Fine structure of the main sequence of NGC 2516 scrutinized with Gaia and ASteCA

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Resumen / Investigamos la estructura fina del cúmulo abierto NGC 2516. Este es un cúmulo abierto extendido y relativamente joven que subtiende más de dos grados en el cielo, situado a unos pocos cientos de PARSECs (< 400 pc) del Sol. Recopilamos datos de Gaia DR2 (magnitud G hasta G=19, índice de color BP-RP, movimientos propios y paralaje) para más de 400 000 estrellas en una región de 6 grados de lado, y aplicamos nuestro algoritmo de membresía PYUPMASK. Los datos de *GAIA* para los miembros más probables se correlacionaron con fotometría UBVI. Finalmente, usamos nuestro código ASTECA para obtener los parámetros fundamentales del cúmulo.

Abstract / The fine structure of the open cluster NGC 2516 is investigated. This is an extended and relatively young open cluster subtending over two degrees in the sky, situated at just a few hundred PARSECs (< 400 pc) from the Sun. We collected Gaia DR2 data (G magnitude down to G=19, BP-RP color index, proper motions, and parallaxes) for more than 400 000 stars in a region of 6 degrees on a side, and applied our membership algorithm PYUPMASK. *GAIA* data for the most probable members was cross-matched with available UBVI data. Finally, we run our ASTECA code to obtain the fundamental cluster parameters.

Keywords / galaxies: star clusters: general — open clusters and associations: general — techniques: photometric — methods: statistical

1. Introduction

NGC 2516 is a middle-age open cluster placed in the Carina constellation at about 20 deg from Carina OB1 at a distance of about 400 pc. Its central region is shown in Fig. 1. It is little affected by reddening and shows a well-defined main sequence. Because of this, it has the been subject of many investigations in the past, particularly spectroscopic ones (Jackson & Jeffries, 2012; Jackson et al., 2016; Bailey et al., 2018; Torres Hernandez et al., 2020; Healy & McCullough, 2020). The area of NGC 2516 is too large to be covered in a typical deep photometric survey. In addition, the recovery of information from faintest stars is a painful task because of the limiting magnitude produced by light contamination of bright stars. For this fact, past studies concerning the determination of the the main cluster parameters and its IMF were usually restricted to the central region. This suggests that distant members shifted by mass segregation were not taken into account.

A relevant feature in NGC 2516 is the presence of a vivid binary star sequence (visible in the CMD of the analyzed frame shown in Fig. 2), but again, incompleteness in the weak part of the sequence for the above mentioned factors does not allow certainty about the binary stars fraction. Despite being a nearby object, values derived for its distance vary by about 90 pc according to different authors.

NGC 2516 is thus an ideal candidate to prove the power of our automatic analysis tool, ASTECA (Perren et al., 2015). We take advantage of the Gaia DR2 deep coverage in photometry, proper motions, and parallax, to perform a re-analysis of the main finding yielded by Sung et al. (2002) who carried out the most extensive work up to now.

2. Methodology

We made use of Gaia DR2 data including positions, parallaxes, proper motions, G magnitudes and color indices BP-RP provided for all the stars in a rectangle 6x6 degrees on a side centered in the adopted cluster center (α=07:58:04, δ=-60:45:27). This way we ensure the whole cluster area is under analysis. This size allows a good estimation of the stellar background and reduces the loss of marginal cluster members produced by mass segregation, if present.

To obtain the subset of most probable members the proper motions were processed with PYUPMASK (Pera et al., 2021); an enhanced version of the UPMASK algorithm by Krone-Martins & Moitinho (2014). This leaves us with almost 1700 estimated members, as shown with blue symbols in Fig 2. The binary sequence slightly above and to the right of the main sequence is clearly visible. This subset is subsequently analyzed with ASTECA, in order to estimate the cluster's fundamental parameters: metallicity, age, distance, extinction, mass, and binary fraction. The process is applied

Figure 1: A 60x53 arcmin image of the central part of NGC 2516. North is up, East to the left.

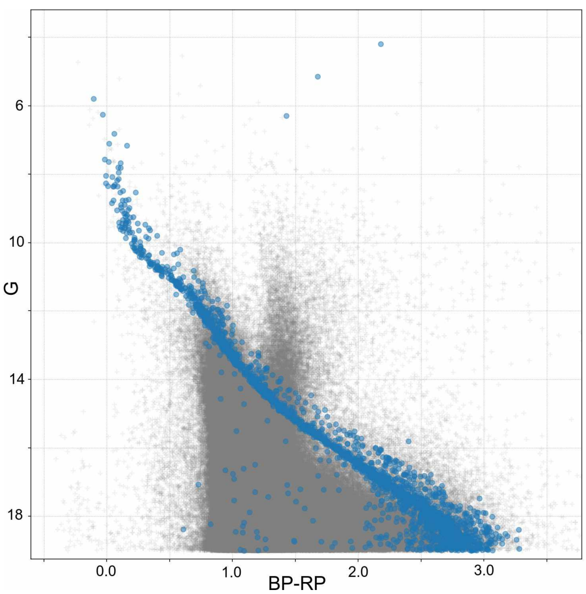

Figure 2: Color-magnitude diagram (CMD) of NGC 2516. Members estimated with pyUPMASK are shown in blue, field stars are shown in grey.

in three stages, starting with a wide range in metallicity and gradually reducing it. As a sub-product of this process ASteCA also estimates individual masses for each probable member, as well as their probability of being a binary system (instead of a single star).

Finally, with the individual masses and binary probabilities estimated by ASteCA, we analyzed the initial mass function (IMF) of the cluster sequence.

3. Results

In Fig 3 we show the fundamental parameters estimated by ASteCA, along with their uncertainties. We employed PARSEC v1.2 isochrones (Bressan et al., 2012).

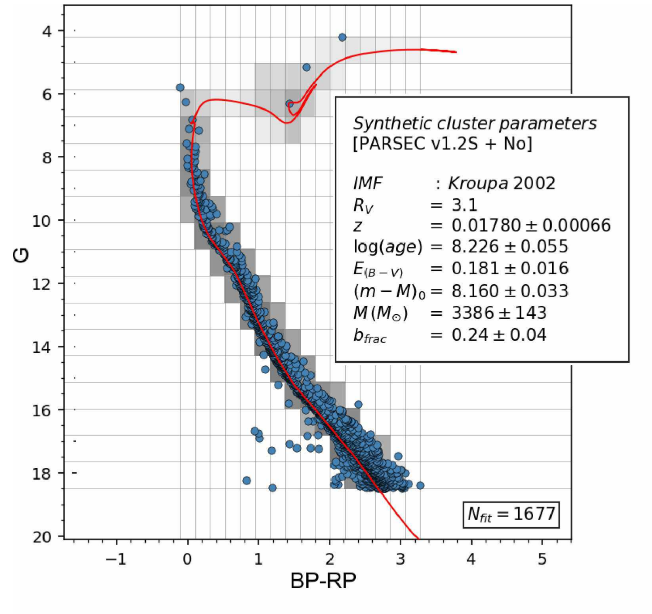

Figure 3: Fundamental parameters estimated by ASteCA for the NGC 2516 open cluster. N_{fit} is the number of members stars used in the analysis.

The mean fit is shown by the red isochrone and the corresponding parameter values in accompanying text box.

Age, extinction and metallicity values are consistent with the findings of Sung et al. (2002), but the distance is not. In fact, these authors assigned a sub-solar value whereas we find Z = 0.0178 a supra-solar value (solar metallicity $Z_\odot$=0.0152). They also estimate a distance modulus of 7.77 mag (360 pc), but our analysis gives a significantly larger value of 8.16 mag (429 pc). This translates to a difference of more than 68 pc.

The distance modulus estimated by ASteCA is comparable to that obtained via parallax analysis which is 2.41 mas (415 pc) using an offset of +0.029 on the parallax as indicated by Lindegren et al. (2018). We are thus confident in the correctness our estimation of the cluster's distance over that of Sung et al.

The binary fraction is also discrepant. Sung et al. estimate a value of around 40%, whereas ASteCA estimates a little less than 25%. Since our value comes from generated synthetic clusters and Sung's estimate comes from counting stars assigned individual distances (a more indirect estimation), we again are confident in its closeness to the real value.

Finally, we applied the maximum likelihood method described in Khalaj & Baumgardt (2013) to estimate the slope of the IMF. This method works on individual mass estimates, and does not depend on binning the masses. The results are shown in Fig. 4 as black dashed lines for the single star sequence (top plot), and binary systems sequence (bottom plot). For comparison we show IMF fits produced using simple histograms with 5, 10, and 25 mass bins (colored crosses), and analytical IMFs (Salpeter, 1955; Miller & Scalo, 1979; Kroupa, 2001; Chabrier, 2003) as colored dashed lines. The vertical scale is normalized.

The slope values found in our analysis are ∼3.23 and

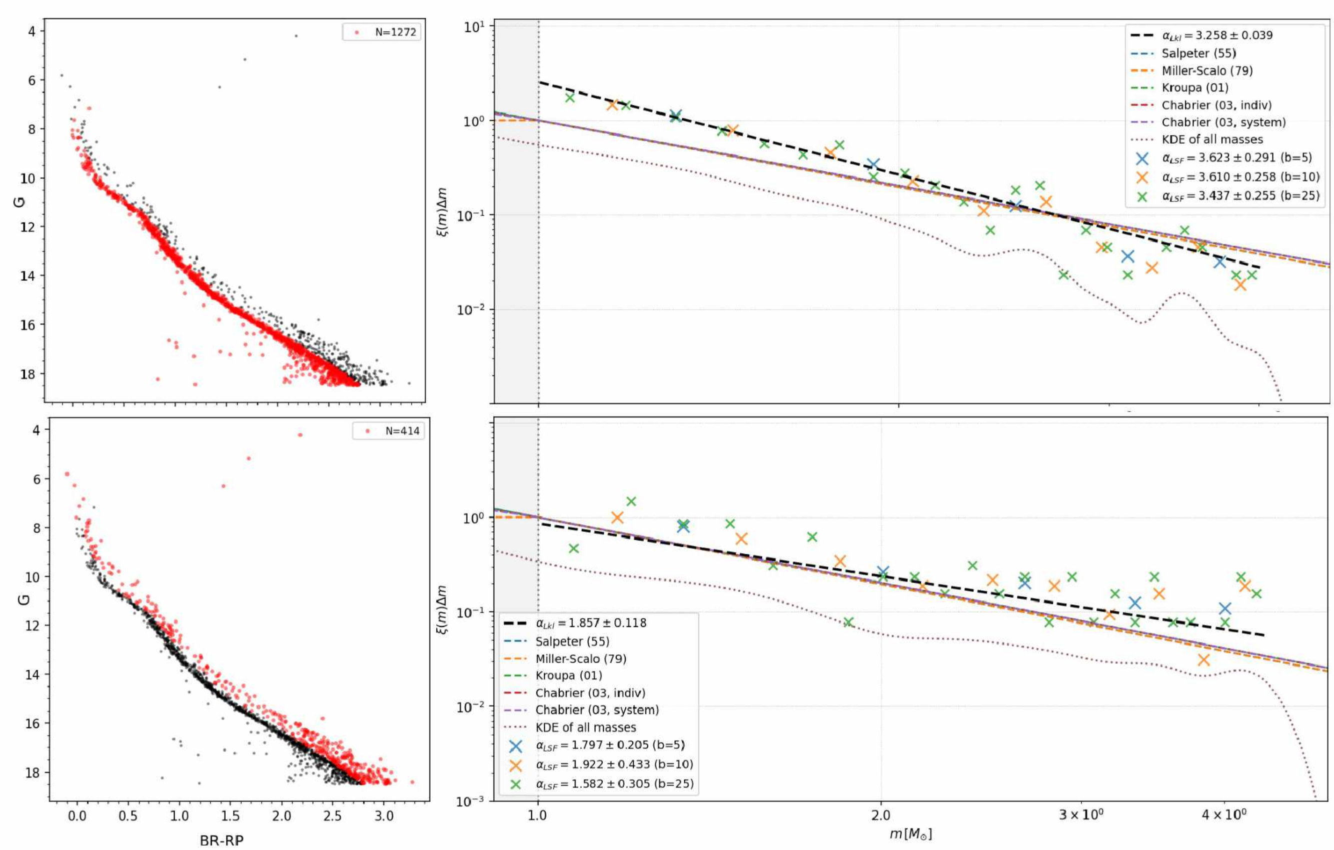

Figure 4: Estimation of the IMF for NGC 2516. *Top left*: CMD with the main sequence in red. *Top right*: IMF for the main sequence as a black dashed line. *Bottom left*: CMD with the binary sequence in red. *Bottom right*: IMF for the binary sequence as a black dashed line. Colored dashed lines represent several published IMFs. Colored crosses are least square fits (LSF) obtained using histograms with 5, 10, and 25 mass bins.

~1.86 for single and binary stars, respectively. These values are quite different from the canonical slope of 2.3 used by almost all the analytical IMFs. We think this is due to an increase in the number of faint members now detected but more analysis is needed.

4. Conclusions and perspectives

We analyzed NGC 2516, a 170 million years old cluster located at a distance ranging from 415 to 442 pc. Gaia DR2 data were employed (coordinates, photometry, parallax, and proper motions) to study a 1.5 deg region around its center. We thus set the cluster radius at 11 pc with a high level of confidence. The membership probabilities were estimated using our pyUPMASK package; the fundamental parameters of the cluster were obtained using the most probable members analyzed simultaneously in a multi-dimensional space by the ASteCA package.

The metal content of NGC 2516 turned out to be slightly supra-solar in contrast to the sub-solar metallicity found in Sung et al. This is consistent with its rather young age.

The distance was estimated through parallax analysis as well as photometrically. Both values are reasonably close given their uncertainties (and the uncertainty in the parallax offset), but around 20% larger than the Sung et al. estimate.

The binary fraction given by Sung et al. for NGC 2516 is almost double of the value found in this analysis, which is close to 24%. The IMF slopes of the single and binary systems for this cluster were estimated. The values differ substantially compared to the one found in Sung et al. of 2.4. We will discuss this point in an upcoming larger version of this analysis.

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