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NGC 6067: A young and populous open cluster

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Abstract

NGC 6067 is a young open cluster hosting the largest population of evolved stars among known Milky Way clusters in the $50-100$ Ma age range. It thus represents the best laboratory in our Galaxy to constrain the evolutionary tracks of $5-7\,M_{\odot}$ stars.
We have used high-resolution spectra of a large sample of bright cluster members (45), combined with archival photometry, to obtain accurate parameters for the cluster as well as stellar atmospheric parameters. We derive a distance of 1.78 ± 0.12 kpc, an age of 90 ± 20Ma and a tidal radius of $14.8^{+6.8}_{-3.2}$ arcmin. We estimate an initial mass above $5\,700\,M_{\odot}$, for a present-day evolved population of two Cepheids, two A supergiants and 12 red giants with masses $\approx 6\,M_{\odot}$.
We also determine chemical abundances of Li, O, Na, Mg, Si, Ca, Ti, Ni, Rb, Y, and Ba for the clump stars. We find a supersolar metallicity, [Fe/H]=$+0.19 \pm 0.05$, and a homogeneous chemical composition, consistent with the Galactic metallicity gradient. The presence of a Li-rich red giant, star 276, is also detected. An over-abundance of Ba is found, supporting the enhanced *s*-process.
The mass of V340 Nor, a Cepheid that seems younger than the cluster itself, suggests that it has been a mass gainer in an interacting binary. The ratio of blue to red giants is smaller than one, in agreement with models with moderate overshooting, but the properties of the cluster Cepheids do not seem consistent with current Padova models for supersolar metallicity.

1 Introduction

Stellar clusters are excellent laboratories for the study of stellar evolution because all the stars in a cluster are formed from the same interstellar cloud, at roughly the same time with a similar chemical composition. Their evolution, thus, will mainly depend on their initial mass. In very populous clusters, such as globular clusters, all the evolutionary stages are represented, and stellar evolution can be directly inferred. On the contrary, in young open clusters, generally rather less populous, only glimpses of the evolution of high- and intermediate-mass stars are provided. As a consequence, the physics of the most massive intermediate-mass stars ($5\,M_{\odot} < M_{*} < 9\,M_{\odot}$) is poorly constrained.

Type II-P SN, the most common SNe in the Local Universe, come from low-luminosity red supergiants [23]. Observationally, the lower limit for the mass of core-collapse SN progenitors is set at $M_{*} = 8.5^{+1.0}_{-1.5}\,\mathrm{M}_{\odot}$ [24], in mild to moderate conflict with stellar models [8] The possibility of explosions from stars with masses as low as $7\,\mathrm{M}_{\odot}$ has lead to renewed interest in the post-MS evolution of stars in this mass range, with emphasis on the super AGB phase [20] or the detectability of massive Oxygen-Neon white dwarfs [7, 3].

NGC 6067 is a young open cluster that occupies a central position in the Norma Cloud, a rich region projected towards the central part of the Galactic disc. It is well known for hosting two classical Cepheids [5]: V340 Nor and QZ Nor. Thackeray et al. [26], performed the first complete study of this cluster, combining UBV photometry, spectral classification and radial velocity.

The age of NGC 6067 is not well known yet and so, one of the main goals of this work is the determination of a reliable cluster age by using two independent methods. Different studies place it in the $50-100$ Ma range. On the one side, the confirmed membership of V340 Nor (a Cepheid with a period of 11.3 d) and the integrated spectrum of the cluster suggest an age around 50 Ma [21]. On the other side, according to the spectral classification published by Thackeray et al. [26], the most complete to date, NGC 6067 is similar to Pleiades in age. Recently, Majaess et al. [13] with new photometry obtained a younger age ($\log \tau = 7.9$) that fits the brightest cluster members (i.e. B-type and red giants).

Already in 1962, Thackeray et al. [26] suggested that NGC 6067 looked like a “young populous cluster”. Mermilliod et al. [15] confirmed via radial velocity measurements the membership of 14 luminous cool stars, most of which have been classified in the past, based on photographic spectra, as K Ib supergiants. The cluster is known to contain a large population of evolved stars: 14 B giants, at least two A/F supergiants, two Cepheids (F/G supergiants) and 12 late-G/early-K giants. Despite this richness, only one paper contains stellar atmospheric parameters and chemical abundances for a few members [12]. In this paper we fill this gap by determining parameters and chemical abundances for several dozen stars, placing NGC 6067 in the galactic context. Among these stars we want to characterise those located in the upper main sequence as well as the more evolved ones, so that we can also compare results provided from models of early stars and those of cool ones. Additionally, the new data presented in this work are not only important for the study of this particular cluster but they will serve to increase the statistics of evolved stars, with the aim of testing theoretical stellar evolution models.

2 Observations and data

We obtained high-resolution *echelle* spectra using FEROS (Fiber Extended Range Optical Spectrograph) mounted on the ESO/MPG 2.2-metre telescope at La Silla Observatory, in Chile. FEROS [9] covers the wavelength range from 3500 to 9200 Å, providing a resolving power of R = 48000. The exposure time of our spectra ranges from 600 to 4800 seconds to achieve a typical signal-to-noise ratio of S/N∼70-80 for the blue stars (in the 4000-5000 Å region) and S/N∼90-100 for the cool stars (6000-7000 Å). The spectroscopic reduction was performed using the FEROS-DRS pipeline. In total, we have spectra for 33 blue stars and 15 cool giants.

In order to complement the spectroscopic data we used the BV photometry of An et al. [1], downloading it from the WEBDA database[1]. We completed our dataset with JHK_S photometry from the 2MASS catalogue [22]. We selected stars with good-quality photometric flags inside a wide circle of radius 30′ around the cluster centre with the aim of determining the size of the cluster.

3 Results

3.1 Cluster parameters

Likely cluster members are selected among the observed stars based on radial velocity, position in the colour-magnitude diagrams (CMD) and chemical composition. Taking into account this selection we employed the isochrone-fitting method, using Padova isochrones [14], to determine the cluster age and distance. From the optical and infrared photometry, whose analysis is compatible within the errors, we derived a value of log $\tau = 7.95 \pm 0.10$ and distance modulus, $\mu = 11.25 \pm 0.15$, which correspond to an age of 90 ± 20 Ma and a distance, $d = 1.78 \pm 0.12$ kpc. Fig. 1 shows the 2MASS CMD, after correcting from reddening and extinction. Note the large number of evolved stars. In fact, this number is the highest found among the known Milky Way clusters studied by Mermilliod et al. [15] in the 50–100 Ma range, standing out NGC 6067 as the most massive cluster.

NGC 6067 is situated in a very rich region, making it hard to distinguish the cluster from the background. In order to estimate the cluster size we used bright B-type stars as tracers of the cluster extent (the neccesary conditions for an efficient selection are described in [18]). Then, with the cluster clearly enhanced, we fit the density profile to a three-parameters King-model [10], obtaining a tidal radius, r_t=$14.8^{+6.8}_{-3.2}$ arcmin (i.e. $7.7^{+4.0}_{-2.2}$ pc). All the stars observed in the present work are inside this radius, including QZ Nor, located ≈ 20 arcmin from the cluster centre, within the tidal radius upper limit, in the halo.

Once we know the cluster size we are able to calculate its mass by employing three different methods. In the first place we estimate the luminosity function in the J-band, after correcting from completeness and field star contamination (quantifying it in an external annulus surrounding the cluster, with the same area). In this way we obtained a cluster mass

[1]Available at http://univie.ac.at/webda/

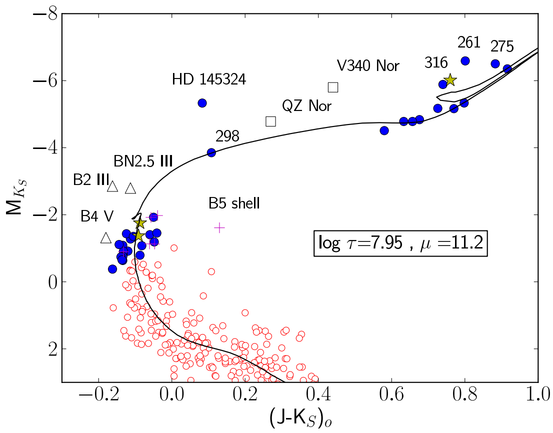

Figure 1: Deredened $M_K/(J - K_S)_0$ diagram. The open squares represent the Cepheids V340 Nor and QZ Nor, crosses are Be stars, binaries appear as star-symbols (note especially star 316), blue-straggler stars are represented by open triangles and all the other stars with spectra are filled circles. Open circles are stars with photometry from An et al. [1], but no spectroscopic observations. The black line is the best-fitting Padova isochrone, corresponding to log τ=7.95 and distance modulus, μ=11.2.

of 2600^{+1500}_{-800} M$_\odot$ down to the completeness limit, which corresponds to $M_J \approx +3.3$, roughly to a G0 V spectral type. Another alternative method for computing the cluster mass is the integration of the initial mass function (IMF). For this purpose we chose the multiple-part power law IMF defined by Kroupa [11] and set the free parameter of the IMF by counting stars at the top of the main sequence, from spectral type B6 V to B9 V, where the separation from the field population is easier. The cluster mass is 4000^{+1200}_{-600} M$_\odot$, compatible with the first method, since the spectral type G0 V represents around half of the IMF mass. Finally, we used the virial theorem once we found mass segregation, inferring a dynamically relaxed cluster. The resulting virial mass is 6100^{+3200}_{-1700} M$_\odot$, compatible within the errors with the two previous determinations.

All three methods seem to agree on a present-day mass around or slightly below 5000 $M_\odot$. The corresponding initial mass is roughly consistent with population synthesis models developed by Messineo et al. [16], who find an initial mass of $\approx 7000 \pm 2000$ for a cluster of 50–100 Ma containing 15 evolved stars. This suggests that NGC 6067 is the descendent of a young massive cluster, similar to those found close to the base of the Scutum arm [19]. The existence of these older populous clusters implies that such massive clusters have been forming regularly in the Galactic disc, and are not necessarily concentrated towards the tips of the long Bar.

3.2 Stellar atmospheric parameters and chemical abundances

We divided the sample in two groups: the early stars and the cool giants. We devised a procedure for both groups trying to ensure a self-consistent spectroscopic analysis. For the blue stars we employed the technique described by Castro et al. [2] to reproduce the main strong lines observed in the range 4000–5000Å. Two different radiative transfer codes were employed to generate two partially overlapping synthetic spectral grids: the first one uses KURUCZ atmospheric models from the ATLAS-APOGEE grid from 7000–14000 K. In hotter stars, the earliest B-types, FASTWIND synthetic spectra were used in order to enable non-LTE calculations. For cool stars we employed a modfied version of the STEPAR code [25] with a list of 83 Fe I-Fe II features and a grid of models from the ATLAS-APOGEE covering the range 3500–7000 K.

We tried to derive chemical abundances for hot stars, but most of our objects have very few metallic lines. Only for the two earliest (hottest) stars have we been able to determine abundances for a few elements (C, N, O, Mg, and Si). For the late-type stars we employed a method based on equivalent widths (EW) measured in a semi-automatic fashion using TAME for Na, Mg, Si, Ca, Ti, Ni, and Ba. We also measured EWs by hand for two special and delicate cases: Li and O. Finally for Rb we used stellar synthesis.

The cluster seems to be chemically homogeneous since all the stars, with the exception of the Cepheid QZ Nor, have within the errors the same chemical composition. The cluster metallicity is supersolar, [Fe/H]=0.19±0.05 dex, consistent with the galactic gradient. We found a Li-rich giant, star 276, with A(Li)=2.41. We derived a roughly subsolar [Y/Fe] against a supersolar [Ba/Fe] in good agreement with the dependence on age and galactic location found by Mishenina et al. [17]. The over-abundance of Ba supports the enhanced "*s*-process" suggested by D'Orazi et al. [4] to explain the enrichment of Ba observed in young open clusters, in apparent conflict with the standard model (see their fig. 2). In the Fig. 2 we plot the abundances derived in this work on top of the galactic trend: our values, within the errors, are compatible with those expected.

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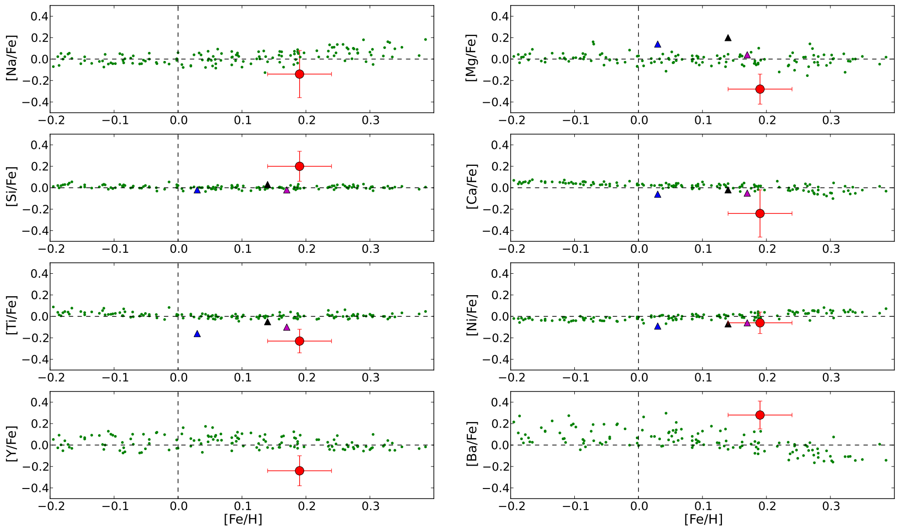

Figure 2: Abundance ratios [X/Fe] versus [Fe/H]. The green dots represent the galactic trends for the thin disc [6]. The much higher quality of their observational data ($R = 110\,000$ and $S/N \approx 850$ on average) is reflected in the low scatter. A red circle represents the average value, for NGC 6067 (error bars show the standard deviation).

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