Mem. S.A.It. Vol. 88, 368

Memorie della

Open clusters as laboratories for the AGB/SN mass transition

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Abstract. Open clusters provide natural laboratories to study stellar evolution, as well as astrophysical context for stars in short evolutionary stages. To investigate the divide between stars that will die as supernovae and those which will end their days as heavy white dwarfs, we are conducting a comprehensive study of open clusters in the age range from ∼30 to 100 Myr. Our sample is limited to clusters with a sizeable population of evolved stars, which can provide constraints individually. The oldest cluster in our sample, NGC 6067, presents a very large population of red giants with masses of $6\,M_{\odot}$ and two Cepheids occurring at supersolar metallicity, for which Padova models predict that blue loops will not extend to the instability strip. Our clusters cover a broad range of metallicities, but the strong effects predicted by evolutionary models are not readily seen in the observational diagrams. The distribution of spectral types seems to be driven mainly by age. Combination of data for our whole sample provides statistically significant data, with more than 70 evolved stars in 8 clusters, for which we will obtain parameters and abundances.

Key words. stars: evolution, stars: supergiants, stars: fundamental parameters, – open clusters and associations – Hertzsprung-Russell and colour-magnitude diagrams

1. Introduction

Evolved stars in open clusters are our best laboratories to carry out bench tests for theoretical evolutionary tracks. While the main sequence (MS) phase is very well reproduced by all existing codes, post-MS evolution is less well understood. After the end of H burning in their cores, stars evolve towards lower effective temperatures, $T_{\rm eff}$, and become, according to their masses, red giants (RGs) or supergiants (RSGs). For initial masses spanning the divide between intermediate and high-mass stars, loops in the HR diagram are expected to bring the stars back to the yellow supergiant region, where they can behave as classical Cepheids (e.g. Chiosi et al. 1992). As an example, in the most recent Geneva tracks (Ekström et al. 2012), stars of solar composition with masses between 5 and 9 $M_{\odot}$ experience these loops both for zero initial rotation and moderately-high initial rotation, while older isochrones showed this behaviour at higher masses (Schaller et al. 1992), up to close to 12 $M_\odot$. Indeed, the exact mass range for which these loops happen depends on the physics of the stellar interior, generally modelled via poorly understood parameters (e.g. Chiosi et al. 1992; Mowlavi & Forestini 1994; Salasnich et al. 1999; Meynet & Maeder 2000).

These effects are not only crucial to understand Cepheid loops. They also determine whether a star of a given mass will explode as a supernova or leave behind a massive white dwarf. Modern models (Poelarends et al. 2008; Doherty et al. 2015, and throughout these proceedings) indicate quite high values (approaching 10 $M_\odot$) for this transition at solar metallicity. On the other hand, observations of SN progenitors in the Local Universe suggest that the frontier can be even below 8 $M_\odot$ (Smartt 2015), though this interpretation is to a large extent dependent on a number of assumptions.

Given these uncertainties, we have started an observational programme to study young open clusters in the age range from ∼30 to 100 Myr. We intend to find answers to a number of questions that can have a bearing on all these issues: Are there observational clues of the transition from intermediate to high-mass stars? Do the observed properties of evolved stars of a given mass depend strongly on metallicity? Is it reasonable to expect an exploding star of a given mass and metallicity to have some preferred spectral type?

Unfortunately, due to the rarity of high-mass stars and the short duration of the post-H-core-burning phase, most young open clusters are only moderately useful as testbeds because of low number statistics (e.g. Ekström et al. 2013). For ages above 100 Myr, on the other hand, the number of red giants (RGs) increases for a given cluster mass, meaning that several clusters are known sporting large populations of RGs (see Mermilliod et al. 2008).

2. Sample, observations and analysis

To beat low number statistics, we have selected a sample of open clusters that contain at least five evolved stars. Since clusters in the age range of interest have their MS turn-offs between B3 V and B5 V, we count as evolved stars, A-type, yellow (F to early-G, including Cepheids) and red (late G to M) supergiants or bright giants.

According to simple stellar population simulations by Messineo et al. (2009) an evolved population of five stars at ∼ 50 Myr implies an initial mass ∼ 2000 $M_\odot$ for the cluster. Unfortunately, we know of no massive clusters in this age range, although the existence of several younger clusters with masses > 10 000$M_\odot$ (e.g. Negueruela 2014) suggests that they should be present in the Milky Way disk. The list of clusters selected for this work is shown in Table 1.

In all these clusters, we have obtained high-resolution spectra of the evolved stars and then performed a homogeneous analysis using MARCS and ATLAS models. The exceptions are the two Berkeley clusters, where the stars are too faint and we have used intermediate-resolution spectra for the analysis.

In addition, we are performing model fits using the FASTWIND code (Puls et al. 2005) to the spectra of blue stars (Fig. 1). For some clusters, comprehensive photometric studies exist and we have simply used archival data to complement our spectroscopic analysis. The first example of this kind of work is our in-depth analysis of NGC 6067 (Alonso-Santiago et al. 2017). In other cases, we have obtained our own deep photometry.

3. Results

The final product of our survey will be a collection of young open clusters for which parameters have been derived in a homogeneous way. This will include metallicities calculated in a consistent way for a sample twice as large as that of Luck (1994). We hope that the global analysis of the whole sample will help constrain the divide between intermediate and high-mass stars. Meanwhile, our observations are beginning to show some limitations of existing stellar evolutionary models.

We find that NGC 6067 is a rather massive cluster (initial mass > 5 000$M_\odot$) of supersolar metallicity (+0.2 dex). The presence of two Cepheids at an age ∼ 90 Myr requires blue loops to reach the instability strip. This does not happen when we use the old (Marigo

Table 1. Clusters included in our sample. Values in italics correspond to parameters that we have not determined yet from our analysis and are taken from the literature.

Cluster Name	Age (Myr)	[Fe/H]	Supergiants Blue	Supergiants Yellow	Supergiants Red
NGC 2345	*60*	−0.4	2	0	6
NGC 3105	35	−0.4	2	1	5
NGC 6067	90	+0.2	2	2	12
NGC 6649	*60*		0	2	3
NGC 6664	*50*		0	1	5
Trumpler 35	*40*		0	1	4
Berkeley 51	40	−0.1	0	4	5
Berkeley 55	*50*		0	1	5

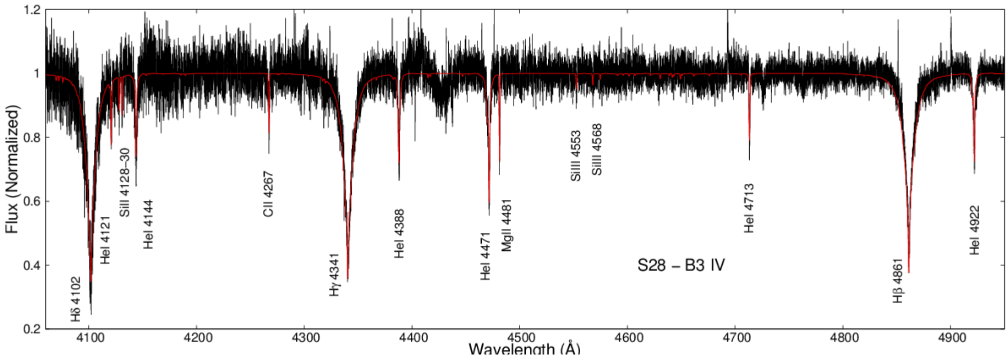

Fig. 1. An example of a model fit. The observed spectrum corresponds to one of the stars close to the turn-off of NGC 2345, while the model has been generated with FASTWIND.

et al. 2008) Padova isochrones that considered $Z_\odot = 0.019$ (see Fig. 2). If we use more modern Parsec isochrones (Bressan et al. 2012) and take $Z_\odot = 0.015$, the loop extends more towards cooler temperatures, but still fails to reach the position of the Cepheids.

Meanwhile, Geneva isochrones that include the effect of rotation (Georgy et al. 2013) predict that stars of $7-9M_\odot$ will spend a significant part (almost half) of their time in the blue loop as blue supergiants (with temperatures typical of A stars). The numbers in Table 1 already show that this is very unlikely to happen. Indeed, all the A-type supergiants that we find in clusters between 30 and 60Myr occupy positions consistent with stars just leaving the main sequence. There is no evidence for any blue supergiant having looped back from the red part of the HR diagram.

Two of our clusters, NGC 3105 and NGC 2345, have very low metallicities for the Galactic disk (≈ −0.4 dex). These have been confirmed through independent analyses. Even at these sub-LMC metallicities, many of the red supergiants have late spectral types (down to M1 Iab in NGC 3105, which is younger). Evolutionary tracks place the bulk of the evolved stars at hotter temperatures (spectral types K0 – K2) at this metallicity. Our data suggest that the typical spectral type of evolved stars in Milky Way clusters is driven mainly by age, as had been suggested by Mermilliod (1981) with metallicity only playing a secondary role. When our study is complete, we will be able to ascertain this hypothesis.

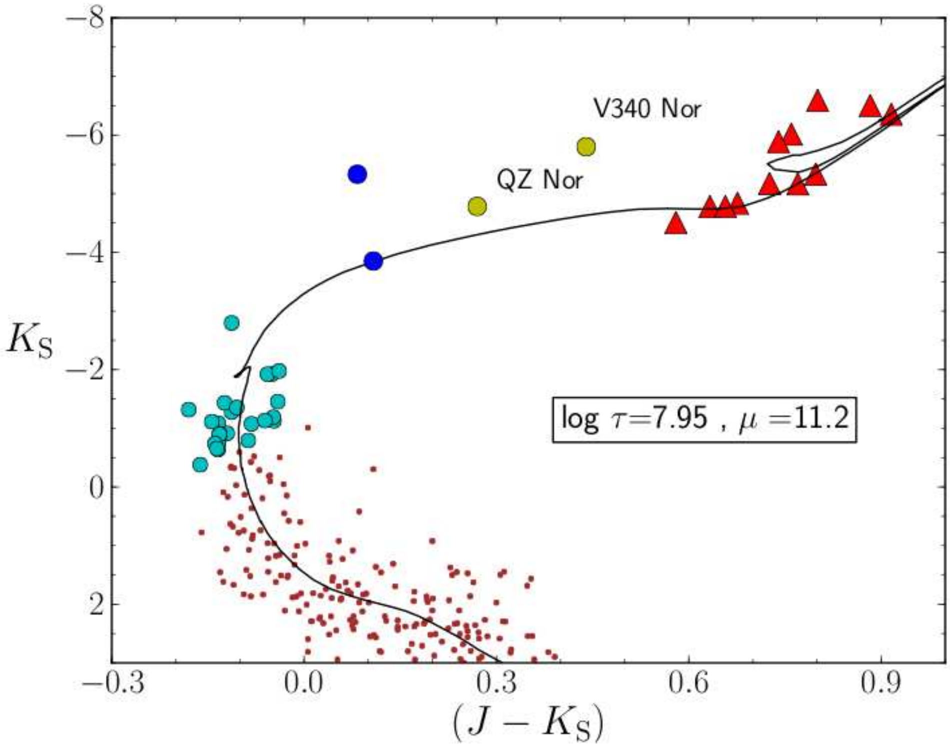

Fig. 2. Colour-magnitude diagram for confirmed members of NGC 6067. The two cluster Cepheids are named. The triangles are twelve red (super)giants that seem to follow the Marigo et al. (2008) isochrone very well. The isochrone, though, does not predict any Cepheid variables at this metallicity.

Acknowledgements. Thanks to the organization of the AGB-SN meeting for a superb work. This research is partially supported by the Spanish Ministerio de Economía y Competitividad (Mineco) under grant AYA2015-68012-C2-2-P (MINECO/FEDER).

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