Supernova Betelgeuse?

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Betelgeuse has been the focus of considerable recent attention – even from the mainstream news media – due to its recent deep minimum, to the extent that 10% of all the light curve data on the star in the AAVSO archive, extending 126 years, have been obtained in just the last six months. While it is not impossible that Betelgeuse will become a supernova in the next few years or decades, what we know about the star makes this unlikely. A large part of the uncertainty comes from the fact that neither the mass nor the distance are well-established. It is not even certain that Betelgeuse will become a core-collapse supernova. Overall, the star appears to have brightened significantly over the last 60 years, but the evidence for similarly deep minima in 1946, 1947 and 1984 relies on fragmentary data and single observers. The entire extreme historical range of Betelgeuse from magnitude 0.1–1.6 appears to have occurred in just the last three years.

Introduction

If you are a variable star observer, you would have to be a hermit not to have heard that something has been happening to Betelgeuse. The Internet bubbled with excitement at the news of this 'unprecedented event', suggesting that Betelgeuse may be about to explode. For the first time that the author can recall, newspapers like *The New York Times* have been covering news of a variable star. The author has even had colleagues asking excitedly over lunch: 'have you heard the news about Betelgeuse?' Many people who would normally never look at a variable star have been tempted to make estimates, to the extent that almost 10% of the data in the American Association of Variable Star Observers (AAVSO) archive for this star, which extends back to 1894, have been obtained in the last six months. (As a point of comparison, for chi Cyg, which is one of the most heavily observed stars in the AAVSO archive, just 0.3% of the data are from the same period, which includes a light curve maximum.)

The interest is mainly due to the fact that Betelgeuse is no ordinary star. It is very massive, very large and very unstable. However, there is a lot of uncertainty about how large and how massive it is because the distance is quite uncertain, and there is even more uncertainty about when its end-of-life crisis will arrive. The stories of imminent explosion seem to be due to a 2009 study that measured the diameter of Betelgeuse in the infrared to be about 43 milliarcseconds (mas), quite a lot smaller than previously accepted values of around 56mas. This led to a popular belief that the star is shrinking rapidly, which would be the prelude to a supernova explosion. In reality, Betelgeuse is pulsating, so its diameter changes with time. There is also no well-defined edge to the star and the size varies according to the wavelength at which it is observed. Similarly, any large structures on the surface will also modify diameter estimates, as will the presence of recently expelled shells of warm dust.

Distance, age, mass & fate

For many years, a value of 520 light-years was given for the distance of Betelgeuse. It is the value quoted in my childhood 'bible', *The Observer's Book of Astronomy*.[1] This inconveniently put Betelgeuse just slightly out of range of the traditional method of calculating stellar distances: measuring the parallax from the surface of the Earth.

In the 1990s, ESA's *Hipparcos* mission measured the parallax of Betelgeuse from space, giving a rather smaller distance of 430 light-years. *Hipparcos* was a game-changer in stellar dynamics, although its data are not without issues. This distance came with an error of around 20%, meaning that there was a one-in-three chance that the true distance was not even in the range of 350–510 light-years.[2] This, in turn, led to an uncertainty of a factor of more than two in the calculated luminosity of the star, which causes uncertainty in its estimated mass, which causes uncertainty in its future evolution… and so on. A later reworking of the *Hipparcos* data gave a best value of 520 light-years, with a likely range from 450–590 light-years.[3]

Other attempts have been made to measure the parallax and thus the distance of Betelgeuse with large radio observatories. One such attempt was made with the Very Large Array (VLA), giving a best distance estimate of 640 light-years and a likely range from 500–790 light-years.[4] Another, combining the telescopes of ALMA in the Atacama Desert of Chile with the e-Merlin array of telescopes in the United Kingdom, gives a best distance estimate of 720 light-years and a likely range from 570–830 light-years.[5]

Hipparcos has now been replaced by *Gaia*, which will soon release its *DR3* catalogue, leading to keen anticipation that it could resolve the issue of the distance to Betelgeuse once and for all. Unfortunately, *Gaia* was designed to measure stars down to magnitude +20, not naked-eye visible stars, which are massively saturated on its detectors. Quite some effort has been expended by the *Gaia* team to find ways of measuring bright, saturated stars, but these techniques are only valid up to magnitude +3. Even at the faintest magnitude at which it has ever been recorded, Betelgeuse would be far too bright to measure with *Gaia*: it has been observed, but in a special observing mode that requires non-standard data processing and would necessitate several months of dedicated attention to make publishable.

In other words, modern techniques of observation can, at present, tell us no more than the fact that Betelgeuse is probably at a distance somewhere between 450 and 830 light-years. It may not even be the closest supernova candidate, as Antares is at a similar distance, is of almost identical spectral type and has a similar estimated mass, but receives much less attention.

As an M2Iab star, Betelgeuse is a massive red supergiant, generally accepted to be in the mass range 10–20 solar masses ($M_\odot$), with a lifetime of around 10 million years, although values as low as $6M_\odot$ and as high as $30M_\odot$ have been suggested. We do know that Betelgeuse must be smaller than $40M_\odot$, because such stars never become red supergiants, but rather strip their outer layers and become blue supergiants such as Sanduleak –69 202, precursor of SN 1987a.

Being a red supergiant, we know that Betelgeuse is at least in the helium-burning phase of its lifetime, but we have no way of knowing how far along it is. The next stage of its evolution is linked to what is going on in the star. Right now, the interior contains a series of shells, rather like a very thick onion. As we dive beneath the photosphere to the heart of the star, we find, first, a very tenuous outer layer of hydrogen and, far below it, a layer in which the temperature (around 15 million kelvin) and pressure (the gas is compressed until it is five times as dense as water) are great enough for hydrogen to be combined to form helium. Hotter and deeper still, we find another layer in which helium is being combined into carbon.

Betelgeuse has probably gone no further than that so far, although we can only argue this statistically for reasons that will become obvious a little further on. At some time in the future, Betelgeuse will suffer the fate of all the most massive stars and develop, if only briefly, a full, seven-layer onion structure. When this happens, as we continue down, each layer will be even hotter and denser than the previous one. After the carbon layer, a layer will form in which carbon combines to form neon, at a temperature of 600 million kelvin and four million times the density of water. Then, inside that, there will be one where neon combines to form oxygen and, next, a shell in which oxygen combines to form silicon at 1.5 billion kelvin. Finally, we will reach the innermost two: one in which silicon combines to form iron and, in the very heart of the star, a nucleus of iron. There are no nuclear reactions that emit energy from combining iron into even heavier elements: every further reaction consumes the star's energy rather than producing more. In other words, Betelgeuse is not only passing through an end-of-life crisis, it is suffering from 'heart problems' that will soon become mortal.

Given that the hydrogen-burning stage of a $20M_\odot$ star lasts about 8–10 million years, helium-burning about 500–600 thousand years, carbon-burning only about 1,000 years, oxygen-burning less than a year and silicon-burning a day or less, it is far more probable that Betelgeuse is still in the helium-burning phase than one of the later ones. Probably it is 80–90% through this phase but, if the lower mass estimates are correct, it could be that Betelgeuse is even further from being a supernova.

Because of the wide uncertainty in the mass, Betelgeuse is not even necessarily going to become a supernova. To give an example of the problem that we face, we can contrast three modern estimates of the mass: the first from fits to theoretical stellar evolution, the second from estimating the surface gravity from spectral line profiles and the third from the H-alpha line profile. The first gives a mass of $19–23M_\odot$,[6] the second a range from $7.7–16.6M_\odot$[7] (with a most likely value of $11.6M_\odot$) and the third an estimate of approximately $9.5M_\odot$.[8]

The eventual fate of a star in the $7–10.5M_\odot$ range depends critically on its exact mass. What will happen to Betelgeuse if it is only $8M_\odot$ will be very different to what will happen if it is $11M_\odot$ or greater. These are the potential scenarios, according to the mass of a star:[9]

Mass ($M_\odot$)	*Fate*
≤ 7	White dwarf. No supernova.
7–9	Neutron star. Electron capture (low luminosity) supernova.
9–10.4	Neutron star. Silicon flash/silicon deflagration supernova.
> 10.4	Neutron star. Normal Type II core-collapse supernova.

If the mass of Betelgeuse is at the lowest end of the estimated range, it would not even be massive enough to become a fully-fledged 'core-collapse supernova', although it would still produce a lower-intensity supernova. Assuming a best guess mass not much over ten times that of the Sun, we believe that Betelgeuse will be towards the lower end of the supernova scale,[10] but a much larger event cannot be ruled out.

Supernova Betelgeuse

Core collapse lasts just a few seconds. In that short time, huge amounts of hydrogen, helium and carbon suddenly meet in unbelievable conditions of temperature and density. The star starts an incredible frenzy of nuclear reactions, leading to a massive explosion of uncontrolled energy. This is a supernova explosion and results in about 90% of the mass of the star being blasted into space. The remaining 10% is the nucleus, which is at the centre of the explosion and has been compressed to quite incredible density by the impact. Normally, in a core-collapse supernova, this core forms a neutron star which may be up to three times the mass of the Sun, compressed into an object just a few kilometres across. However, if the surviving core of the star is more than three times the mass of the Sun, it is too massive even to form a neutron star: such a star continues to collapse for ever, into a black hole. It is very unlikely though that Betelgeuse is massive enough for this to happen.

Would we see evidence in the light curve of core collapse happening? Sadly for *The New York Times*, it seems not. When SN 1987a appeared on 1987 Feb 23, not only had the rise of the supernova to maximum brightness immediately after the explosion been captured, but there were images that showed Sanduleak –69 202 in the days and weeks before explosion, demonstrating that it had not done anything particularly unusual in that time; even the night before, the star appeared completely normal. It was not obviously variable in any of the photographs of the Large Magellanic Cloud taken over the previous century. There was no big fade or tell-tale in the light curve that the explosion was imminent. Presumably, during that last century before its explosion, Sanduleak –69 202 passed from carbon-burning to neon-burning, then oxygen-burning and, finally, silicon-burning, with no obvious light-curve signature of the transitions.

There was just one, clear early warning to astronomers that Sanduleak –69 202 had exploded. At 07:35:35 UT on 1987 Feb 23, three neutrino telescopes around the world detected a sharp burst of neutrinos that lasted a fraction over 12 seconds, during which time 25 neutrinos were detected. For comparison, the famous solar neutrino experiment in Homestake Gold Mine in South Dakota typically detected one to two neutrinos per day. The arrival of these neutrinos marked the exact moment of the sudden death of Sanduleak –69 202. The first optical detection of the supernova was at 05:40 UT on 1987 Feb 24, although made on a photographic exposure that had started three hours earlier, at a time when the brightness of the supernova was already increasing rapidly.

Similarly, for Betelgeuse, the first news of the core collapse will be the detection of a massive neutrino burst. Here, if we scale from SN 1987a, we are talking about a burst of not 25 but one to two million neutrinos: when it comes, if it comes, it will be unmistakable.

Supposing that Betelgeuse does become a fully-fledged core-collapse supernova, just how bright would it get? The supernova that formed the Crab Nebula, in 1054, was about 6,000 light-years away and yet it was visible in daylight. Betelgeuse is about ten times closer and would thus become around one hundred times as bright. It would, most likely, get to be at least as bright as a half Moon, around magnitude –10 (remember that, for a half Moon, the light is spread over a significant area of sky – for supernova Betelgeuse, it would be concentrated into a tiny point of light of dazzling brilliance). However, other estimates suggest a much brighter peak, around magnitude –12 to –13: again, this depends critically on the mass and the distance.

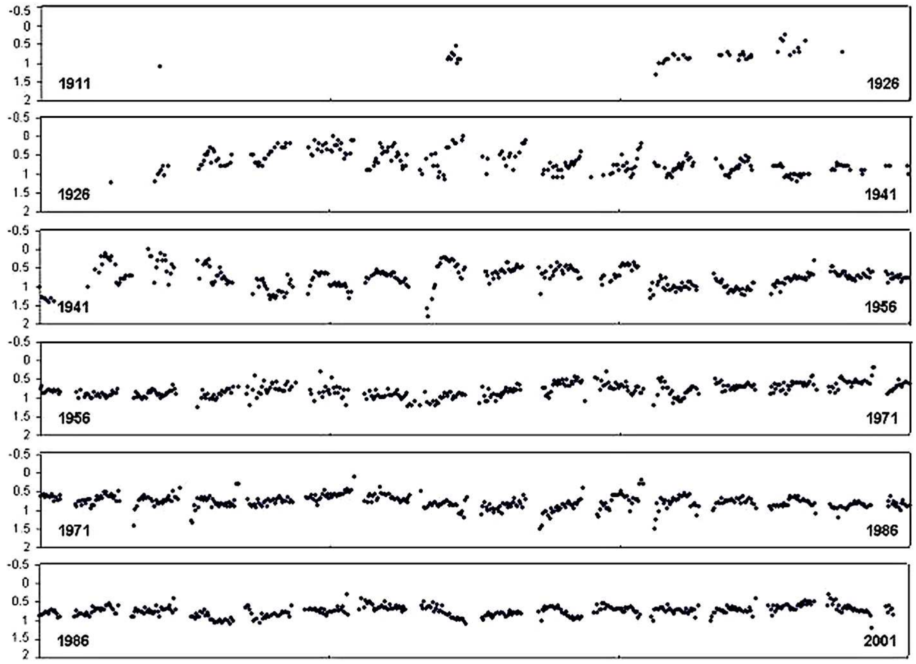

Figure 1. 10-day means of Betelgeuse from 1911 to 2001. On many occasions the mean is based on a single point (see notes in caption to Figure 2). *(AAVSO database)*

Supernova Betelgeuse would provide a substantial problem for astronomers. Not only would its light be as disruptive as having another Moon in the sky, it would be far too bright to be studied by normal telescopes and instruments. At brightest, quite likely only solar telescopes would be able to get useful data. As it faded, there would be a real danger of a brightness gap in which it would be too faint for solar telescopes and too bright for normal telescopes to observe. Quite possibly, the heavy-duty neutral density filters that were in common use a few decades ago for observing brighter stars with photon-counting detectors will make a rapid return.[11]

The historical light curve

Betelgeuse is, along with such stars as Megrez (delta UMa), an anomaly in the Bayer classification of stars,[12] which in general does follow the relative brightness of stars in a constellation quite well. Here, Bayer assigned 'alpha' to a star that is clearly not the brightest in the constellation, ranking both Betelgeuse and Rigel as *luminis primi* (first magnitude), with Betelgeuse ahead of Rigel. We know that, on some occasions (chi Cygni, omicron Ceti…) variability influenced his choices. (Others (*e.g.* Sagittarius) were simply bizarre, but unlikely to be his own choices.[13])

There has been some speculation that Betelgeuse possibly had a particularly bright maximum at the time that Bayer assigned his letters. Bayer does not explain his choice of ranking Betelgeuse ahead of Rigel, limiting his discussion to a description of the relative positions of the stars in the figure of Orion, so we will never know with certainty. However, Sigismondi (2019) notes that in 1852 Betelgeuse 'became the brightest star in the northern hemisphere',[14] suggesting that a maximum in that year must have reached negative magnitude, brighter than any maximum in the last century; and that particularly bright historical maxima may have occurred.

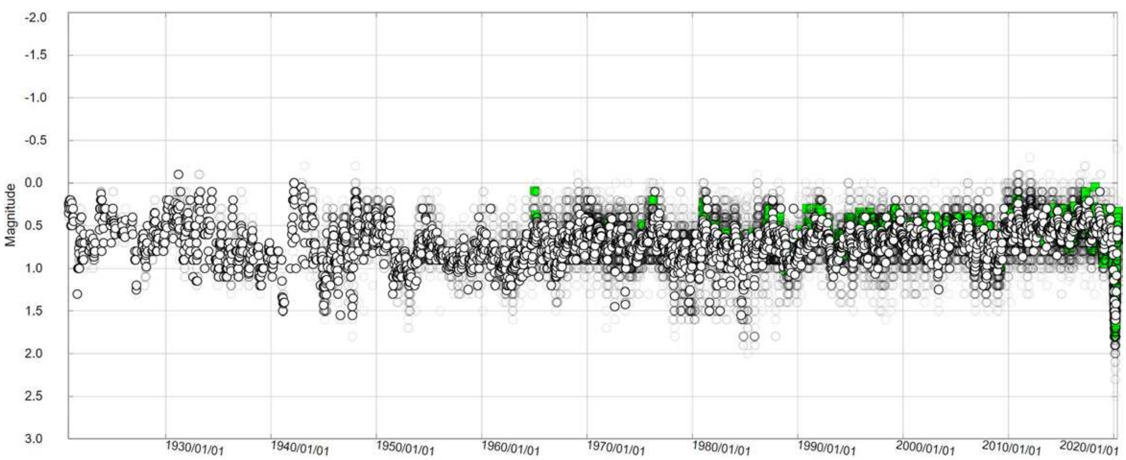

Figure 2. An alternative presentation of 10-day means of Betelgeuse for the 100 years from 1920 Jan 1 to the present. The very deep 1946/47 and 1984 minima have disappeared. On many occasions the mean is based on a single point: changing the starting point for the 10-day means by a few days can change radically the aspect of the light curve at poorly-sampled epochs, hence the difference to Figure 1. *(AAVSO database)*

The total of 39,740 visual estimates or V-band photometry measures in the AAVSO database between 1894 and 2020 looks impressive, although there is a 12-year gap from 1906–'18 with almost no data, with all the earliest estimates in the AAVSO database BAA Variable Star Section data. Over 126 years of light curve record, the average number of observations per year is 315. However, 78% of that data was obtained after 1970, 42% since the start

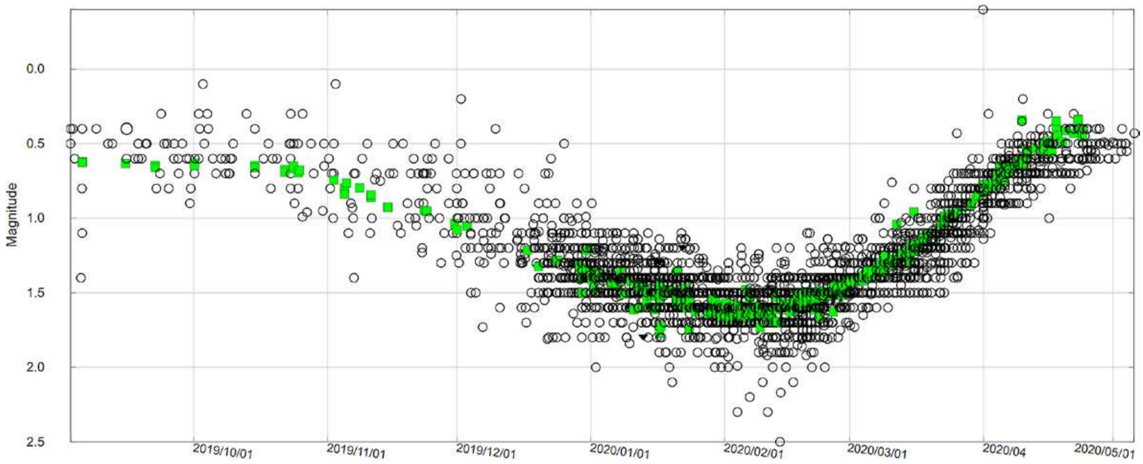

Figure 3. The AAVSO database for Betelgeuse from 2019 September to the present. The extraordinary increase in the number of observations from 2019 mid-December, when knowledge of the deep minimum was extensively publicised (*e.g.* Guinan *et al.*, *ATel #13341*, 2019) is evident. *(AAVSO database)*

of the year 2000, and 10% just in the last six months, so the light curve sampling is by no stretch of the imagination even. Lack of homogeneity greatly complicates its analysis.

Previous deep minima of Betelgeuse have occurred, apparently, in 1946/1947 and 1984 according to widely-shared plots published on social media based on 10-day means. These plots suggested that the 2020 minimum was not the deepest one observed in the historical record (Figure 1). However, poor sampling means that which point or points enter in a particular bin due to the selection of the starting date can completely change the resultant light curve.

As always, it is interesting to go back to the source data and investigate. What the database shows is that the 1946 minimum, nominally on 1946 Jul 26, may have been as deep as the recent one, although this conclusion depends on around 10 estimates made shortly before conjunction and just two, very faint estimates made immediately after conjunction. That of 1947, which may have been around 1947 Oct 13, is also based on post-conjunction data in the morning sky that show a great deal of dispersion. If we take the 1947 data at face value, Betelgeuse *may* have brightened from about magnitude +1.6 to +0.2 in just three months. The data from 1984 is even worse, with a dispersion of a magnitude in the estimates at the time of the potential minimum, and with most of the very faintest points coming from a single observer (Figure 2).

In contrast, an interesting phenomenon of the 2020 minimum is the relatively small dispersion of the data compared to previous minima. Most of the estimates fall within a range of ±0.25 magnitudes. Although a small fraction of the data is very much more discrepant, the global trends are clear and few observers deviate much from them. Given the wide availability of recent light curve data it is tempting to wonder to what extent observers were influenced in their estimates by prior knowledge.

Another interesting phenomenon is that, if we look at the data over just the last one hundred years, we see that up until about 1963, the 'typical' average magnitude of Betelgeuse was in the range +0.8 to +0.9. Since then, there has been a steady rise in average level until, over the last decade, Betelgeuse has averaged magnitude +0.5. A corollary of this is that, in recent years, Betelgeuse has reached exceptionally bright maxima. In 2017 Betelgeuse was, just before conjunction, as bright as Rigel, at magnitude +0.1; a datum confirmed by photoelectric photometry. Only once in the entire AAVSO record, in early 1942, was Betelgeuse as bright as this (excluding outliers).

The 2020 minimum

The AAVSO light curve for the winter 2019/2020 observing season is shown in Figure 3. Early post-conjunction observations show Betelgeuse stable around magnitude +0.6, about 0.2 magnitudes down on its pre-conjunction level. The fade started around 2019 Oct 10, initially slowly, before accelerating at the end of the month to almost exactly 0.01 magnitudes/day.

Two-day means show a minimum of magnitude 1.64 ± 0.02 on 2020 Feb 3, although the minimum is essentially flat at magnitude +1.61, without statistically significant deviations, from Jan 25 to Feb 17. This indicates a mean date for the minimum of Feb 6. Since then, the rise has been more rapid than the decline, reaching +0.5 by mid-April, at which point the magnitude stabilised.

There has been a considerable increase in the amount of high-precision photoelectric photometry in the last 10 years (Figure 4). The photoelectric light curve shows that, from 2010 to 2014, the annual amplitude was 0.3–0.4 magnitudes: at the limit of what is detectable visually, even by experienced observers. Since 2015, the amplitude has increased steadily and quasi-periodic oscillations have become increasingly evident, culminating in the deep 2020 minimum.

Even a cursory glance at Figure 4 suggests that there is an oscillation of a little more than a year. Fourier analysis of the light curve (Figure 5) shows a strong signal at a period of 430 ± 10 days.[15] The broadness of this peak, even after 20 cycles have been covered, suggests that the light curve is not purely periodic, but rather that this is the *characteristic period* in the light curve. Extrapolation of this 430-day period led to a predicted date of minimum of 2020 Feb 21, with an uncertainty of ±7 days,[16] in reasonable agreement with the observed date of Feb 6. How stable this period will be in the future, though, is not guaranteed.

The average amplitude of the 430-day cycle over the last 20 years has been only about 0.4 magnitudes, insufficient to give such a deep minimum. One possibility, supported by the increasing depth of the minima in the last few years, is that the amplitude of the 430-day period is modulated by the 2,200-day period and that the two minima coincided in 2020. While the timing of the supermaximum of 2017 would be fairly consistent with this model, the absence of any clear previous supermaxima and superminima in the light curve argues against it. Another possibility is that for inscrutable reasons of its own the 430-day period, which has only been detected unequivocally relatively recently, has simply become stronger or more stable in recent years and is now the dominant mode of variation. Sigismondi (2019) analysed eight years of CCD differential photometry,[14] from late 2011 to early 2020, pointing out that the 430-day period has only been present strongly in the light curve for the last three cycles. This suggests that we may, unknowingly, be seeing some previously unknown aspect of stellar physics playing out before our very eyes. Evidence for this is provided by the fact that an analysis of 60 years of AAVSO data by Karovska (1987) finds a rather different set of periodicities – 20.5, 8.8, 6.5, 5.7 & 1.05 years – to those in Figure 4.[17] While the mean of the 6.5 and 5.7-year periods is in good agreement with the 6.08-year period seen in Figure 4, the 1.05-year period, which has low significance in the Karovska analysis, corresponds to 385 days, in some disagreement with the 430 ± 10 days found by Guinan *et al*. (2019).[15] Thus the 430-day period may be both recent and only temporary.

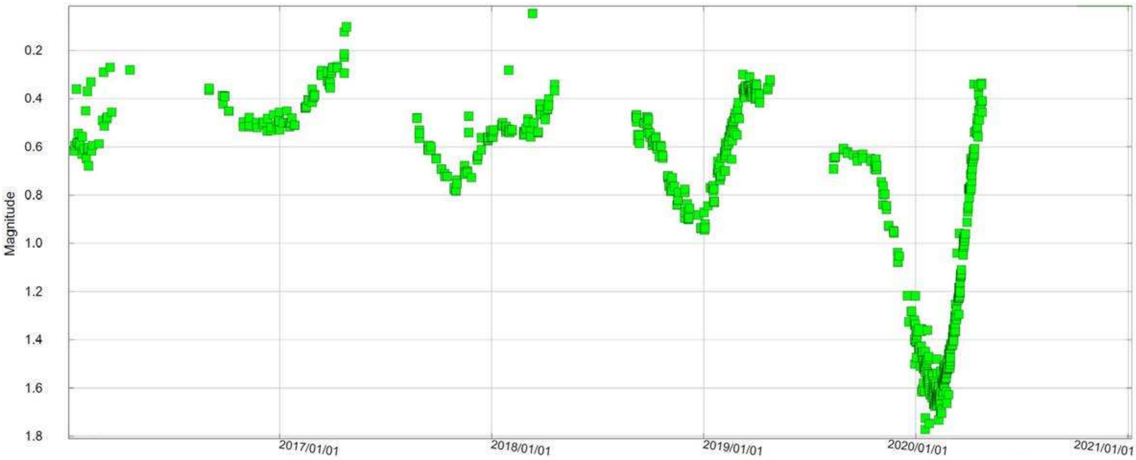

Figure 4. The photoelectric V light curve of Betelgeuse from 2010 to date. From 2010–2014 the typical amplitude was just 0.3–0.4 magnitudes. Since 2015, there is a clear increase year-on-year in the amplitude of the annual maxima and minima. *(AAVSO database)*

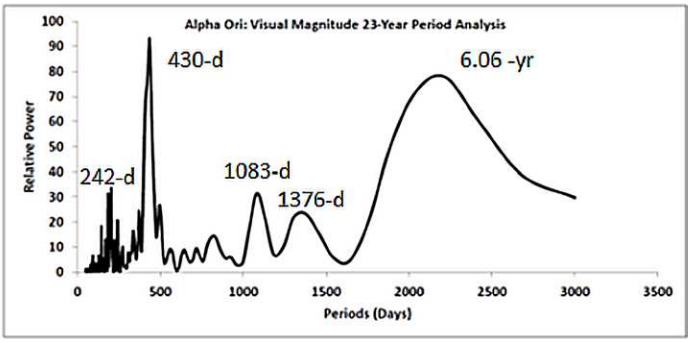

Figure 5. Fourier spectrogram of the light curve of Betelgeuse (1997–2020). The predominant period is 430 days, with a broad peak at 6.06 years (2,200 days). The periods at 242 and 1,376 days appear to be harmonics of the main periods. *(Peranso)*

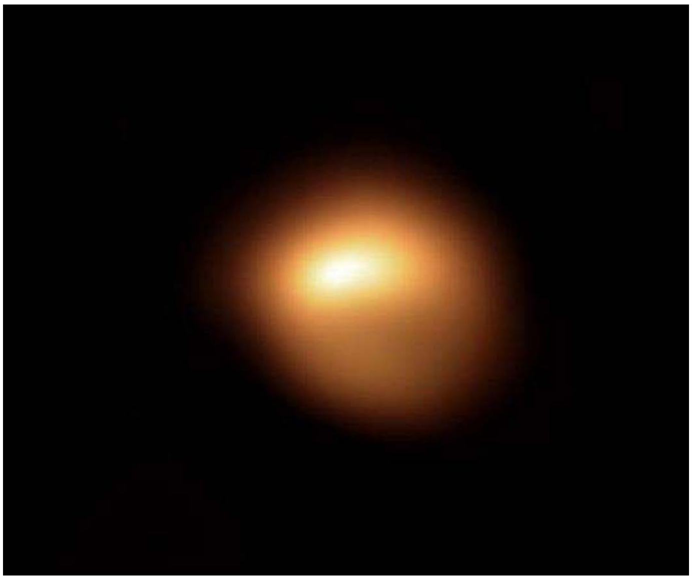

Figure 7. This image of Betelgeuse's photosphere, taken with the SPHERE instrument on ESO's Very Large Telescope in late 2019, is among the first observations to come out of an observing campaign led by Miguel Montargès at the Catholic University of Leuven (KU Leuven) aimed at understanding why the star is becoming fainter. *(ESO, VLT, Miguel Montargès)*

The variations in brightness happen because Betelgeuse is pulsating erratically, shedding mass as it does so, trying to attain a stability that it can never achieve. We can see this lost mass as shells around the star (Figure 6). Each time that it expands, it loses a little of its outer layer, which gets puffed out into interstellar space. This is the standard process of mass loss, which has resulted in seeding the interstellar medium with the heavy elements that form the vast bulk of our planet and a goodly part of our own bodies: truly, we are stardust and owe our existence to the noble sacrifice of stars such as Betelgeuse. Due to this mass-loss process, over its lifetime Betelgeuse has become surrounded by the huge shell of expanding gas and dust – its shed outer layers – that was observed in the infrared by *Herschel*.

What happened to Betelgeuse?

Betelgeuse is one of the few stars that can be resolved by telescopes on Earth as a tiny disc. Of all the stars in the sky, there is just one (excluding the Sun), R Doradus, which has a (slightly) larger apparent diameter as seen from Earth – although it is closer and, in real terms, smaller. Betelgeuse has a diameter about 900 times larger than our Sun. If we take the published angular diameter of 0.052″ (there are both higher and lower figures, too) and a distance of 600 light-years, the diameter comes out at 9.6au. At the higher end of the distance estimates, if Betelgeuse were placed in the centre of the solar system even Jupiter would be inside its photosphere.

Not only can we see the star as a disc, but we can even resolve some detail. Historically, the technique of speckle interferometry has been used for this. If you take high-speed images of a star like Betelgeuse with a large telescope, it breaks up into a myriad of individual speckles, each of which is a perfect, diffraction-limited image (assuming the telescope optics are perfect). Speckle images have shown bright spots, interpreted as plumes of hot gas, or what appear to be giant convection cells in the photosphere. More recently, instruments such as SPHERE (a high-resolution, adaptive-optics, optical/near-infrared imager on ESO's Very Large Telescope) have been capable of obtaining diffraction-limited, resolved images in the near-IR such as that in Figure 7, obtained at the end of 2019 as the star dimmed to well below magnitude +1.

It is well known that pulsating stars change diameter and temperature simultaneously (Figure 8). So, intuitively, one would expect a decrease in temperature and brightness to indicate an increase in diameter. Interestingly, the published results for Betelgeuse though appear to show a small *decrease* in effective radius during the minimum.[16]

Betelgeuse shows strong metal oxide lines towards the red end of the spectrum, with titanium oxide (TiO) particularly prominent.[19] The strength of the TiO lines is strongly temperature sensitive. We see this in the fact that Betelgeuse is an M2Iab star, while Mira Ceti and rho Persei, which are M7IIIe and M4II respectively and thus cooler than Betelgeuse, have much stronger TiO lines.

This means that if we compare photometry with results from narrowband filters centred on the strongest TiO band at 7190Å, with the nearby reference continuum at 7520Å, the ratio of the intensity observed in the two filters is sensitive to the temperature of the star. A third, relatively line-free window at 1024Å (these three bands are known as the Wing Bands A, B & C respectively) is used as a good indicator of the bolometric (total) luminosity of the star. Photometry in these bands reveals that the mean photospheric temperature dropped from 3,650K in 2019 September, to 3,565K at the end of 2020 January.[16] However, while the visible brightness dropped by one magnitude (*i.e.* to 40% of its pre-fade level), the bolometric luminosity, as estimated from Wing Band C, only dropped to 77% of the pre-fade value. From these various measures, if one assumes that the whole surface of the star has the same temperature and brightness (like a spotless Sun at solar minimum), one can use the ratio of temperature and total luminosity to estimate the change in the radius of the star.[20]

The surprising result is that the calculated effective diameter came out to be 8% *smaller* than it was, pre-fade, in 2019 September.[16] Imaging with SPHERE (Figure 9) has however shown that the assumption of spherical symmetry does not hold. Images were taken using the H-alpha filter in 2019 January and again in 2019 December; the former close to the previous minimum (magnitude +0.9), the latter during the decline to the 2020 February minimum (magnitude +1.2). These show that not only was Betelgeuse not spherically symmetrical when approaching minimum, but apparently the visible photosphere was not even approximately spherical. Thus, the assumptions made by Guinan & Wasatonic (2020) break down badly.[16] The shape of the star is irregular and there is something that could be either an intervening dark cloud, or a much cooler area in the lower right-hand quadrant.

Infrared photometry at longer wavelengths shows that the infrared brightness did not fade when the visible brightness did. Infrared light penetrates dust efficiently, which is why we use infrared images to investigate star formation inside nebulae that may have 100 magnitudes of visible extinction. However, it also explains why the brightness measured in the Wing C filter showed a much smaller drop: the wavelength passed by this filter is far enough into the infrared for it to penetrate the dust much better than the shorter wavelength of the TiO band, so it could still see Betelgeuse shining relatively clearly through what the evidence shows was a dust cloud emitted by the star.

Other ESO infrared images show huge plumes of dust around Betelgeuse that have been ejected in previous episodes, while the far-infrared images obtained with *Herschel* suggest

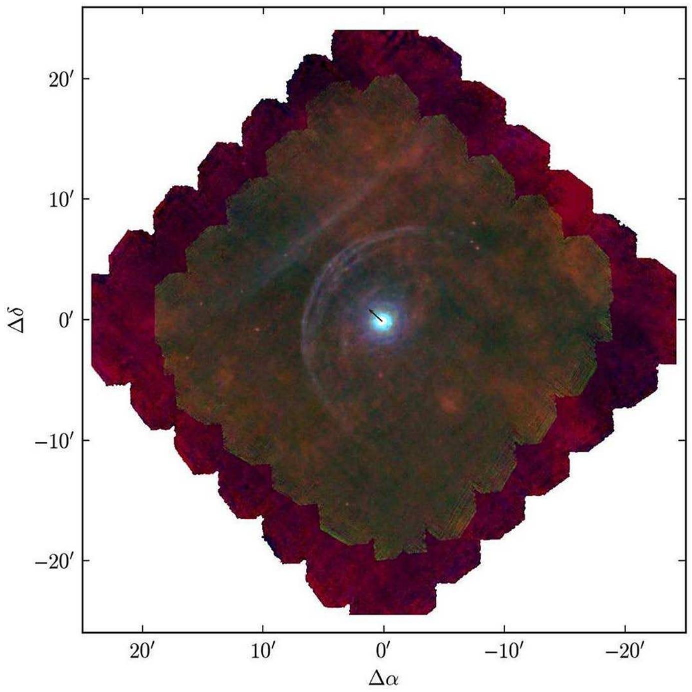

Figure 6. RGB picture of the *Herschel* PACS images of Betelgeuse. North is up, east to the left. Blue is the PACS 70μm image, green the PACS 100μm, and red the PACS 160μm. The black arrow indicates the direction of motion of Betelgeuse. Image from Decin L. *et al.* (2012).[18]

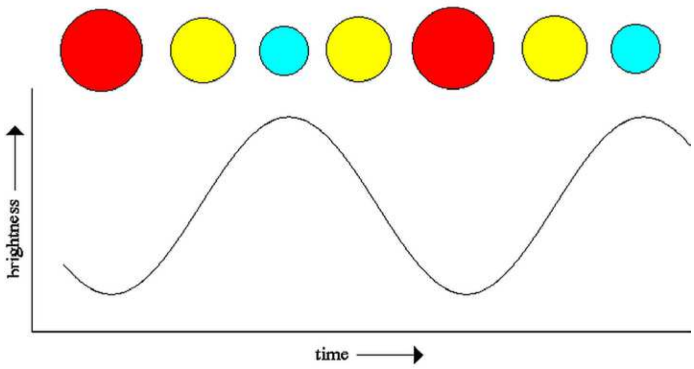

Figure 8. The classical temperature/brightness relationship for a pulsating star over its light curve cycle. The increasing temperature as it contracts leads to the star being brightest when smallest. *(University of Oregon)*

that violent dust ejection has been going on for at least 30,000 years – the large dust shell observed by *Herschel* is expanding at 30km/s.[21]

Together, the evidence indicates that the fade was due to a massive dust ejection of 'large' (about micron-sized) dust particles that partly hid the star, temporarily blocking the visible light, but not the infrared. In other words, Betelgeuse is, or maybe *is becoming*, somewhat analogous to R Coronae Borealis.[22] Intriguingly though, the recent, increasingly deep minima seem to be quasi-periodic: something that is certainly not a characteristic of episodic dust producers.

Conclusions

Observations suggest that minimum was reached around 2020 Feb 6, in reasonable agreement with the recent 430-day period in the light curve, and that the unusual depth was due to a combination of the minima of the 6.1-year and 430-day periods and the ejection of a massive cloud of opaque dust, obscuring part of the visible disc. How stable and enduring the 430-day period is remains uncertain but, if it continues to be present in the light curve, we would expect a new minimum of around magnitude +1.0 to occur around 2021 Apr 12.

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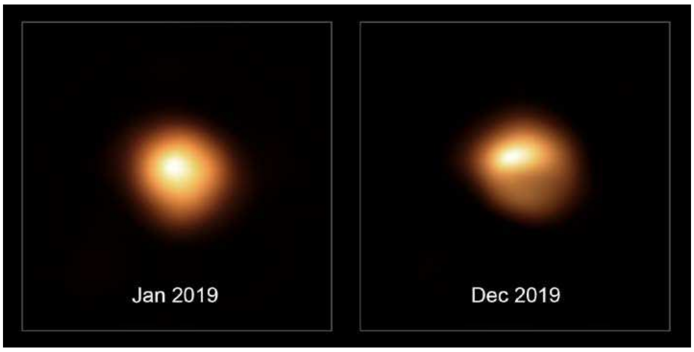

Figure 9. This comparison image shows the star Betelgeuse before and after its unprecedented dimming. The observations, taken with the SPHERE instrument on ESO's Very Large Telescope in 2019 January & December, show how much the star has faded and how its apparent shape has changed. *(ESO/M. Montargès et al., 2020)*

References & notes

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10 To become a core-collapse supernova a star must, as the table shows, be more than ten times the mass of the Sun (**https://iopscience.iop.org/article/10.1088/0004-637X/810/1/34**). The current 'best guess' for the mass of Betelgeuse puts it only just over this limit, so its exact fate is uncertain.
11 One of my memories of my first observing run with the Isaac Newton Telescope on La Palma is of the pained look on the face of my support astronomer when I wanted to observe a 15th-magnitude calibration star. He informed me that 'this telescope was not designed to observe such bright stars'.
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13 In his Table 30, Bayer assigned 'alpha' and 'beta' to two fourth-magnitude stars, too far south to be observed from his observing location in Germany, while at the same time classing them as second magnitude. His star chart also shows these two stars as the most brilliant, above epsilon and sigma, which are by some way the brightest stars in the constellation. It seems that, in this case, Bayer based his choices on bad information from an unknown party, although he may well have been guided in such discrepant cases by the classification of Ptolemy in the *Almagest*. This is evidenced by the fact that Bayer follows Ptolemy in various widely-discussed cases of discrepancy in the Bayer classification, such as Megrez and Denebola. Ptolemy describes Betelgeuse solely as 'The bright, reddish star on the right shoulder' and assigns it magnitude 1.[23]
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22 To be clear, R CrB and Betelgeuse are of very different types. R CrB is a hydrogen-depleted G0Iep yellow supergiant star, although of slightly less than solar mass, so we cannot take this analogy too far.
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Note added in proof, 2020 November

After the brief fade to magnitude +1.0 during and after conjunction, which was followed by the *STEREO-A* mission (Dupree *et al.*, 2020, *ATel* #13901), the latest photometry suggests that a new fade may have started. There is an apparent monotonic drop from magnitude +0.68 at the start of October, to +0.80 in mid-November. A recently-proposed alternative explanation of the infrared data, that show there was no decrease in bolometric luminosity at minimum when longer wavelengths are taken into account, is that giant starspots may be a more likely reason for the deep minimum than dust ejection, although this is still subject to lively debate. It is suggested that the dark patch observed in the SPHERE images is actually a giant starspot. Observations at any further deep minimum that may occur in the coming months should help to clarify which of the two models is correct.

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