Highlights on Spanish Astrophysics X, Proceedings of the XIII Scientific Meeting of the Spanish Astronomical Society held on July 16 – 20, 2018, in Salamanca, Spain. B. Montesinos, A. Asensio Ramos, F. Buitrago, R. Schödel, E. Villaver, S. Pérez-Hoyos, I. Ordóñez-Etxeberria (eds.), 2019

Clusters with K-type (super)giants.

J. Alonso-Santiago, I. Negueruela, A. Marco, and H. M. Tabernero

Dpto de Física, Ingeniería de Sistemas y Teoría de la Señal. Escuela Politécnica Superior. Universidad de Alicante. Apdo.99 E-03080. Alicante (Spain).

Abstract

Young open clusters are the natural laboratories to constrain stellar evolution models. During my PhD thesis we studied the red (super)giants hosted in six open clusters with the aim of exploring the boundary between AGB stars and RSGs. These clusters (NGC 2345, NGC 3105, NGC 6067, NGC 6649, NGC 6664 and Trumpler 35) were selected taking into account that their evolved stars, K (super)giants, covered the mass transition (5.5–$9.5\,\mathrm{M}_{\odot}$) around the minimum mass which produces a supernova explosion.
By combining photometry and low/moderate-resolution spectroscopy, we studied the clusters in order to obtain accurate ages (and masses) for their evolved stars. From FEROS spectra of the FGK (super)giants contained in the clusters we derived their stellar atmospheric parameters as well as their chemical abundances.
Besides the characterization of each cluster, the most complete to date, two remarkable results are found: i) the over-abundance of Ba found in young clusters (30-90 Ma), which supports the enhanced s-process and the role of i-process and ii) the relationship between spectral type and evolutionary stage of stars in open clusters: the AGB/RSG boundary could be related to the presence or lack in the cluster of K/M supergiants at solar metallicity.

1 Introduction

The initial mass with which a star is born is the fundamental parameter that will determine the evolution and properties of the star. According to their mass, stars follow two different evolutionary branches: either the red giant or the red supergiant phase (RSG). In the first case, the red giant evolves into an AGB star and ends its life expelling its outer layers in the form of a planetary nebula, leaving as a remnant a white dwarf. In the second, the RSG suffers a core collapse which releases a large amount of energy, exploding as a supernova (SN); the residual object is very compact (a neutron star or a black hole). The boundary between both scenarios would be approximately around 8–$9\,\mathrm{M}_{\odot}$, depending on models.

In recent years, several programmes for the search of SNe progenitors have been carried out ([21]). Their results are questioning the classical paradigm which explains the origin of these objects. The minimum mass to produce a SN explosion might be up to two solar masses below the limit traditionally accepted: stars of only 6–7 $M_\odot$ could become a SN in low-metallicity environments and binary systems [20], [12], [19]).

With the aim of exploring the border between stars that explode as a SN and those that do not, we resorted to the best laboratories to study stellar evolution: stellar clusters. In this work our goal is to provide for the first time a series of observational evidences that may serve to constrain theoretical models ([17]). To do this, we have studied a sample of evolved stars contained in young open clusters.

2 Sample, observations and analysis

We performed a literature search ([15]) for young open clusters with ages between 30–100 Ma, which cover the AGB/RGB mass transition according to recent works (6–9 $M_\odot$). We found that clusters in this age range have on average only two red (super)giants. Nevertheless, for our sample we selected the clusters statistically more significant, those containing at least five evolved stars, listed in Table 1. In total, they host half a hundred of (super)giants, comprising blue (A-type), yellow (F to early-G, including some Cepheids) and red ones (late-G to M). Most of them have K spectral types.

Table 1: Sample of bright giants and supergiants, i.e. (super)giants, contained in the target clusters.

Cluster	Age (Ma)	(Super)giants		
		Blue	Yellow	Red
NGC 2345	60	2	0	6
NGC 3105	30	2	1	5
NGC 6067	90	2	2	12
NGC 6649	60	0	2	3
NGC 6664	50	0	1	5
Trumpler 35	40	0	1	4

On the one hand, we carried out a classical photometric analysis study of every cluster in a consistent way by strengthening the photometry (our own or archival) with low- or moderate-resolution spectroscopy. In this manner, besides the characterisation of the cluster itself, we obtain the age and mass of its evolved stars. On the other hand, from high-resolution spectroscopy (R = 48 000) taken with FEROS ([13]), an échelle spectrograph mounted on the 2.2-m telescope at the La Silla Observatory (Chile), we characterised these stars by calculating both their atmospheric stellar parameters and chemical abundances.

In every cluster we performed the spectral analysis, when possible, for both blue (i.e. B-type giants and A supergiants) and FGKM stars. In the first case we used the technique described by [5] with a grid of FASTWIND synthetic spectra for deriving the atmospheric stellar parameters and, only for the earliest stars, some chemical abundances (C, N, O, Si, and Mg). For the FGK stars, the bulk forming our sample, we employed a tailored version of the STEPAR code [22] based on equivalent widths with the iron linelist of [10] an a grid of MARCS synthetic spectra. For these stars we obtained the abundances for Li, O, Na, Mg, Si, Ca, Ti, Ni, Rb, Y, and Ba. Finally, for the M-type stars we only could roughly estimate their stellar parameters by using the method described by [8] with the same grid used for the FGK stars.

3 Results

In this work we have performed the most complete study to date of the clusters contained in our sample. The in-depth analysis of NGC 3105 (see [2]) and NGC 6067 ([3]) are already available. For the remaining clusters the studies are going on and final results will still take some time.

For the first time, a detailed spectroscopic analysis has been carried out on stars of NGC 3105, NGC 6649, NGC 6664 and Trumpler 35. For the other two clusters, NGC 2345 and NGC 6067, the number of objects studied here is higher than that reported in the only paper previously published in each case. In this age range, our sample represents half the clusters observed spectroscopically and 87% of the evolved stars analysed.

We have worked in a very consistent way and our results show a great reliability. Stars according to their $\log g$ and $\log T_{\rm eff}$ (derived spectroscopically) occupy positions on HR diagrams in good agreement with their expected evolutionary stage for the cluster age, inferred photometrically from the best-fitting isochrone (see Fig. 1).

For all clusters, using iron abundance as a proxy, we obtained metallicities compatible with the Galactic gradient derived from Cepheids ([9]), although our values are systematically somewhat lower (see Fig. 2). Chemical abundances are also compatible with the Galactic trend observed in the thin disc ([6], [1]) as well as the theoretical scenario which describes the chemical evolution of the Milky Way ([14]). Particularly noteworthy is the overabundance of [Ba/Fe] found in our sample, which probably supports the enhanced *s*-process and the additional contribution of the *i*-process suggested to explain the enrichment of Ba in young open clusters (see e.g. [7] and [16]).

Some of our obsevations conflict with current stellar evolution models. By the one hand, PARSEC models ([4]) fail when predicting the existence of Cepheids at supersolar metallicity in the age range in which we have worked. At metallicity higher than the solar value the blue loop decreases rapidly and moves away from the instability strip, where Cepheids spend almost their entire life. By the other hand, the observed ratios of evolved supergiants do not agree with those predicted by Geneva models ([11]), in which stars of 7–9 $M_\odot$ pass a significant fraction of their lifetime as blue supergiants in the blue loop, whereas these objects are usually observed leaving the main sequence.

Finally, we have covered a range of masses between 5.5–9.5 $M_\odot$. We have not found any significant trend in the chemical composition from red luminous giants to supergiants. We have not spotted any super-AGB star either. From an observational point of view, the transition of the spectral types observed in our sample, from medium- or late-K II/Ib to

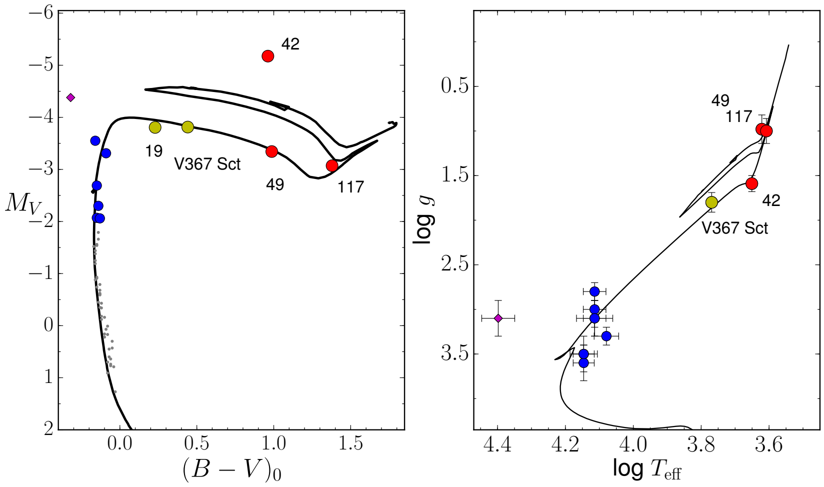

Figure 1: An example of the reliability of our results in the analysis of NGC 6649. Left: Dereddened $M_{\rm V}/(B-V)_0$ diagram. Right: $\log g\,/\log T_{\rm eff}$ Kiel diagram. Symbols are the same in both diagrams: the black line is the best-fitting isochrone (the same in both panels), the magenta diamond represents an extreme Be star, blue circles represent B stars (dwarfs and giants), whereas yellow and red circles are for F and K supergiants, respectively. Because of its binary nature star 42 occupies a wrong position on both diagrams. It has only been included in the figure to show all the cluster supergiants.

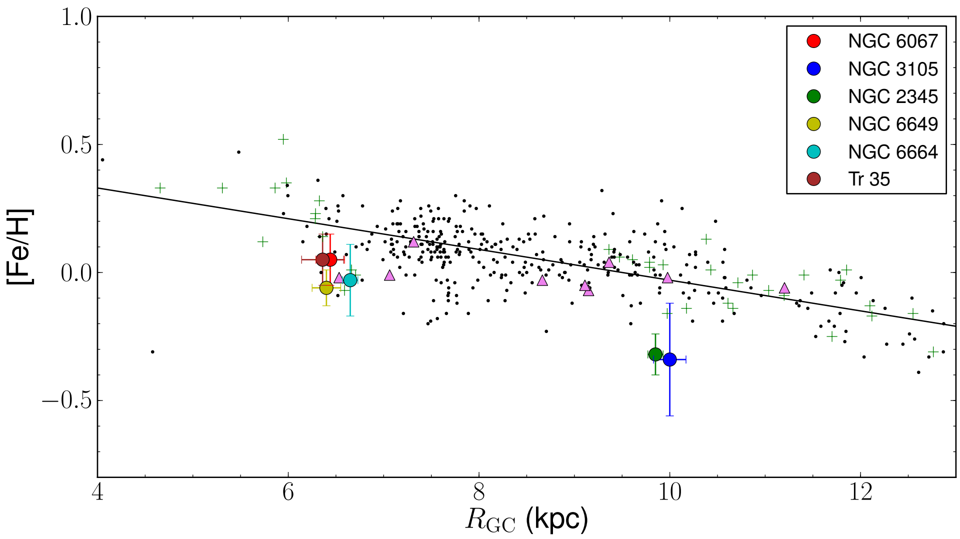

Figure 2: Iron abundance gradient in the Milky Way (black line) found by Genovali et al. 2014 ([9]) from Cepheids studied by them (green crosses) or taken from the literature (black dots). Pink triangles represent young open clusters (<500 Ma) compiled by [18]. Finally, coloured circles are the clusters studied by us.

early-M Ib, might be related to the AGB/RSG mass boundary at solar metallicity.

Acknowledgments

This research is partially supported by the Spanish Ministerio de Economía y Competitividad (MINECO) under grants BES-2013-065384 and AYA2015-68012-C2-2-P.

References

[1] Adibekyan, V. Th., Sousa, S. G., Santos, N. C., et al. 2012, A&A, 545, 32

[2] Alonso-Santiago, J., Negueruela, I., Marco, A., et al. 2018, A&A, 616, 124

[3] Alonso-Santiago, J., Marco, A., Negueruela, I., et al. 2017, MNRAS, 469, 1330

[4] Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127

[5] Castro, N., Urbaneja, M. A., Herrero, A., et al. 2012, A&A, 542, 79

[6] Delgado-Mena, E., Tsantaki, M., Adibekyan, V. Th., et al. 2017, A&A, 606, 94

[7] D'Orazi, V., Magrini, L., Randich, S., et al. 2009, ApJ, 693, 31

[8] García-Hernández, D. A., García-Lario, P., Plez, B., et al. 2007, A&A, 462, 711

[9] Genovali, K., Lemasle, B., Bono, G., et al. 2014, A&A, 566, 37

[10] Genovali, K., Lemasle, B., Bono, G., et al. 2013, A&A, 554, 132

[11] Georgy, C., Ekström, S., Eggenberger, P., et al. 2013, A&A, 558, 103

[12] Ibeling, D. & Heger, A. 2013, ApJ, 765, 43

[13] Kaufer, A., Stahl, O., Tubbesing, S., et al. 1999, The Messenger, 95, 8

[14] Magrini, L., Sestito, P., Randich, S., & Galli, D. 2009, A&A, 494, 95

[15] Mermilliod, J. C., Mayor, M., & Udry, S. 2008, A&A, 485, 303

[16] Mishenina, T., Pignatari, M., Carraro, G., et al. 2015, MNRAS, 454, 1585

[17] Negueruela, I., Alonso-Santiago, J., Tabenero, H. M., et al. 2017, MmSAI, 88, 368

[18] Netopil, M., Paunzen, E., Heiter, U., & Soubiran, C. 2016, A&A, 585, 150

[19] Podsiadlowski, Ph., Langer, N., Poelarends, A. J. T., et al. 2004, ApJ, 612, 1044

[20] Smartt, S. J. 2015, PASA, 32, 16

[21] Smartt, S. J. 2009, ARA&A, 47, 63

[22] Tabernero, H. M., Dorda, R., Negueruela, I., & González-Fernández, C. 2018, MNRAS, 476, 3106