The shifting hues of BETELGEUSE

How can you track changes in the colours of stars across hundreds of years, through differences in technologies, concepts and even languages? Dagmar L Neuhäuser and Ralph Neuhäuser show how ancient observations can still inform astrophysics today.

Observations of stars made in pre-telescopic times are a valuable source of data for modern astrophysics. Both historical and scientific methods suggest that Betelgeuse (αOrionis) was yellow-orange some 2000 years ago; it is now deep red. The earliest report of a clearly red Betelgeuse comes from Tycho Brahe in comparison with the supernova of 1572. This recent rapid colour change informs astrophysicists about the exact evolutionary state of Betelgeuse, as well as its parameters such as mass, age and distance.

Some 450 years ago, a new star appeared, just a few degrees off the five stars of the celestial W in Cassiopeia. It was first discovered on 6 November 1572 by Maurolyco (Sicily, Italy), Schuler (Wittenberg, Germany) and by astronomers in Korea. "Behold, almost directly overhead, some strange star was suddenly seen, as flashing its light with radiant gleam, and it struck [my] eyes. Amazed, and as if delighted and shocked, I stood still, and I gazed for a while with my eyes fixed on it, and thereby I noticed that this same [star] is located close to the stars which antiquity attributed to the constellation Cassiopeia." (*Astronomiae instaurate progymnasmata*, Brahe 1602, see Dreyer 1913 for Latin; our translation).

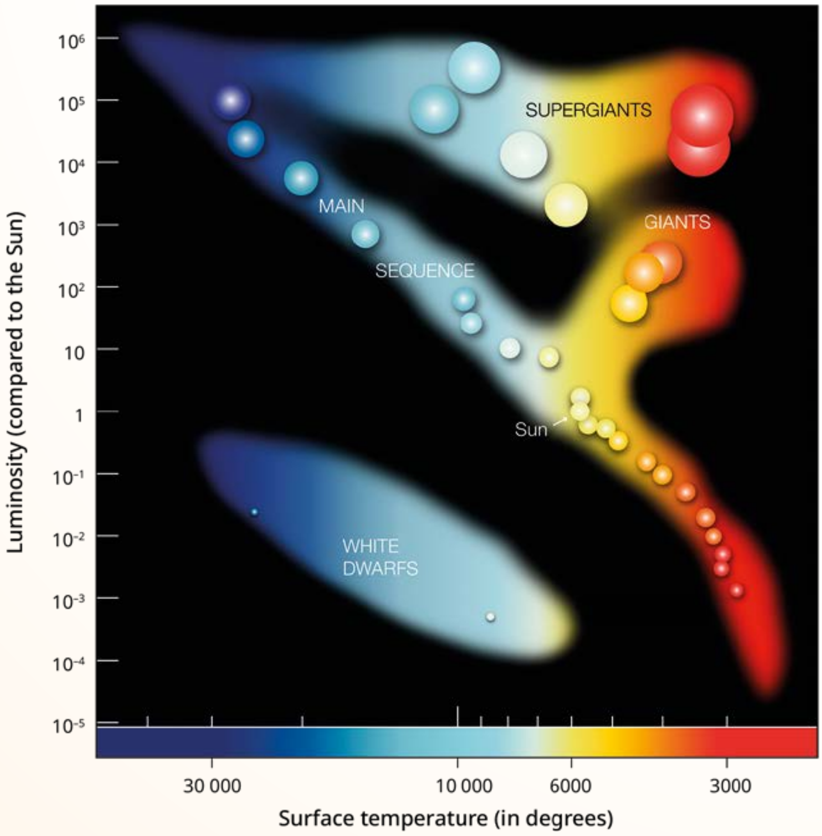
This is how the young Danish astronomer Tycho Brahe (1546–1601) described his own first detection of the *nova stella* on the evening of 11 November 1572; overcast sky conditions had inhibited the usual sky patrol in the preceeding days. While Brahe, later to became resident astronomer with Emperor Rudolf II in Prague, was not the first to observe what we now call supernova 1572, he did obtain and leave the most detailed and most precise measurements – published completely in his posthumous work *Astronomiae instaurate progymnasmata* (*Introduction of the New Astronomy*). "I began (immediately, with an equipped instrument) to measure its location and separation from the neighbouring stars of Cassiopeia and to note very carefully those things which were visible to the eyes regarding its visible magnitude, form, colour, and other aspects." (Brahe 1602; Dreyer 1913, our translation). Brahe's observations of the supernova position and the variations in brightness and colour are the prime example of the value of pre-telescopic observations to derive new scientific knowledge – both then and today.

Stars change colour and brightness as they evolve. Betelgeuse is currently among the supergiants in the top right region of the Herzsprung-Russell diagram, which plots star temperature against luminosity (ESO)

As Danish court astronomer with a significant budget, Brahe would later develop and build ever larger instruments in his dedicated workshop, in order to achieve better astrometric precision. But in the winter of 1572–73, he had to measure the nova position with a small hand-held sextant. Still, in this first publication (in 1573) on the supernova, he could conclude: "After the lapse of six months it had not advanced by its own motion a single minute from that place in which I first saw it; ... Therefore, this new star is neither in the region of the Element, below the Moon, nor among the orbits of the seven wandering stars, but it is in the eighth sphere, among the other fixed stars." (Brahe 1573, translation by J H Walden).

Tycho's considerations here are based on the classical Aristotelian-Ptolemaic geocentric system. While he was also open to – and lectured about and improved – Copernican theories, he also saw correctly that there was no observational evidence, at that time, for either the motion of Earth around the Sun nor the rotation of Earth around its own axis. Instead, he developed an intermediate scheme, now called the Tychonic system, in which the Sun and the Moon orbit Earth, but the other planets orbit directly around the Sun.

Brahe was meticulous in monitoring not only the position of the new star, but also variations in its brightness: "... when first seen, the nova outshone



all fixed stars, Vega and Sirius included. It was even a little brighter than Jupiter, then rising at sunset, so that it equalled Venus when this planet shines in its maximum brightness ... The nova stayed at nearly this brightness through almost the whole of November. On clear days it was seen by many observers in full daylight, even at noontime ... the nova was as bright as Venus in November. In December it was about equal to Jupiter." (Brahe 1602, translated by Baade 1945).

Tycho's positional measurements were used in the 20th century to determine precise coordinates of the supernova (e.g. Böhme 1937), which led to the identification of the supernova remnant, in 1952 by radio observations. Also, his data on brightness could be used to derive the light curve and to classify the *nova stella* as supernova of type I (today Ia) by Baade (1945). Brahe always gave comparison objects with his observations, so that we can today convert them to precise magnitude values. He used a similar technique for the colour variation: "Regarding the colour of this star, it did not always keep the same, but at the beginning it was seen whitish, and it came closer to a Jupiter-like gleam: as time went by, its light degenerated by contracting and inspiring, into the fire [fulgorem] of Mars: it was like Aldebaran, or the one, which is red in the right shoulder of Orion [i.e. Betelgeuse]. But it was not as red like the one in the shoulder, but more like the colour of Aldebaran" (*De nova stella* 1573, Dreyer 1913, our translation). It is difficult to imagine more precise determinations and specifications of colours and their small differences with the unaided eye.

"It was not as red like the one in the shoulder of Orion, but more like the colour of Aldebaran" Tyco Brahe, 1573

A practical test

Today in the instrumental epoch, we use the so-called colour index to quantify the colour of a star or planet. This is the difference in brightness of two wavelength ranges measured using filters, e.g. B–V in the blue and visual (yellow-green) parts of the spectrum, the unit is magnitude (mag). Such colour indices are again qualified with colour terms: 'red' as B–V≥1.4 mag, 'orange' B–V=0.8–1.4 mag, 'yellow' B–V=0.6–0.8 mag, 'white' B–V=0.0–0.3 mag and 'blue' B–V≤0.0 mag. The category 'green' (B–V=0.3–0.6 mag) is not discernible as star colour by the human eye, but stars with this profile appear as either yellowish or whitish because of too much admixture of white. The star Vega in the constellation of Lyra is defined as the zero point with B=V, giving B–V=0.0 mag.

Although the exact borders between the colour ranges are somewhat secondary, the scale thus defined of the colour indices coincides by-and-large with our everyday colour perception of stars – and with pre-telescopic naked-eye experts. We do not think it is justified to consider the perception of star colours as purely subjective, neither individually nor for a whole culture. Our large compilation of all known pre-telescopic star colour studies shows that, when pre-telescopic observers specified a star colour, it mirrors approximately the respective B–V colour index (Neuhäuser *et al.* in prep.).

The Spanish astronomer Pilar Ruiz-Lapuente (2004) used colour data from Tycho Brahe and others to derive the respective colour indices and to classify SN 1572 again as type Ia (thermonuclear explosion of one or two white dwarfs). At the 2022 annual meeting of the European Astronomical Society in Valencia, Spain, during Special Sessions celebrating the 450th anniversary of Brahe's supernova observations, we showed that a few subtle issues with dating, super-saturation at excessive brightness around the peak, and conversion from text to indices – also taking into account further observations from Europe, Arabia, and East Asia – can lead to further details about the subtype of this supernova.

Indeed, the experienced eye can discern small colour index variations and differences even without telescopes and instruments – something that can easily be verified. The northern winter sky offers useful targets, e.g. comparing Betelgeuse itself on the eastern shoulder of Orion, with the nearby Aldebaran, the eye of the bull (in Taurus), and Pollux in Gemini and Capella in Auriga – while the latter appears clearly yellowish to most eyes (B–V=0.8 mag), Pollux has some rose tint (B–V=0.97 mag), and Aldebaran even more (B–V=1.48 mag) and Betelgeuse is now the reddest of them (B–V=1.78±0.05 mag). (The colour index *range* given for Betelgeuse originates from various, overlapping variability phenomena.)

Further reddish stars visible at winter time are found in Andromeda (Mirach with B–V=1.59 mag) and Aries (Hamal with 1.16 mag), as well as in the circumpolar area also Kochab (beta UMi with B–V=1.48 mag) or Dubhe (alpha UMa with just 1.06 mag); Antares in Scorpio is the reddest bright star (its primary Antares A has B–V=1.88 mag), but is hardly visible during the northern winter.

Colour-magnitude diagram

"It was like Aldebaran, or the one, which is red in the right shoulder of Orion. But it was not as red like the one in the shoulder, but more like the colour of Aldebaran," noticed by Tycho Brahe, when the new star was showing its maximal redness. This text not only exemplifies the technique that Brahe used, namely giving comparison objects, but clearly says that Betelgeuse was redder than Aldebaran, even if only slightly. Today, Aldebaran and Betelgeuse differ in colour index by 0.3 mag, something easily discernible by the unaided eye. Was the difference smaller at Tycho's time? Or does this tell us how star colours change with time?

The colour of a star depends mainly on its mass and age. Massive stars are either blue-white or red

– few are in the transition phase where they appear yellow or orange. And because there are only few stars in this transition, it must take place quickly. Stars with some 8 to 18 times the mass of our Sun can cross this Hertzsprung gap within some ten thousand years, a short time-scale for astronomers. This implies that certain changes in colour might even have happened in historical time, over the past few millennia. The physics behind this special evolutionary phase is that core hydrogen burning ceases and core helium fusion and shell hydrogen burning set in, so that the star leaves the main sequence in the Hertzsprung-Russell (or colour-magnitude) diagram, evolving from a blue-white dwarf star to a red giant.

In Neuhäuser *et al.* (2022), we placed all 236 stars down to an apparent brightness of 3.3 mag into the colour-magnitude diagram (figure 1), i.e. down to the naked-eye limit for colour detection, one of the faintest is ι Draconis. Only around a dozen of the more massive stars populate currently that Hertzsprung gap between blue-white and red – including e.g. Sadr (γ Cygni) and Wezen (δ Canis Majoris); Canopus (α Carinae) just entered this instable phase in its life. Betelgeuse has just left that gap, while Antares has been a red supergiant for quite some time. Aldebaran is already a red giant, but it has only about one solar mass, so that its evolution is slow; Pollux, at two solar masses, is also changing slowly.

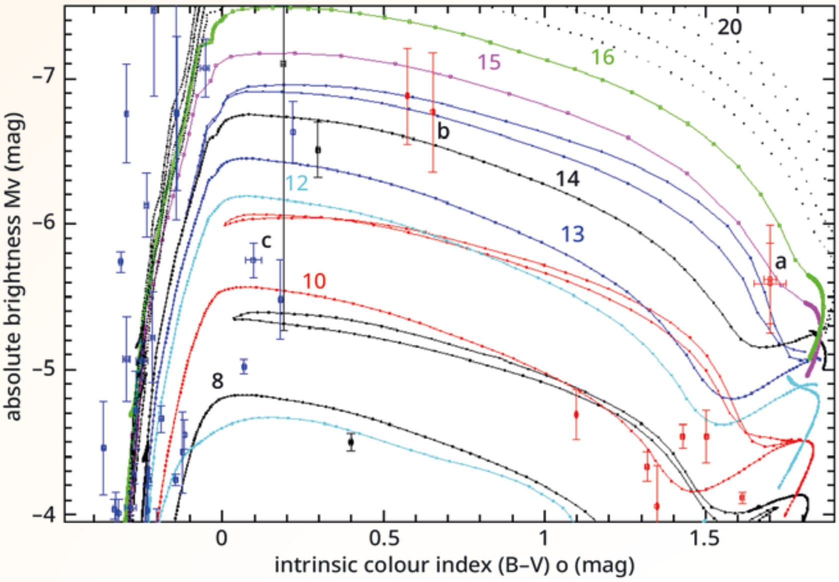
From the location of Betelgeuse in the colour-magnitude diagram, one could expect a rapid colour change over the past few millennia, but this can indeed also be confirmed and quantified precisely with historical sources from antiquity.

Historical observations of colour

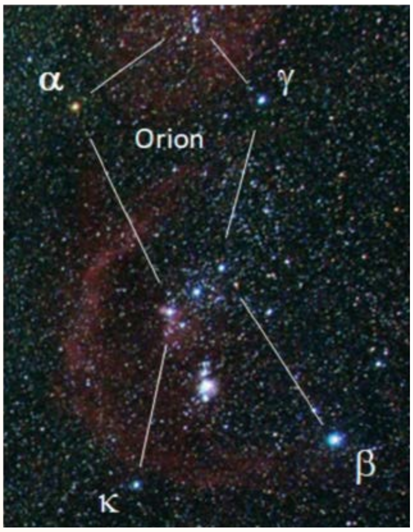
Historical celestial observations can be found in many cultures and they constitute a valuable archive for modern astronomy. However, they are not simply data quarries; using these data for quantitative science calls for special care, which has not always been applied in the past.

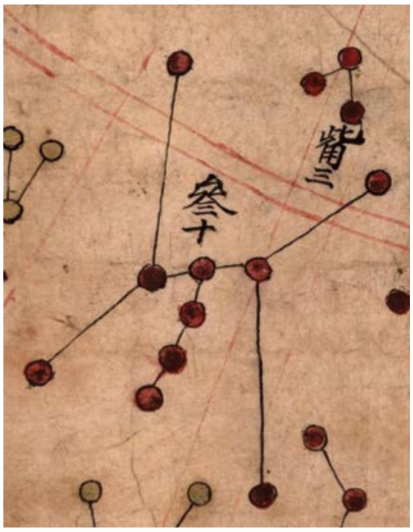
One unfortunate example is the discussion on the presumable colour change of Sirius from reddish in antiquity to white now (B–V=0.01 mag). Such a colour change would not be expected from physics; the white dwarf companion in the Sirius binary star is far too cool to have formed from a red giant in historical time. A thorough application of historical-critical methods would have shown other records of antiquity that reported Sirius correctly as blue or white – or variegating, i.e. showing rays of different (including red) colours within a few seconds as a result of strong scintillation. For all the details, see Ceragioli (1995). A critical examination of the sources calls for trans-disciplinary work with scholars with expertise in history, philology (languages), and natural philosophy. Given the long and deep gap between us and the distant past, proper understanding of historical transmissions is not trivial.

It is in Ptolemy's *Almagest* that Sirius seems to be described as somewhat reddish – together with Pollux, Betelgeuse, Arcturus, Aldebaran and Antares. They are all specified there as *hypokirros* in the original Greek. In Ptolemy's other main work, the *Tetrabiblos*, only the latter three were so described. In the *Almagest*, *hypokirros* describes a range of colour indices: the yellowish, but bright Capella (α Aurigae with B–V=0.8 mag) is not included, while the slightly more reddish Pollux (B–V=0.97 mag) is listed as *hypokirros* which includes all tints up to Antares A (B–V=1.88 mag).



1 *This colour-magnitude diagram, similar to the Hertzsprung-Russell diagram, shows all stars with at least ~8 solar masses and at least as bright as (apparent) 3.3 mag, so that the colour can in principle be perceived by the naked eye. We plot absolute magnitude versus the intrinsic (extinction-corrected) colour index. Most of these stars are on the main sequence (left: blue or white) during the long-lasting stable core hydrogen fusion; most of the rest are either red giants or red supergiants (such as Betelgeuse and Antares, see label 'a'). Only few are in-between, constituting a poorly populated gap, e.g. 'b' for Wezen and 'c' for Canopus. Since there are only a few stars in this transitional phase, massive stars must cross this so-called Hertzsprung gap rapidly. Betelgeuse is just past the gap. The lines (with dots showing the time resolution) are evolutionary tracks for different masses (as given in solar mass) from the MESA/MIST series; here, only the 10 and 13 solar mass tracks show a blue loop. For Betelgeuse, its current properties and, hence, location in this diagram together with the rapid colour change over the last few millennia are best consistent for the 14 solar mass track (within less than 1.5σ). See Neuhäuser et al. (2022) for details.* (Figure by the authors, after Neuhäuser et al. 2022)





2 **(above left)** *The main stars of Orion as seen on sky during the Great Dimming (turn of 2019/20) of Betelgeuse (α Orionis 'hand of the female giant') in the upper left, which remained red; the blue Bellatrix (γ Orionis 'female warrior') in the upper right; also Rigel (β Orionis) in the lower right, and Saiph (κ Orionis) in the lower left. In the middle, one can see the three belt stars with Orion's sword below, in the top is the star cluster around λ Orionis. Image taken on 2019 Dec 30 near La Serena, Chile, three exposures of 3200 s each with a Canon EOS 70D at ISO 3200, f=10mm with Blende f/D=3.5* (M Mugrauer, AIU Jena)

(above right) *The constellation Shen in the Chinese tradition is quite similar to Orion (shoulders, feet, and belt, sometimes the sword is also included). This is a scan from a 14th century star chart from Korea from the Astronomical Collection of University Jena.*

It is relevant to notice that, according to their current location in the colour-magnitude diagram, the other stars listed (Pollux, Arcturus, Aldebaran, Antares) did not change significantly in colour over the last two millennia. The selection in *Tetrabiblos* seems to show a consensus of which stars were labeled as *hypokirros* in antiquity, namely Arcturus, Aldebaran and Antares but not Betelgeuse, even though the latter is now about as red as (and even brighter than) Antares. Other scholars of the Mediterranean antiquity give consistent specifications of star colours: Germanicus, Manilius and Cleomedes list a few bright stars as red, in particular Antares, and also Aldebaran and Mirach, but again not Betelgeuse.

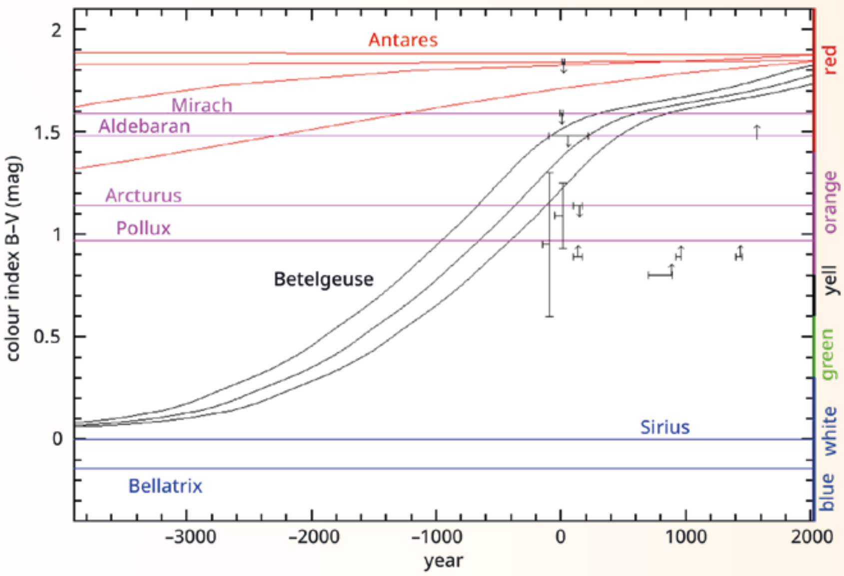
For Betelgeuse, there are two main and independent sources from antiquity, which meet the 'Tychonic' gold standard by comparing the colours to standard stars or planets. Hyginus from Rome (died c17 BC) wrote in Latin (see Le Boeuffle, 1983, *Hygin l'Astronomie*, Latin and French, Les Belles Lettres, Paris) in book IV of *De Astronomia*: "*17. Iouis autem stella ... corpore est magnus, figura autem similis Lyrae ... 18. Solis stella ... corpore est magno, coloure autem igneo, similis eius stellae quae est in humero dextro Orionis; ... Hanc stellam nonnulli Saturni esse dixerunt ... 19. Reliquum est nobis de Martis stella dicere, quae nomine Pyrois appellatur; hic autem non magno est corpore, sed figura similis est flammae ...*" In translation: "17. The star of Jupiter ... body is large [bright], and appearance [colour] similar to Lyra [i.e. Vega] ... 18. The Sun's star ... body is large [bright], and colour fiery/burning; similar to that star which is in the right shoulder of Orion [Betelgeuse] ... Many have said that this star is [the star] of Saturn ... 19. It remains to speak about the star of Mars, which is also called by its name Pyrois [i.e. the fiery]; its body of course is not large, yet its appearance [colour] is similar to a fire/flame ..." (our translation).

Jupiter, Saturn and Mars are noted and compared in both brightness and colour: Mars was described by all cultures as fiery red, as seen in its colour index B–V=1.30–1.56 mag. That Jupiter is compared here in colour to α Lyrae, the prototypical white star (and also given as whitish in most other sources from antiquity) is acceptable, because, indeed, for very bright stars and planets (like also Venus), the large admixture of white leads to the visual appearance of white, although in fact Jupiter has B–V=0.87±0.01 mag).

That planet Saturn with B–V=0.93–1.25 mag, being yellow-orange and differentiated from Mars in all transmissions, is compared here in colour to the star in the right shoulder of Orion, i.e. to Betelgeuse, may therefore be surprising given its colour today (in the Greek-Babylonian tradition, Orion faces us, so that the right shoulder is clearly the eastern one, see figure 2). Planets are very useful as comparison objects for colour (and brightness), because they are all but constant over long periods in atmospheric composition and, hence, colour. The range in colour indices reflects their small variability in amplitude and/or different phase angles towards the Sun.

Transmissions from ancient China are independent from Mediterranean sources. The *Tianguan Shu* from c100 BC defines, in the context of stars, 'yellow' with Betelgeuse, while 'red' is connected to Antares and 'white' to Sirius; additionally, Saturn is given as 'yellow' and Mars as 'red'. The text was authored by the two most prominent astronomers of the Han dynasty, Sima Qian and his father Sima Tan, who formulated the basics of the classical Chinese astronomy in their main work, where we can read: "*Taibo bai, bi Lang; chi, bi Xin; huang, bi Shen zuo jian; cang, bi Shen you jian; hei, bi Kua da xing.*" Our translation of this reads: "For [Venus] white, compare Lang [Sirius]; for red, compare Xin [α Sco]; for yellow, compare the Left Shoulder of Shen [α Ori]; for blue, compare the Right Shoulder of Shen [γ Ori]; and for black/dark, compare the large star of Kui [β And]."

For orientation, the Chinese asterism Shen consists of basically the same main stars as the western Orion, but with 'right' for west and 'left' for east (figure 2). Bellatrix, the 'right' shoulder of Shen, indeed has B–V=–0.14 mag, so that it is a good example for a blueish star. "The large star of Kui" is Mirach (β And), given here as a 'dark' or even 'black' star, which may seem problematic, but Mirach is just rather faint for a deep red star (B–V=1.59 mag with V=2.08 mag), so that this remark is some kind of compromise in order to include all five *wuxing* colours – depending on context, the term *hei* can stand for dark red.



3 *The observed colour index B–V (mag) versus the time for key stars. While most stars discussed (with colours given in either the Almagest or by the Simas) show a constant colour over the last few millennia, Betelgeuse (black lines) did change colour significantly. The lines are obtained from the MESA MIST tracks and corrected for extinction, e.g. for 14 solar masses for Betelgeuse. We plot three lines for Betelgeuse for the nominal colour index and ±1σ uncertainty; the black data points with uncertainties and upper and lower limits correspond to the historical observations of Betelgeuse during the time spans indicated. Given the current evolutionary state of Antares (top), several possibilities are plotted including one where the colour did evolve slowly until a few millennia ago.* (Figure by the authors, after Neuhäuser et al. 2022)

Changing hue

All these comparative specifications from antiquity yield, as with Brahe's texts, quantitative results on the colour indices of these stars at those times. Observations from other cultures in later centuries, in particular from Arabia – the name Betelgeuse is derived from Arabic *Yad al-Jauza* for 'hand of the female giant' – plus the specification by Tycho Brahe from 1573, together then give a coherent picture. Betelgeuse evolved from yellow-orange two millennia ago (B–V≈1.0 mag) to a deep red star today (B–V=1.78±0.05 mag, as shown in figure 3).

Alexander von Humboldt may have been one of the first to use historical texts to study possible colour changes of stars in the middle of the 19th century. Later, it became clear that stars evolve, e.g. massive stars change from blue-white main-sequence dwarfs to red supergiants. But a colour change as a result of such to secular evolution was never explicitly noticed among the bright naked-eye stars. In addition to Betelgeuse, another good candidate is Wezen (δ Canis Majoris, B–V=0.70 mag), whose location in the colour-magnitude diagram indicates a colour change in recent history, but there is only one text that mentions a colour different from now – from the 9th century Bedouins, known as very good observers.

Historical observations as epistemic key

Both our two approaches – the astrophysical location in the colour-magnitude diagram and the historical transmissions – yield the same main conclusion, namely that Betelgeuse has undergone a colour change within the last few millennia. This then allows new astrophysical insights.

Our multi-disciplinary method offers a further benefit. Because the exact distance of Betelgeuse is not well known (as supergiant star, it is larger than its parallax), therefore its mass and age and its evolutionary state is also not well constrained. The latter is usually determined indirectly using theoretically calculated evolutionary tracks that are calibrated with many observations, in particular of binary stars. They indicate the evolution of all externally visible stellar parameters (colour, temperature, spectral type, brightness, radius, etc.) with ongoing fusion in the centre of the star.

Our new historical finding can now be used as additional strong constraint to determine distance, mass, and age of this famous star. Any such theoretical calculations must be consistent with the historical colour change within few millennia. Both the currently available track for 14 solar masses and all the historical evidence show that Betelgeuse indeed was only marginally redder than Aldebaran by around 1573, when Brahe used them to specify the colour of his supernova (B–V≈1.6 mag). Further work, together with the conclusions from the recent Great Dimming of Betelgeuse for a few months at the turn from 2019 to 2020, will improve our understanding of the late evolution of supergiants before supernova even better.

"All this evidence shows that Betelgeuse indeed was only marginally redder than Aldebaran by around 1573, when Brahe used them to specify the colour of his supernova"

Our new constraint pertains to either the single-star model of Betelgeuse or any merger model: Since its rotational velocity (15 kms^{-1}, Dupree *et al.* 1987) is relatively large for a supergiant, it was suggested that it might be a result of a merger of two stars, which added mass and angular momentum (Wheeler *et al.* 2017); however, if the more massive star in such a merger were a red supergiant already, such a merger might not meet our colour change constraint. Alternatively, the extra angular momentum could have been added to Betelgeuse by a former, even more massive, close companion, before that star went supernova and released Betelgeuse from the binary – so that it has been a single star for a long time. Betelgeuse has a large velocity (30 km/s at 150 pc) and is therefore likely to be a runaway star.

Our research field, conducted with scholars of various fields around the world, uses historical celestial observations as the epistemic key for astrophysical problems, which can hardly be solved otherwise. We deduce that the future supernova of Betelgeuse – expected sometime 'soon' after the Great Dimming – will take place 1.5 million years in the future, given Betelgeuse's mass and current evolutionary phase after the rapid colour change through the Hertzsprung gap (Neuhäuser *et al.* 2022).

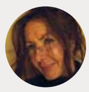
In our discipline – Terra-Astronomy – we work with terrestrial archives (historical texts as well as natural archives like radioisotopes) to study astrophysical phenomena. Historical celestial observations are also used in other astrophysical fields, such as the study of past solar activity, supernova ages and ancient comet orbits (e.g. Neuhäuser *et al.* 2021); changes in the Earth's rotation period over the past three millennia are determined from records of total solar eclipses. Historical records are also valuable in the study of earthquakes, volcanic eruptions and climate variability. ●

Table 1 *Colours of stars (sorted by colour index from red to blue)*

Name Star	Brightness V [mag]	Colour index B–V [mag]
Antares A	1.1	1.88±0.02
Betelgeuse	0.57	1.78±0.05
Mirach	2.08	1.59
Aldebaran	0.99	1.48
Arcturus	0.16	1.14
Pollux	1.22	0.97
Capella	0.08	0.80
Wezen	1.84	0.70
Sirius	–1.44	0.01
Vega	0.00	0.00
Rigel	0.28	0.02
Bellatrix	1.66	–0.14
Saiph	2.06	–0.18
Planets		
Mars	–2.9 to 1.8	1.43±0.13
Saturn	–0.5 to 1.3	1.09±0.16
Mercury	–1.5 to 3.0	0.97±0.03
Jupiter	–2.9 to –1.7	0.87±0.01
Venus	–4.9 to –3.9	0.81±0.11

Sources for stars: ESA (1997). For planets: Tholen, D J et al. 2000, Mallama A et al. 2017

AUTHORS



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Ralph Neuhäuser (ralph.neuhaeuser@uni-jena.de) Astrophysical Institute, University Jena, Germany, DLN as anthropologist and RN as astrophysicist together initiated the new research project in Terra-Astronomy to use historical observations as an epistemic key to solve astrophysical problems. This work is strongly trans-disciplinary and emphasises a stringent methodology. They publish on solar activity reconstruction, pre-telescopic comet orbits, stellar evolution, and historical novae and supernovae in journals such as *Monthly Notices*, *Icarus*, *Astronomical Notes*, and *Nature Scientific Reports*.

See also https://www.astro.uni-jena.de/index.php/terra-astronomy.html.

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