The Ages of Open Clusters: the Case of NGC6405

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Abstract: The purpose of this research is to determine the physical properties of an open cluster, including its age, using standard methodology. It is based on a photometric analysis of the stars in the area covered by the cluster, but astrometry is also needed to segregate cluster stars from field stars. The colour-magnitude diagram is used for distance and age determination. The study focuses on NGC6405, a relatively young nearby open cluster.

I. INTRODUCTION

A. The study of open clusters

When one thinks about star clusters, the first that comes to mind is the Pleiades. It is indeed easily visible to the naked eye as a group of stars and was recognized since antiquity, being actually the most well-known example of an open cluster. Open clusters typically contain from a few hundreds to a few thousands of members, are located in the disk of the Galaxy and have little or no structure, by contrast with globular clusters, which contain hundreds of thousands of stars, are located in the halo of the Galaxy, have an almost spherical structure and are older and more metal-poor than open clusters. Moreover, open clusters are loosely bound by gravity, implying a loss of members due to collisions with other objects during their lifetimes, while globular clusters are more gravitationally bound.

Open clusters are assumed to be formed from the same giant molecular cloud, which implies that their members share approximately the same properties. In other words, they are a sample of stars of constant age, chemical composition and distance to the Sun. As all the stars spend most of their lifetimes in the main sequence of the colour-magnitude diagram, the same applies for clusters and many interesting properties, such as the age of the cluster, can be deduced from this diagram.

Open clusters can then be used to study properties depending on the mass, which is variable among the members. This is precisely why they are the basis of many studies of stellar formation and evolution. From the astrophysical point of view, open clusters are a very interesting research topic. As individual objects, their formation, evolution, internal structure, kinematics and dynamics are studied, as well as their survival and destruction in collisions with massive clouds and their initial mass function (empirical distribution of initial masses for a population of stars). Furthermore, they play a key role in the study of the galactic disk properties, spiral structure, kinematics (Galaxy rotation curve), formation and evolution. Lastly, open clusters are used to establish the scale of distances in the Universe [4].

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B. The study of NGC6405

Informally known as the Butterfly Cluster, NGC6405, located at (17h40m20s,-32°1512) in Sagittarius constellation, is a relatively young open cluster, 487 pc away from the Sun [7]. Its discovery is usually attributed to Chéseaux, but it has also been claimed that it was observed by Hodierna before 1654. It was included in the Charles Messier catalogue of clusters in 1764.

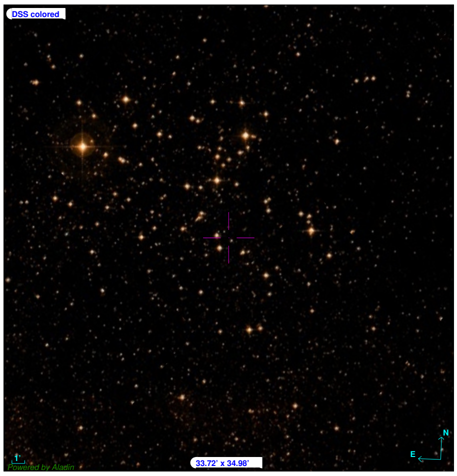

FIG. 1: Digital Sky Survey image of the region of NGC6405.

The cluster has been chosen among a survey of open clusters with proper motions determined with meridian circles observations [1]. The choice of working on this particular cluster was made for various reasons. The first is the distance to the Sun: to make the study of the cluster properties easier, it should not be too far from the Sun to be more distinguishable from field stars. A good choice as a first filter is to only take into consideration clusters at a distance $d <1$ kpc from the Sun. One must also take into account the richness of the cluster, in the sense that it must have a number of members large enough so that the statistical properties can be properly computed, and NGC6405 is one of the most suitable targets among the whole sample.

Despite being close to the Sun, NGC6405 is not a deeply studied open cluster, most probably because it lies in an area with a highly differential reddening, which is a significant issue we will be bound to deal with through the study, but at the same time makes it more interesting.

C. Methodology

As cluster stars have the same age and different masses, they will draw a sequence in the colour-magnitude diagram. Photometry is the key tool that allows us to represent such a diagram and compare it with known isochrones to obtain the one that best fits our data, being the main principle of this methodology. But a previous segregation of cluster and field stars, based on their proper motions, is needed to obtain the real sequence. As the internal cluster motions are typically small compared to the deviations of the total motion [4], cluster members will share similar proper motions and draw a certain distribution of proper motions around some mean value. Therefore, the proper motion vector point diagram [4], i.e. a two-dimensional histogram of both components of the proper motion, contains valuable information. Plotted only for cluster or field stars, it yields the corresponding probability density function (PDF). As stars are not yet segregated, it is impossible to plot such a histogram only with cluster members, but it is still possible to plot it for a subarea of the whole region observed, where we can assume that there are very few cluster stars and many field stars, obtaining a good approximation of the field PDF. Instead, if we draw the same histogram for the central area of the region, the obtained plot will be the sum of the cluster PDF and that of the field. Consequently, we can obtain the cluster PDF by subtracting the known field PDF to the cluster + field PDF. The main difficulty here is to find a representative area for the field, especially when the field is irregular, as in our case.
There are two ways to estimate these PDFs. The classical or parametric approach is based on some assumptions for the shape of both PDFs. The cluster PDF is assumed to be a circular two-dimensional normal distribution, while the field PDF is an elliptic two-dimensional normal distribution. The idea is then to fit the parameters of those distributions (mean value for the proper motions in each of both directions and standard deviations) to obtain an expression for the PDFs. The non-parametric approach, instead, does not assume any shape for the PDFs, conceding total freedom to draw the best empirical PDF from the data available [4]. We will perform a non-parametric study.

II. IDENTIFYING THE MAIN SEQUENCE: QUALITATIVE ANALYSIS

A. The data

The main source for data is the *Kinematic study of Open Clusters* project from the Gaia Group of the University of Barcelona [1], based on automatic meridian circles observations. It contains astrometric (proper motions) data for most of the stars. Missing astrometry for bright stars, due to saturation, has been taken from the Tycho-2 Catalogue [2]. Photometry has been taken from the Guide Star Catalogue (GSC) [3], because it is the only photometric survey that covers the full astrometric survey (1.5º×1.5º, three times the quoted diameter of the cluster). An additional source of photometry for intermediate magnitude stars was added from [8], but has finally not been used for the computation of the stellar parameters.
The proper motion of a star can be defined as its angular change in position in the sky over a period of time [4]. They are obtained by comparing images from two or more different epochs: in our case, data from 1958 are compared with data from 2009 and 2012. In this study, we are dealing with absolute proper motions included in the above mentioned survey.

B. First approximation

Taking all the available data for the area of the cluster, a first colour-magnitude diagram has been built, in which a sequence of bright stars is easily identifiable in the top left corner of Fig. 2. Those stars have a high probability of belonging to the cluster sequence due to their clear alignment. On the contrary, for dim stars, the sequence is hidden by the many field stars. This group of bright

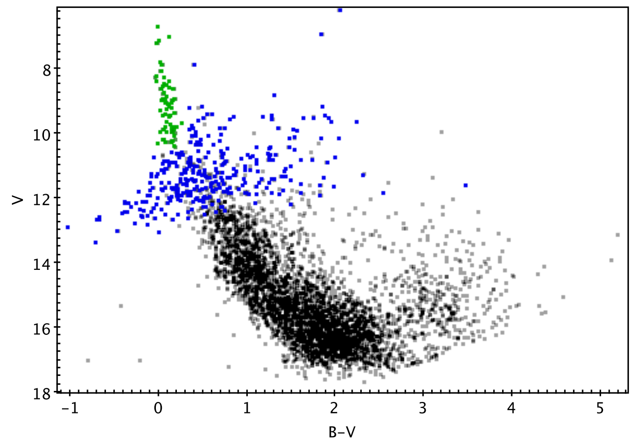

FIG. 2: Colour-magnitude diagram. Black: data from GSC. Blue: data from Tycho-2. Green: bright stars (mainly from Tycho-2).

stars can be taken as a reference to define a central region of the cluster. When plotted in an α-δ diagram (Fig. 3), one can observe a higher density of stars belonging to the bright group in the center of the plot. Those stars have been assumed and labelled as the centre of the cluster and will be used for further analysis.
Taking the center of the cluster as reference, one can now draw several concentric circles around it, expanding the area covered towards the field. As we make the circles bigger, there should be fewer cluster stars added and a larger proportion of field stars. This phenomenon is es-

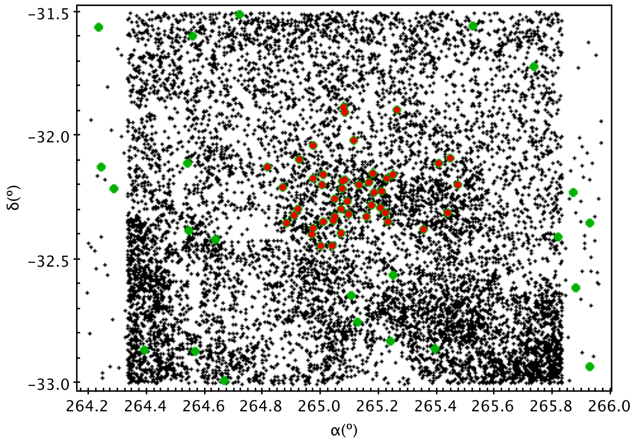

FIG. 3: Map of the region studied. There is a strong inhomogeneity in stellar surface density over the region. Green: bright stars. Red: centre of the cluster. Black: rest of the stars.

pecially visible for bright stars in the colour-magnitude diagram. This is, then, a possible way to define an area for the cluster, considering that the cluster "ends" when no more stars are added to the visible part of the sequence. This process consisted of eight circles, three of which, having approximate radii 0.1, 0.15 and 0.25°, will be used as references. The results for data within the third one, which defines the area of the cluster, can be seen in Fig. 4, where the sequence is now clearer than in Fig. 2. As this is still a qualitative analysis, the circles have not been traced rigorously.

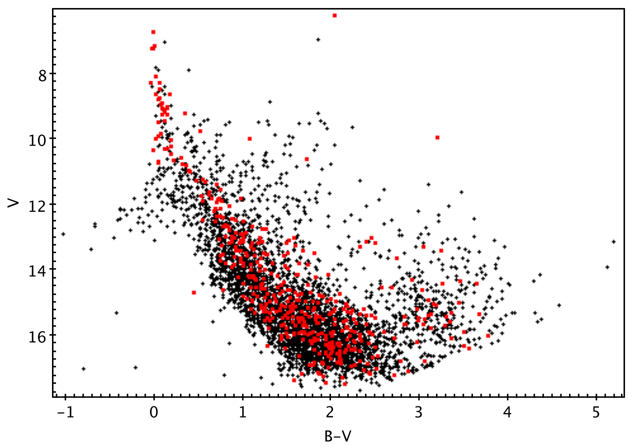

FIG. 4: Colour-magnitude diagram. Red: stars within a circle of 0.25° taken as the cluster area. Black: rest of the stars.

C. Proper motion analysis

The aim of this section is to find a range of values for proper motions in which most of the members are included, working with the already defined circles. Unfortunately, the cluster motion is not much distinguishable from that of the field in the α direction. In the δ direction, we have defined a range of [-8,-2] mas/yr for the most probable members (Fig. 5). Only with this qualitative treatment, we have obtained a good approximation of the sequence, being able to try to fit an isochrone to the sequence in Fig. 6 and compute a range for the age of the cluster. According to this first fit, the age of the cluster should be about 10^8 years.

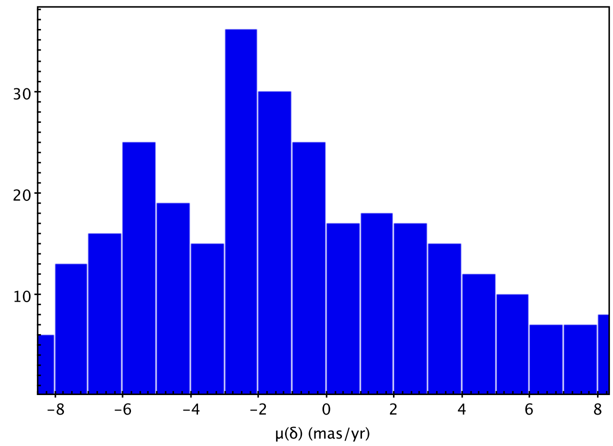

FIG. 5: Proper motion histogram in the δ direction for the stars within the circle of 0.15°.

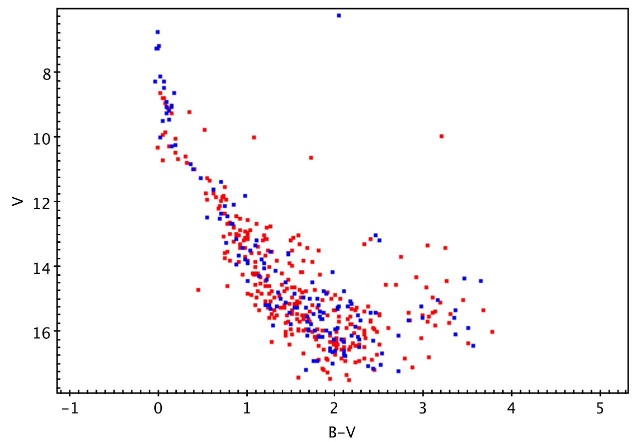

FIG. 6: Colour-magnitude diagram. Red: cluster area. Blue: cluster area with restricted proper motions.

III. SEGREGATING THE STARS: RIGOROUS ANALYSIS

A. Computing the PDFs

To obtain the cluster PDF, we must choose an area around the center. For the sake of simplicity, the area taken is a square of side 0.4° that basically corresponds to the area of the third concentric circle. Regarding the field PDF, it is more difficult to find a field representative of that of the central area (see Fig. 3). One must then study and compare the properties of the field in each of the four sides of the cluster area and discard the areas of inhomogeneous field (we took squares of side 0.5° in each side). The bottom area was found to have proper motions centred around a nonzero value, which clearly reveals a field inhomogeneity in this region. The shapes of the resulting cluster PDFs were found to be better defined in the left and right areas than in the top area. Therefore, those areas were chosen as representatives of the field and the field PDF was taken the average of both.

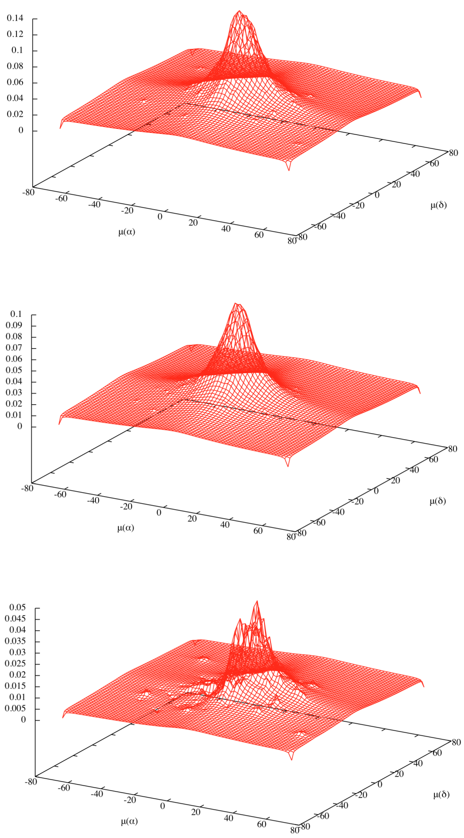

FIG. 7: Proper motion PDFs. Top: cluster+field, mixed sample from the square of side 0.4°. Centre: field, average from the left and right regions. Bottom: cluster population of NGC6405. All proper motions are in mas/yr.

One can then find the mean proper motion of the cluster by taking the projections in both directions and fitting a normal distribution to the upper envelope of each. Moreover, the volume of the cluster PDF is the expected number of members, N. The error for this last quantity can be taken as the fluctuations of the PDF, i.e. the amplitude of the negative values appearing when the field PDF is subtracted to the cluster + field PDF. The obtained values for those three parameters are:

$$\overline{\mu_\alpha} = 4.27 \pm 1.06 \text{ mas/yr}$$
$$\overline{\mu_\delta} = -7.48 \pm 0.96 \text{ mas/yr}$$
$$N = 104 \pm 2$$

B. Fitting an isochrone

The isochrones have been taken from [6], and are obviously providing absolute magnitudes M_v and $(B-V)_0$. The relation between those and the apparent magnitudes included in our data is simply [5]:

$$(B-V) = (B-V)_0 + E_{B-V}$$
$$V = M_v + 5\log r - 5 + A_v,$$

where E_{B-V} is the colour excess and A_v is the interstellar absorption. As the distance to the Sun r can be taken as a constant for all the cluster stars, the term $5\log r - 5$ is just an additive constant. If, in addition, E_{B-V} and A_v, which are related by $A_v = 3.1E_{B-V}$, are taken as constants, absolute and apparent magnitudes for cluster stars differ only in an additive constant. Therefore, in a first approximation, one must only shift the values of the magnitudes of the isochrone to fit it to the observed data. Apart from the age of the star, which is the main parameter involved in the isochrone, the metallicity of the star has also an important role to play. A two-parametric fit will then be performed using the distance r and the age t, while $A_v = 0.62$ mag and the metallicity $Z = 0.022$ are fixed to the values from [7]. The sample used for the fit are the N most probable members according to the obtained cluster PDF and properly filtered using photometry: stars which are too far from the sequence are assumed to be field stars and the next probable member is taken as a cluster star. Some members have also been added *ad hoc* from the photometric selection in Sec. II.C. The first step is to determine an approximate value for the constant $5\log r$-5 by shifting the value of V for the isochrone points until they are aligned with the probable members. Then the two-parametric fit is performed as follows: the distance to the isochrone can be defined as the distance to the closest isochrone point for each probable member, and the mean distance D is then the sum of distances to the isochrone for all the stars of the sample. D is the quantity to minimize to obtain the best values for both parameters. The results are:

$$r = 398 \pm 37 \text{ pc}$$
$$t = (8.6 \pm 0.2) \cdot 10^7 \text{ yr}$$

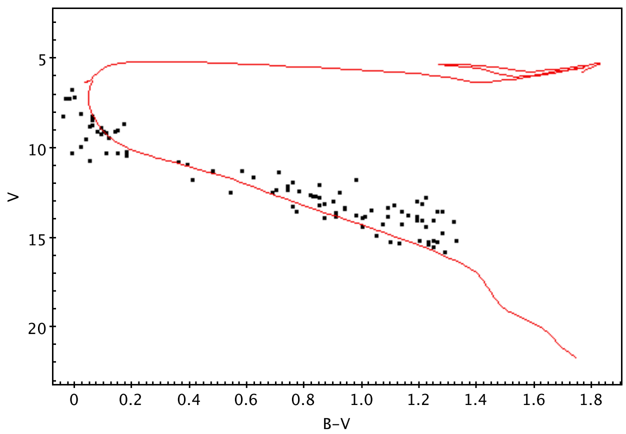

FIG. 8: Black: most probable members of the cluster. Red: isochrone $t = 8.6 \cdot 10^7$yr.

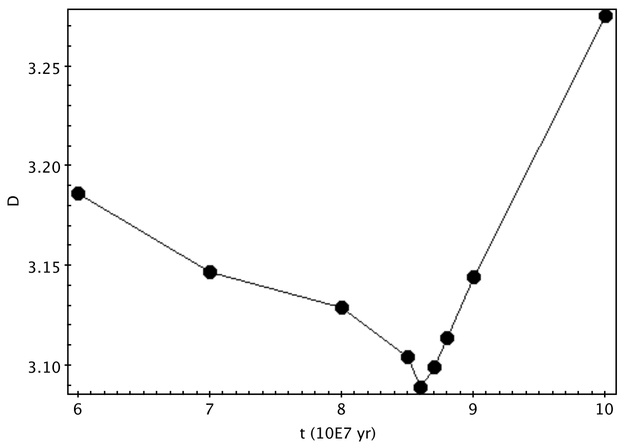

FIG. 9: Results for the fit of the age of the cluster t.

Compared to the values from [7], deduced only from photometry, $r = 487$ pc and $t = 9.4 \cdot 10^7$ yr, the relative discrepancies of the results are, respectively, of 18% and 8.5%, which are due to differences in the selection of members and differences in the set of stellar isochrones used. We remark that we found difficulties to obtain a convincing proper motion PDF for the cluster.

IV. CONCLUSION

The age of the open cluster NGC6405 has been determined using a systematic methodology based on observational data. A first qualitative photometric analysis has been performed as a first filter to segregate cluster members from field stars. A rigorous analysis of proper motions has allowed us to establish a second filter, computing an empirical PDF for the members, evaluating an approximate number of members, and deriving for the first time the absolute proper motion of the cluster. Combining both filters, a selection of roughly the hundred most probable members has been used for the isochrone fitting. The obtained results for the age of the cluster and its distance to the Sun are in accordance with the data from Webda [7], but could be improved with a deeper analysis. For instance, the third component of the stellar motion, referred to as radial velocity, also correlates the members and is useful to obtain a better PDF, but for now these data are not available. It is worth mentioning, though, that this cluster is especially difficult to study due to the differential reddening of the nearby field.

Acknowledgments

The advisory work of Dr. C. Jordi is greatly acknowlegded, as well as her help and encouragement in achieving this work. I also thank my friends and family for their support. Special thanks to my colleague Xavier Roderic Hoffmann, for his help with some computational issues that appeared in the course of this labour.

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