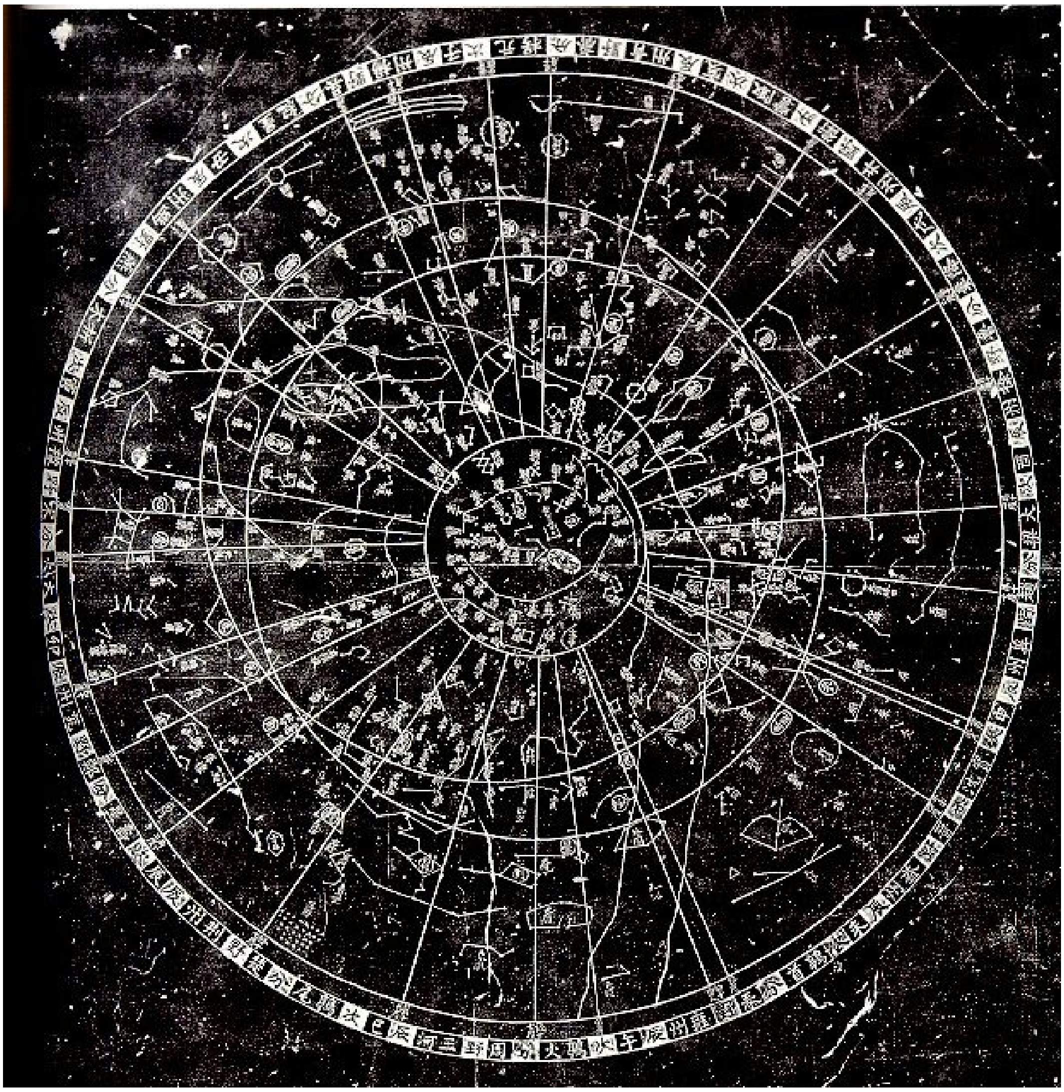
UNIVERSITAT DE BARCELONA

DEPARTAMENT D'ASTRONOMIA I METEOROLOGIA

Astrophysical Studies on Open Clusters:

NGC 1807, NGC 1817, NGC 2548 and NGC 2682



Memoria presentada por
María de los Dolores Balaguer Núñez
para optar al grado de
Doctora en Física
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思玄赋

我走出清幽幽的“紫微宫”，到达明亮宽敞的“太微垣”；
让“王良”驱赶着“骏马”，从高高的“阁道”上跨越扬鞭！
我编织了密密的“猎网”，巡守在“天苑”的森林里面；
张开“巨弓”瞄着了，要射杀嶓冢山上的“恶狼”！
我在“北落”那儿观察森严的“壁垒”，便把“河鼓”敲得冬冬直响；
款款地登上了“天潢”之舟，在浩瀚的银河中游荡；
站在“北斗”的末梢回过头来，看到日月正在不断地回旋。
(注：以上引号内的内容是古代天文星座。)

张衡 (78-139)

Thinking about Mysteries

Out of the quiet and beautiful "Purple Court Palace", I reach the bright and spacious "Privy Council walls";
I let "legendary charioteer, Wang Liang" drive the "Steed", striding across the "Steepest road through the Milky Way"!
I wove a tight "Hunting Net" and patrol the forest of "Celestial Orchard".
I opened up the "Giant Bow" and aimed at the "Ferocious Wolf"!
I observed the "Fortified Wall" at the "Northern backgate" and then heavily beat the "Drum at the river".
Boarding the boat of "Celestial pond" I wander in the vast Milky Way.
At the tip of the "Northern dipper", I look back at the Sun and Moon perpetually revolving.

(Note: The words in quotation marks are the ancient Chinese names of the constellations. English names taken from the study of Kistemaker (1992).)

Zhang Heng (78 - 139)

1 Introduction

As the first foreign student of Astronomy in China in modern times, I have often been asked about the motivation of this thesis, devised as a collaboration between Europe and China. The reasons for such an endeavour may seem peculiar. However, if one thinks about Chinese culture and long scientific tradition, one would expect a greater number of scientific exchanges than have ocurred in recent times. Thus I was indeed curious about the history of my predecessors, and proud to discover that I was part of a very long tradition which, I believe, will continue for some time to come[1].

In 1246, during the Yuan dynasty, as Zhang Kai (2003) relates, the Spanish Muslim Muhyi al-din al-Maghribi (1226-1308), also known as Abi-I-Shukr[2], was probably the first known Spanish astronomer to arrive in China through Syria. Being an expert in astronomy, mathematics, medicine and other sciences, he got a high position under Kublai Khan (1215-1294). With the Chinese name of Ai Xue, he worked in cooperation with Chinese astronomers in the study of calendars, and published a book *Risalat al Khita wal-ighur* about the Chinese and Uygur calendars. His knowledge of Chinese and Arab mathematics and astronomy helped in the spread of methods, applications and construction of astronomical instruments. In 1273 he introduced in China Euclidean geometry and the theory of celestial bodies of Ptolemy. However, the Euclidean geometry that he introduced to the academic circles did not spread fully until much later, with the arrival of Mateo Ricci in 1606. Ai Xue's works and contributions were important as a reference for Chinese astronomers, and his research is specially reflected in three of the volumes of the *Yuan Shi* (*History of the Yuan dynasty*).

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[1] This section is indebted to the classical *Science and Civilization in China* (Needham 1959).

[2] His complete name was Muhyi al-Milla aldin Yahya ibn Muhammad ibn Abi-I-Shukr al Maghribi al Andalusi.

Another Spanish Muslim, Jabir ibn Aflah[3] (c. 1130-1160), invented an observational instrument known as the *torquetum*, a mechanical device to transform spherical coordinate systems. While the Egyptians, Greeks and later Europeans concentrated their attention on heliacal risings and settings —that is, in the ecliptic and the horizon—, the Chinese centred their attention on the polar star —connected with the emperor— and on the circumpolar stars which never rise and never set. Their astronomical system was thus closely associated with the concept of the meridian (the great circle of the celestial sphere passing through the pole and the observer's zenith), and they determined systematically the upper and lower culminations (meridian passages) of these circumpolar stars. The rest of the stars of the sky were divided into the 28 lunar lodges or constellations of the Chinese traditional division of the sky. During the first millennium B.C. the Chinese built up a complete system of equatorial divisions in hour-angle segments, the 28 *xiu*. Each lunar lodge is named from a constellation which provided the determinative star. These determinative or reference stars are linked to the circumpolar stars through hour-circles, having approximately the same right ascensions. Thus they were able to know their exact location, even when invisible below the horizon, simply by observing the meridian passages of the constantly visible circumpolar stars keyed to them.

The Chinese astronomer Guo Shoujing (1231-1316) designed the astronomical observatory in Beijing (see Mercier 2003 and references therein) in 1276 and was famous for his high-precision observational instruments. One of this instruments was the so called "simplified instrument" or equatorial torquetum. Its name was probably referred to as "simplified" because the ecliptic components had been removed. This instrument constitutes the precursor of the equatorial mounting of modern telescopes. Thus within the span of two generations (to c. +1270), what started as an original, though not very practical, idea in Andalusia far in the West, had evoked a really important practical invention in Beijing. They adapted the ecliptic Western instruments to the equatorial coordinates useful to them. Guo Shoujing, who had no telescope —but a sighting tube—, was the inventor of its polar axis mounting, essentially identical with that used for modern equatorial telescopes.

Based upon his own diagrams and with the aid of information collected by Ai Xue among others, Guo Shoujing worked out a new improved calendar (the *Shou Shi Li*) and determined the length of a tropical year to be 365.2425 days. The same figure was adopted in the Gregorian calendar about 300 years later.

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[3] Al-Ishbili Abu Muhammad Jabir ibn Aflah, also known as Geber.

In China, astronomers —contrary to the Greek tradition— were intimately connected with the sovereign pontificate of the Son of the Heaven, part of an official government service, and virtually accommodated within the very walls of the imperial palace. There was a belief that the emperor received his right of rule from heaven and had the duty of holding the proper balance between Heaven, Earth and Man. Changing the calendar was seen as one of the duties of the office, establishing the emperor's heavenly link on earth. After a change of ruler, and even more significantly after a change of dynasty, the new emperor would seek a new official calendar thus establishing a new rule with new celestial influences (Cullen 1996; Hashimoto 1988).

The first known stellar catalogue is the Chinese classical *Xing jing*, that certainly goes back to the three schools of astronomers in the mid-fourth century B.C., namely Shi Shen, Gan De and Wu Xian. It was previous to that of Hipparchus in 135 B.C. Besides the equatorial coordinate system and the first modern mounting for astronomical instruments, another of the outstanding Chinese inventions is the first water clock drive. Zhang Heng (78-139 A.D.) appears to have been the first to construct an equatorial armillary sphere. It consisted of a system of rings corresponding to the great circles of the celestial sphere with a central sighting tube which was used to line up stars and planets. He constructed two: one for observing and one equipped with a water clock drive for computational use. With this instrument he was able to make more accurate star maps than earlier Chinese astronomers: "North and south of the equator there are 124 groups which are always brightly shining. 320 stars can be named. There are in all 2500, not including those which the sailors observe. Of the very small stars there are 11520."

Apart from the Babylonian records, so many of which are presumably wholly lost, those of the Chinese show that they were the most persistent and accurate observers of the celestial phenomena anywhere in the world before the Arabs. The Chinese astronomers compiled not only the records of eclipses dated from as far back as 1362 B.C., but also various kinds of records of "unusual" phenomena that appeared in the sky. Even today there is a long period (from about centuries 5 B.C. to 10 A.D.) for which Chinese records are the only ones available, and modern astronomers have in many cases had recourse to these records with valuable results. (e.g. the recurrent apparitions of comets, like the appearence of Halley's comet first recorded in 486 B.C., see Ryabova 2003, or the long term studies of Earth's rotation, see Stephenson & Morrison 1995). An outstanding instance is the appearance of novae and supernovae, for which the Chinese records cover the whole of the period between Hipparchus and Tycho Brahe, during which the rest of the world remained in almost complete ignorance of the fact that "new stars" sometimes appeared in the heavens; or the regular observation of sun spots by the Chinese for centuries, while Europeans not only ignored them as atmospheric features, but would have found utterly unacceptable in their preconception of the cosmos, as happened with the discovery of solar wind by the Chinese in the 6th century; or the earliest conception of an infinite universe.

In spite of the belief of the importance of these observations for prognostication for State affairs, Chinese astronomy participated in the fundamental empiricism characteristic of all Chinese science. That had at any rate the effect of allowing a more open-minded view than the Ptolemaic-Aristotelian world-view. After all, astrology in Europe lasted until the time of Kepler and was not fully abandoned till the 18th century.

The spherical astronomy of the ancient Chinese and the ancient Greeks may be said to be still in use in modern astronomy. In sharp contrast with other sciences, like biology or medicine, it is possible to make a presentation of general astronomy in which spherical geometry and the observations of the ancients find their place in a story continuous with the post-Renaissance discoveries which depended on new science, such as optics and electricity, unknown to the ancients.

1.1 Star clusters and stellar proper motions in Chinese history of astronomy

The Pleiades seems to be the first group of stars mentioned in astronomical literature, appearing in the Chinese annals of 2357 B.C. It is interesting to investigate the ancient descriptions of the stars in the light of modern astronomical knowledge with a view to determine their degree of exactness and penetration. Hence the interest of the famous historian and astronomer of the Han dynasty, Sima Qian's (c. 145-90 B.C.) description of the Pleiades open cluster (in Chinese *Mao*) as *Mao tou* "the hairy head", to which he adds the words "the white robe assembly" (*bai yi hui*), a very appropriate term for this noticeable star cluster.

As early as the Tang dynasty, the Buddhist monk Yi Xing (683-727 A.D.) gathered observations made with an armillary sphere and compared them with past records. He discovered that the observed polar distances of the determinative stars for fourteen lunar lodges (from *Qian niu* —8th— to *Dong jing* —22nd—) were shorter than the previous values, while those of the other fourteen lunar lodges were longer (see Ang Tian Se 1979 for a complete review). In addition to these 28 reference stars, he further located about 130 more stars, the positions of which as found by him also differ from past records. Yi Xing's calculations were based on data taken 600 years apart, being the first observations made in the Late Han dynasty. It is unlikely that Yi Xing could do as well as Tycho's (supposed) accuracy of one minute of arc, but he may have been able to detect 2 or $3'$; medieval Chinese astronomers often gave fractions of under four minutes of arc. Thus the possibility that he really saw some movement cannot quite be excluded. One notices the curious fact that of the nearest stars which seem to be moving very fast none appears on the list, not even the brightest, some of which have outstanding proper motions. Most of the stars in Yi Xing's sample are faint ones, and about half are at the limit of visibility (mag 5.5), though none would have been really impossible to see with the naked eye and a sighting tube.

Yi Xing did not, however, draw any conclusion from his own observations nor did he try to advance any explanation for the variation in positions. Being a pragmatic person, "his mind was entirely open to the possibility of such manifold stellar motions" (Needham 1959). Chinese astronomers after all did not have any fixed idea about the "fixed stars", as did their Greeks counterparts.

Mei Wenting (1633-1721) of the Qing dynasty reasoned that if Yi Xing had pursued further he would have discovered the fact that the positional differences were due to the "proper motion" of the fixed stars. His specious reasoning had a tremendous impact in the history of Chinese astronomy. For well over two hundred years, many historians of science were led to believe that Yi Xing had discovered the proper motion of the "fixed stars" about a thousand years earlier than Edmund Halley (1718).

Xi Zezong (Xi 1958), however, did not agree with this claim and, with the equations for precession, he proved conclusively that the variation was essentially due to the observational errors mixed with precession. Precession is indeed a problem too intrincate to have it compounded by the single-rings of the equatorial and ecliptic circles in Yi Xing's armillary sphere, even if Yi Xing was aware of precession.

In any case and more importantly, even if Yi Xing did not observe a true effect, it is clear that his mind was entirely open to the possibility of such stellar motions. That is to say, he accepted the reliability of the measurements of his far-distant predecessors and did not simply believe that he was correcting their values with up-to-date methods.

1.2 Shanghai Observatory

The Shanghai Astronomical Observatory (SHAO) is an institute of the Chinese Academy of Sciences (CAS). It was formally established in 1962 following the amalgamation of the former Xujiahui (originally spelt Zikawei) and Sheshan (Zǒ-Sè) observatories; these were founded by the French Mission Catholique in 1872 and 1900 respectively, but both came under government jurisdiction in 1950.

The observatory's main observing facilities include a 25 m radio telescope and associated very-long baseline interferometer (VLBI) system, a 1.56 m optical telescope, a 60 cm satellite laser-ranging (SLR) system, a 40 cm double astrograph and hydrogen atomic clocks. The 40 cm double-tube refracting telescope, which was commissioned in 1900, was built by P. Gautier in France and its twin is still preserved in the Paris Observatory. The excellent optics of this telescope, still in operation, has made it possible to maintain an almost continuous production of photographic plates. The abundance, quality and homogeneity of this material enable the very accurate determination of proper motions. The advent of CCDs marked the end of photographic glass plates production, which disappeared from the market in the late 90's. The last big glass plates at the Shanghai Observatory were used for the work described in this thesis. The use of film substrates for big format photographic emulsions was considered a possible alternative, at least until CCD technology would be able to cover wide fields with enough astrometric quality. The astrometric and photometric performance of one of those film-based plates compared to classical glass plates was studied by Galadí-Enríquez et al. (1998b). They found the film-based plate had excellent photometric accuracy but very poor astrometric performance producing strong deformations and systematic patterns. Fortunately, high-precision astrometry with CCD detectors is improving very fast (see e.g. Anderson & King 2000).

Undoubtedly, the biggest treasure of the Shanghai Observatory is its impressive plate library. About seven thousand plates have been accumulated since 1900. Prof. Li Heng (1898-1989) was the first director of SHAO (1962-1981) and the first in a long tradition in astrometry at the Shanghai Observatory and to publish proper motions of star clusters from the Zŏ-Sè station (*Études photographiques de cinq amas galactiques, NGC 1750, 1817, 2286, 2548, 7380*; Li 1954). The methods of analysis were rapidly developed and in the 1980's a complete analysis of 42 open clusters was published (Zhao & Tian 1985b). This tradition has been continued and improved (e.g. Zhao & He 1990) up to the present day.

Following this tradition, this PhD work is intended to study a set of open clusters combining astrometric studies based on the Shanghai material with photometric studies based on observations made using Spanish telescopes.

1.3 Astrophysical interest of Open Clusters

Due to their low central concentration and to the fact that they lie near the Galactic plane, where they tend to be heavily obscured and can easily be lost amongst the high density of field stars, the Messier Catalogue only lists 27 open clusters. Nevertheless, the database compiled by Lyngå (1987) lists some 1200 open clusters, but even this covers only a small fraction of the Galaxy.

Since 1987, the database for stars in Galactic open clusters known as *Base de Données des Amas* (BDA) and implemented as a Web site (WEBDA[4]), has been developed and maintained by Mermilliod (1995). The most recent list of open clusters and candidates enumerates 1567 objects (Dias et al. 2002a) that are being added to the WEBDA when astrophysical observations are published.

About 400 open clusters have CCD photometry, only around 200 have measurements of proper motions and some 120 have radial velocities. But in spite of the scarceness of data, open clusters have played a key role in the development of our understanding of Galactic astronomy and stellar astrophysics. In fact, its relevance and importance in astronomy has grown faster in the last few decades than astronomy in general (von Hippel 2005). The areas of interest can be listed as follows:

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[4] `http://obswww.unige.ch/webda/`

- Open clusters are interesting as individual objects: the study of their formation and evolution processes, the initial mass function and the percentage of binaries; their internal structure, kinematics and dynamics; the processes of equipartition and the significance of mass segregation and the evaporation of stars; their rate of destruction/survival after tidal encounters with massive molecular clouds.

- Open clusters are commonly believed to be excellent tracers of Galactic disk properties. Since it is believed that many of the stars in the disk of the Milky Way originated in open clusters, the properties of these systems must dictate many of the properties of the stellar disk as a whole. The spatial distribution of open clusters yields a useful probe of the structure of the Galactic disk: the younger systems delineate the spiral structure of the Galaxy while the older systems trace the kinematics of the outer Galaxy.

- They cover the whole interval from a few million years to about 10 Gyr, so they can be used to study both the present day disk structure and its temporal evolution (Janes & Phelps 1994; Friel 1995). Their relative ease in determining parameters such as distance, reddening, metallicity and age with considerable precision, make them useful objects to study the gradient of age as a function of galactocentric distance. And moreover, the presence of a gradient of metallicity as a function of galactocentric coordinates.

- They are an ideal tool for studying the formation and evolution of stars. The study of colour-magnitude diagrams and their corresponding theoretical HR diagrams is a powerful check for the theoretical models of stellar evolution.

- The Hyades, and other nearby clusters, have played an important role in establishing the scale of distances and the size of the entire Universe. The study of Cepheids, supergiants and early-type stars in open clusters are of fundamental importance to extend the scale of distance to the extragalactic domain.

1.4 Selection of Open Clusters

The selection of clusters to be studied astrometrically and photometrically in this work is based on the available and not yet studied plate material at the Shanghai Observatory and the capability to take plates at modern epoch. In a previous

Figure 1.1: An image of the area of NGC 1817. Bright stars on the right of the picture form the asterism known as NGC 1807.

study by our team (Galadí-Enríquez 1998), the overlapping clusters NGC 1750 and NGC 1758 were already analysed. From a detailed revision of SHAO plates, we found that there were three more open clusters with quality plate material and not yet fully analysed: NGC 1817/NGC 1807, NGC 2548 and NGC 7380. The long time-baseline (81, 82 and 45 yr, respectively) is an important ingredient for accurate proper motions derivation. NGC 7380 is a young cluster located at about 3 kpc and it belongs to Cep OB1 association. Although it is intrinsically interesting, its distance and reddening made us concentrate on the other two clusters. In addition, NGC 2682, already studied by Zhao et al. (1993) with similar plate material, was used for the transformation of instrumental to standard photometry and this led to the obtention of a very good set of photometric data for this stellar system. Therefore it too has been analysed in this work.

The open cluster NGC 1817 (C0509+166), in Taurus (Fig. 1.1) [$\alpha_{2000} = 5^{\rm h}12^{\rm m}\!.1$, $\delta_{2000} = +16^\circ42'$], is an old and rich but poorly studied open cluster (Friel 1995). NGC 1817 seems to be as old as the Hyades, with a lower heavy-element abundance. Its location at 1800 pc almost directly towards the Galactic anti-centre and 400 pc below the plane [$l = 186^\circ\!.13$, $b = -13^\circ\!.12$] and its metallicity, lower than solar, make it an object of special interest for the research of the structure and chemical

Figure 1.2: An image of the area of NGC 2548.

evolution of the Galaxy (Salaris et al. 2004, Chen et al. 2003 and references therein).

NGC 1807 (C0507+164), also in Taurus [$\alpha_{2000} = 5^{\rm h}10^{\rm m}\!.7$, $\delta_{2000} = +16°32'$] shows up as a group of bright stars on a mildly populated background, located close to NGC 1817 (Fig. 1.1). The status of NGC 1807 is debatable but it still appears listed as an open cluster (Rapaport et al. 2001). Some authors do not consider it a physical open cluster (Becker & Fenkart 1971, Purgathofer 1961), while others have proposed that it could constitute a multiple system with NGC 1817 (Barkhatova 1963). A binary cluster is a pair of clusters that is gravitationally linked. The existence of binary clusters in the Galaxy is a poorly studied subject. The Large Magellanic Cloud possesses a large proportion of candidate binary clusters, having no counterpart in our Galaxy where only a few open clusters are candidate to be binary (Subramaniam et al. 1995). The only confirmed binary cluster is h $+\chi$ Persei which consists of two rich, young clusters NGC 869 & NGC 884, located at a distance of about 2 kpc. In the LMC the existence of binary clusters was disclosed more than a decade ago (Bhatia 1990 and references therein). However, on theoretical grounds, their physical status and their properties (formation process, survival time,...) remain unclear. To disentangle the ambiguity between a double or a binary cluster from two clusters close in the line of sight, we need to study their physical parameters. Age, distance, metallicity and kinematics can help to know their condition. Binary clusters born from the same molecular cloud should share similar parameters. To study the true nature of this asterism NGC 1817/NGC 1807 is one of the objectives in this work. In the study already mentioned by our team, the Shanghai plate material already helped to clarify the structure of another region in Taurus, where up to three overlapping open clusters had been proposed (Galadí-Enríquez et al. 1998b).

The open cluster NGC 2548 (C0811-056), also known as M 48, in Hydra (Fig. 1.2) [$\alpha_{2000} = 8^{\rm h}13^{\rm m}48^{\rm s}$, $\delta_{2000} = -5°48'$; $l = 227\overset{\circ}{.}93$, $b = +15\overset{\circ}{.}39$] has an estimated distance of 630 pc (Pesch 1961) or 530 pc (Clariá 1985). It is surprisingly very poorly studied in spite of being an extended object with an apparent diameter of $30'$ (Trumpler 1930) or even $54'$ (Collinder 1931) and brilliant enough to be in the Messier list (XVIII century) as number 48 (Messier 1850). It was even considered inexistent for several years due to the fact that Messier quoted its coordinates with an error in declination of five degrees. There is no feasible estimation of its age but it seems an intermediate-age open cluster, around $\log t = 8.5$ (Lyngå 1987), with a slightly poorer CN abundance than the giants of the Hyades but significantly richer than the K giants of the solar neighbourhood (Clariá 1985; Twarog et al. 1997).

NGC 2682 (C0847+120), also known as M 67 (Fig. 1.3), in Cancer [$\alpha_{2000}{=}8^{\rm h}51\overset{\rm m}{.}3$, $\delta_{2000} = +11°50'$; $l = 215\overset{\circ}{.}66$, $b = +31\overset{\circ}{.}91$] is probably the most thoroughly studied old open cluster in the Galaxy, thanks to its small distance from us (estimated around 900 pc). Typically quoted values for the age of the cluster (around 4 Gyr) place it among the oldest open clusters. Photometric standard stars were taken from this cluster, thus high-quality Strömgren wide-field CCD photometry of it also resulted from our observations. Given the quality and wide area coverage of these data, we decided to include this cluster in our astrophysical analysis. The existence of a similar quality proper motions study (based on the same plate material and methods, by the Shanghai Astronomical Observatory, as in the other clusters under study), gave us the possibility of applying the same protocol to this cluster.

More details on the individual clusters, and on the observations, will be given in the chapters of this work devoted to their study.

Figure 1.3: An image of the area of NGC 2682.

1.5 Methodology

The main tools for the observational study of star clusters are astrometry, photometry and spectroscopy:

a) Precise astrometry permits the accurate determination of positions and proper motions of the stars and, thus, is an efficient tool to segregate cluster members from field stars. It is useful as well to derive the angular diameter and to study the morphology of clusters.

b) Multiband photometry is the usual technique to measure distance, reddening, metallicity and age. Because cluster stars have the same age, but different masses, each cluster defines an isochronous sequence in the colour-magnitude diagram. Such sequences are computed from grids of evolutionary stellar models and compared with the observed data through the corresponding transformations to determine the above mentioned parameters.

c) Spectroscopy is a powerful technique but a rather cumbersome method to implement, as it requires a large amount of telescope time. Spectra give the most precise determination of metallicity and it is the only way to derive radial velocity. It may provide indication of binarity or multiplicity and it is also a very efficient criterion for membership segregation.

In this work, we have acomplished astrometric and photometric studies, while spectroscopy data have been taken from the literature, when available.

1.5.1 General Principles

- Proper motions:

  The proper motion of a star is its angular change in direction in the sky over a period of time, often expressed in arcseconds per year. Its definition is specific with regard to the location of the observer, usually considered to be placed at the Sun or the barycentre of the Solar System, and to the frame of reference against which the motion is compared. Most stars in our Galaxy (the ones in the disk) are revolving in the same way around a distant point, the Galactic centre, at different speeds and in slightly different directions.

  The Galactic open clusters share the motion of the stars in the disk. And within each cluster, each star moves in an orbit around the centre of mass. Proper motion is just one of the two components into which the space motion of a star can be decomposed, the other being radial velocity. Therefore, we need to measure proper motions and radial velocities in order to draw the pattern of Galactic motions for stars and clusters, as well as for stellar motions within clusters. The open clusters and the bulk of the stars near the Galactic plane have heliocentric motions of a few tens of kilometers per second, with some well over 100 km s^{-1}. Large heliocentric motions prevail for globular clusters and most halo stars, which reach several hundred kilometers per second. Internal motions in star clusters are typically around a few km s^{-1} (Binney & Merrifield 1998).

  Absolute proper motions have been measured on photographs for around 200 open clusters, using photographic star catalogues for the reference frame. The Hipparcos Catalogue provides astrometric and photometric data for 241 clusters ranging from one star per cluster to over 100 stars (e.g. Hyades).

- Determination of proper motions:

  The determination of proper motions is based on the comparison of images of a star field obtained at suitably spaced epochs of observation. The images may be photographic plates or frames from electronic detectors. Precision coordinate measuring machines provide rectangular coordinates from photographic plates, while software associated with electronic detectors provides such coordinates directly.

  The Photometric Data System (PDS) Microdensitometer is the machine currently in use by most observatories in the world for this purpose. The original model was built in the early 1970's and since then several improvements have been made to it. It is fully automated, transfers the images directly into a computer for further analysis, and is more accurate than previous devices. Although it is still widely used by photographic astronomers, it has several limitations which will have to be rectified in future measuring engines. For instance, the instrument is quite slow. It takes many hours to measure a single photographic plate.

  The basic idea of microdensitometry is as follows. A lamp emits a light beam of a certain brightness which is focused by an inverted microscope onto the area to be measured on a photographic plate. The part of the beam which is transmitted is collected by another microscope and directed towards a photoelectric tube which then determines the intensity of light which has been transmitted. This gives the optical density of the photographic plate at that position. Therefore, when the plate is scanned in this way, we get a digitalised map of optical densities on the plate. It is easy to imagine that this method would be rather slow to scan an entire plate, so usually only the areas of interest are scanned, ignoring everything else. For faster processing, it can use arrays of receivers to scan several areas of the plate at the same time. The MAMA (Machine Automatique à Mesurer pour l'Astronomie) is a realisation of this idea. In this thesis we have used both kinds: the PDS 1010 MS microdensitometer at the Nanjing Observatory and the MAMA at the Observatoire de Paris.

  Basically, the proper motion is resolved into components, nominally aligned along right ascension and declination, expressed by coordinates' differences divided by epoch difference Δt, as $\mu_x = \Delta x/\Delta t$ in x and $\mu_y = \Delta y/\Delta t$ in y. In practise the case is more complex. Each plate is exposed and measured with small differences in centring and alignment of axes. The telescope contributes with effects such as guiding errors, optical distortion, flexure, plate tilt and others, which are not precisely the same for each exposure. Variations in atmospheric refraction and chromatic effects, depending on the colour of the star, contribute to the image formed on each plate. The plates may even be taken with different telescopes. These effects must be accounted for in astrometric reductions.

In order to map precisely each plate of a series of two or more plates into one selected to define the standard frame, we use a model that accounts for the above-cited effects. For a pair of plates ($\Delta t \ = t_2 - t_1$), we have in each coordinate the form

$$x_2 - x_1 = \mu_x \Delta t + F(x, y, m, c : a_i) \ ; \ i = 1, n$$

where the model F is some function of position (x, y), stellar magnitude (m), and colour (c). The n unknown parameters a_i are called plate constants.

The simplest case is a linear model, often adequate for small fields, where we have for the x coordinate (similarly in y) $\Delta x = \mu_x \Delta t + a_1 x + a_2 y + a_3$ with unknown plate constants (a_1, a_2, a_3). Two basic approaches exist for finding the plate constants. If a subset of the measured stars is also contained in a star catalogue of positions and proper motions, they may be used as reference stars to evaluate the plate constants. This permits the calculation of proper motions close to the astrometric system of the parent catalogue for all the other stars in the field, thus deriving *absolute* proper motions.

If no external astrometric data exists, then we fall back on a solution for relative proper motions, which has an unknown zero-point offset. In practical terms, all (or part) measured stars are used as reference stars and we solve for relative plate constants, and then compute *relative* proper motions for all stars.

Techniques for evaluating the plate constants include simple least squares adjustment for pairs of plates. The more complex method of plate overlap (Eichhorn 1960) solves simultaneously by least squares both plate constants and star parameters (coordinates and proper motions) for a series of plates. This forces the star to always be at the same position at the same epoch, while simultaneously forcing the star's path with time to be a straight line in the tangent plane, i.e. the star's path is along a great circle on the celestial sphere. Overlap condition may be enforced by solving all the equations of conditions simultaneously, as in the restricted overlap techique (Eichhorn & Gatewood

1967; Eichhorn & Russell 1976) or iteratively as in the central overlap technique (Gatewood & Eichhorn 1973; Gatewood & Russell 1973).

- Cluster membership:

  Proper motions provide the means for isolating members of open clusters from foreground and background field stars. The internal motion in clusters is usually very small. This translates into very nearly equal and parallel proper motions, in contrast to the wide range of motions displayed by field stars. The proper-motion vector point diagram —plot of the two components of proper motion— forms the basis for estimating stellar membership in star clusters. The diagram displays two distributions of points with centroids representing the cluster (usually with small dispersion) and field stars.

  The classical approach to the segregation of cluster and field stars, is to model the field and cluster as bivariate Gaussian distributions. Usually, a circular normal distribution is assumed for the cluster population, while the field is considered to be represented by an elliptic normal distribution (Vasilevskis et al. 1958). By contrast, the non-parametric approach performs an empirical determination of the distribution of cluster and field populations, without any need to know their shapes a priori (Cabrera-Caño & Alfaro 1990). Once the distributions have been obtained, using either of the two methods, membership probabilities of belonging to the cluster can be assigned to each star.

  The membership probabilities of open clusters based on proper motions can be refined with photometric criteria based on colour-magnitude diagrams.

- Photometry:

  As already mentioned, photographic plates have dominated direct imaging for over a century. Only the last decades of the 20th century saw electronic imaging sensors, such as the CCDs, becoming the detectors of preference. The CCD was invented in 1969 by W.S. Boyle and G.E. Smith of the Bell Laboratory, but was first used in astronomy in 1976 when J. Janesick and B. Smith obtained images of Jupiter, Saturn and Uranus. Its advantages include high quantum efficiency, large dynamical range, linearity, direct digital recording and rapid real-time data processing by computers. Its main disadvantage is that it can cover only a small region of sky and that to cover a larger field of view, the spatial resolution has to be sacrificed.

  Open clusters are usually studied using broadband filters. Few clusters have been studied with intermediate or narrow bands because they require longer exposure times to reach the same limiting magnitude. However, intermediate-band photometry offers distinct advantages over standard broadband photometry in the study of field stars and star clusters. In particular, the most important features are that it can provide precise estimates of effective temperature, heavy element abundance and surface gravity for individual stars. In this work, we have preferred to take the advantages and we have chosen the Strömgren-Crawford system (Strömgren 1966).

The Strömgren-Crawford system consists of four intermediate-band filters: y, b, v and u, whose effective wavelengths are 5505Å, 4695Å, 4110Å and 3480Å, respectively, with passbands of widths 150 to 330Å, and a narrow-band pair $(\beta_{\mathrm{n}}, \beta_{\mathrm{w}})$ measuring the streght of H_{β}-line, being β_{n} at 4879Å and β_{w} at 4895Å, 30 and 175 wide, respectively. The usual colour indices employed in this system are $(b-y)$, $(u-b)$, $c_1 \equiv (u-v)-(v-b)$, and $m_1 \equiv (v-b)-(b-y)$. Although it was primarily designed to study early main sequence stars, it has also been used to investigate late type, metal deficient, supergiant stars, etc.

The y magnitude is well-correlated with Johnson V magnitude. Both $(b-y)$ and $(u-b)$ serve as temperature indicators; c_1 is a temperature indicator for hot stars and a luminosity indicator for stars cooler than about 8500 K; $(\beta_{\mathrm{n}}-\beta_{\mathrm{w}})$ is a luminosity indicator for hot stars and a temperature indicator for stars cooler than 8500 K. For late A to G type stars, m_1 measures the amount of line-blanketing, the dimming of the blue part of the spectrum caused by millions of heavy-element absorption lines. Whereas the colour $(b-y)$ is rather insensitive to metallicity, the Strömgren v filter includes several iron absorption lines as well as the CN band at 4215Å, and therefore m_1 is a metallicity sensitive index.

1.5.2 The conflict of two minds: A-priori, parametric method vs non-parametric approach

> If we spoke a different language, we would perceive a somewhat different world.
> — L. Wittgenstein

Classical Chinese language is not based on conceptual constructions but upon written signs full of meanings. It is valuable not for its descriptive or analytic capability, but for its instrumentality. Far from being a concatenation of phonetic elements without meaning, each character constitutes an entity full of meaning. When a Chinese author speaks about “Nature”, he thinks of the written character *xing* —composed of the element *sheng*, which indicates what is living or what is born, and of the radical *xing* from heart (= mind)—, which directs his thinking to nature, human in particular, in a vital way. For the particular essence of its written language, Chinese thought is located in the real instead of superimposed on it. Instead of elaborating ideas from a critical distance, the Chinese way of thinking tends to remain immersed in the real, to experiment and to better preserve its harmony.

Moreover, the grammatical structure of classical Chinese has no prefixes nor suffixes, there are no marks of gender, number, declination, conjugation... Relations are only indicated by the position of words in the sentence and their relationship with the rest, while classical Greek and Latin philosophy is mostly based on a judgment about grammatical categories: the difference between noun and adjective, object and subject, active and passive. In comparison with Indo-European languages, one of the most striking aspects is the absence, in classical Chinese, of the verb “to be” as predicate. Reality is just expressed by simple juxtaposition. Chinese thinking is linked to the real and is a living process; instead of building closed concepts, ideas develop in the big game of context, relationship and reference.

As thoroughly discussed by Cheng (2002), the Chinese mind does not proceed in a lineal or dialectical way but in a spiral. The absence of theorisation in the Greek way explains the Chinese trend towards syncretisms. Absolute and eternal truth does not exist, only in doses. Contradictions are not irreducible but are perceived as alternatives. Opposites complement each other and evolve with imperceptible transitions.

While Chinese science has traditionally been a direct view from Nature without any aprioristic knowledge, European science has been based on the strong Euclidean view and suffered from a complete lack of freedom. Only predicted events were perceived, measured and calculated. The absence of such mathematical underpinnings has saved Chinese astronomy from a tight constraint. What Europeans have cultivated in prognostication ability, the Chinese have succeeded in observing and recording skills. Chinese astronomers measured what they looked at, not what they were looking for.

The modern counterpart will be seen when the Gaia mission will begin sending results. In contrast with the Hipparcos mission where a predefined catalogue was measured, the modern design of the Gaia mission allows the measurement of all the objects found within the technical limits. Nowadays science is trying to overcome the shortfalls of an aprioristic view of events that has dominated Western science since the time of the Greeks. A variety of advanced mathematical techniques (statistical simulations, chaotic modelling, neural networks...) still in development is helping with this.

In this PhD work parametric, aprioristic methods —coming nowadays from the Shanghai Observatory— and non-parametric approaches —adopted at the University of Barcelona— are compared and combined in a modern, syncretic way in the search for taking the best from these two ways of thinking.

1.6 Objectives

The goals of the present work are to characterise the clusters NGC 1807, NGC 1817, NGC 2548 and NGC 2682 and to put them into the context of the Galactic clusters system. To characterise these clusters we have as objectives:

1. To obtain an astrometric and photometric catalogue of the areas under study, from accurate proper motions and Strömgren photometry;
2. To determine in a conclusive way the reality or inexistence of NGC 1807 and its relation to NGC 1817;
3. To generate lists of candidate cluster members of each object with the most efficient criteria by combining astrometry and photometry;
4. To determine the fundamental physical parameters of each cluster;
5. To determine their luminosity and mass functions as well as their degree of mass segregation, distinguishing, when possible, the different types of objects they contain (more and less massive stars, blue stragglers, binaries, etc); and
6. To include them in the context of Galactic open clusters.

With this aim we will perform the following tasks:

1. The selection of the available photographic plates from the Shanghai plate library;

2. The completion of the longest possible epoch difference with newly taken plates at the Zŏ-Sè station for NGC 1807/1817 and NGC 2548;

3. The digitalisation of all plates in the measuring machines at our disposal first from the Nanjing Observatory (PDS microdensitometer), then from the Paris Observatory (MAMA). The production of a catalogue of positions and absolute proper motions from this data;

4. The CCD photometric observation of wide areas of the cluster regions under study. The observations are acquired with the telescopes available in Spain: CAHA 1.23 m, OAN 1.52 m, JKT 1 m and the INT+WFC, with Strömgren filters;

5. The segregation of cluster and field stars from the astrometric and photometric information obtained. Two different statistical approaches to the cluster-field segregation problem will be applied to the sample of proper motions:

   i) the classical parametric approach, with an improved likelihood method, will be applied to the kinematic plane and the inclusion of spatial information will be discussed; and

   ii) the non-parametric method based on empirical determination of the probability density functions, without relying on any previous assumption about their profiles. The non-parametric approach will also be applied to the spatial and photometric planes.

   A comparison of both methods and results from our data will lead to a more reliable membership determination;

6. The segregation obtained from proper motions is completed for faint stars with the help of colour-magnitude diagrams from the photometry and the standard relations based on observational ZAMS;

7. The determination of the fundamental parameters of age, distance, reddening, metallicity, spatial characteristics and total mass from the u, v, b, y, H_β photometry of each cluster;

8. The determination of space velocity and Galactic orbits of the clusters with their orbital parameters;

9. The analysis of their age, distance and metallicity in the context of the Galaxy;
10. The determination of the luminosity and mass functions to get some insight into the different amounts of mass segregation and the radial distribution of stars, including the analysis of the distribution of blue stragglers; and
11. The comparison of astrophysical results between clusters of different ages and metallicities from the same observational material and methods gives us a very coherent framework that lets us study some features of the colour-magnitude diagrams and the search for gaps in their main sequences.

The following chapters detail all of this work from the reduction steps to the analysis, with an account of the different methods used and the conclusions obtained from the methodology, as well as from the data itself. Different approaches are analysed and combined in an innovative way trying to get the best from each method and taking into account all the limitations involved in each case. The intrinsic difficulty of modelling sparse and extended clusters of stars needs a careful combination of tools for realistic and meaningful results.

Chapters 2 and 3 are devoted to disentangling the NGC 1817/NGC 1807 region as well as to describing in detail the methods necessary for their characterisation through astrometry and photometry, respectively. Chapters 4 and 5 are dedicated to the study and characterisation of the NGC 2548 (M 48) area using astrometry and photometry, respectively. Chapter 6 is devoted to the study of NGC 2682 (M 67). Chapter 7 studies the physical analysis of the three clusters in the general framework of the open cluster system. Chapter 8 is dedicated to the conclusions and the description of prospects for future work.