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The Star Formation History of the Young Open Cluster NGC 2244: Study of the Binary Fraction

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Abstract

A star formation history (SFH) is the stellar record of the various processes that shaped a galaxy and star clusters since its birth to its current physical state. Studying the young open cluster NGC 2244, and in particular its massive stellar population, can improve our understanding of its formation mechanism, stellar evolution, feedback, and provide a basis for a better understanding of the formation of extragalactic star clusters. In this contribution, we present the first steps towards the derivation of the SFH of NGC 2244. We discuss the first results concerning the membership determination and the observed binary fractions of O- and B-type stars among NGC 2244. Finally, an overview of the forthcoming steps is also presented.

Keywords: Star Formation History, massive star, binary star

1. Introduction

Intermediate- and high-mass stars play an important role in the evolution of galaxies. Their impact on galaxies ranges from the trigger of stellar and planetary formation thanks to their powerful wind and energetic radiation (Bromm et al., 2009) to the production of compact remnants such as neutron stars or black holes during the end of their life as core-collapse supernovae, with such compact objects possibly leading to the formation of gravitational waves (Abbott et al., 2016). A detailed study of the initial conditions of massive star formation (e.g. Initial Mass Function, initial rotation, multiplicity status, initial chemical composition) among open clusters, and in our case among NGC 2244, will therefore bring key information to derive the birth conditions and early-stage properties (projected rotational velocity distribution, 3D kinematics, etc.) of the cluster. Obtaining such information is a crucial step towards the determination of the formation mechanism and life cycle of high- and intermediate-mass stars which, despite the importance of massive stars for a variety of branches in astronomy (e.g., nucleosynthesis, radiative, mechanical and chemical feedbacks, GW sources, Galaxy formation, among others), remains one of the most important unresolved problems in stellar astrophysics.

A key point to consider when carrying such a study, and especially when considering high- and intermediate-mass stars, is their multiplicity status. Indeed, it is now widely known that a substantial fraction of OB-type stars, up to $\sim 70\%$, are expected to be found in binaries (Sana et al., 2012; Moe and Di Stefano, 2017; Offner et al., 2023). What is presented in this contribution are the first steps towards the determination of the SFH of the NGC 2244 cluster, which consist in an accurate membership determination (Section 2) as well as a characterization of the binary status of the stars in our sample (Section 3). This binary status determination is of crucial importance as unrecognised binaries will lead to the wrong determination of fundamental properties and surface abundances of the stars.

2. Membership Determination

The membership determination has been done by making use of the last Gaia Data Release (Gaia DR3) and took into account all the stars with a G magnitude ≤ 14 and located in a radius of $45'$ around the center of NGC 2244, the star HD 46150 being used as the center reference. The condition on the magnitude in the G-band ensures that all the stars with a spectral type earlier than B9 ($M > 2$–$3M_{\odot}$), in a certain range of separations around the center to NGC 2244, are considered. The Gaia DR3 data allowed us to obtain the proper motions and parallaxes of the targets of interest where the parallaxes have been corrected for the parallax zero-point offset (Lindegren et al., 2021; Maíz Apellániz, 2022). The membership selection has been done based on the various criteria mentioned in Lim et al. (2021) in which the first selection is parallax-based. However, in parallel to this parallax constraint which consists in only keeping stars with a parallax in between 0.5 and 1 mas, we also analysed the stars with a parallax out of that range in order to hint possible runaway stars that could have been ejected from the cluster and for which we calculated their space motions. In the cases where a space motion larger than $30\,\mathrm{km\,s^{-1}}$ has been obtained, the runaway status could be confirmed (Blaauw, 1961).

After performing those selection criteria, our database consists of 63 O- and B-type stars (9 O-type and 54 B-type stars) for which we have spectroscopic data. A representation of the sample, using an optical image of the Digitized Sky Survey (DSS), can be found in Fig. 1 in which the red dots refer to B-type stars and the yellow ones to O-type stars.

3. Multiplicity Status Determination

The multiplicity status of the stars in our sample is derived by combining several observational techniques. Two different methods were used to measure the radial velocities of the stars in our sample for each epoch. In case of availability of multiple epoch observations, a Cross-Correlation Function (CCF) method (Zucker, 2003) has been used to detect radial velocity (RV) variations larger than a certain threshold defined by a statistical test in Sana et al. (2013). In the case where only one epoch of observation is available, we had no choice but to perform a Gaussian fit on a chosen spectral line in order to obtain the RV. In addition, it is interesting

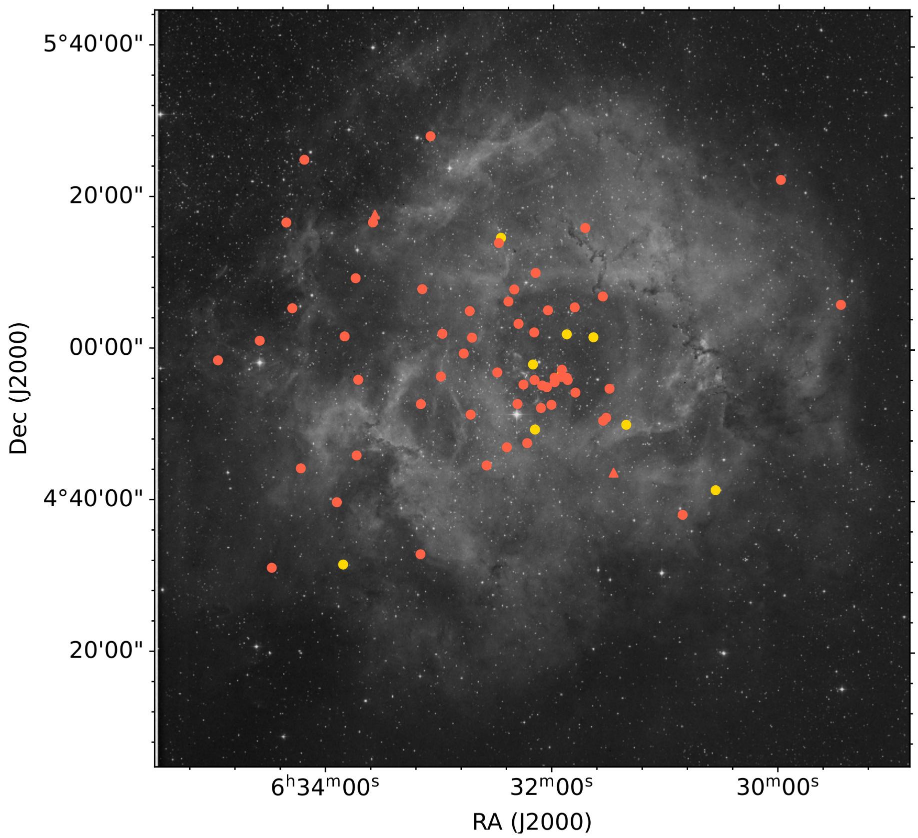

Figure 1: Representation of our sample superimposed on the optical image taken from the Digitized Sky Survey (DSS). Yellow dots refer to O-type stars and red dots to B-type stars. The positions of stars are relative to the coordinate R.A. = $06^{h}31^{m}55.^{s}52$, DEC. = $+04°56'34''.29$ (J2000). The spectral classification is drawn from Simbad.

to note that seven stars, among which two B-type stars have passed the membership selection, have been flagged as binary candidates due to the presence of asymmetry in given spectral lines.

The second technique that has been used to complement this search for binary stars is the photometry. For this purpose, light curves obtained by the TESS space mission have been extracted and analysed to detect eventual eclipsing binaries. This search retrieved the binary nature of two known binary stars and detected pulsation or the presence of ellipsoidal variations due to the deformation of stars for a few stars. Concerning the detection of unknown binary stars, the study of the light curves is still ongoing and will soon complete the search for binaries.

The last analysis that will be made concerning the binarity concerns two parameters that can be drawn from the Gaia DR3 data. The first one is the *Image Parameter Determination goodness of fit harmonic amplitude*, namely the `IPDgofha` parameter. As its name indicates, it measures the amplitude of the variation of the Image Parameter Determination goodness of fit as a function of the position angle of the Gaia scan detection. A significant value of this parameter could hint that the source has some non-isotropic structure (e.g. as a binary system) at least partially resolved by Gaia. The second parameter of interest is the *Image Parameter Determination fraction multi-peak*, namely the `IPDfmp` parameter. This parameter gives, in percentage, the fraction of windows of observation in which the IPD algorithm has detected a double peak. This would mean that the target may in fact be a visually resolved double star. For a more in-depth explanation of those parameters, the reader can refer to https://gea.esac.esa.int/archive/documentation/GDR3/. What has been done in the frame of this work is the construction of a database of O- and B-type stars with known companions at different separations based on different catalogues (SMASH+: Sana et al. (2014), all-sky survey made with the Fine Guidance Sensor on the Hubble Space Telescope: Aldoretta et al. (2015); Caballero-Nieves et al. (2014), AstraLux: Maíz Apellániz (2010); Peter et al. (2012); Maíz Apellániz et al. (2019), long baseline and speckle interferometry: Lanthermann et al. (2023); Le Bouquin et al. (2017); Mason et al. (2009) and adaptative optics: Roberts et al. (2007); Turner et al. (2008)). The two previously mentioned parameters have then been retrieved for every star of the database to see how those parameters behave for known binary stars. The idea is to use those parameters as a calibration and to check for similar behaviours when retrieving those parameters for the stars in our NGC 2244 sample. To ensure that the conclusions will be reliable, no concrete and definitive conclusion can be drawn at this point as this analysis is still ongoing.

The current distribution of the number of epochs as well as the distribution of the RV obtained by a gaussian fit can be found in Fig. 2.

4. Results

The combination of the three methods detailed in Section 3 will allow a census of short and long-term binary stars in our sample. For the sake of completeness, the first method of binary detection making use of the CCF method has been applied to our entire spectroscopic sample, regardless of the membership selection. This spectroscopic analysis detected a RV

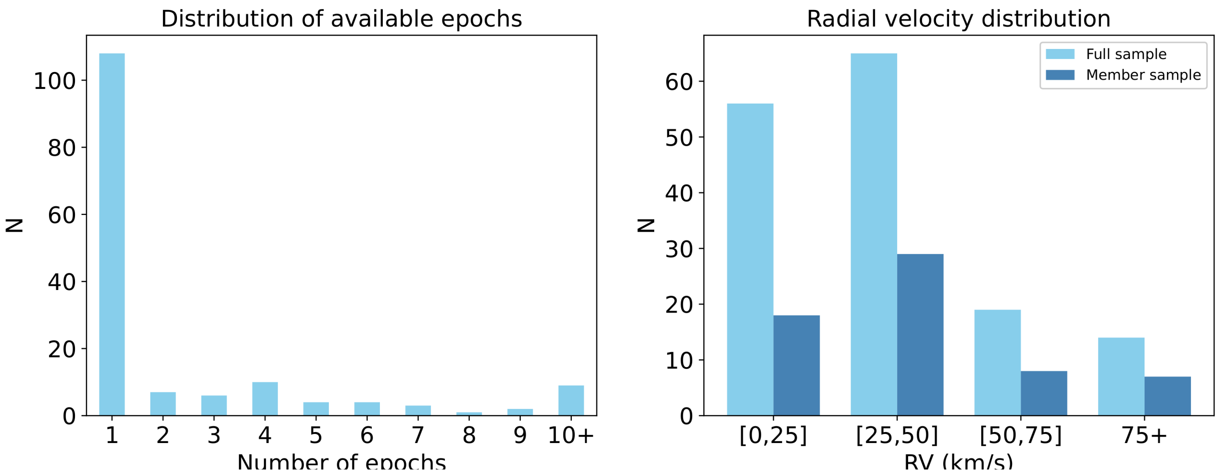

Figure 2: (*Left*) Distribution of available epochs in our database. (*Right*) Distribution of RV obtained by Gaussian fit for the entire sample in light blue and for the member sample in dark blue.

shift that hints towards a binary nature for four O-type stars (all have passed the membership selection) and eight B-type stars (six of them have passed the membership selection). Let us stress once again that, in addition to the results of this spectroscopic analysis, seven stars of the initial sample (two of them have passed the membership selection) are flagged as possible binary candidates because of asymmetry of given spectral lines.

Thanks to the results of the multiplicity status determination, it is possible to derive the *observed* binary fractions of O- and B-type stars inside NGC 2244. It is important to keep in mind that, firstly, those numbers might be submitted to changes when the results of the two last techniques mentioned in Section 3 will be available. And secondly, those fractions will then be corrected for the observational biases that one might encounter when studying massive stars in open clusters. It is only after such corrections that the intrinsic binary fractions will be obtained and therefore, the fractions drawn at this point are said to be the *observed* binary fractions. After the membership selection and only taking into account the stars for which the CCF method detected a RV shift hinting towards a binary nature, the observed binary fractions are found to be equal to $\sim 57\%$ for O-type stars and $\sim 11\%$ for B-type stars. If one also considers the binary candidates to calculate the observed binary fraction, the fraction rises up to $\sim 15\%$ for B-type stars while remaining unchanged for O-type stars.

5. Future Perspectives and Conclusions

Even if the multiplicity status determination is only the beginning towards the derivation of the stellar and cluster properties, it is a crucial step. It ensures a larger reliability in the following steps as it will allow to apply spectral disentangling for binary stars to separate the individual contributions of each component from the observed spectra and study them as if they were single stars. All the stellar parameters such as projected rotational velocities, effective temperatures, surface gravities, and surface abundances, will then be constrained either for the presumably single stars or for the individual components of binary systems by applying non-Local thermodynamic equilibrium (non-LTE) atmosphere modelling codes. Those parameters will then be compared to evolutionary tracks to predict the ages and initial masses of the stars. On the one hand, the global age distribution will be scrutinised to spot possible different formation episodes. On the other hand, the predicted initial masses will be used to describe the Initial Mass Function. The inferred ages and masses will be combined to finally infer distributions of age and initial mass in various samples of stars.

Further Information

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Author contributions

This work is part of a collective effort with contributions from all the co-authors.

Conflicts of interest

The authors declare no conflict of interest.

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