RMxAC, **58**, 4–7 (2024)

VERY MASSIVE STARS IN NGC 3125-A1 ($Z \sim 0$) AND CDFS131717 ($Z \sim 3$)

A. Wofford[1], A. Sixtos[1], G. Bruzual[2], S. Charlot[3], F. Cullen[4], L. Smith[5], and S. Hernández[6]

RESUMEN

La masa máxima que puede poseer una estrella es desconocida. Revisamos algo de lo que se sabe actualmente sobre las estrellas más masivas del Universo cercano. En particular, presentamos evidencia de estrellas con masas ZAMS por encima del límite superior de masa canónico (~ 150 M$_\odot$) en la galaxia de brotes de formación estelar cercana, NGC 3125, y la galaxia de mediodía cósmico, CDFS131717. En ambos casos, la evidencia se basa en espectroscopia UV en el marco de reposo, donde estas estrellas tienen las principales líneas de diagnóstico: O V λ1371, N IV] λ1468, He II λ1640, and N IV λ1720. El reciente descubrimiento de estrellas similares en nueve galaxias de mediodía cósmico resalta la importancia de continuar los estudios de estas estrellas en galaxias cercanas, donde se pueden obtener vistas detalladas sobre las condiciones favorables para su presencia, retroalimentación y destinos.

ABSTRACT

The maximum mass that a star can possess is unknown. We review some of what is currently known about the most massive stars in the nearby Universe. In particular, we present evidence for stars with ZAMS masses above the canonical upper mass limit (~ 150 M$_\odot$) in nearby starburst galaxy, NGC 3125, and cosmic-noon galaxy, CDFS131717. In both cases, the evidence is based on rest-frame UV spectroscopy, where these stars have the main diagnostic lines: O V λ1371, N IV] λ1468, He II λ1640, and N IV λ1720. The recent discovery of similar stars in nine cosmic-noon galaxies highlights the importance of pursuing studies of these stars in nearby galaxies, where one can obtain details views about conditions favorable to their presence, feedback and fates.

Key Words: galaxies: starburst — techniques: spectroscopic — ultraviolet: galaxies — ultraviolet: stars

1. INTRODUCTION

Massive ($\geq 8\,\mathrm{M}_\odot$) stars define the upper limits of the star formation process, dominate the energetics of their local environments, and significantly affect the chemical evolution of galaxies. Their role in starburst galaxies and the early Universe is likely to be important, but we still don't know the maximum mass that a star can possess. Stars with masses significantly above the "canonical" upper limit of e.g. the Galactic Center (Figer 2005), i.e., with $>> 150$ M$_\odot$, are known as Very Massive Stars (VMS; Vink 2015). By re-analyzing the most massive hydrogen-and-nitrogen rich Wolf-Rayet (WNh) stars in the center of R136, which is the main ionizing cluster of the Tarantula Nebula in the Large Magellanic Cloud (LMC), Crowther et al. (2010) found that stars originally assumed to be below 150 M$_\odot$ were actually more luminous and massive, i.e., VMS. VMS R136a1 is the most massive star known to date. According to multiple mass determinations (Crowther et al. 2010; Bestenlehner et al. 2020; Brands et al. 2022; Kalari et al. 2022) its initial mass is ≥ 200 M$_\odot$. In addition, it is putatively single. This is based on multi-epoch spectroscopy showing the absence of a radial velocity shift in excess of 50 km/s. Such an excess would indicative the presence of a close companion star (Shenar et al. 2023). Two other VMS in R136 are also putatively single according to this criterion (Shenar et al. 2023). Another indication that the latter three VMS in R136 are very massive is that they show strong broad He II λ1640 emission that can be modeled by formation in the wind of a very luminous (and massive) star that approaches the Eddington limit (Vink et al. 2011), where the force of radiation balances that of gravity. If R136a1 was composed of 10 main sequence stars of $\sim 20\,\mathrm{M}_\odot$ instead of a single 200 M$_\odot$ star,

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México, Unidad Académica en Ensenada, Km 103 Carr. Tijuana−Ensenada, Ensenada, B.C., C.P. 22860 México (awofford@astro.unam.mx).

[2]Centro de Radioastronomía y Astrofísica, UNAM, Campus Morelia, Apartado Postal 3–72, 58090, Morelia, Michoacán, México.

[3]Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France.

[4]Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK.

[5]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA.

[6]AURA for ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA.

it would show He II absorption, but it doesn't. Unfortunately, the formation mechanism(s), evolutionary path(s) and fate(s) of VMS are poorly known. This is a problem for understanding their role in the Universe. However, one can obtain clues about the environments that are favorable to their presence by considering the properties of R136. This dense cluster is $2-2.5$ Myr old (Brands et al. 2022); has a binary-corrected virial mass of $4.6-14.2\times10^4$ $M_\odot$ (Hénault-Brunet et al. 2012) that is consistent with its photometric mass ($\sim5\times10^4$ $M_\odot$, Andersen et al. 2009); and has an ionized-gas oxygen abundance of 12+log(O/H)=8.39±0.01 (Domínguez-Guzmán et al. 2022). This is half of the solar reference value, where 12+log$(O/H)_\odot$=8.69±0.05 (Asplund et al. 2009). The R136 cluster is massive and considered to be strongly star-forming. It thus qualifies as a mini-starburst.

Beyond the Local Group, due to distance, VMS located in the centers of clusters like R136 cannot be resolved individually. In the rest-frame UV, VMS have spectral signatures that are similar to those of classical Wolf-Rayet (cWR) stars, which are the core He-burning descendants of stars with $\gtrsim 25$ $M_\odot$ (Crowther 2007). In particular, both types of stars produce strong P-Cygni like profiles of N V $\lambda\lambda$1239, 1243 and C IV $\lambda\lambda$1548, 1551, as well as strong broad (FWHM$\sim$ 1000 km/s) He λ1640 emission. By analyzing the UV spectrum of R136, Crowther et al. (2016) found that seven VMS dominate its integrated He II λ1640 emission. In addition, Crowther & Castro (2024) analyzed a more extended 30 pc x 30 pc region of NGC 2070, which is the dominant giant H II region of the Tarantula nebula and includes R136. The individual stars in the extended region have ages between 1 and 7 Myr. Crowther & Castro (2024) found that a combination of classical Wolf-Rayet (cWR) and main sequence WNh + transition Of/WN stars (including VMS), dominate the He II λ1640 emission. cWR stars appear in a single stellar population at $\sim3-4$ Myr, i.e., after the VMS WNh stars. Because VMS are very shot lived (<2.5 Myr, e.g., Wofford et al. 2023) signatures of their presence are indicative of a very young massive star region.

In a recent compilation, Martins et al. (2023) use a combination of UV + optical criteria to establish that a region is VMS-dominated. These are: presence of broad (FWHM≈1000 km/s) and strong (equivalent width, EW$\gtrsim$3 Å) He II λ1640 emission, and weak or absent red bump at ∼5801-–12 Å, as the latter is produced by carbon-rich cWR stars. According to these criteria, Martins et al. found that in nearby galaxies beyond the Local Group, only two galaxies, J1129+2034/SB179 (12+log(O/H)=8.29, Senchyna et al. 2021) and J1200+1343 (12+log(O/H)=8.26, Berg et al. 2022), have VMS-dominated dominated clusters (considering known galaxies with UV spectra). In addition, they classify two regions as having VMS and/or cWR: NGC 3125-A1 (12 + log(O/H) = 8.32 (Wofford et al. 2023; hereafter, W23) and a region in J1215+2038/SB191 (12+log(O/H)=8.30 (Senchyna et al. 2017). According to other authors, VMS candidates are present in two additional nearby galaxies: NGC 5253 (cluster 5; 12+log(O/H)=8.26, Smith et al. 2016 and Mrk 71 (12+log(O/H) =7.89, Smith et al. 2023. Excitingly, there have been several claims of detections of VMS at much larger distances ($z=2-3$), i.e., during the epoch when galaxies present a peak in their star formation rate density (Koushan et al. 2021), which is known as cosmic noon. Upadhyaya et al. (2024) show that in addition to strong broad He II emission, VMS-dominated regions also show strong broad emission lines of N IV] λ1486 and N IV λ1720. Finally, O V λ1371 blueshifted absorption has also been proposed as an indicator of the possible presence of VMS (Wofford et al. 2014, 2023). Other stars that show O V λ1371 are O-type and carbon-rich WR stars (WC; Martins & Palacios 2022). However, if WC stars dominate the O V absorption, then the so-called red bump at ∼5801-12 Å will be strong in the optical (Martins et al. 2023).

In § 2 and § 3, we discuss the evidence for VMS found in NGC 3125 and CDFS131717, respectively. In § 4, we provide our conclusions.

2. NGC 3125-A1

Super star cluster (SSC) A1 ($3.1\times10^5\,M_\odot$) in NGC 3125 has one of the strongest ($EW=4.6\pm0.5$ Å) broad ($FWHM=1131\pm40\,\mathrm{km\,s^{-1}}$) He II λ1640 emission lines in the nearby Universe and constitutes an important template for interpreting observations of extreme He II emitters out to redshifts of $z\sim2-3$ (W23). In W23, we present observations of A1 obtained with the Cosmic Origins Spectrograph (COS) on board of the *HST*, using gratings G130M (PI Leitherer, PID 12172) and G160M (PI Wofford, PID 15828). Figure 1 shows an *HST* image of NGC 3125 with the COS aperture overlaid and A1´s position indicated. In W23, we show that there is no significant contamination of the He II line with nebular emission and that the line is redshifted by $121\pm17\,\mathrm{km\,s^{-1}}$ relative to ISM lines. In addition, we compare the COS observations of A1 to recent single-star Charlot & Bruzual (CB19, Plat et al. 2019) simple stellar population (SSP) models with VMS of up

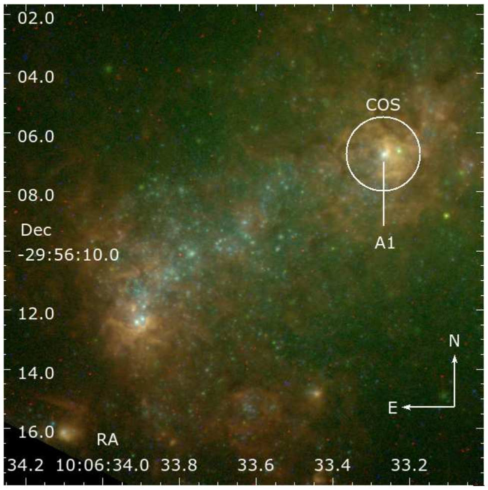

Fig. 1. HST ACS HRC composite image (R: F658N, G: F555W, B: F330W; PI Chandar, PID 10400) of NGC 3125 with 2.5″COS aperture overlaid. We indicate the position of SSC A1. At a distance of ≈ 14.84Mpc (Mould et al. 2000), the COS aperture spans a projected distance of ≈ 179.27pc.

to 300 $M_\odot$. We find that a model with $Z = 0.008$, age = 2.2 Myr, and VMS approaching the Eddington limit provides an excellent fit to the He II emission and fits reasonably well N V $\lambda\lambda1238, 1241$, N IV] $\lambda1486$, C IV $\lambda\lambda1548$, 1551, and N IV $\lambda1720$. This can be seen in Figure 2.

In W23, we also show that BPASS version 2.3 models with close binaries (Byrne et al. 2022) currently fail to reproduce strong stellar He II emission. However, it is clear that population synthesis models should allow for close binary evolution (Sana et al. 2012). Finally, W23 present O V $\lambda1371$ line-profile predictions showing that this line constitutes an important tracer of youth and VMS in galaxies. O V is also seen in O-type and WC stars.

3. CDFS131717

Broad He II $\lambda1640$ emission is the strongest stellar line in the stacked UV spectrum of 811 Lyman Break Galaxies (LBGs) located at $z \sim 3$ produced by Shapley et al. (2003). Lyman Break Galaxies are star-forming galaxies that are selected using their differing appearance in several imaging filters due to the position of the Lyman limit. In stacked spectra, the uncertainties in the redshifts of the galaxies that make up the spectrum contribute to some extent to the width of the composite He II line profile. However, a recent deep (20 hr) observation of a UV bright (M_{UV} = -21.7) non-lensed star-forming galaxy (ID = CDFS131717) that is located at $z_{spec} = 3.071$ and is part of the deep public ESO spectroscopic survey

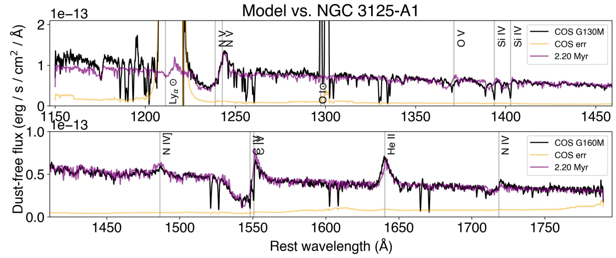

Fig. 2. Comparison of HST COS G130M (top) + G160M (bottom) UV spectrum of NGC 3125-A1 with best-fit $Z = 0.008$ CB19 model accounting for VMS (black and purple curves, respectively). We indicate the positions of relevant stellar and geocoronal lines.

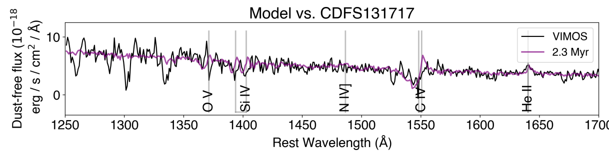

Fig. 3. Comparison of VLT VANDELS spectrum with model accounting for VMS. (black and purple curves, respectively). We indicate the positions of relevant stellar lines.

with VIMOS on the *Very Large Telescope (VLT)*, VANDELS (McLure et al. 2018; Garilli et al. 2021), clearly shows the existence of broad He II 1640 emission in single objects (Stanton et al., in prep.). In Figure 3, we show the rest-frame UV spectrum of CDFS131717 with a $Z = 0.006$ model accounting for VMS overlaid (see W23 for more details). Given the simultaneous tentative detection of O V $\lambda1371$, this coscmic-noon galaxy could contain a mix of VMS and cWR. As previously mentioned, nine other VMS-dominated candidates are reported in (Upadhyaya et al. 2024), highlighting the importance of accounting for VMS in population synthesis models and the need for further nearby spatially-resolved studies of VMS-dominated stellar populations, so that we can learn about the environments that are favorable to their formation, effects of their feedback, and also their fates.

4. CONCLUSIONS

In conclusion, population synthesis models should include binaries, VMS, modern mass-loss prescriptions, and rotational mixing. Our results show the effect of the improved formulation of stellar mass loss rates.

REFERENCES

Andersen, M., Zinnecker, H., Moneti, A., et al. 2009, ApJ, 707, 1347

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Berg, D. A., James, B. L., King, T., et al. 2022, ApJS, 261, 31
Bestenlehner, J. M., Crowther, P. A., Caballero-Nieves, S. M., et al. 2020, MNRAS, 499, 1918
Brands, S. A., de Koter, A., Bestenlehner, J. M., et al. 2022, A&A, 663, A36
Byrne, C. M., Stanway, E. R., Eldridge, J. J., McSwiney, L., & Townsend, O. T. 2022, MNRAS, 512, 5329
Crowther, P. A. 2007, ARA&A, 45, 177
Crowther, P. A., Caballero-Nieves, S. M., Bostroem, K. A., et al. 2016, MNRAS, 458, 624
Crowther, P. A. & Castro, N. 2024, MNRAS, 527, 9023
Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, MNRAS, 408, 731
Domínguez-Guzmán, G., Rodríguez, M., García-Rojas, J., Esteban, C., & Toribio San Cipriano, L. 2022, MNRAS, 517, 4497
Figer, D. F. Astrophysics and Space Science Library, Vol. 327, The Initial Mass Function 50 Years Later, ed. E. CorbelliF. Palla & H. Zinnecker, 89
Garilli, B., McLure, R., Pentericci, L., et al. 2021, A&A, 647, A150
Hénault-Brunet, V., Evans, C. J., Sana, H., et al. 2012, A&A, 546, A73
Kalari, V. M., Horch, E. P., Salinas, R., et al. 2022, ApJ, 935, 162
Koushan, S., Driver, S. P., Bellstedt, S., et al. 2021, MNRAS, 503, 2033
Martins, F. & Palacios, A. 2022, A&A, 659, A163
Martins, F., Schaerer, D., Marques-Chaves, R., & Upadhyaya, A. 2023, A&A, 678, A159
McLure, R. J., Pentericci, L., Cimatti, A., et al. 2018, MNRAS, 479, 25
Mould, J. R., Huchra, J. P., Freedman, W. L., et al. 2000, ApJ, 529, 786
Plat, A., Charlot, S., Bruzual, G., et al. 2019, MNRAS, 490, 978
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444
Senchyna, P., Stark, D. P., Charlot, S., et al. 2021, MNRAS, 503, 6112
Senchyna, P., Stark, D. P., Vidal-García, A., et al. 2017, MNRAS, 472, 2608
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Shenar, T., Sana, H., Crowther, P. A., et al. 2023, A&A, 679, A36
Smith, L. J., Crowther, P. A., Calzetti, D., & Sidoli, F. 2016, ApJ, 823, 38
Smith, L. J., Oey, M. S., Hernandez, S., et al. 2023, ApJ, 958, 194
Upadhyaya, A., Marques-Chaves, R., Schaerer, D., et al. 2024, arXiv e-prints, arXiv:2401.16165
Vink, J. S., ed. 2015, Astrophysics and Space Science Library, Vol. 412, Very Massive Stars in the Local Universe
Vink, J. S., Muijres, L. E., Anthonisse, B., et al. 2011, A&A, 531, A132
Wofford, A., Leitherer, C., Chandar, R., & Bouret, J.-C. 2014, ApJ, 781, 122
Wofford, A., Sixtos, A., Charlot, S., et al. 2023, MNRAS, 523, 3949