Characterisation of the open cluster M67

Author: Pol Massana Zapata
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.**

Advisor: Carme Jordi Nebot, Eduard Masana Fresno, Lola Balaguer Núñez

Abstract: In this study a characterisation of the physical parameters of the open cluster M67 is made by using empirical calibrations in the Strömgren-Crawford filter system. A group of 316 stars contributed to the results. The photometric analysis leads to an extinction of $E_{b-y} = 0.03 \pm 0.03$, a distance modulus $V_0 - M_v = 9.6 \pm 0.3$ (or 830 ± 60 pc), a metallicity $[Fe/H] = 0.0 \pm 0.3$ and the age of the cluster is approximated to be $\log t(\mathrm{yr}) = 9.57 \pm 0.05$ (or 3.72 ± 0.19 Gyr).

I. INTRODUCTION

M67 (or NGC 2682) is one of the oldest open clusters in the Galaxy and it has been widely studied. It is located in the constellation of Cancer ($\alpha_{2000} = 8^{\mathrm{h}}51.^{\mathrm{m}}3$, $\delta_{2000} = +11°50'$) and has two special characteristics, age and metallicity. Both are very similar to those of the Sun. It has been even suggested [1], that it originally formed in M67 and the gravitational forces caused it to separate from the cluster.

This study aims for a new characterisation of the cluster. New photometry and proper motions have been obtained recently [2], giving the opportunity for a new membership segregation and physical characterisation.

The characterisation of the cluster will consist in giving four fundamental parameters: extinction, age, metallicity and distance. In this section a few details of the followed procedure are given. Relevant physical parameters of the cluster have been obtained using a Fortran program called *pf.f* (for "Paràmetres Físics"). Full description of how this program works and the exact calibrations it uses are given in [3], only the general steps are explained here.

The program uses empirical calibrations in the Strömgren-Crawford filter system ($uvby - H_\beta$) to compute a set of physical parameters, magnitudes and colours for each star in the input. The following list shows the data that the program uses:

- Colour: $b - y$
- Apparent magnitude: V
- Colours: m_1, c_1
- Index: H_β

All are specially chosen for their characteristics. Each of them gives information about physical properties of the star: $(b-y)$ is related to the effective temperature of the star, m_1 to the metallicity, c_1 to the strength of the Balmer discontinuity and H_β index measures the intensity of the H_β spectral line.

*Electronic address: pmassaza7@alumnes.ub.edu

Spectral type for each star can also be added in the input data. Though it is not necessary and this feature is not used, since there is no information about it.

Most of the stars have also been divided into two groups following an astrometric analysis of proper motions, with the aim of selecting the probable members. The procedure in this selection is not a part of this work and details about it can be found in [4]. The most probable member stars from this analysis will help to determine more precisely the physical parameters. Using all the stars in the field would cause a contamination of the results because of stars not belonging to the cluster.

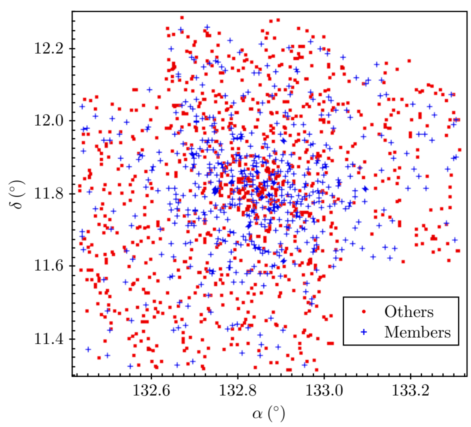


FIG. 1: Distribution of stars classified as members (blue crosses) and stars that have been either classified as not members or are not classified (red dots).

II. DATA TREATMENT

A. Description of the input data

All the data used in this work is presented in [2]. The initial set was formed by a total of 1518 stars down to mag ~19. The astrometric study of proper motions and the membership segregation goes down to mag 17, with 524 identified possible members. For the faintest magnitudes there is no classification of the cluster members. This is clearly seen in Fig. 1 because the red dots are also concentrated in the center of the cluster, indicating that there are also member stars that have not been classified. There are two groups of stars: probable member stars and non-members including the not classified ones.

After looking at the uncertainties for all stars, Fig. 2, it is clear the presence of outliers. These do not follow the general trend and thus it has been decided to reject them. The applied criterion is to only consider the stars that fulfil all the following requirements: $\sigma_{b-y} < 0.05$, $\sigma_V < 0.05$, $\sigma_{m_1} < 0.2$, $\sigma_{c_1} < 0.2$, $\sigma_{H_\beta} < 0.06$.

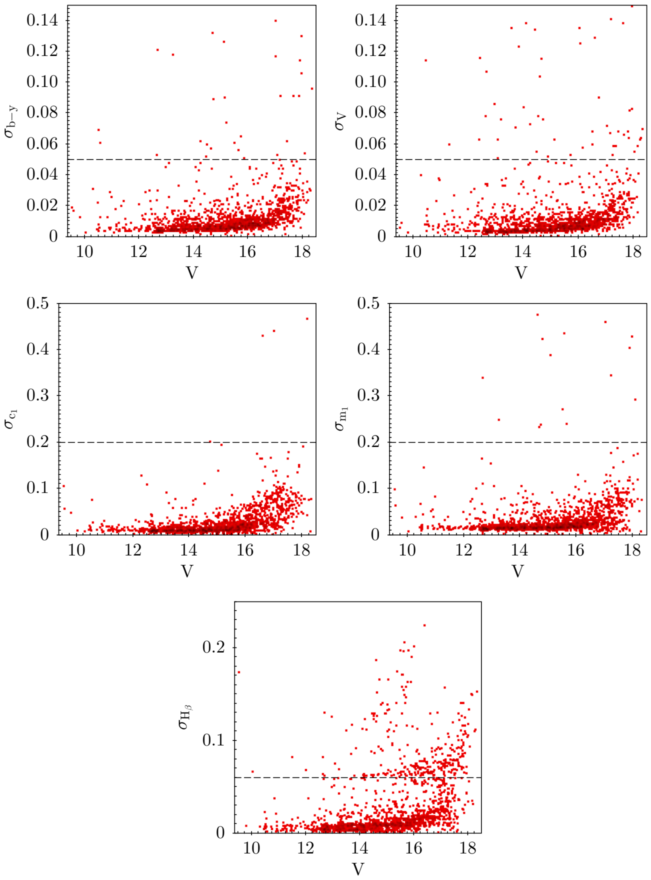


FIG. 2: A look in the uncertainties for each input magnitude and colour as a function of V. Dashed lines mean the cut-off for the input data.

At the end of the procedure there was a total of 1153 stars, 453 of them astrometric members. These members are the basis for the determination of the astrophysical parameters.

B. Analysis

The resultant data from the first filtering is sent to the *pf.f* for the analysis. First, the program assigns one spectral region to every star and compares with the input spectral type. Since there is no such input in our study, the program keeps its own classification. Then, it uses empirical calibrations to find the intrinsic colours and magnitudes. Finally, some relevant physical parameters are computed with this data.

The output file contains the following:

- Extinction: E_{b-y}
- Intrinsic colours: $(b-y)_0$, c_0, m_0
- Intrinsic apparent magnitude: V_0
- Absolute magnitude: M_v
- Distance: $V_0 - M_v$, r(pc)
- Metallicity: $[Fe/H]$

The extinction will be supposed to be the same all over the cluster, which is justified due to the fact that it is old. The relation between the extinction E_{b-y} and the absorption A_v is $A_v \simeq 4.27E_{b-y}$, as explained in [5]. Actually, it depends on the spectral type of the star, but it can be considered constant in the spectral range of M67.

The classification in spectral regions is made through an algorithm that puts stars in 5 different regions for main sequence and giant stars, and in 3 for the supergiants. Each of them has its correspondence with the well known spectral types (O, B, A,...) and luminosity classes (I, II,...). Regions 1-5 are composed by the luminosity classes V-III and 6-8 are intended for the supergiants (I, II).

All this classification is made to optimize the calibrations for every spectral region. The following relations are defined in the program: 1 → O-B; 2 → A0-A3; 3 → A4-A9; 4 → F0-G2; 5 → G3 and later; 6 → B; 7 → A0-F5; 8 → F5-G5.

There is also the possibility that stars fall outside the range of validity of calibrations. The program itself can identify these stars and put them into separate groups. Group 1 (Gr1) is for the stars inside the range of validity, Group 2 (Gr2) is for the ones outside. From Table I it is possible to see that most of the stars are within the validity of the calibrations, but there is a relevant 35% out of them.

	Gr1	Gr2
Field	444 (63,4%)	256 (36,6%)
Members	316 (69,8%)	137 (30,2%)
All	760 (65,9%)	393 (34,1%)

TABLE I: Number of stars in each classification group.

For the purposes of the characterisation of the cluster, it will suffice to take only into account the stars in Gr1 and the results given here will only be for the stars in this group.

Despite all this treatment there are still stars for which the program fails in computing the relevant physical parameters, in particular the stars in the giant branch and for late G and K main sequence stars. For them the calibrations are not accurate because the program assigns a M_v as if they were main sequence stars, which are fainter than they should, and, to match the apparent magnitudes, the distance computed is much closer than what it should be.

In order to be confident with the results, only the ones computed with main sequence stars from Gr1 will be used. In addition, if characteristic parameters of the cluster are desired, the most reliable way is to consider the set of member stars, as it has the highest possible percentage of actual members.

In theoretical models of the evolutionary tracks of a star, to express the metallic content the variable Z is used. It is the fraction of the mass of a star composed by all the elements heavier than He. For stars in the main sequence $Z \ll 1$. In order to relate this metallicity with the one in the output it is required to do a couple of approximations, described in Eq. (1).

$$\log\left(\frac{Z}{Z_{\odot}}\right) \simeq [M/H] \simeq [Fe/H] \qquad (1)$$

The relation between $[M/H]$ and $[Fe/H]$ is just a multiplicative constant, in general takes values close to 1 because most elements are produced in the same proportion during the lifetime of a star.

Finally, the procedure to determine the age of the cluster is plotting ischrones of different ages in the colour-magnitude diagram and evaluate which one fits better the turn-off point. The PARSEC isochrones from [6] are used here, taking into account the mean parameters of the cluster previously derived from the *pf.f* such as distance, metallicity and extinction. Two approaches can be done: taking the isochrones with no extinction and plotting them with the intrinsic magnitudes from the output, or taking the mean extinction computed and plot them in the observed data.

III. RESULTS AND DISCUSSION

A. Extinction, distance and metallicity

It is possible to know the type of stars there are by looking at the spectral classification of the output. From the sample of 1153 stars that went through the classification process the following information is obtained:

- Region 1 (O-B): 6 stars (0.52 %)
- Region 2 (A0-A3): 4 stars (0.35 %)
- Region 3 (A4-A9): 15 stars (1.30 %)
- Region 4 (F0-G2): 520 stars (45.10 %)
- Region 5 (G3 and later): 608 stars (52.73 %)

There are no stars in regions 6-8, meaning there are no supergiants. The vast majority of stars are in regions 4 and 5, so spectral types F and G prevail over the rest. This is already telling much about, for example, the age of the cluster.

As it has been said, it is very important to have a set of probable member stars as it helps to clean the results. This can be seen in Fig. 3, where the path of the isochrone is clearer in the members groups comparatively to the set of all stars.

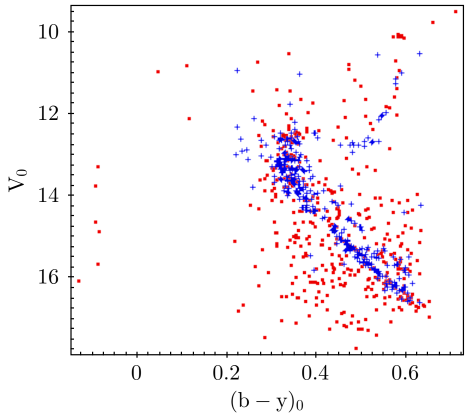


FIG. 3: Colour-magnitude diagram of the cluster showing member stars as blue crosses.

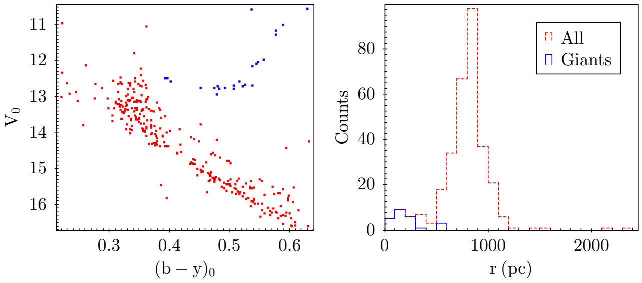
An important feature to discuss about Fig. 3 is the group of stars that fall above the main sequence and follows it perfectly. This effect is caused by unresolved binaries, which are binary stars that appear as single stars and are brighter than they should. They are better seen in Fig. 4 (a) where only member stars are plotted. All this has to be taken into account, because including binaries in the final computation of characteristics would also give problems, and for this reason they will not be used for the computation of the results (as in the case of stars of Gr2 and giants).

The giant branch is perfectly appreciated in the colour-magnitude diagram, but as it has been said these stars are not within the calibrations handled by the program. To show this in Fig. 4 the giant branch has been marked and the histogram of the distance shows where these stars are located in front of all the others. Instead, they will be useful in the determination of the age of the cluster when starting from observed magnitudes and colours.

Final determination from histograms is made without field stars contamination, which gives more reliable results. Figure 5 shows the final selection of member stars that will be used to compute the results.

Histograms of Fig. 6 show that all the parameters are clearly picked at one region. The histogram of the extinction now justifies what has been previously said about the fact that all the stars have very similar extinction, caused by the vanishing of the initial interstellar medium that originated the cluster.

Table II shows the final results for M67, that will be



(a)Selected giant stars. (b)Distance histogram.

FIG. 4: Colour-magnitude diagram and histogram for member stars to show the wrong determination of distances in the giant branch.

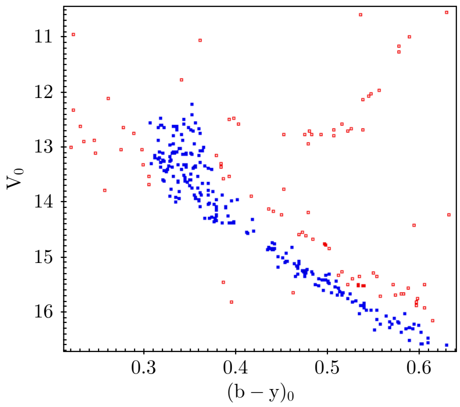


FIG. 5: Colour-magnitude diagram of member stars where blue dots mean selected stars for the final computation of results.

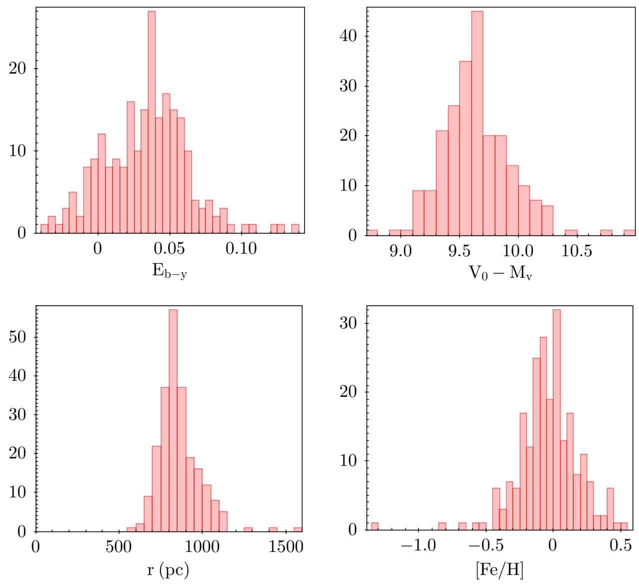


FIG. 6: Histograms of the cluster physical parameters using the stars in Fig. 5. Vertical axes show the number of stars for every bin.

later used in the determination of the age of the cluster. They are the mean values for the selected stars in Fig. 5 with the uncertainty being the standard deviation among them.

E_{b-y}	$V_0 - M_v$	r (pc)	$[Fe/H]$
0.03 ± 0.03	9.6 ± 0.3	830 ± 60	0.0 ± 0.3

TABLE II: Physical parameters for the open cluster M67.

Results can be validated by comparing with the literature. The extinction value is in good agreement with the one calculated by [7] and [8]. The result from the metallicity also matches the ones obtained by [8] and [9]. The distance of the cluster is very similar to the ones taken by the authors before mentioned.

It is important to compare the results also with [4], because the methodology followed was very similar than the one used here. In fact, they are in concordance despite having a much smaller set of stars, and hence less statistics.

B. Age

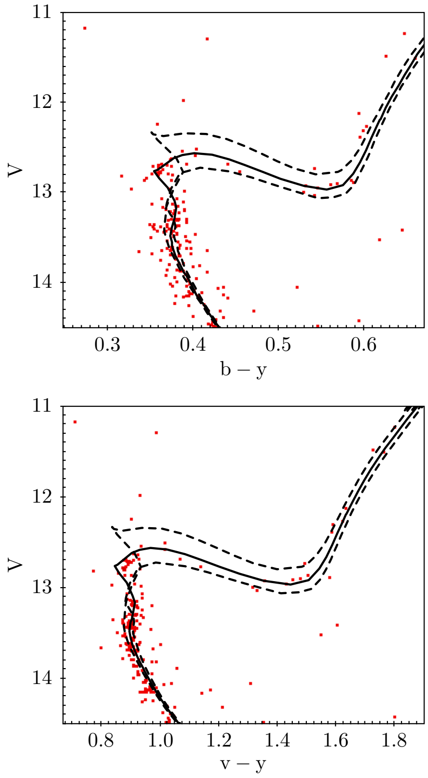


FIG. 7: PARSEC isochrones plotted with the observed colours and magnitudes (that is, with extinction) for member stars in the region of the turn-off point. All the isochrones have the same metallicity $Z = 0.0152$, which is solar metallicity and corresponds to the $[Fe/H]$ found in the previous section. The continuous line shows the determined age for the cluster and dashed lines are the limits in age uncertainty.

Determining the age of an individual star from its own photometry is not an easy task. For this reason open clusters are important, because all the stars have roughly the same age and one can determine it by using stellar evolution models, which is a fairly straightforward study.

From Fig. 7 an estimation of the age of the cluster can be extracted. The values for metallicity, age and extinction of the previous section have been taken as valid and they seem to be consistent with the isochrones, as they fit the observed main sequence very well. This is important because it helps to validate the value for the age that will be extracted from here.

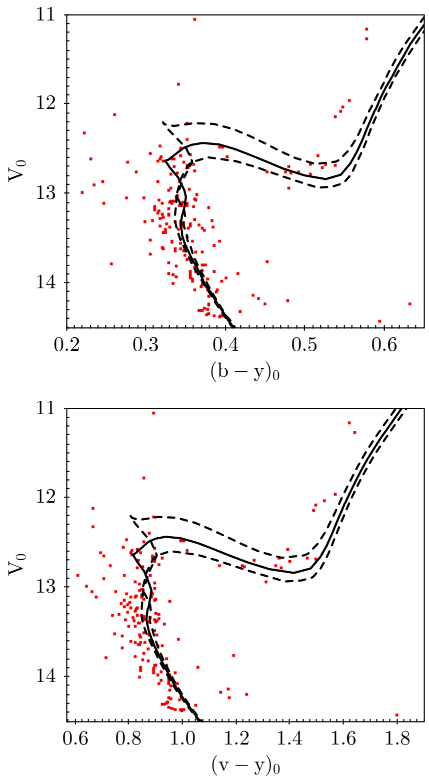


FIG. 8: Same plots as in Fig. 7 but with the intrinsic values of the output and the isochrones without the extinction.

There is a common feature in both Fig. 7 and 8, the data in the $v-y$ diagram makes a more defined turn-off and fits much better the isochrones. So, for the purpose of determining the age this diagrams are more useful and reliable.

Figure 8 shows that the giant branch does not match the isochrones, as the calibrations used to derive the intrisinc values are not fully correct

After looking at all the plots, one can realise that they are all consistent (if the giant branch is omitted) and the resultant age for the cluster turns out to be $\log t(\mathrm{yr}) = 9.57 \pm 0.05$, 3.72 ± 0.19 Gyr. The uncertainty was decided after looking at all the possible isochrones that went along with the data.

IV. CONCLUSIONS

Making use of an astrometric study of the stars in M67, a segregation of stars according to its membership based on proper motions was made. A detailed characterisation of the physical parameters of the cluster has been made. The process was based in empirical calibrations using Strömgren-Crawford photometry. Individual physical parameters have been derived for 760 stars in the area of M67. The results for the cluster characterisation are the followings: $E_{b-y} = 0.03 \pm 0.03$, $V_0 - M_v = 9.6 \pm 0.3$, $r = 830 \pm 60$ pc, $[Fe/H] = 0.0 \pm 0.3$ and $\log t(\mathrm{yr}) = 9.57 \pm 0.05$.

The results taken from this work turned out to be satisfactory. In particular, it is good that they are consistent with [4], because the methodology used has been very similar and it is a convenient way to check the results.

Acknowledgments

I would like to specially thank C. Jordi, E. Masana and L. Balaguer-Núñez for all the help provided and for giving me the opportunity to work with real data. I also would like to thank all of my friends that have helped me in all possible ways.

[1] Pichardo, B., Moreno, E., Allen, C., et al. 2012, AJ, 143, 73

[2] Balaguer-Núñez, L., Casamiquela, L., Jordi, C. 2015, Highlights of Spanish Astrophysics VIII, 593

[3] Masana, E. 1994 Master Thesis, Universitat de Barcelona

[4] Balaguer-Núñez, L., Galadí-Enríquez, D., & Jordi, C. 2007, A&A, 470, 585

[5] Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, Astrophys. J. , 345, 245

[6] Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127

[7] Pasquini, L., Biazzo, K., Bonifacio, P., Randich, S., & Bedin, L. R. 2008, A&A, 489, 677

[8] Taylor, B. J. 2007, AJ, 133, 370

[9] Önehag, A., Gustafsson, B., & Korn, A. 2014, A&A, 562, A102