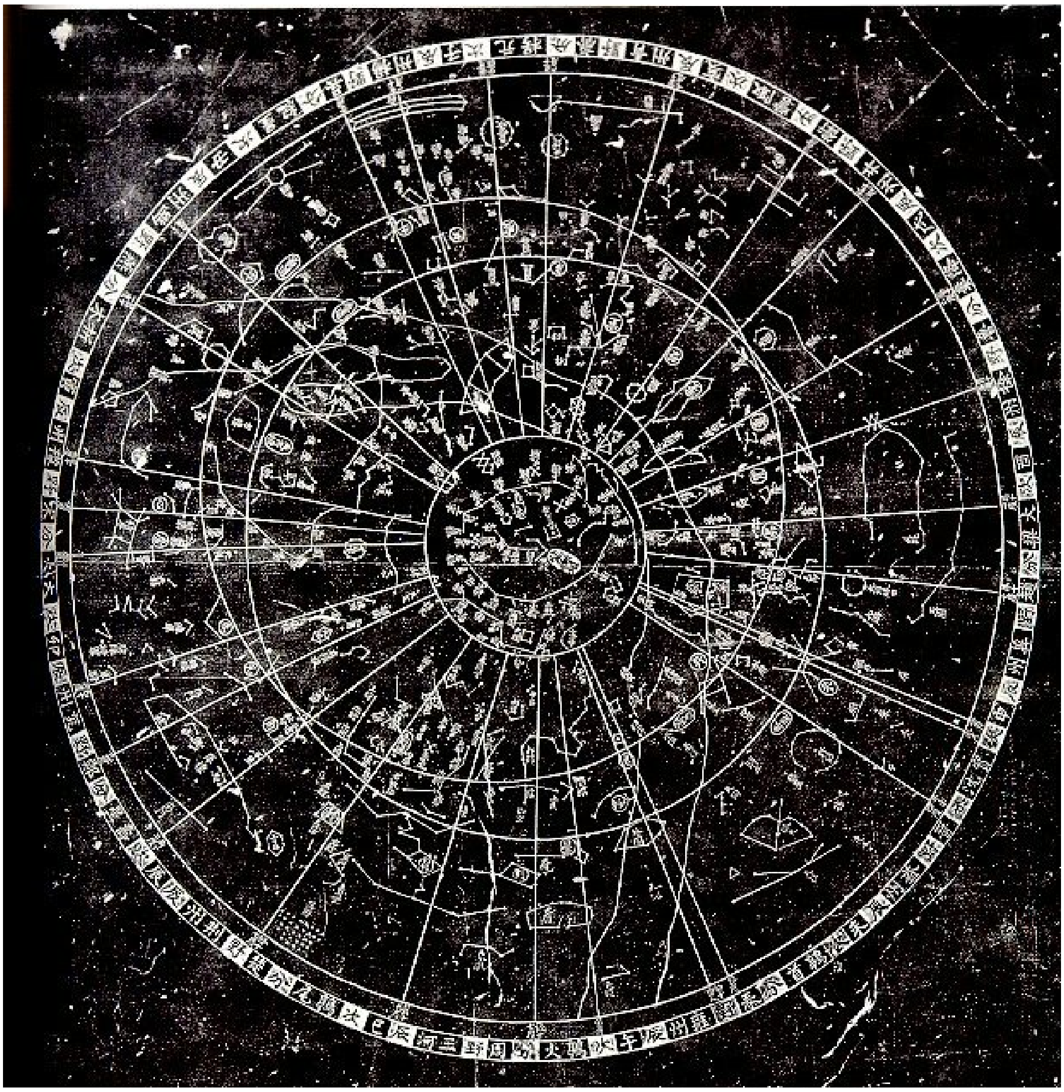
UNIVERSITAT DE BARCELONA

Departament d'Astronomia i Meteorologia

Astrophysical Studies on Open Clusters:

NGC 1807, NGC 1817, NGC 2548 and NGC 2682



Memoria presentada por

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月下獨酌

花間一壺酒，
獨酌無相親。
舉杯邀明月，
對影成三人。
月既不解飲，
影徒隨我身。
暫伴月將影，
行樂須及春。
我歌月徘徊，
我舞影零亂。
醒時同交歡，
醉後各分散。
永結無情遊，
相期邈雲漢。

李白 (701-762)

Drinking Alone under the Moon[a]

A jug of wine amidst the flower:
Drinking alone, with no friend near,
Raising my cup, I beckon the bright moon;
My shadow included, we're a party of three.
Although the moon's unused to drinking
And the shadow only apes my every move
For the moment I'll just take them as they are,
Enjoying spring when spring is here.
Reeling shadow, swaying moon
Attend my dance and song,
Still sober, we rejoice together;
Drunk, each takes his leave.
To seal forever such unfettered friendship
Let's rendezvous beyond the Milky Way.

Li Bai (701 - 762)

[a]Translated by Wilson & Zhang (1995)

8 Conclusions

The work undertaken in this thesis allowed us to reach the conclusions that are summarised here. We have structured this chapter in four parts: the conclusions related to the data analysis and the methods used, the observational results (astrometric and photometric) and the physical conclusions we can obtain from this set of clusters. To conclude, we will comment the future work we intend to pursue with the obtained experience and data, and the plans for new observations.

8.1 Data analysis and comparison of methods

We have studied different approaches to obtain the most suitable models for the analysis of our data. Our standpoint has been always based on the data and trying to avoid as much influence as possible from the models concerned. We have developed a protocol in the treatment of cluster data flexible enough to allow the analysis of very disperse clusters, and very rich ones as well.

- The choice of the plate model for the proper motions calculations is very delicate. Apart from the amount of available quality reference stars, the model should be appropriate for the plate material used (Sections 2.2, 2.5 and 4.1.2).
- After undergoing through difficulties with the segregation of members from proper motions in the two supposed clusters NGC 1817 and NGC 1807 (Section 2.5), we realised the shortcomings of the parametric approach. In the parametric approach you get what you expect while in the non-parametric you rely on few a priori judgements. The parametric (Sections 2.6.1, 4.2.1 and 6.2.1) and non-parametric models (Sections 2.6.2, 4.2.2 and 6.2.2) for the membership segregation in the kinematic plane were carefully compared to

Table 8.1: Comparison of parametric and non-parametric methods for the segregation of members in the three clusters. First line gives the probability limit for member stars for each method, $P_{\rm cut}$. Second line is the agreement between the two methods. Third line is the agreement with the segregation from radial velocities. Radial velocity data do not exist for NGC 2548. Fourth line is the agreement with radial velocities for each method, individually. Fifth line gives the effectiveness E.

	NGC 1817		**NGC 2548**		**NGC 2682**	
	P_P	P_{NP}	P_P	P_{NP}	P_P	P_{NP}
$P_{\rm cut}$	0.74	0.72	0.92	0.82	0.55	0.87
Agree	92%		91%		97%	
Agree_{V_r}	82%				87%	
Agree_{V_r}	79%	71%			85%	87%
E	0.67	0.52	0.77	0.67	0.82	0.87

conclude that the best approach was the combination of both (Sections 2.6.4, 4.2.4 and 6.2.3). They serve as a mutual check for the validity of their different assumptions. The parametric fit functions must converge towards a solution physically meaningful and compatible with the shapes of the non-parametric distributions. Likewise, the main assumption of the non-parametric method, namely the possibility to model the field distribution in the cluster area from a region outside that occupied by the cluster, can be tested from the results of the parametric approach. That way, we can get complementary information from the available data. In low-contrast, disperse clusters the choice of a model is crucial. In Table 8.1 we can see that the general agreement between the two methods, when taking appropriate parameters, is quite good. Being statistical methods, a level of disagreement is unavoidable. In the case of NGC 2682 such an impressive agreement is coherent with a rich and relatively high contrast cluster. In clusters like this one the choice of the method is almost irrelevant. The agreement with radial velocities is also reasonably good. It looks higher for the parametric method in the NGC 1817 case while, in the case of NGC 2682, it is slightly higher for the non-parametric approach.

- As discussed in Section 2.3.1.1, the index E is not really a measure of the effectiveness of a given method, but a good measure of the "signal to noise ratio" of the separation between field and cluster, depending on the density of field stars and on the intrinsic nature of the cluster. As it can be seen in Table 8.1, the difference of the E values between the methods for each cluster gets greater the lower contrast the cluster has, reaching the maximum difference between methods for NGC 1817 and the minimum for the case of NGC 2682. It seems to show some trend with the chosen limiting probability of a cluster member, $P_{\rm cut}$, and even to reflect a similar trend to that followed by the comparison with the radial velocities segregation.

All this can be understood in the following framework:

- membership probabilities are computed both from the cluster and field kinematic distributions,
- a poor sampling of any of those two distributions, due to a low number of stars, will lead to a fit parametric function of low significance and, at the same time, to a noisy, "bumpy", non-parametric function, and
- when the field population is very sparse, the parametric field function gets too wide, making parametric probabilities to decrease but still being a good measure of membership. This is the case of NGC 2682 (M 67).

• In principle, parametric and non-parametric methods can also be applied to spatial planes (Sections 2.6 and 4.2.3). However, our incursions in these calculations have not given good results. A classical parametric modelling of the spatial information forces the stars to be spatially distributed as the model imposes. The Gaussian distribution is not necessarily real for low-contrast clusters as the ones studied here. For the case of NGC 1817/NGC 1807, this information only contributed in increasing the confusion. The kinematic plane is much more meaningful.

Besides, introducing spatial considerations into the member selection process could have biased the radial spatial gradients and profiles results (luminosity profiles, mass segregation). Selecting members on kinematic and photometric criteria leaves the spatial information untouched, ready for a cleaner interpretation of radial and spatial trends.

• The non-parametric method can also be used even in the photometric plane (Sections 3.2.1 and 5.2.1). Again, our tries have not succeeded, in contrast to the study of NGC 1750/NGC 1758 by Galadí-Enríquez et al. (1998a). Our mosaic photometry is a weighted mean of many different observations from different telescopes. For this reason, it does not have a Gaussian profile in the scattering of the measurements. The profiles of the different regions have different scatter. The choice of an area as representative of the field, is also critical and the area coverage of our photometry is not wide enough to assure an area completely free of cluster stars. To avoid this problem, we have used Galaxy models from Besançon (Robin et al. 2003) to represent the field. But again, the distribution of errors is too complex to be modelled successfully.

8.2 Observational results

NGC 1817

- Six new photographic plates of modern epoch were taken at the Zǒ-Sè station of Shanghai Observatory with the 40 cm doble astrograph in the area of NGC 1817/NGC 1807 (Section 2.1).
- A list of absolute proper motions and their corresponding errors for 810 stars within a $1.^{\circ}5 \times 1.^{\circ}5$ area in the NGC 1817 region were determined from PDS measurements of 25 plates with a baseline of 81 years. A comparison with the Tycho-2 Catalogue shows good agreement and underlines the precision of the proper motions derived in this work. These proper motions are then used to determine membership probabilities of the stars in the region. By combining parametric and non-parametric approaches, this new membership study leads to a much better segregation of the cluster stars than previous studies. We obtained a list of 169 probable member stars (Section 2.6.4).
- A catalogue of accurate $uvby - H_\beta$ and J2000 coordinates for 7842 stars in an area of $65' \times 40'$ around NGC 1817 has been obtained through the analysis of 273 CCD images with $V_{\rm lim} \sim 22$. A selection of probable members, combining this photometric study with the previous astrometric analysis, gives us a list of 1592 stars in that area with magnitude limit of $V = 21$ (Section 3.2.2).
- Cross-identification of astrometric and photometric catalogues with Hipparcos, Tycho-2, USNO-2 and the BDA have been performed.

NGC 2548

- Five new photographic plates of modern epoch were taken at the Zǒ-Sè station in the area of NGC 2548 (Section 4.1).
- Absolute proper motions and their corresponding errors for 501 stars within a $1^\circ\!.6 \times 1^\circ\!.6$ area in the NGC 2548 region were determined from automatic MAMA measurements of 10 plates. Comparison with Tycho-2 and Hipparcos catalogues shows good agreement and underlines the precision of the proper motions derived in this work. These proper motions are then used to determine membership probabilities of the stars in the region. Combining parametric and non-parametric methods we give a list of 118 probable member stars (Section 4.2.4).
- A catalogue of accurate Strömgren $uvby - H_\beta$ and J2000 coordinates for 4806 stars in an area of $34' \times 34'$ around NGC 2548 has been obtained through the analysis of 115 CCD images with $V_{\rm lim} \sim 22$. A selection of candidate members combining the photometric and astrometric studies gives a list of 331 stars with magnitude limite of $V = 18$ (Section 5.2.2).
- Cross-identification of astrometric and photometric catalogues with Hipparcos, Tycho-2, USNO-2 and the BDA have been performed.
- The secondary clump on the tidal tail proposed by Bergond et al. (2001) from star counts in NGC 2548 is not noticeable from our astrometric member selection (Section 4.2.4).

NGC 2682

- A new selection of probable members of NGC 2682 from relative proper motions using parametric as well as non-parametric approaches gives 412 candidate cluster members in an area of $1^\circ\!.5 \times 1^\circ\!.5$ with a magnitude limit of $V = 14.5$ (Section 6.2.3).
- A catalogue of accurate Strömgren $uvby - H_\beta$ and J2000 coordinates for 1843 stars on an area of $60' \times 34'$ around NGC 2682 has been obtained through the analysis of 106 CCD images with a $V_{\rm lim} \sim 19$. This is the deepest and more extense photometry in Strömgren system of M 67 up to now. Combining

this photometric study with the astrometric analysis we found 776 candidate members in the area with magnitude limit of $V = 18$ (Section 6.3.1).

- Cross-identification of astrometric and photometric catalogues with Hipparcos, Tycho-2, USNO-2 and the BDA have been performed.

8.3 Physical implications

- The determination of the physical parameters of NGC 1817 based on our accurate photometry from its members gives: $E(b-y) = 0.19 \pm 0.05$, [Fe/H] = -0.34 ± 0.26, a distance modulus of $V_0 - M_V = 10.9 \pm 0.6$ and an age of $\log t = 9.05 \pm 0.05$, i.e. 1.1±0.1 Gyr (Section 3.3).

- We have not found any support for considering NGC 1807 a real physical cluster (Section 3.4).

- An improved determination of the physical parameters of NGC 2548 (M 48) gives: $E(b-y) = 0.06 \pm 0.03$, [Fe/H] = -0.24 ± 0.27, a distance modulus of $V_0 - M_V = 9.3 \pm 0.5$ and an age of $\log t = 8.6 \pm 0.1$, i.e. 0.4±0.1 Gyr (Section 5.3).

- A new determination of NGC 2682 (M 67) physical parameters based on our highly accurate photometry gives: $E(b-y) = 0.03 \pm 0.03$, [Fe/H] = 0.01 ± 0.14, a distance modulus of $V_0 - M_V = 9.7 \pm 0.2$ and an age of $\log t = 9.62 \pm 0.02$, i.e. 4.2±0.2 Gyr (Section 6.4).

- Eleven blue stragglers have been identified in NGC 1817. From the seven already found in the catalogue by Ahumada & Lapasset (1995), two of them are not astrometric members, while six more are new identifications (Section 3.3.3). In the case of NGC 2682, we found 23 blue stragglers coherent with our cluster/field segregation (Section 6.4.2).

- Space velocity and Galactic orbits have been calculated for the three clusters and their orbital parameters obtained. The apogalactic radius for the model with four arms is $R_a = 9.56 \pm 0.07$ kpc for NGC 2548, $R_a = 10.92 \pm 0.40$ kpc for NGC 1817 and $R_a = 9.13 \pm 0.01$ kpc for NGC 2682, and the $z_{max} = 239.4 \pm 2.3$ pc for NGC 2548, $z_{max} = 424.8 \pm 12.7$ pc for NGC 1817 and $z_{max} = 461.4 \pm 4.6$ pc for NGC 2682 (Section 7.1).

- Age, distance and metallicity relations have been analysed on the view of the results obtained for these clusters (Section 7.2). A radial metallicity gradient from the bibliography of -0.063 dex kpc^{-1} is coherent with our results. We cannot ascertain any gradient with the maximum distance above the plane, $z_{\rm max}$, nor with age.

- Mass functions and the corresponding slopes have been calculated (Section 7.4). From a power law fitting in the common range $0.8 - 1.3\ M_{\odot}$, the slopes are found to be of $\alpha = 2.4\pm0.5$ for NGC 2548, 2.7 ± 0.5 for NGC 1817 and 1.7 ± 0.2 for NGC 2682.

- Mass segregation from luminosity functions, radial profiles of the different populations and relaxation times have been studied (Section 7.5). Relaxation times for the clusters give lower limit values of $t_{\rm rh} = 2.1\times10^7$ yr for NGC 2548, $t_{\rm rh} = 8.98\times10^7$ yr for NGC 1817 and $t_{\rm rh} = 2.8\times10^7$ yr for NGC 2682.

  - NGC 2682 is well relaxed (around 150 relaxation times elapsed) and has all its bright stars in the centre. Its red giants are even more concentrated than the blue stragglers. The r_c of blue stragglers is similar to that of the stars in the main sequence region between $13.5 < V < 15.5$. And the range of masses covered by the BS is calculated to be between 1.5 to $2.7\ M_{\odot}$.
  - NGC 1817 with an age 12 times its relaxation time, shows to be relaxed, with a distribution of blue stragglers very concentrated with a $r_c = 2.8$ pc very similar to that of the red giant spectroscopic binaries, but still keeping few blue stragglers far out in the halo of the cluster, pointing to a primordial binary origin of the blue stragglers. The range of masses of its BS is calculated to be 1.9 to $3.3\ M_{\odot}$.
  - The youngest of the set, NGC 2548 shows mass segregation to be still in process in spite of the short relaxation time deduced for this system, what indicates that its mass is very clearly underestimated. No blue straggler detected in this cluster.

- The angular diameter of the clusters can be compared with previous determination of sizes. Our measurements of the half-sample radius using the astrometric data give a $r_{\rm h}$ of $11.75'$ (6 pc) for NGC 1817, $14.38'$ (3 pc) for NGC 2548 and $9.90'$ (2.6 pc) for NGC 2682 (Sections 3.3.4, 5.3.4 and 6.4.4).

Table 8.2: Comparison of the angular half-sample diameters of the clusters obtained by this study with those by Lyngå (1987).

	NGC 2548	NGC 1817	NGC 2682
$2 \times r_{\mathrm{h}}$	$28.76'$	$23.50'$	$19.79'$
$D_{Lyngå}$	$29'$	$20'+12'^{*}$	$25'$

(*) Diameters of NGC 1817 and NGC 1807, respectively.

Lyngå (1987) quotes angular diameters of those clusters from visual inspection that corresponds rather closely to our calculated half-sample radii (see Table 8.2), except maybe for NGC 1817 as the quoted value does separate the inexistent NGC 1807.

- We perform a search for possible gaps in the main sequence of these clusters and, also, of the Pleiades and the Hyades (Section 7.6). They have been added as a check of the method and to construct a sequence of ages and metallicities. We find four gaps in the effective temperature interval 4000–8000 K. The coldest gap, around 4900 K, had not been previously reported.

8.4 Future work

- It would be convenient to enlarge the area covered by the photometry up to the extension of the astrometry coverage. This would make possible to cover all the clusters area, including the clusters halo, so we could better determine the mass segregation effect.

- It would be very useful to obtain radial velocities for more stars in these clusters. Our candidate members will help in targeting the measurements towards significant stars. NGC 2548 lacks of any comprehensive radial velocity study. This will help to verify the membership of stars from the candidate list used to define the cluster proper motion. A precise mean radial velocity and mean proper motion will allow us to better determine the orbits. Moreover, the intrinsic dispersion of the velocities would help to obtain a realistic value of the dynamical mass.

- In addition to radial velocities, spectroscopy will also determine independently and accurately the metallicity of the known cluster members.

- Binarity will be likewise better determined thanks to spectroscopic studies, that will help in disentangling the mistery of the formation of blue stragglers.

- An improvement in the proper motions would make possible the study of the internal dynamics and possible anisotropies of the clusters. This will be possible thanks to the future ESA's Gaia mission that will determine proper motions up to 20 mag with a precision of about 10 μas yr^{-1} at $V = 15$ (Perryman 2005).

- Investigation of the variability behaviours and physical properties of variables can undoubtedly provide important information for understanding the structure and evolution of these stars and the host cluster. NGC 1817 has its turn-off on the instability strip and has already shown a rich population of variables (e.g. δ Scuti), as it is also the case with the better-known NGC 2682.

- The tools developed to derive physical information from astrometry and photometry will be applied to the available published data to deepen into the properties of the Galactic system of open clusters.

- To disentangle the distance, age and metallicity relation, it is necessary to enlarge the number of high-quality studies of open clusters. The highly complementary combination of tools developed in this work should help in the study of further clusters in a coherent way, in spite of their sparseness and extension.

- Distant open clusters have been poorly studied and there are many questions related to the origins of some of them. They can be used to probe the structure of the disk in its outskirts, as tracers of the Galaxy streams (GASS/Monoceros and/or Canis Major). Ongoing surveys of Galactic structure like SDSS-II/SEGUE should provide ideal databases for indentifying sub-structures in the disk, and high-resolution multi-object spectrographs will provide unprecedented elemental abundance data. Four possible distinguishing features which might identify clusters likely to be of external origin are the chemical abundance patterns, ages, spatial motions (and distributions), and cluster structures. The techniques developed in these thesis are appropiate to study all these features.