ASTRONOMY ✦ BEAT

Number 60 • November 16, 2010

www.astrosociety.org

Publisher: Astronomical Society of the Pacific
Editor: Andrew Fraknoi
Designer: Leslie Proudfit

390 Ashton Avenue, San Francisco, CA 94112

Monster Stars: How Big Can They Get?

Paul Crowther
University of Sheffield

Editor's Introduction

Stars are born with a wide range of masses. One of the most interesting unsolved problems in astronomy is the question of how massive a new-born star can be before it must fragment into a pair or system of stars? Recently, some new work has pushed the limit upward for the most massive possible stars, and we asked the key scientist involved in this work, Professor Paul Crowther, to describe the advance for *Astronomy Beat* readers.

A star's mass is the fundamental quantity that dictates its properties and life story, although it is often the most difficult to determine. There is a robust lower limit to stellar masses, at approximately 1/12th the mass of the Sun. At that point, the star is simply unable to sustain nuclear reactions and thus to qualify as a star. The quest for a corresponding *upper* limit to the stellar mass scale has proved rather more elusive.

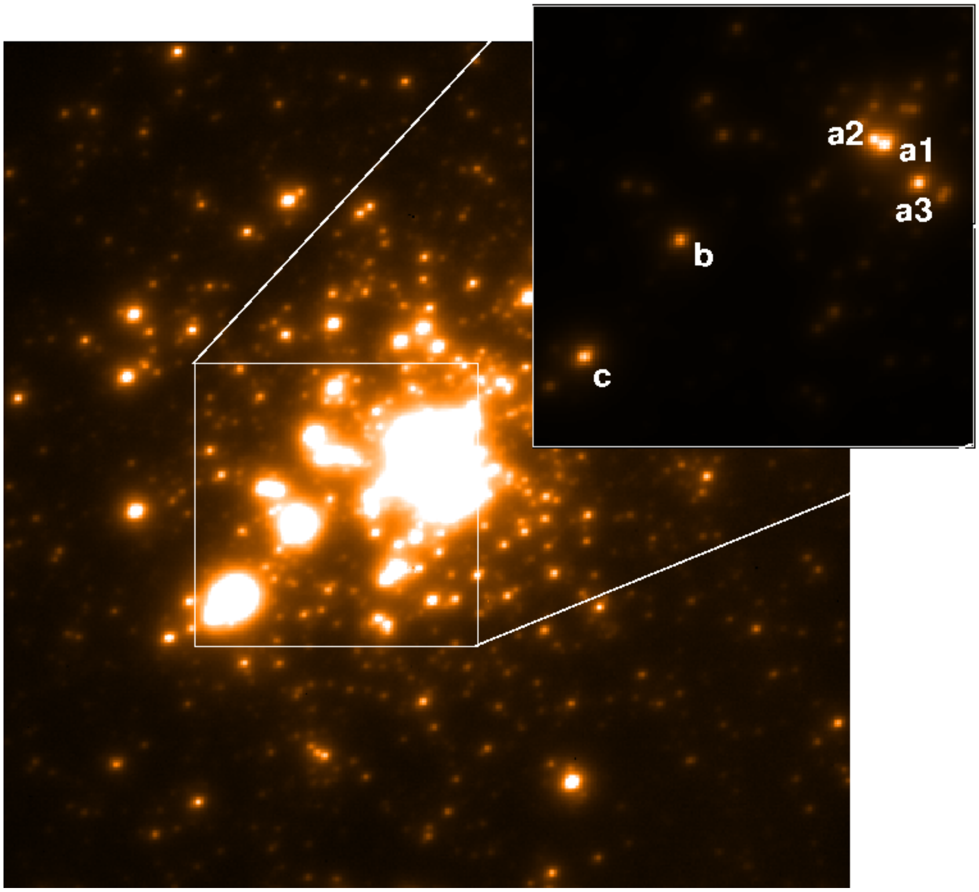
Stars are generally grouped into three categories by mass — low, intermediate and high. By far the vast majority of stars in the Milky Way and other galaxies have low masses — in fact a factor of two lower than our Sun on average. These stars either appear red, orange or yellow for most of their lives, and those lives are measured in billions of years. Intermediate mass stars are somewhat less common, and shorter lived, and appear white or blue-white. Low and intermediate mass stars share a common fate, namely a slow demise as the dying ember of a white dwarf.

A Hubble Space Telescope image of the Tarantula Nebula, within which R136 may be seen to the centre right *(NASA, ESA, F. Paresce, R. O'Connell & the WFC3 Science Oversight Committee).*

In contrast, high mass stars are incredibly rare. They appear blue, shine so brightly (give off so much energy) that their lives are measured in only millions of years, and tend to go out with a bang — their cores collapse and the rest of the star blows itself apart in a gargantuan explosion astronomers call a supernova. Astronomers classify the types of stars by a letter code, which have the improbable order from hottest to coolest of O, B, A, F, G, K, and M (which students remember with the mnemonic "Oh Boy an F Grade

Kills Me!") The most massive stars are in the first category and thus called O-type stars.

Our Galaxy probably hosts only a few tens of thousands of O-type stars — whose masses are measured in tens of solar masses — from a total census of a hundred billion. Despite their rarity, O stars are exceptionally hot, and so supply huge quantities of ultraviolet light to their parent galaxy. Consequently, they illuminate their surroundings, producing ionized regions each of which can be seen as a glowing *nebula*. The closest of these is the Orion Nebula, visible on dark nights as a spot of "blood" on the sword of Orion the hunter. The largest stellar nursery found relatively nearby is the Tarantula Nebula, in the Milky Way's most massive satellite galaxy, the Large Magellanic Cloud.



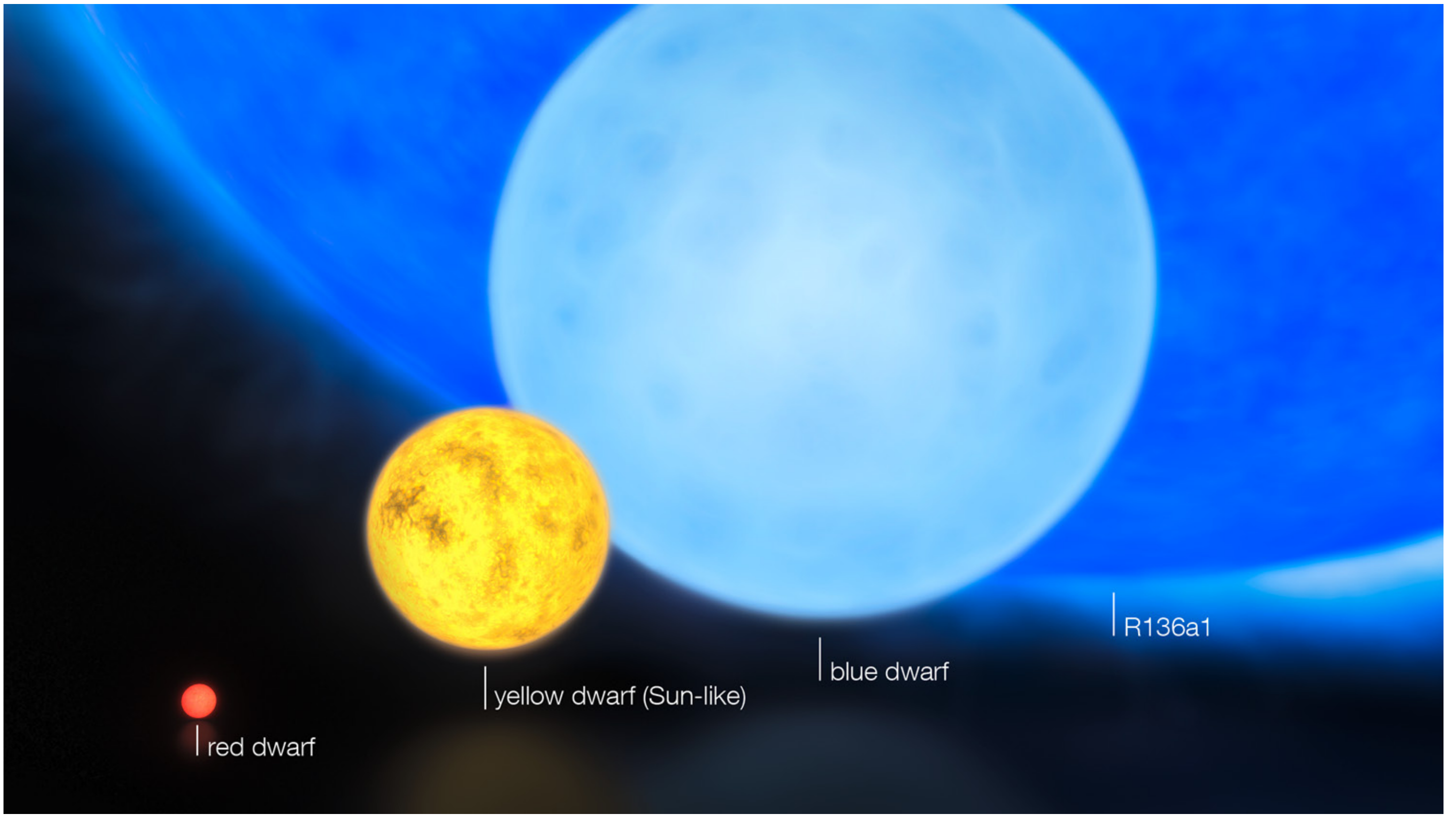
A Very Large Telescope image of R136 obtained with the Multi-conjugate Adaptive Optics Demonstrator showing the R136a cluster (main panel) and the identity of the brightest stars including R136a1 (sub panel).

Historically, various theoretical stability arguments have argued for a range of upper mass thresholds for O-type stars, including values as low as 60 solar masses. Observationally, Joe Cassinelli (at the University of Wisconsin) argued in the early 1980's that R136a, the central object of the Tarantula Nebula, was a single star with a mass of several thousand solar masses. Soon thereafter, technological advances resolved R136a into a dense cluster of stars, with individual components labeled a1 for the brightest, a2 for the next brightest and so on. Still, as recently as a decade ago, Phil Massey (of the Lowell Observatory) argued that there was no evidence in support of any upper mass limit for stars on the basis of his Hubble observations of R136a.

In the middle of the last decade, the question of the upper mass limit appeared to be settled, once and for all, courtesy of the Arches cluster. This star group is located close to the super-massive black hole at the heart of the Milky Way, and is sufficiently young and massive that one would expect it to host some exceptionally massive stars, should they exist. From Hubble infrared images, Don Figer (at the Rochester Institute of Technology) set an upper limit of 150 solar masses. Although this figure rapidly received widespread acceptance in the community, subsequent observational and numerical advances have enabled us to revisit this question.

Last year, my then postdoctoral fellow Olivier Schnurr had been on the hunt for the highest mass *binary* stars (stars in orbit around each other) using an infrared instrument mounted at the Very Large Telescope in Chile. He established that the brightest component of the star cluster inside the nebula called NGC 3603 was a pair of stars with about 100 times the mass of the Sun, orbiting each other roughly every 4 days. This was the current record holder for binary stars, and buoyed by his success, he set about searching for binaries in R136a too. To his surprise, and disappointment, no new record holders were identified.

However, the datasets accumulated by Schnurr were of sufficient quality to allow me to reassess the physical properties of the brightest "single" stars within R136.



An artists impression of the relative sizes of young stars, from the smallest red dwarfs (0.1 solar masses), through yellow dwarfs (Solar-like, 1 solar masses) to blue dwarfs (8 solar masses) and R136a1 *(ESO, M. Kornmesser)*. In reality, R136a1 exceeds the luminosity of the red dwarf by a factor of ten billion.

Studies from the 1990s, employing Hubble's ultraviolet and visible-light spectrographs, suggested stellar masses less than 150 solar masses for R136a1, etc. However, a1 and a2 appear so close together that even the Hubble observations of the brightest component, a1, were contaminated by a2, and vice versa.

The new Very Large Telescope observations finally enabled the two stars to be separated. Still, this dataset alone was insufficient for their stellar masses to be reassessed. We also needed to know precisely how *luminous* (bright) the individual stars were, for which high-resolution infrared images were necessary; I was able to get these courtesy of another colleague, Chris Evans in Edinburgh. Armed with them, plus an application of the latest theoretical calculations about the atmospheres of stars, I was able to calculate record-breaking properties for R136a1 and a2 — namely, that they were 9 and 6 million times more luminous than the Sun, respectively. Now we were ready to use all this work to calculate star masses. For this we needed the theoretical calculations of how such massive stars evolve (change through their lives).

There is an intimate relationship between mass and luminosity for stars converting hydrogen to helium in their cores. Stars whose masses are 150 times higher than the Sun are predicted to shine up to 4 million times brighter than the Sun. If the two stars in R136a were much more luminous than this limit, we realized that R136a1 had to be even more massive. We asked Raphael Hirschi from Keele University to calculate evolutionary models for higher masses. The best agreement was found for an age of 1.5 million years, allowing us to trace the models backwards to the original star mass. Initial mass estimates from this work greatly exceeded the limit identified by Figer for the Arches cluster, reaching an astounding 320 solar masses for R136a1. We were able to use various arguments to counter (legitimate) concerns that R136a1 might be a binary system of a pair of 150 solar mass stars. Nonetheless, we remained naturally skeptical about our reliance on theoretical models for our analysis of these stars and their inferred masses.

Fortunately, Schnurr's previous study of NGC 3603 came to the rescue. I carried out a near-identical study of the high mass binary within this cluster, and the results were borne out by the masses that were derived from the pair's motion. This provided the much-needed independent support for the approach that found exceptional masses for the R136a stars. Indeed, R136a1 was subsequently dubbed the 'monster star' in the media.

Although we had found convincing evidence for tremendously massive stars, the question of a physical upper limit remained unaddressed. To assess this, I asked a colleague in Sheffield, Richard Parker, to carry out simulations of star clusters by populating them with stars randomly selected from the initial mass function (the relative numbers of stars of different masses), using various upper mass limits. Both R136a and NGC 3603 supported a limit close to 300 solar masses. Indeed, we also found that the Arches cluster is consistent with the new limit, on the basis of recent Very Large Telescope observations.

Hubble Space Telescope image of NGC 3603, containing at its heart the high mass binary star used to provide a sanity check on the R136 stars *(NASA, ESA, R. O'Connell, F. Paresce, E. Young, the WFC3 Science Oversight Committee & the Hubble Heritage Team)*

Is the doubling of the stellar limit above 150 solar masses merely an incremental result or does it tell us something new about the lives and deaths of stars? Let us return to the start of this tale, recalling that high mass stars die an explosive death as core-collapse supernovae. They leave behind exotic remnants — either a neutron star or black hole — depending on the final stellar mass. According to theory, stars whose initial masses are in the 140 to 260 solar mass range may explode as so-called 'pair instability supernovae' (PISNe). These would be exceptionally bright supernovae that blow themselves apart, without leaving any remnant.

Up until recently, the observational focus for such exceptional supernovae was restricted to the very early Universe. During this era, high mass stars were thought to be much more common than at present, where common wisdom has led us to believe that stars do not exceed about 150 solar masses. Might opening up the mass regime above this value mean that pair instability supernovae occur in the nearby Universe? Indeed, recent transient surveys have discovered some exceptionally bright supernovae, some of which might correspond to PISNe.

We now understand that the issue of how a massive star explodes is affected not only by its "genetic endowment" (its birth mass, etc.) but also by its "environment." In galaxies that are severely deficient in *metals* (the term astronomers use for all elements other than hydrogen and helium), only the very highest mass may produce such 'super-supernovae'. This is because outflows from high mass stars become more powerful if they are richer in metals. Very massive stars in large, metal-rich galaxies would largely boil away, whereas an equivalent star in a very metal-poor dwarf galaxy might retain sufficient mass for it to produce a PISN. R136a1 is located in a galaxy whose properties lie between these two extremes, such that its eventual fate still remains uncertain at present, although calculations are currently in progress.

Our observations also raise fresh questions as to how very massive stars actually form. High mass stars are believed to form much quicker than low mass stars — in a time perhaps as short as a hundred thousand years. Such a short birth period means a star must gather its material from its "mother cloud" rather quickly, requiring accretion rates of 0.001 solar masses per year for R136a1. This is challenging, since radiation pressure from massive proto-stars hinders further accretion, once they become sufficiently hot and luminous. However, some high mass stars might form through mergers of lower mass stars, although very high stellar densities would be required for this to be a plausible formation route.

As usual in astrophysics, resolving one issue (perhaps) just raises a number of intriguing related questions. Future technological advances will likely allow searches for other examples of very massive stars beyond our immediate neighborhood. Until then, the Tarantula Nebula remains the best place to study such extreme stars within our entire Local Group of galaxies.

About the Author

Paul Crowther is a professor of astrophysics at the University of Sheffield in the UK. He has co-authored a technical monograph *From Luminous Hot Stars to Starburst Galaxies* with Peter Conti and Claus Leitherer, and edited the proceedings of several scientific meetings, most recently IAU Symposium 250, *Massive Stars as Cosmic Engines*. He serves on the Organizing Committee for the IAU Working Group for Massive Stars and has chaired a number of telescope allocation sub-panels, including ESO, Gemini and Hubble Space Telescope.

Resources for Further Information

Answers to frequently asked questions about R136a1 can be found at:
http://pacrowther.staff.shef.ac.uk/r136a1.html

For an introduction to the life story of the stars, see:
http://www.pbs.org/seeinginthedark/astronomy-topics/lives-of-stars.html

For a more technical discussion, see: Conti, Crowther & Leitherer, *From Luminous Hot Stars to Starburst Galaxies*, 2008, Cambridge University Press. ✦

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