218. Red supergiants: the biggest stars

THE BIGGEST stars have radii $\sim 1500 R_\odot$, far larger than the naked-eye monsters Antares ($680 R_\odot$) or Betelgeuse ($640 R_\odot$). Scaled to the solar system, their photospheres would extend beyond the orbit of Jupiter. The largest of those reliably known is WOH G64 in the LMC, $R \sim 1540 \pm 77 R_\odot$, discovered by Westerlund et al. (1981).

Stars larger than a few hundred solar radii are mostly red supergiants, or the still rarer hypergiants, occupying the upper-right region of the HR diagram.

Observationally, the former are 'cool' ($T_{\rm eff} \lesssim 4200$ K), luminous ($L/L_\odot \geq 10^4$) objects, highly evolved descendants of main-sequence stars of initial mass $10-40 M_\odot$ (Iben, 1974; Messineo & Brown, 2019, §3), with their high masses distinguishing them from the lower mass ($0.5-8 M_\odot$) AGB stars. They are amongst the brightest stars in the infrared, detectable out to Mpc distances.

Early catalogues of red supergiants include those of Humphreys (1978), Elias et al. (1985), and Jura & Kleinmann (1990), the latter reporting just 21 (20 M-type, one L-type) within 2.5 kpc of the Sun. Skiff (2014) provided the most recent compilation of about 1400 Galactic candidates. But this census remains highly incomplete, given our location within the disk and the associated dust obscuration, distance uncertainties, and the overlapping luminosities of red supergiants and subgiants.

DURING the M supergiant phase, lasting 200 000–400 000 yr, a star of initial mass $20 M_\odot$ returns some $3-10 M_\odot$ into the interstellar medium (Jura & Kleinmann, 1990). Their late-stages of nucleosynthesis, stellar winds, and eventual explosions as supernovae represent key processes in a galaxy's chemical enrichment.

Nonetheless they remain a poorly characterised evolutionary phase, with models failing to match some cool or luminous objects (Massey & Olsen, 2003; Levesque et al., 2009; Wing, 2009). Challenges include their molecular opacities, extended atmospheres, sonic velocities of the convective layers, and supersonic velocities in their atmospheres, resulting in shocks, photospheric asymmetries, and imprecise radii, as evident in the case of Betelgeuse (Young et al., 2000; Freytag et al., 2002).

TECHNIQUES FOR MEASURING stellar radii include the use of spectroscopic indicators of surface temperature and luminosity, angular size measurements using interferometry, or, in a few cases, from eclipsing binaries (e.g., VV Cep), all requiring distance estimates.

The former method rests on the Stefan–Boltzmann law, $L = 4\pi R^2 \sigma T_{\rm eff}^4$, where L is the bolometric luminosity, R the radius, and the use of an 'effective temperature', $T_{\rm eff}$, sidesteps the assumption of blackbody radiation. Noteworthy is the fact that since L is a steep function of temperature, a cool star must be huge to be as luminous as a hotter star. But the underlying assumptions that the star is spherical, and that the radius is well-defined, break down for the very largest. More on the challenges of spectral (and luminosity class) classification, and measurement of their diameters and distances, is given by Levesque et al. (2005), and Wing (2009).

The supergiant nature of the prototypes Betelgeuse (α Ori), Antares (α Sco), and Herschel's Garnet Star (μ Cep), was known since the early 20th century from their insignificant parallaxes and proper motions. Hipparcos gave $\varpi = 6.55 \pm 0.83$ mas (152 pc), 5.89 ± 1.00 mas (170 pc), and 0.55 ± 0.20 mas (1800 pc), respectively.

THE COOLEST and most luminous stars in the study by Levesque et al. (2005), viz. KW Sgr, Case 75, KY Cyg, and μ Cep, have $R \sim 1500 R_\odot$ (7 au), in agreement with the largest radii predicted from their MARCS models using improved molecular opacities inspired by the anticipation of the Gaia data (Gustafsson et al., 2003; Plez, 2003). *'It is believed'*, they state, *'that stars above this radius would be too unstable and simply do not form'*.

Stars seemingly unaware of the MARCS models include the interacting binary VV Cep, with a radius variously estimated as $1200-1600 R_\odot$, and the 'humongous' VY CMa for which Keck interferometry found a photospheric radius of $3020 R_\odot$ (Monnier et al., 2004), implying an extremely cool star, 2225 K, or some 'unique evolutionary state' (Humphreys et al., 2005). More recently it is considered to be linked to episodic mass-loss clumps (Kamiński, 2019; Humphreys et al., 2024).

Availability of the Gaia astrometry has brought the possibility of significantly improving both the census of red supergiants and, perhaps more importantly, the knowledge of the distances to individual objects.

Messineo & Brown (2019) started with the 1400 candidate Galactic red supergiants compiled by Skiff (2014), and presented a catalogue of those with a Gaia DR2 entry. They included a revised spectral type for each object, and a unified $T_{\rm eff}$ based on the temperature scale of Levesque et al. (2005). Parallaxes were found for 1342 stars, with a high-quality subset of 889. Most are located along the Galaxy's spiral arms (their Fig. 6), although generally in isolation, with only some 13% known to be associated with open clusters, reinforcing questions about their Galactic distribution, as well as how and where they formed (Messineo et al., 2016).

Healy et al. (2024) used distances from Gaia DR3, infrared photometry from 2MASS, and a Galactic dust map, to select a distinct sample of luminous bright late-type stars. Bolometric luminosities and effective temperatures were compared to Geneva stellar evolution tracks to determine likely candidates, and to identify contamination using a catalogue of Galactic AGB stars of similar L and $T_{\rm eff}$. This resulted in a quality sample of 578 probable (and 62 likely) Galactic red supergiants, along with multiplicity, variability, and classification as a runaway as given by the proper motions.

I have already referred to the very short evolutionary lifetimes of these red supergiants, the consequence being that they are particularly important as potential future core-collapse supernova progenitors.

Healy et al. (2024) assessed their catalogue's use for the Supernova Early Warning System (SNEWS, Molla, 2021), and showed that exploiting neutrino fluxes and their 3D positions as an early warning trigger, the number of candidates can be reduced significantly, improving prospects of observing the progenitor pre-explosion and the early phases of core-collapse supernovae.

While many occur in isolation, some open clusters do host concentrations of red supergiants, amongst them χ Per, NGC 7419, and Westerlund 1 (essay 106), all now with well-determined distances from their mean Gaia DR2 parallaxes (Davies & Beasor, 2019).

They put it eloquently in their abstract: *'Galactic, young massive star clusters are approximately coeval aggregates of stars, close enough to resolve the individual stars, massive enough to have produced large numbers of massive stars, and young enough for these stars to be in a pre-supernova state. As such these objects represent powerful natural laboratories in which to study the evolution of massive stars. To be used in this way, it is crucial that accurate and precise distances are known, since this affects both the inferred luminosities of the cluster members and the age estimate for the cluster itself.'*

There have also been a number of recent discoveries of remarkably massive clusters of red supergiants at the near-end of the Galactic bar, at distances of around 6–7 kpc, seen only in the infrared (Messineo et al., 2016), with several designated as Red Supergiant Clusters: RSGC1 (Figer et al., 2006); RSGC2, aka Stephenson 2 (Stephenson, 1990; Davies et al., 2007); RSGC3 (Alexander et al., 2009; Clark et al., 2009); RSGC4, aka Alicante 8 (Negueruela et al., 2010; Asa'd et al., 2023); RSGC5, aka Alicante 7 (Negueruela et al., 2011); and RSGC6, aka Alicante 10 (González-Fernández & Negueruela, 2012).

The evolutionary and mass-loss histories of three of these clusters, RSGC1–3, along with NGC 7419, have been assessed by Humphreys et al. (2020).

Beyond our own Galaxy, red supergiants have been identified in the Magellanic Clouds, and in M31 and M33, all making use of the Gaia parallax and proper motion as membership discriminants. The 1098 identified in the LMC are being used to place constraints on their lower mass limit (Yang et al., 2024). Reasonably complete samples of 5498 and 3055 objects have been identified in M31 and M33 respectively (Ren et al., 2021).

Many of the largest objects have their own literature detailing classification, mass-loss, etc., although with limited insights yet from Gaia. They include:

WOH G64, with $R \sim 1540 \pm 77 R_\odot$ (Levesque et al., 2005; Beasor & Smith, 2022). The DR3 parallax, $\varpi = -0.2477 \pm 0.0430$ mas, is consistent with its LMC membership.

Stephenson 2–18, aka St2–18, Stephenson 2 DFK1, and RSGC2–01, located close to RSGC2 (Fok et al., 2012). A radius of $2150 R_\odot$ is given in its wiki entry, presumably with large uncertainties, although I was not able to trace the reference. It is not included in Gaia DR3.

UY Scuti, with $R \sim 1708 \pm 192 R_\odot$ derived from VLTI–AMBER observations and PHOENIX model atmospheres (Arroyo-Torres et al., 2013). This is based on their assumed distance of 2.9 kpc, while Gaia DR3 yields the significantly smaller $\varpi = 0.5166 \pm 0.0494$ mas, or 1.94 kpc.

Others include **RSGC1–F01** (in RSGC1), with $1530 R_\odot$ (Humphreys et al., 2020); **AH Sco**, with $1411 \pm 124 R_\odot$, also from VLI–AMBER and PHOENIX models (Arroyo-Torres et al., 2013); and **RW Cep**, with $900 - 1760 R_\odot$ making use of the Gaia parallax (Anugu et al., 2023).

We are in the early stages of what Gaia will inform us about the biggest stars, and in particular their place in the evolution of red supergiants.

And having noted their non-sphericity, I'll add that, at the other extreme, KIC–11145123, with $P_{\rm rot} \sim 100$ d, has been claimed as the 'roundest' object in Nature, with asteroseismology-based $\Delta R/R = (1.8 \pm 0.6) \times 10^{-6}$ which, for $R_\star = 2.3 R_\odot \sim 1.5$ Mkm, implies $\Delta = 3 \pm 1$ km between its polar and equatorial radii (Gizon et al., 2016).