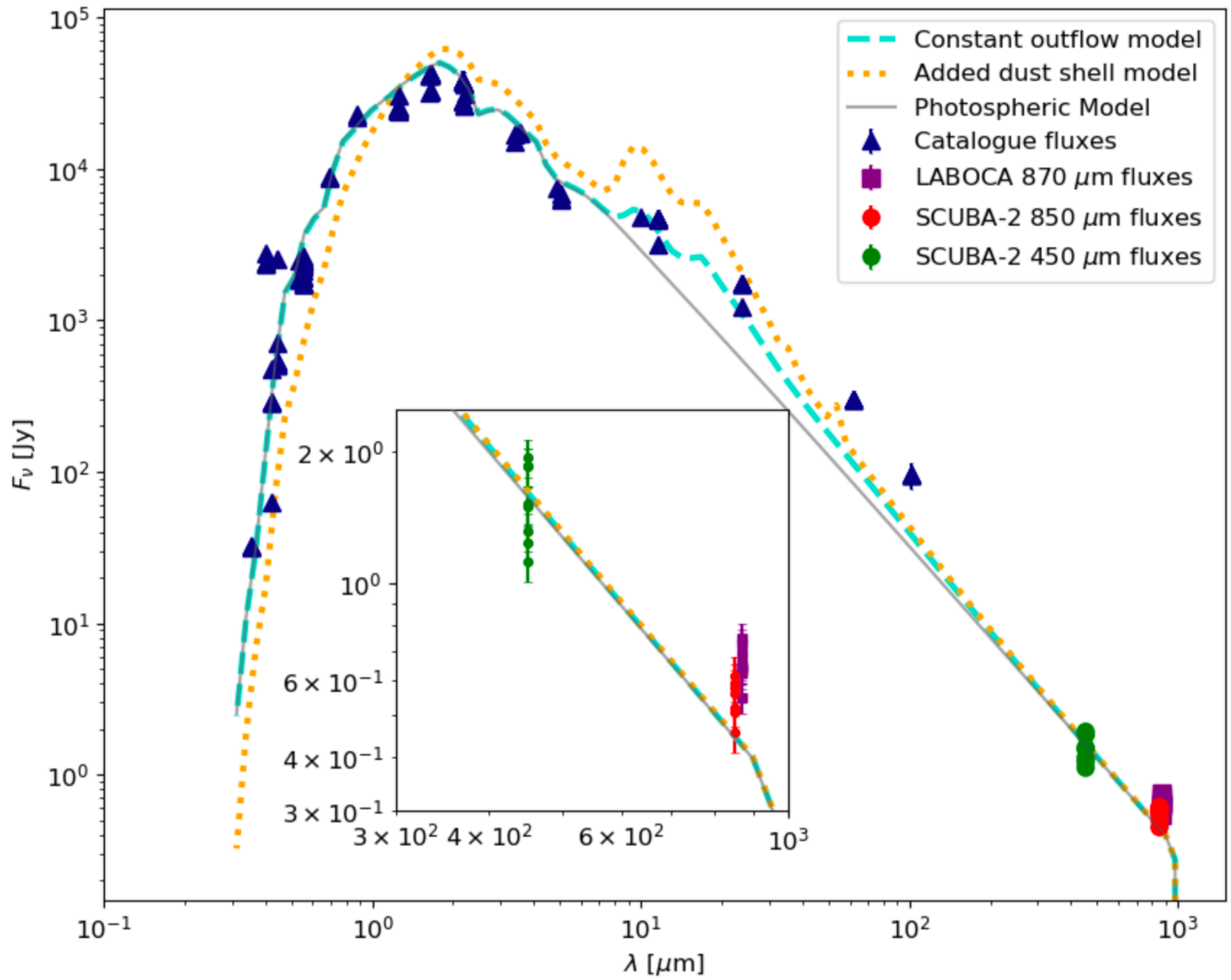

Figure 2. From Dharmawardena et al 2020. Radiative-transfer models (lines) compared with observations of Betelgeuse. Blue triangles show fluxes, taken from Vizier (see Dharmawardena et al 2020 for more details), and the green, red and purple points indicate the submillimetre data at 450, 850, and 870 μm, matching Figure 1. The blue dashed line represents a qualitative fit from Hyperion to the 0.3 – 30 μm photometry, and the orange dotted line a model that is identical other than the addition of an extra shell of dust from 2 – 4 $R_\star$. The grey solid line shows the underlying photospheric model at the same spectral resolution as the radiative-transfer models. The inset panel highlights the submillimetre fluxes.