

Colour evolution of Betelgeuse and Antares over two millennia, derived from historical records, as a new constraint on mass and age

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Presented by Joris Josiek

Introduction

- Goal: pre-telescopic colour records of stars → new test of evolutionary models
 - HRD crossed within $\sim 10^4$ yr (for 8 to 18 Msol) → noticeable change possible between antiquity and today.
 - Constraints on mass, age, evolutionary state of supergiants
- Main objects of focus: **Betelgeuse** and **Antares** (among other candidates for recent colour change)
 - Today, both are red supergiants

	Color (B-V)	Absolute mag. (V)
Betelgeuse	+1.78	-5.59 or -6.14
Antares	+1.88	-5.62

- Authors present an interdisciplinary study involving astronomy, history and physiology.

Selecting stars

Searching for stars that may have undergone a colour change in historical times.

- Compile colour indices (B-V) of the 236 stars down to an apparent magnitude of 3.3
 - Mainly from Tycho catalog (1997) and Hipparcos catalog (1997) and single sources.
- Figure 2: brightest stars and MIST tracks for solar metallicity and $v/v_{\text{crit}}=0.4$
- Select Antares and Betelgeuse (located towards the end of the Hertzsprung gap) as prominent stars.

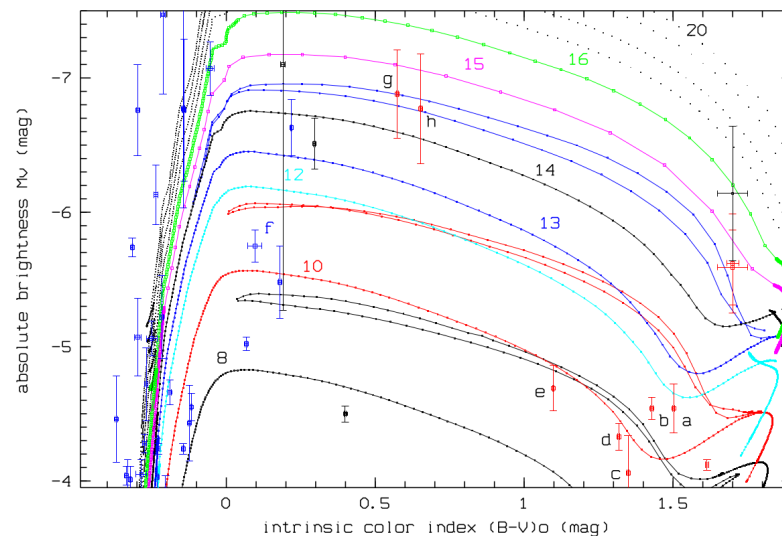


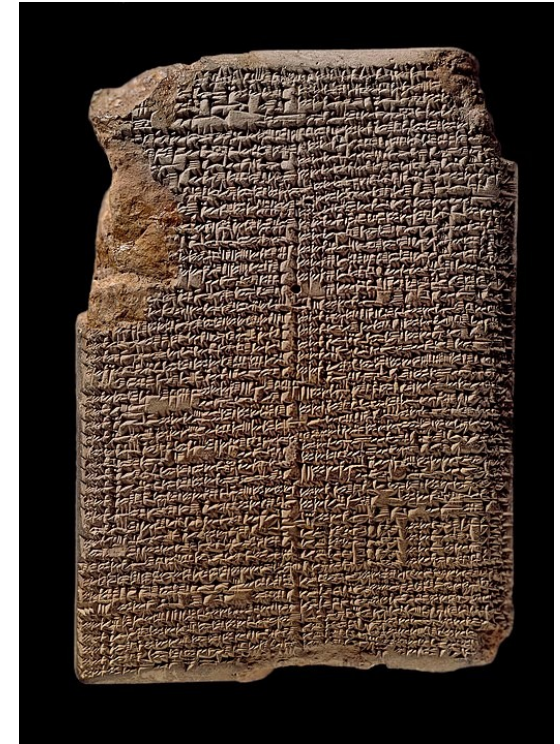
Figure 2. Colour-magnitude-diagram (CMD) for the brighter stars ($M_V \leq -3.9$ mag), similar to Fig. 1, with tracks for 8, 10, 12, 13, 14, ... 20 M_{\odot} (most labeled) from the MIST series (Choi et al. 2016); dots indicate the (unequal) MIST time resolution. While the MIST tracks for 8, 10, and 13 M_{\odot} show pronounced blue loops, those for 12 and $\geq 14 M_{\odot}$ do not. Betelgeuse and Antares A are seen on the upper right in red with overlapping error bars. Betelgeuse is also plotted once in black for the larger Harper, Brown, & Guinan (2008) distance. Other stars in the Hertzsprung gap discussed in the Sects. 3.4 & 3.5 are indicated as follows: a: π Pup (Ahadi), b: ϵ Peg (Enif), c: β Ara, d: ϵ Gem (Mebсутa), e: ϵ Car (Avior), f: α Car (Canopus), g: γ Cyg (Sadr), and h: δ CMa (Wezen); the star just below the 8 M_{\odot} track is Polaris.

Historical method – Sources

- Search historic records before 1609 CE for any star in the sample of 236 brightest stars.

Sources: (some direct, some secondary)

- Greek and Latin manuscripts from Mediterranean antiquity
 - Aratos 'Phaenomena' (3rd century BCE) + Latin translations by Cicero and Germanicus
 - Similar works by Eratosthenes, Manilius, Hyginus, Cleomedes, Avienus, and others.
- Pre-telescopic star catalogs
 - Ptolemy (2nd century CE)
 - Al-Sūfi (10th century CE)
 - Ulug Beg (15th century CE)
 - Bayer and Brahe (~1600 CE)
- Assyrian texts
 - MUL.APIN (2nd millenium BCE)
- Chinese sources
 - Classical sources (2nd millenium BCE onward)
 - Sima Qian (2nd/ 1st century BCE)
 - Jin shu (7th century)
- Arabic manuscripts (since the 8th century CE)
- First Nations reports



One tablet of the MUL.APIN

British Museum

<https://www.britishmuseum.org/collection/image/152339001>

Historical method – Interpretation

- **Main problems:**
 - Obtaining quantitative information from qualitative statements about colour
 - Historical differences in the colour ranges associated with a colour term.
i.e. 'red' today may not have the same scope as 'red' 2 000 years ago
 - Translational inaccuracies for colour terms
- **Useful information:**
 - Documented comparisons with static objects such as other stars and planets
- **Focus of study:**
 - Pre-telescopic records show: *the colour of Betelgeuse was credibly different from today.*
 - Consider Antares for comparison (similar position in CMD).

Results

- **Betelgeuse's colour is compared to that of Saturn** by G.J.Hyginus (c. 64 BCE – AD 17)
 - He wrote in the context of the five naked-eye planets:

“Solis stella ... corpore est magno, colore autem igneo, similis eius stellae quae est in humero dextro Orionis”

“The Sun's star ... body is large, and colour fiery/burning, similar to the star that is in the right shoulder of Orion”

- Saturn (the Sun's star) : B-V = 1.09 (orange) → *4.1 σ from Betelgeuse today!*
 - Betelgeuse today (B-V=1.78) is even redder than Mars (B-V=1.43), which is consistently reported as 'red' in antiquity.
- Hyginus relied on colour theory of Plato: white (Jupiter, Venus); yellow (Saturn, Mercury); red (Mars)
 - The naked eye can easily distinguish the color of Mars and Saturn!
- Similar, independent report by Simas (China, ca. 100 BCE)
- **Antares' colour has been reported as red for at least 3 millennia**: e.g. Greek Ant-ares = like Ares (Mars)

Results

Table 3: Betelgeuse and Antars colour indices from historical reports:

Author	dating	range	Sect.	Betelgeuse		pred. (2)	Antares	Antares
				B–V [mag]	sign. (1)		B–V [mag]	evidence
Oracle bones	BC 1300	BC 1400-1200	3.3	-		-	≥ 1.43	like fire/Mars
Book Odes	BC 1000	BC 1100-900	3.3	-		-	≥ 1.43	like fire/Mars
Zuozhuan	BC 600	BC 722-468	3.3	-		-	≥ 1.45	Alphard
Greek	BC 200	BC 1000-AD 150	3.3	-		-	≥ 1.43	'like Mars'
Simas	BC 90	BC 150–87	3.2.7	0.95 ± 0.35 (3)	2.3σ	1.16	≥ 1.43	like Mars
Hyginus	AD 15	BC 50–AD 17	3.2.1	1.09 ± 0.16 (4)	4.1σ	1.23	-	-
Germanicus	AD 7	BC 5–AD 19	3.2.4	< 1.59 (β And)		1.22	≥ 1.59	Mirach
Manilius	AD 20	AD 10–30	3.2.5	< 1.84 (α Sco)		1.23	-	-
Cleomedes	AD 60	BC 100–AD 220	3.2.3	< 1.48 (α Tau)		1.25	≥ 1.48	Aldebaran
Almagest	AD 138	AD 100–170	3.2.2	> 0.80 to 0.97 (α Aur - β Gem) (5)		1.30	≥ 0.89	as Betelgeuse
Tetrabiblos	AD 150	AD 100–170	3.2.2	< 1.14 (α Boo) (5)		1.31	≥ 1.14	Arcturus
Hephaistos	AD 415	AD 415	3.3	-		-	≥ 1.43	like Mars
Bedouins	AD 889	AD 700–1000	3.2.8	≥ 0.80 (α Aur)		1.60	≥ 0.80	Capella
Al-Šūfī	AD 964	AD 920–964	3.2.8	> 0.80 to 0.97 (α Aur - β Gem)		1.61	≥ 0.89	as Betelgeuse
Al-Biruni	AD 1000	AD 1000	3.3	-		-	≥ 1.43	like Mars
Al-Tusi	AD 1200	AD 1200	3.3	-		-	≥ 1.43	like Mars
Ulug Beg	AD 1440	AD 1400–1449	3.2.8	> 0.80 to 0.97 (α Aur - β Gem)		1.66	≥ 0.89	as Betelgeuse
T. Brahe	AD 1572/3	AD 1572/3	3.2.8	> 1.48 (α Tau)		1.67	-	-

Notes: (1) Significance for being different (smaller) than the current value of $B-V=1.78 \pm 0.05$ mag.

(2) Predicted $B-V$ (mag) colour index for Betelgeuse from the lower, best-fit line for Betelgeuse in Fig. 5.

(3) 'yellow', (4) like Saturn.

(5) Upper and lower limit together yield a range of 0.80 to 1.14 mag, or 0.97 ± 0.17 mag (4.6σ significance).

Results

Betelgeuse: Black
Antares: Red

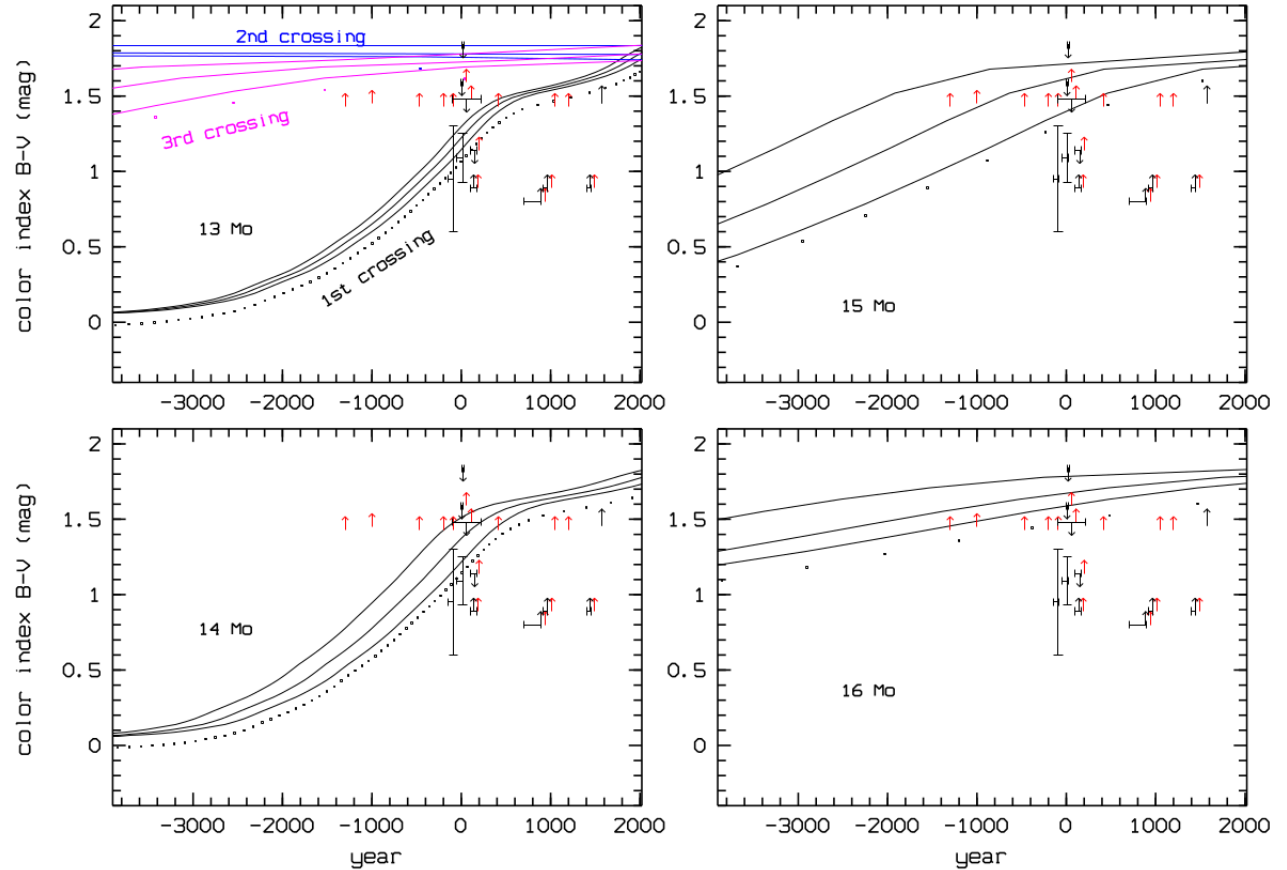
Only 13, 14, 15, 16 M_{\odot} consistent within 1.5 sigma for Betelgeuse considering its CMD position today.

→ Determine current age and plot colour index vs. time

MIST models end in 2022 with current colour index:
- 1.73, 1.78, 1.83

→ For Betelgeuse, only the 14 M_{sol} track is consistent with historical documents!

→ Antares is either 13 M_{sol} on the blue loop, or on the 15/16 M_{sol} track



Conclusions

- The colour of Betelgeuse was significantly different 2 millenia ago, as confirmed by multiple independent reports.
 - Therefore, Betelgeuse only recently crossed the HRD
- Its initial mass was further constrained to 14 Msol.
- Authors also investigate other aspects, including:
 - results for some other stars
 - colour evolution of Betelgeuse during the Great Dimming (2019-2020)
 - possibility of merger history of Betelgeuse
- MIST tracks show that Betelgeuse should have dimmed by about 1 mag during the last 2 millenia → not yet confirmed by historical reports

