



UNIVERSITÀ
DEGLI STUDI
FIRENZE

**DOTTORATO DI RICERCA IN
FISICA E ASTRONOMIA**

CICLO XXXI

COORDINATORE: Prof. D'Alessandro Raffaello

**Formation and Evolution
of Open Star Clusters
with The *Gaia*-ESO Survey**

Settore Scientifico Disciplinare FIS/05

Dottorando

Dott. Bravi Luca

Tutor

Dr.ssa Randich Maria Sofia

Co-Tutor

Prof. Marconi Alessandro

Coordinatore

Prof. D'Alessandro Raffaello

Anni 2015/2018

This Thesis work was done as part of the research activity of the
Osservatorio Astrofisico di Arcetri - Istituto Nazionale di Astrofisica
(INAF) in Firenze.

Alla mia famiglia

Contents

List of Tables	v
List of Figures	vii
List of Acronyms	ix
Abstract	xi
1 Star Clusters	1
1.1 Open Clusters	2
1.2 Properties of Open Clusters	3
1.2.1 Radii and Timescales	3
1.2.2 The Initial Mass Function	5
1.2.3 Spatial Distribution in the Galaxy	7
1.3 Age of Open Clusters	9
1.4 The Hertzsprung-Russell and Color-Magnitude Diagrams	10
1.4.1 Pre-Main Sequence Evolution	12
1.5 Lithium Abundances	13
1.6 The Surface Gravity	16
2 Formation and Evolution of Star Clusters	17
2.1 Star and Cluster Formation	17
2.1.1 Models of Cluster Formation	18
2.2 Cluster Evolution	19
2.2.1 The Hills Model (1980)	20
2.2.2 Residual Gas Expulsion Scenario	21
2.2.3 Models without Stellar Feedback	25
2.2.4 Observations	28
2.3 Open Questions and Requirements	29
3 Data and Methods	33
3.1 The <i>Gaia</i> -ESO Survey	33
3.1.1 Instrument: FLAMES	34

3.1.2	Cluster Sample	35
3.1.3	Open Cluster Target Selection and Observing Strategy . . .	36
3.1.4	GES Workflow	39
3.2	Methods	40
3.2.1	Spectroscopic Members Selection in Young OCs	40
3.2.2	Kinematic Analysis	45
3.2.2.1	Uncertainties in Radial Velocities	45
3.2.2.2	Radial Velocity Distribution of Star Clusters	46
3.2.3	Cluster Mass and Radii Determination	49
4	Young Open Clusters	53
4.1	Sample of Clusters	53
4.2	Data and Allocated Targets	54
4.2.1	Completeness	57
4.3	Selection of Spectroscopic Candidates	58
4.4	Kinematic Analysis	60
4.4.1	Effect of Binary Systems	61
4.4.2	Assumptions on Binary Properties and Robustness of Fits .	64
4.5	Velocity Dispersion from TGAS Data	65
4.6	Total Mass and Radii	68
4.6.1	Total Cluster Mass from TGAS Data	70
4.7	Discussion	81
4.7.1	GES versus TGAS Velocity Dispersion	81
4.7.2	Effect of Feedback on the Cluster Dissipation Mechanism . .	83
4.7.2.1	Anisotropy in the Velocity Distribution	85
5	Old Open Clusters	87
5.1	Sample of Clusters	87
5.2	Data and Allocated Targets	89
5.3	Completeness	90
5.4	Kinematic Analysis	91
5.4.1	The Effects of Binaries on Velocity Dispersion	96
5.5	Cluster Parameters	97
5.5.1	Star Masses	97
5.5.2	Total Cluster Mass and Cluster Radius	99
5.6	Preliminary Discussion on Cluster Evolution	100
5.6.1	Anisotropic Velocity Distribution	107
6	Summary and Conclusions	109
	List of publications	115
	Bibliography	117

CONTENTS

iii

Acknowledgements

127

List of Tables

1.1	Typical values of properties of Galactic open clusters	5
2.1	Models for cluster formation	19
2.2	Models for cluster evolution	27
3.1	Setups of UVES and GIRAFFE	35
3.2	Available data from GES archive and their application during this work	39
3.3	Values of constants for the empirical derivation of uncertainties on RV for the setup HR15N	46
4.1	Properties of young clusters	54
4.2	Number of targets observed in the four clusters	54
4.3	J magnitude range, radius of GES observations, and completeness of the four clusters.	58
4.4	Best parameters from the fits of the RV distributions in young OCs	61
4.5	Robustness of the fits assuming different conditions of the binary properties	64
4.6	Velocity dispersion estimates obtained with the maximum likelihood procedure using the Nelder–Mead method	67
4.7	Velocity dispersion estimates obtained with the maximum likelihood procedure using the Newton Conjugate Gradient method	68
4.8	Total mass and half-mass radius of the four young clusters	70
4.9	Total mass of the four young clusters calculated with the GES and TGAS sample	70
4.10	Properties of spectroscopic candidates of IC 2602	71
4.11	Properties of spectroscopic candidates of IC 2391	73
4.12	Properties of spectroscopic candidates of IC 4665	74
4.13	Properties of spectroscopic candidates of NGC 2547	77
4.14	Properties of four young clusters	83
5.1	Properties of old clusters	89
5.2	Number of targets observed in the seven old clusters	89

5.3	Radius of observations and completeness for stars in MS and post-MS phase of the seven clusters	90
5.4	Best parameters from the fits of the RV distributions in old clusters with a binary fraction fixed at 50%.	91
5.5	Central velocity and velocity dispersions obtained with different fractions of binaries	96
5.6	Derived masses of the seven old open clusters	100
5.7	Velocity dispersions and properties of old clusters in the sample . .	101
5.8	Properties of Berkeley 31 obtained using a binary fraction of 0.8 . .	102
5.9	Derived properties for the seven old open clusters	105

List of Figures

1.1	Types of star clusters	1
1.2	Functional forms of the IMF	6
1.3	PDMF of open clusters with different ages	7
1.4	Distribution of the OCs projected onto the Galactic plane.	8
1.5	Distribution of OCs on the plane Y versus Z	9
1.6	Age distribution of Galactic OCs	10
1.7	Theoretical isochrones in the HR diagram of PARSEC model	11
1.8	Evolutionary tracks of PMS stars	13
1.9	HRD for low-mass stars and Li depletion	14
1.10	Theory prediction of the PMS lithium depletion	15
2.1	Fraction of stellar mass lost with time due to star expulsion	22
2.2	Variation of the dynamical-mass-to-true-mass ratio with time	24
2.3	Evolution of the average virial ratio	26
3.1	Age distribution of the clusters selected by GES	34
3.2	Distance from the Sun versus age of GES clusters	36
3.3	Target selections of young and old open clusters	37
3.4	Spatial distribution of targets in IC 2602	38
3.5	Spectra of MS and giants stars in the wavelength range 6750 - 6780 Å	41
3.6	Gravity index γ versus temperature index τ	42
3.7	Gravity index as a function of the surface gravity for IC 2602	43
3.8	Equivalent width of Li I line versus effective temperature	44
3.9	Probability density function for RV offset from the mean velocity .	47
4.1	Spatial distribution of GES initial targets and allocated stars in cluster IC 2391	55
4.2	Spatial distribution of GES initial targets and allocated stars in cluster IC 4665	56
4.3	Spatial distribution of GES initial targets and allocated stars in cluster NGC 2547	56
4.4	Completeness of observation in the four young clusters	57
4.5	Gravity index γ as a function of the stellar effective temperature T_{eff}	58

4.6	Equivalent width of the lithium line as a function of T_{eff}	59
4.7	Radial velocity distribution of the sample of young clusters	62
4.8	Spatial distribution of allocated targets, known members from the literature, and candidate members weighted for p_{cl}	63
4.9	Radial velocity distribution of the sample of young clusters	65
4.10	Hertzsprung–Russell diagram of the sample of young clusters	69
4.11	Spatial distribution of GES and TGAS stars in the four clusters.	81
4.12	GES velocity dispersion versus virial velocity dispersion	84
5.1	Distribution of the seven old OCs projected onto the Galactic plane	88
5.2	Radial velocity distributions of Berkeley 31, Berkeley 44, NGC 2243, NGC 2420, NGC 2516, and NGC 6067	92
5.3	Radial velocity distribution of Trumpler 20	93
5.4	Spatial distributions of allocated targets weighted for p_{cl} for Berkeley 31	93
5.5	Spatial distributions of allocated targets weighted for p_{cl} for Berkeley 44, NGC 2243, and NGC 2420	94
5.6	Spatial distributions of allocated targets weighted for p_{cl} for NGC 2516, NGC 6067, and Trumpler 20	95
5.7	The V versus B – V CMD for Berkeley 31 and Berkeley 44	97
5.8	The V versus B – V or the V versus V – I CMDs for NGC 2243, NGC 2420, NGC 2516, NGC 6067, and Trumpler 20	98
5.9	Comparison between σ_c and σ_{vir} for the seven old clusters	102
5.10	Comparison between velocity dispersions obtained with f_{bin} fixed at 0.5 and 0.8 for the OC Berkeley 31	103
5.11	Distribution of the seven old open clusters in the $r_{vir} - N$ plane	106

List of Acronyms

2MASS: Two Micron All Sky Survey
4MOST: 4-meter Multi-Object Spectrograph Telescope
APOGEE: Apache Point Observatory Galactic Evolution Experiment
AURA: Association of Universities for Research in Astronomy
BC: Bolometric Correction
CASU: Cambridge Astronomy Survey Unit
CMD: Color-Magnitude Diagram
EC: Embedded Cluster
ESA: European Space Agency
ESO: European Southern Observatory
EW: Equivalent Width
FLAMES: Fibre Large Array Multi Element Spectrograph
FoV: Field of View
FPOSS: Fibre Positioner Observer Support Software
GES: Gaia-ESO Survey
GC: Globular Cluster
GIRAFFE: Medium-high resolution spectrograph
GMC: Giant Molecular Cloud
HRD: Hertzsprung–Russell Diagram
IMF: Initial Mass Function
ISM: InterStellar Medium
LDB: Lithium Depletion Boundary
LF: Luminosity Function
MOONS: Multi-Object Optical and Near-infrared Spectrograph
MS: Main Sequence
MSTO: Main Sequence Turn-Off
MW: Milky Way
MWSC: Milky Way Star Cluster project
NASA: National Aeronautics and Space Administration
OAA: Osservatorio Astrofisico di Arcetri
OACT: Osservatorio Astrofisico di Catania
OB: Observing Block
OC: Open Cluster

PARSEC: Padova And TRieste Stellar Evolution Code
PDF: Probability Density Function
PDMF: Present Day Mass Function
PMS: Pre-Main Sequence
RGB: Red Giant Branch
RC: Red Clump
RV: Radial Velocity
SGB: Sub-Giant Branch
TGAS: Tycho-*Gaia* Astrometric Solution
TO: Turn-Off
UVES: UV-Visual Echelle Spectrograph
VLT: Very Large Telescope
WEBDA: Web version of the Base Données Amas
WG: Working Group
ZAMS: Zero-Age Main Sequence

Abstract

Open star clusters are key objects in the framework of the study of our Galaxy, and their origin and evolution are important topics in stellar astrophysics. In particular, the majority of stars form in clusters and associations inside giant molecular clouds. However, most clusters dissipate within 10 – 100 Myr, leaving more than 90% of the stellar population dispersed in the Galactic field. Only a small fraction of clusters are able to survive for several Gyr. The scientific debate on the origin of bound and unbound open clusters, along with the processes driving their evolution and those leading to their dissolution, is still open. Several models have been proposed and they can be tested by examining the kinematic and dynamical properties of several systems over a wide range of ages and masses.

The present Ph.D. thesis focuses on open clusters, and the goal is the investigation of the kinematic properties and dynamical evolution of this kind of objects, in order to achieve a full understanding of their origin and fate. In this work, I analyzed a total sample of 11 open clusters using the *Gaia*-ESO Survey products; these clusters have an age between 20 Myr and 3.5 Gyr. The main goal of this work is to study and compare the kinematic and dynamical properties with the predictions of the models proposed in the literature for cluster survival and disruption, using for the first time a homogeneous cluster dataset.

In the first part of work, I focused on a sample of four OCs in the age interval between 20 and 50 Myr. This is an interesting phase for the early dynamical cluster evolution because the embedded phase is over (first 2 - 5 Myr) and the molecular gas of the parent cloud has been expelled ($\sim 5 - 10$ Myr). Thus, the OCs have already completed the process of violent relaxation predicted by the models based on stellar feedback and gas expulsion, while the tidal effects caused by outer gravitational fields have not had the time to modify the system properties since their timescales are longer ($\sim 100 - 300$ Myr) than the age of these clusters. After a detailed cluster membership analysis, using a maximum likelihood technique which takes into account the errors on the radial velocities and the presence of binaries, I performed a dynamical analysis. I determined the intrinsic velocity dispersion; then, using the total cluster mass and the half-mass radius, I derived the virial velocity dispersion. Under the assumption of isotropic velocity distribution, I found that three out of the four clusters are supervirial. This result is in agreement with the hypothesis that these objects are dispersing after gas expulsion by feedback of high-mass stars, as predicted by the “residual gas expulsion” scenario. However, recent simulations show that the virial ratio of young star clusters may be overestimated if

it is determined using the global velocity dispersion since the clusters are not fully relaxed.

In the second part of work, I analyzed a sample of seven open clusters with age greater than 100 Myr. Determining the kinematic and dynamical properties in clusters with age until several Gyrs is fundamental to understand how internal and external processes, such as stellar interactions or tidal shocks, affect the cluster evolution and dissipation on a longer timescale. Clusters at these ages were survived to both early gas expulsion and late tidal interactions. Therefore, they are expected to be in a virialized state. As in the case of young clusters, I derived both the intrinsic and virial velocity dispersion and I found that six out seven clusters are in virial equilibrium, while one is slightly supervirial. In this cluster the discrepancy between the virial and observed velocity dispersion may be due to a high fraction of binaries.

Furthermore, I studied the possible internal evolution of these seven clusters following the model proposed by O’Leary et al. (2014). I found that four out of seven clusters did not and will never undergo to core collapse as a result of the binary heating and they will expand for their entire life. Conversely, I found that in the other three clusters the external parts expand while the internal ones contract. This will lead eventually to core collapse in their future evolution. However, these results are preliminary and further detailed investigations, both theoretical and observational, will be needed to confirm them and to compare the observational results with other evolutionary models.

The outline of this Ph.D. thesis is as follows. Chapter 1 presents an introduction on open clusters, with particular attention on their properties and the main characteristics of their stellar components. In Chapter 2 I describe the models proposed in the literature for the cluster formation and evolution and I report the main questions still open in this astrophysical field. Chapter 3 introduces the *Gaia*-ESO spectroscopic Survey and the methods used in this thesis work. In Chapter 4 I report the analysis performed in the sample of young open clusters and the main results on their dynamical evolution. Chapter 5 presents the dynamical analysis performed for the sample of old open clusters. Finally, Chapter 6 presents the main conclusions.

Chapter 1

Star Clusters

Star clusters are aggregates of stars born roughly at the same time and from the same Giant Molecular Cloud (GMC). Therefore, these stars have the same age, chemical composition, as well as the same distance from the Sun. They allow us to study how stars evolve as their member share similar properties and they provide information about the structural and chemical evolution of the Galaxy.

Star clusters are divided in two main types: the Globular Clusters (GCs) and the Open Clusters (OCs). GCs are massive ($10^4 - 10^6 M_{\odot}$) and old (~ 12 Gyr) systems containing thousands to hundreds of thousands of stars closely packed in a symmetrical spherical shape. GCs are found in the bulge and halo of Milky Way (MW) and they are dynamically relaxed systems. OCs are typically young systems, with the majority of them with ages below 1 Gyr. They contain from a hundred to few thousands of stars. The typical masses range from 10^2 to $10^4 M_{\odot}$. They are



Figure 1.1: Example of types of clusters: the left panel shows a typical globular cluster with an age of ~ 11.5 Gyr (Omega Centauri, credit by ESO - <http://www.eso.org/public/outreach/press-rel/pr-2008/phot-44-08.html>), while the right one shows an example of open cluster of ~ 100 Myr (the Pleiades, credit by NASA, ESA, AURA/Caltech, Palomar Observatory - <http://hubblesite.org/newscenter/archive/releases/2004/20/image/a/>).

continuously forming inside the GMCs in the Galactic disc. To date, the number of OCs in the MW is calculated to be of $\sim 10^5$ (e.g., Piskunov et al. 2006; Bonatto et al. 2006). Images of the two types of star clusters are shown in figure 1.1.

1.1 Open Clusters

Several definitions are given to characterize the OCs. In Friel (1995) OCs are defined as “*commonly thought of as sparsely populated, loosely concentrated, barely gravitationally bound systems of a few tens or hundreds of stars*”. A more quantitative definition was given by Lada & Lada (2003). They considered as cluster “*a group of 35 or more physically related stars whose stellar mass density exceeds $1.0 M_{\odot} \text{ pc}^{-3}$* ”. They adopted the criteria that the density has to be sufficiently high to render the group of stars stable against tidal disruption by the Galactic field (i.e., $\rho_* \geq 0.1 M_{\odot} \text{ pc}^{-3}$; Bok 1934), and by GMCs (i.e., $\rho_* \geq 1.0 M_{\odot} \text{ pc}^{-3}$; Spitzer 1958), and that the cluster has enough stars to guarantee that the time to eject all its members by internal stellar encounters (i.e., the evaporation time τ_{ev}) should be greater than the typical lifetime ($\sim 3 \times 10^8$ Myr).

Two main stages distinguish the early phases of OC evolution. When an OC is born, it is entirely or partially embedded in the parent molecular cloud. Objects in this phase are known as embedded clusters (ECs). ECs are very young systems, with age less than 10 Myr, and their stars are generally disposed in an unsymmetrical shape. The majority of young stars is found within these objects (e.g., Lada & Lada 2003). In contrast, only 10% of the total stars in the Galaxy is found in OCs with ages greater than 10 Myr. This suggests that the majority of ECs should disperse in the Galactic field within the first Myrs and only a small fraction of them remains in a bound state and evolves as distinct OCs. Therefore, when the molecular gas is dissipated (within the first 5 – 10 Myr) the embedded phase is over and only the ECs which are able to survive to gas expulsion evolve towards the final phase of OC. These systems have ages between 10 Myr and 10 Gyr, with a median age of 300 Myr. They have a spherical form and, in most cases, they are found as bound systems.

The study of the internal kinematic and dynamic in OCs with different ages allows us to understand how they form, evolve, and dissipate in the Galactic field. Furthermore, stellar populations in OCs cover all evolutionary stages and masses. In this context, each OC is a snapshot of stellar evolution. Finally, the presence of OCs at different ages and locations in the Galaxy allow us to investigate the formation and evolution of the thin disc, since OCs are tracers of its past star formation history.

1.2 Properties of Open Clusters

In this section, I will give a brief description of the main properties of the OCs, such as the typical radii, timescales, and the fundamental parameters.

1.2.1 Radii and Timescales

It is possible to define four useful radii of OCs: the half-mass radius, the core radius, the tidal radius, and the virial radius. In the case of the very young ECs, these radii are very difficult to define since the shape of these systems is often irregular.

The half-mass radius, r_{hm} , is the radius that contains half of the total cluster mass. Frequently an observer uses the projected half-light ratio since the luminosity of a star is a proxy of its mass. The second important radius is the core radius, r_c . From an observational point of view, this is generally defined as the distance from the center of the cluster at which the surface brightness has fallen to half its central value. Instead, the tidal radius, r_t , indicates the radius where the stellar density drops to zero. The last useful radius is the virial radius, r_{vir} , defined as

$$r_{vir} = \frac{GM^2}{2|U|} \quad (1.1)$$

where M is the total cluster mass, U is the total potential energy and G is the gravitational constant. Given that the potential energy is not directly observable, it is possible to use this theoretical definition to obtain a more useful quantity in terms of observations. In virial equilibrium

$$U = -2T, \quad (1.2)$$

where T is the cluster total kinetic energy, and

$$\frac{T}{M} = \frac{1}{2}\langle v^2 \rangle = \frac{3}{2}\sigma_{1D}^2 \quad (1.3)$$

for an isotropic system. Here, σ_{1D} is the line-of-sight cluster velocity dispersion and it is directly observable. Consequently, r_{vir} is determined as

$$r_{vir} = \frac{GM}{6\sigma_{1D}^2}. \quad (1.4)$$

In the context of observations, to determine the cluster mass at the virial equilibrium (i.e., the dynamical mass M_{dyn}) a dimensionless parameter is introduced. This is defined as

$$\eta \equiv 6r_{vir}/r_{hm} \quad (1.5)$$

and it allows us to define M_{dyn} as

$$M_{dyn} = \eta \frac{\sigma_{vir}^2 r_{hm}}{G} \quad (1.6)$$

where σ_{vir} is the cluster velocity dispersion at the virial equilibrium. The parameter η depends on the cluster density profile. For a Plummer sphere profile (Plummer 1911) $\eta \approx 10$ (corresponding to $r_{vir} = 1.698 r_{hm}$; Spitzer 1987; Fleck et al. 2006; Portegies Zwart et al. 2010). However, Elson et al. (1987) and Fleck et al. (2005) found that deviation of the density profile from a Plummer sphere can lead to a value of η that is lower by a factor 2. Therefore, the value of ~ 10 should be used with care. Equation 1.6 gives a powerful tool to test the dynamical state of OCs, since the comparison between σ_{vir} and σ_{1D} allows to determine if the region is supervirial ($\sigma_{vir} > \sigma_{1D}$) or subvirial ($\sigma_{vir} < \sigma_{1D}$).

In the theory, there are several fundamental timescales to evaluate the dynamical state of a self-gravitating system. The first one is the crossing time t_{cr} . This timescale is defined as the time needed to a star with a velocity equal to the cluster radial velocity dispersion to cross r_{hm} , thus

$$t_{cr} = \frac{r_{hm}}{\sigma_{1D}}. \quad (1.7)$$

Another timescale is the dynamical time t_{dyn} and it is the time necessary to the system to establish the dynamical equilibrium. It is given by the equation (Spitzer 1987)

$$t_{dyn} = \left(\frac{GM}{r_{vir}^3} \right)^{-1/2}. \quad (1.8)$$

Finally, the relaxation timescale, t_{rel} , is defined as the time needed for a star to modify its velocity due to stellar interactions, or more specifically, the time needed to the two-body encounters to transfer energy between individual stars and to lead the star system to the thermal equilibrium. It may be defined as $t_{rel} = n_{rel} t_{cr}$, where n_{rel} is the number of cluster crossings that is required to a star to change its velocity. It can be demonstrated that $n_{rel} \sim \frac{N}{8 \ln N}$. Here, N is the number of stars in the system. Therefore, the relaxation time is

$$t_{rel} = \frac{N}{8 \ln N} t_{cr} \quad (1.9)$$

(Binney & Tremaine 2008). For an open cluster with $N = 500$ and with a $t_{cr} = 7$ Myr, the relaxation time is $\simeq 7.0 \times 10^7$ yr, which is less than the mean age of the Galactic clusters ($\simeq 3 \times 10^8$ yr from Portegies Zwart et al. 2010). A stellar system is defined as collisionless if t_{rel} is much greater than the age of the system, t_{age} . In this case, stars move under the influence of the mean potential generated by all the other stars. On the other hand, if t_{rel} is lower than t_{age} the system is collisional and individual stellar encounters play a significant role in the perturbation of the star trajectories. OCs are collisional systems given that for most of them $t_{rel} < t_{age}$. The typical values of the main properties for Galactic OCs are shown in Table 1.1 (values from Friel 2013).

Table 1.1: Typical values of properties of Galactic open clusters (values from Friel 2013).

core radius r_c	1 - 2 pc
half-mass radius r_{hm}	2 - 4 pc
tidal radius r_t	10 - 25 pc
central velocity dispersion σ_{1D}	$\sim 0.3 - \sim 2.0 \text{ km s}^{-1}$
crossing time r_{hm}/σ_{1D}	5 - 10 Myr
total mass M_{tot}	$10^2 - > 10^4 M_\odot$
lifetime t_{age}	1 Myr - 10 Gyr

1.2.2 The Initial Mass Function

The initial mass function (IMF) describes the number of newly formed stars per mass interval and in astrophysics it is really important since many observable properties of a galaxy or stellar population depend on the IMF. The IMF was introduced by Salpeter (1955), who found that for stellar masses greater than $1 M_\odot$ the function is a power-law in the form

$$\Phi(\log m) = dN / d\log m \propto m^{-\Gamma} \quad (1.10)$$

where m is the mass of a star, N is the number of stars in the logarithmic mass range between $\log m$ and $\log m + d \log m$, and Γ is the index slope and for the IMF of Salpeter (1955) is ~ 1.35 . This formula can be formulated in the linear mass unit as

$$\xi(m) = dN / dm \propto m^{-\alpha} \quad (1.11)$$

where $\alpha = \Gamma + 1$. Even now, the power-law index $\alpha = 2.35$ derived by Salpeter (1955) is commonly used as the standard number for the IMF of stars above $1 M_\odot$. At low masses there is a break in the mass distribution given that the power-law changes its slope (e.g., Miller & Scalo 1979).

To date, several functional forms have been proposed to describe the IMF. Miller & Scalo (1979) found that between 0.1 and $30 M_\odot$ the function can be described with a log-normal distribution although recent works show that this form underestimates the number of more massive stars (see Bastian et al. 2010, for a review). Figure 1.2 shows the different IMF suggested by several other authors (e.g., de Marchi & Paresce 2001; Kroupa 2001; Chabrier 2005; Thies & Kroupa 2007). These distributions are obtained fitting the galactic field IMF in a restricted mass range and then extrapolated in all the range of masses. All the IMFs (except for the Salpeter) show the same peak at $\sim 0.1 - 0.3 M_\odot$ in the mass distribution, which is a characteristic mass associated with the process of star formation. In any case, the IMF in low-mass regime is not yet well understood and this is clear from the difference among the slopes shown in the figure.

In the determination of cluster present-day mass function (PDMF), should be taken into account the effects due to the system evolution. Indeed, moving on

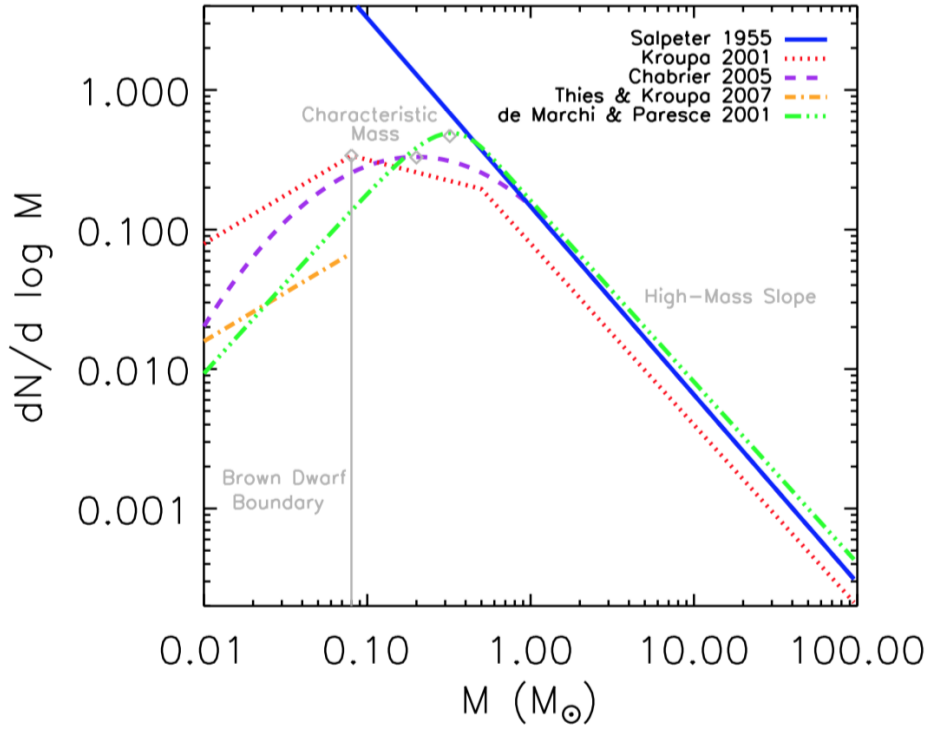


Figure 1.2: Functional forms of the IMF from different authors (figure from Offner et al. 2014).

with the cluster age, the interactions between members change the velocities of the stars involved in these encounters. Low mass stars gain velocity during the interaction with high mass members and these low mass objects escape from the system if their velocity is larger than the escape one. As a consequence, the PDMF of clusters shows a deficit of stars in the low mass region as the cluster evolves. This is clear from the figure 1.3 (from Moraux 2016), that shows the observed PDMFs of three OCs with different ages. In the oldest OC (the Hyades, ~ 625 Myr) the mass function has a number of low mass stars much smaller than that in the young systems. Moreover, as the age increases, also the peak of mass function shifts towards higher masses.

Studies of the field and star clusters suggest that the vast majority of them were drawn from a “universal” IMF (Bastian et al. 2010, and reference therein). Different studies of the IMF carried out in several OCs show that their PDMFs, which are a good approximation of the IMFs in young OCs (age between 1 Myr and 100 Myr), are formally consistent with a dynamically evolved Kroupa-/Chabrier-type IMF. In the context of the Ph.D. work, I decided to adopt the IMF proposed by Kroupa (2001) as the reference for the OCs. They derived a multi-part power-law IMF for the full mass range defined as

$$\xi(m) \propto m^{-\alpha_i} \quad (1.12)$$

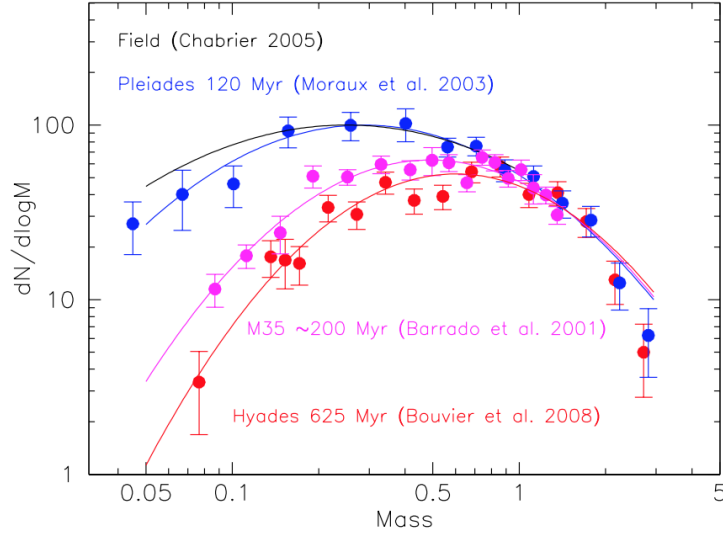


Figure 1.3: The present day mass functions of three OCs with different ages (from Moraux 2016). The clusters are the Pleiades (blue line and dots, ~ 120 Myr), M35 (magenta line and dots, ~ 200 Myr), and the Hyades (red line and dots, ~ 625 Myr). The mass function of the field stars proposed by Chabrier (2005) is shown for the comparison. Data are taken from Barrado y Navascués et al. (2001); Moraux et al. (2003) and Bouvier et al. (2008).

where the power-law index α_i depends on the mass range and it has two changes at $0.08 M_{\odot}$ and $0.5 M_{\odot}$

$$\alpha_0 = +0.3 \quad 0.01 M_{\odot} \leq m < 0.08 M_{\odot} \quad (1.13)$$

$$\alpha_1 = +1.3 \quad 0.08 M_{\odot} \leq m < 0.5 M_{\odot} \quad (1.14)$$

$$\alpha_2 = +2.3 \quad m \geq 0.5 M_{\odot}. \quad (1.15)$$

1.2.3 Spatial Distribution in the Galaxy

The distribution of the OCs in the Galaxy changes with their age. Indeed, the older OCs (i.e., clusters with age greater than 100 Myr) have a wide distribution in the X, Y Galactic coordinates, that correspond to the Galactic longitude and latitude projected onto the Galactic plane, and Z, that is the height with respect to the Galactic plane. Compared to the young OCs the older ones are more distant from the Galactic plane.

Figure 1.4 shows the spatial distribution of a sample of OCs projected on the Galactic plane. The cluster data are taken from the catalog produced by Kharchenko et al. (2016), the Milky Way Star Cluster (MWSC) project. The vast majority are OCs and I divided them into young clusters (age < 100 Myr, red squares) and old clusters (age ≥ 100 Myr, blue squares). From this figure, it stands

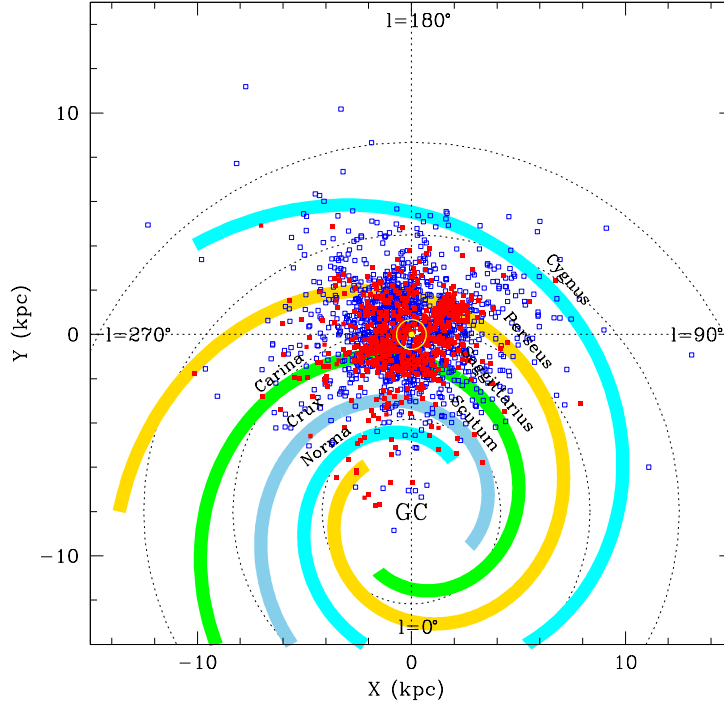


Figure 1.4: Distribution of the OCs projected onto the Galactic plane. The blue empty squares are OCs with age greater than 100 Myr, while the filled red squares are the young (age < 100 Myr) OCs. The location of Galactic center is indicated in figure with GC. The yellow symbol at the center marks the position of the Sun (distance Sun - Galaxy center = 8 kpc.), while the colored stripes indicate the approximate position of the different Galaxy spiral arms (Vallée 2005). Data of OCs are taken from Kharchenko et al. (2016).

out that older OCs have bigger distances from the Sun (yellow symbol in figure) than the younger ones. Also, the figure shows that OCs are mainly distributed around the Sun. This is obviously due to the detection limit of observations and to the subsequent incompleteness of the sample determined by Kharchenko et al. (2016), in particular in the region near Galactic center, where the extinction is extremely high in the optical band.

Figure 1.5 shows the height (Z) of OCs above the Galactic plane. Also from this figure is clear that depending on the age, OCs have different height with respect to the Galactic plane. Only few young OCs have a Z between 0.3 and 1 kpc (maximum height ~ 0.8 kpc) in modulus, while they are more concentrated within the first 0.2 kpc under and above the plane of the disc (dispersion of ~ 0.4 kpc). Instead, a big part of the old OCs is located well beyond the region occupied by the young ones. Considering the short dynamical history, the young OCs trace directly their birthplace. In particular, ECs (age < 10 Myr) trace the molecular clouds in which they form (e.g., Lada & Lada 2003; Bastian 2011). Therefore, since the majority

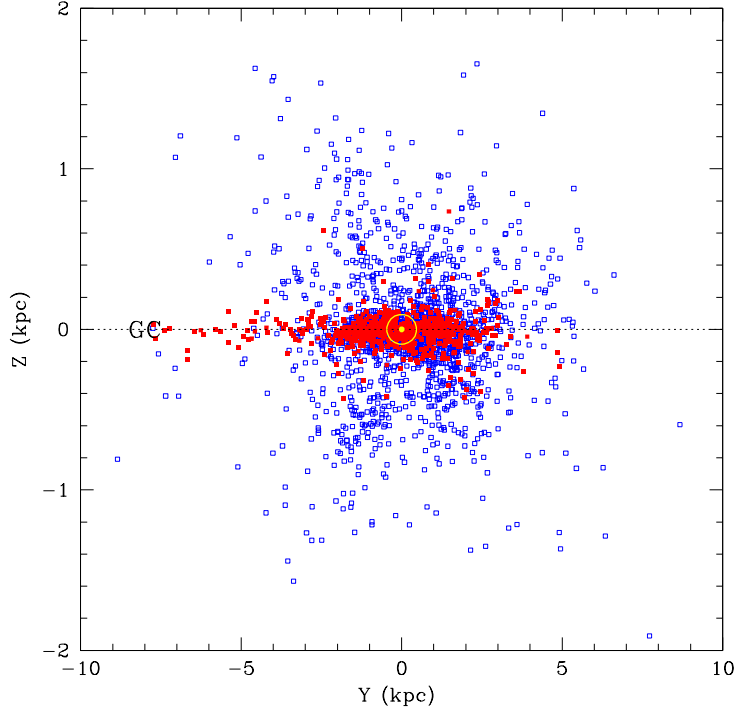


Figure 1.5: Distribution of OCs on the plane Y versus Z. The symbols are the same of the Figure 1.4. The plot is centered on the Sun position.

of gas and dust clouds lie in the spiral structure of the Galaxy, young OCs are a meaningful tool to study the evolution of the spiral arms of the MW.

1.3 Age of Open Clusters

The ages of OCs have a range between about 1 Myr and 10 Gyr. Commonly, the stellar populations of OCs are considered as single stellar populations since stars of a cluster are formed at about the same time. Lada & Lada (2003) found that young clusters have an age spread with a mean value of 3 Myr. Typically, the survival of the parent primordial molecular cloud is of the order of 5 - 10 Myr. In Figure 1.6 the age distribution of OCs based on the catalog of Kharchenko et al. (2016) is shown. From this histogram, it is clear that the vast majority of OCs are young and only a small fraction of them survives for a time longer than 1 Gyr. In this catalog, $\sim 26\%$ of the OCs have age less than 100 Myr and the fraction of OCs with ages less than 1 Gyr is 75% of the total sample.

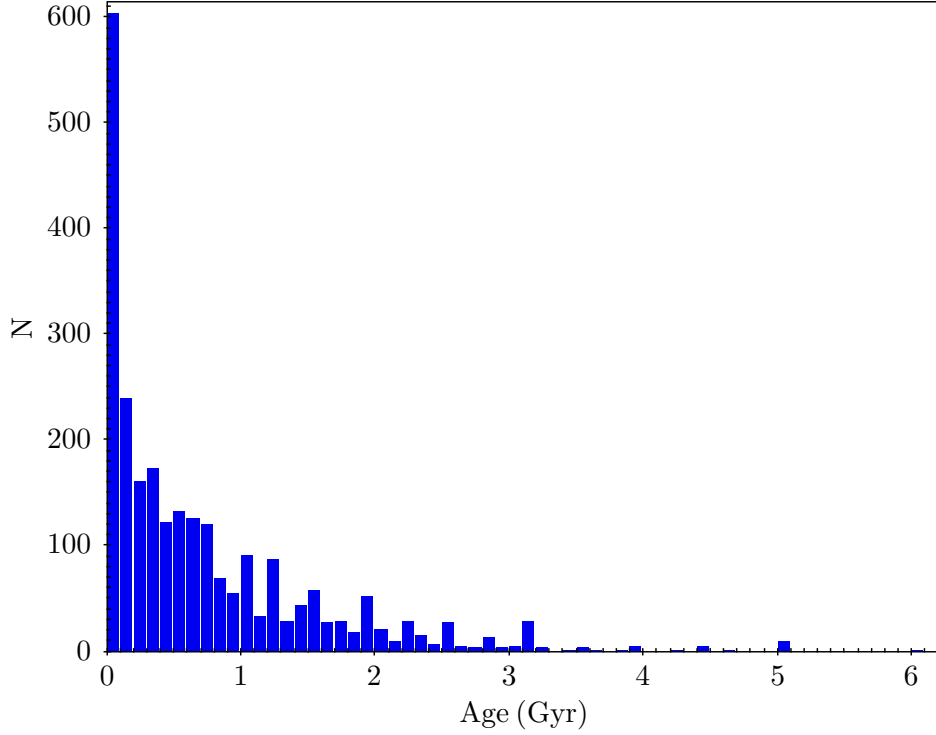


Figure 1.6: Age distribution of Galactic OCs based on the catalog of Kharchenko et al. (2016).

1.4 The Hertzsprung-Russell and Color-Magnitude Diagrams

Valuable tools to derive the properties of OCs are the Hertzsprung-Russell diagram (HRD) and/or the Color-Magnitude diagram (CMD), which is the observational counterpart of the first one. The HRD draws the relation between the bolometric luminosity, L_{bol} , and the effective temperature, T_{eff} , while the CMD draws the relation between the magnitude and color index of the stars.

To a first approximation, the position on the HRD (or CMD) of a star depends by its mass and age. This can be estimated from theoretical models of stellar evolution, which predict how a star of a given mass evolves and they allow the generation of sets of theoretical isochrones and tracks, which are the curves on the diagrams that represent a population of stars with the same age and the same mass, respectively.

An important quantity derived from these diagrams is the age of the clusters. The age derivation is based on the position of the main sequence turn-off (MSTO) point, which is the point in the diagram that identifies the age when the hydrogen in the core of a star is exhausted and it is being burnt in a shell around the core. It roughly corresponds to the hottest and brightest point of the Main Sequence (MS, i.e., the phase in which hydrogen is burning in the core) and moving on with cluster

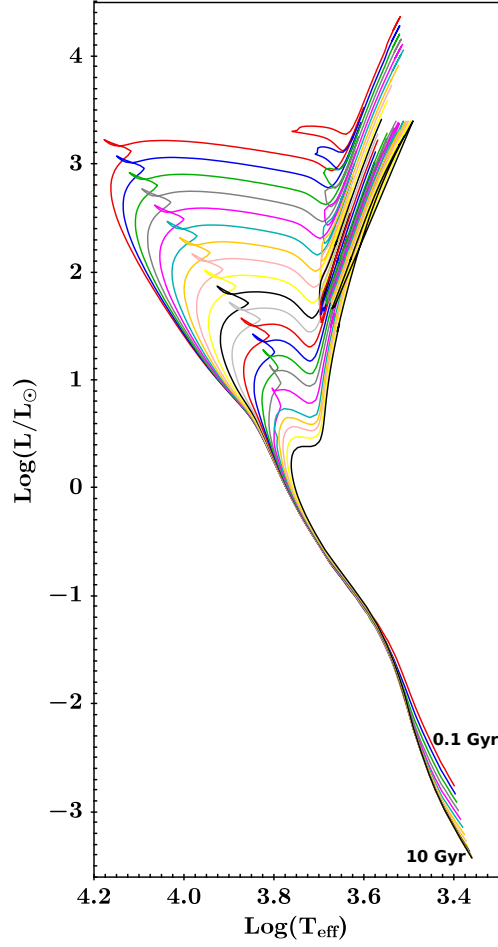


Figure 1.7: Theoretical isochrones in the HR diagram of PARSEC model (Bressan et al. 2012). The ages ranging between $\log(t/\text{yr}) = 8$ (100 Myr) and $\log(t/\text{yr}) = 10$ (10 Gyr) with a separation of $\Delta \log t = 0.1$. The metallicity is fixed to the solar one.

age the MSTO point decreases its L_{bol} and T_{eff} .

In my Ph.D. work I used the isochrones produced by Bressan et al. (2012) with the Padova And TRIeste Stellar Evolution Code (PARSEC)¹, while for the Pre-Main Sequence (PMS) stars I used those developed by Tognelli et al. (2011)². These stellar isochrones have been computed assuming a scaled-solar composition and a solar metallicity of $Z_{\odot} = 0.0152$. In figure 1.7 is shown a set of these stellar isochrones between 100 Myr and 10 Gyr. As described above, from an observational point of view, stars with different mass lie in different part of HRD and the shape of the isochrone depends on the age of the stellar population. In particular, in a young OC ($\sim 1 - 100$ Myr) the majority of low-mass stars are still in the PMS phase (see

¹The web interface of the stellar isochrones is available at: <http://stev.oapd.inaf.it/cgi-bin/cmd.3.0>

²The pre-main sequence models are available at: <http://astro.df.unipi.it/stellar-models>

the next section for the details of the PMS evolution), while the high mass stars are in the Zero-Age Main Sequence (ZAMS) phase. The ZAMS is the phase in which stars start to burn hydrogen in their cores. At ages greater than 100 Myr, the high-mass stars have evolved off the MS and they are found in the sub-giant branch (SGB) and red giant branch (RGB), while the other low mass stars are in MS phase.

1.4.1 Pre-Main Sequence Evolution

A proto-star is not optically visible due to the obscuration by interstellar dust, and when this object emerges from the gas of molecular cloud, it takes place on a curve called birth-line in the HRD. Now, this object enters in the phase of PMS. This is the phase between the proto-stellar phase and MS phase. The position of PMS stars in the HR diagram is a crucial aspect in the theory of star formation, especially because it allows us to derive the star mass. In the literature several theoretical evolutionary tracks are developed and in this work, for clusters with age less than 100 Myr, I considered the PMS evolutionary tracks developed by Tognelli et al. (2011).

During the PMS phase the energy for the luminosity of the PMS stars is given by gravitational contraction since its central temperature is too low for nuclear burning. The gravity gradually compresses the object to higher density and the temperature, the luminosity, and the radius change with the time. Also, during the PMS evolution the gravity of the star evolves with time since it is proportional to R^{-2} , where R is the star radius. For this reason, the PMS stars have a surface gravity lower than in the MS stars (for fixed mass). In particular, when a star is fully convective (i.e., stars with $M < 0.4 M_{\odot}$) for the entire duration of PMS phase, the star luminosity and star radius decrease while the central temperature increases as $T_c \propto 1/R$. When this star appears in the HRD, it begins to descend a vertical path due to the contraction (i.e., T_{eff} remains approximately constant), as one can note in figure 1.8 from Stahler & Palla (2005). Instead, a different PMS track is expected in stars in which a radiative core is developed (stars with $M > 0.4 M_{\odot}$). In this case, when the radiative core is formed, the luminosity stops falling and begins to increase slowly, as $R^{-1/2}$, and also T_{eff} starts to increase its value as $R^{-5/8}$ (see as example the tracks for stars with a mass of 0.6 and 1.0 $M_{\odot}$ in figure 1.8). In these stars the central temperature continues to increase approximately as $T_c \propto 1/R$. If a star has a mass greater than 0.08 $M_{\odot}$, then contraction continues until the central temperature becomes high enough ($\sim 10^7$ K) for nuclear hydrogen fusion reactions (the black points in figure 1.8). Once the energy generated by hydrogen fusion compensates for the energy loss at the surface, the star stops the contraction and settles on the ZAMS. The time that a star spends in the PMS phase depends on its mass, and massive stars reach the ZAMS much earlier than lower-mass ones. Instead, in stars with mass lower than 0.08 $M_{\odot}$ the temperature

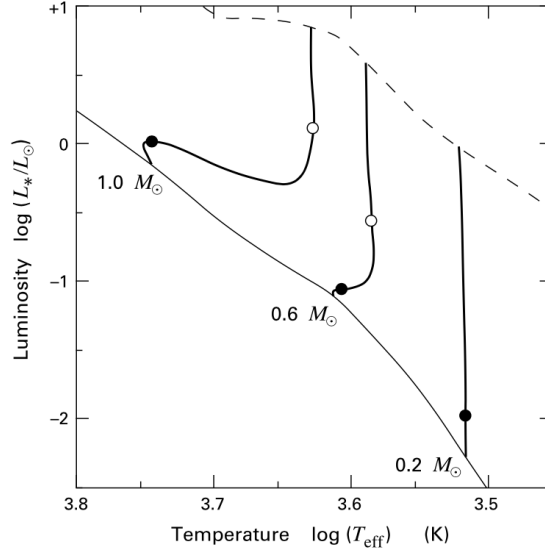


Figure 1.8: Evolutionary tracks for PMS stars with different masses (figure from Stahler & Palla (2005)). The open circle marks the moment when a radiative core is developed, while the black one marks the beginning of the hydrogen burning in the core. The black and dashed lines are the ZAMS and birthline, respectively.

is not able to ignite the fusion of the hydrogen and the star becomes a brown dwarf, which is an object supported by the electron degeneracy pressure.

1.5 Lithium Abundances

Before the star begins to burn hydrogen in its core, several nuclear reactions have already set in. In particular, when the star core reaches a temperature of $\sim 3.0 \times 10^6$ K, lithium starts burning. In this condition, the dominant isotope, the ${}^7\text{Li}$, reacts with a proton in the reaction



(Basri et al. 1996; Chabrier et al. 1996; Bildsten et al. 1997). This reaction is core temperature dependent ($\propto T_c^{20}$, Bildsten et al. (1997)). The time necessary to T_c to reach the start of Li ignition is strongly dependent on the mass of the star. Indeed, stars with low masses reach this temperature later than the massive ones. Moreover, stars with different mass have a different stellar structure and this leads to a different duration of the Li depletion.

Figure 1.9 (from Jeffries 2006) shows the epochs on which lithium is burned for different values of star mass. It is clear from this figure that the age at which Li starts burning in a star decreases with the mass. Stars with $M < 0.4 M_\odot$ are fully convective for the entire duration of the PMS phase. In this case, the

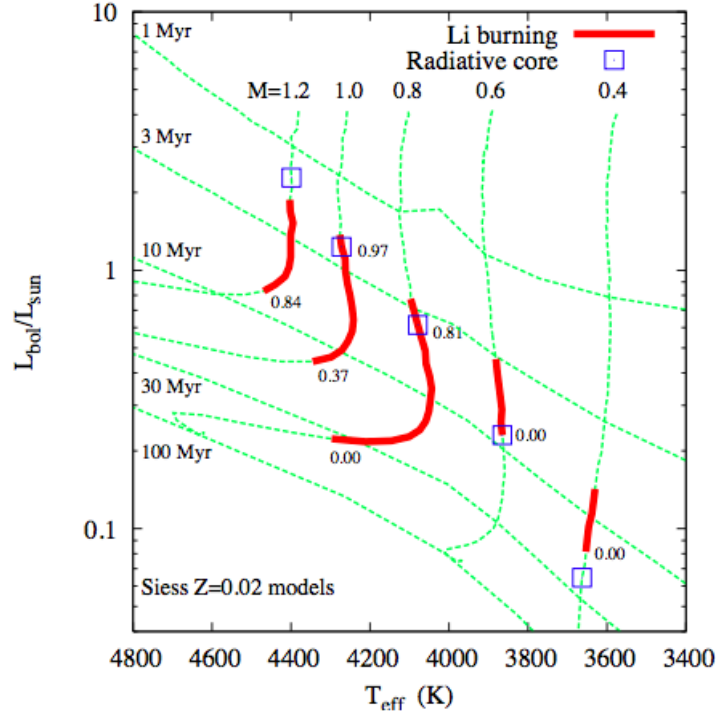


Figure 1.9: HRD for low-mass stars from Jeffries (2006) with the pre-main sequence evolutionary tracks and isochrones developed by Siess et al. (2000) (in $M_{\odot}$ and Myr, respectively). The red lines indicate the Li depletion while the empty blue squares indicate the formation of a radiative core. The remaining fraction of Li is also indicated when the radiative core is develop and when the Li burning is terminated.

material depleted of Li in the core is convectively mixed and moved to the outer layers, while the lithium present in the surface is convectively transported in the core. In this way, all the Li is depleted in a timescale of $\sim 10 - 30$ Myr. For more massive stars instead a central radiative core is formed and the depletion of lithium is more complicated. In stars with a radiative core, Li depletion depends on the temperature of the convection zone base (T_{BCZ}). For a star with $0.4 M_{\odot} < M < 0.6 M_{\odot}$ all the lithium is depleted before the radiative core is developed. For higher masses instead the radiative core is developed before all the Li is depleted. When T_{BCZ} falls below the temperature required for the lithium burning, the Li depletion ceases. Stars with $M > 1.0 M_{\odot}$ deplete only a fraction of the initial Li and when $M > 1.3 M_{\odot}$ the T_{BCZ} is never high enough to burn Li and therefore the abundance of Li remains at its initial value.

In figure 1.10 (from Stahler & Palla 2005) is shown the lithium depletion at the surface of PMS stars. Stars within the white region have their lithium abundance equal to the interstellar value ($[Li/H] \approx 2 \times 10^{-9}$), while the light and dark grey zones are the regions where the stars have depleted their Li at most a factor 10 and at least a factor 10 the initial abundance, respectively. Using the isochrone at

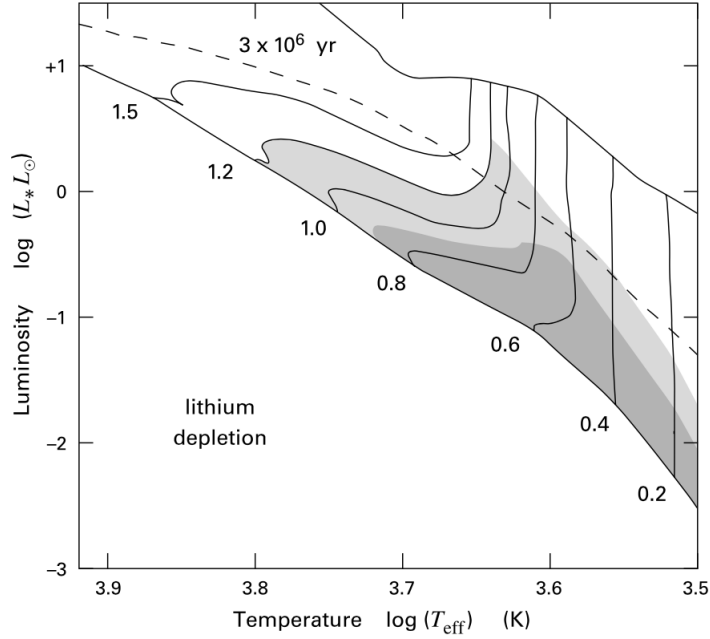


Figure 1.10: Prediction of the lithium depletion in PMS stars. The black lines are the evolutionary track for masses star between 0.2 and 1.5 $M_{\odot}$. The light grey zone identifies the region where the stars which have depleted the lithium at most a factor 10 the interstellar value of this element. Instead, the dark grey zone identifies the region where the stars have depleted their lithium by at least this factor. The dashed black line is the isochrone at 3 Myr.

3 Myr, it can be noted that stars with this age and with a mass between 0.5 and 1.2 $M_{\odot}$ should be partially depleted of their initial lithium, while stars with same age but outside this mass range should have all their initial lithium. Therefore, the mass range of PMS in which Li depletion occurs increases with the age.

Although the abundance of Li in the interstellar medium is small, lithium is well observed in the stellar atmosphere, in particular the neutral species Li I strongly absorbs in an electronic transition at 6708 Å, which is a resonance doublet. A very useful tool to estimate the age of young OCs is the equivalent width (EW) of this line used in combination with the temperature or the color index of the star. As described above, the age determination using the Li depletion varies with the mass and the temperature of the stars. The use of the EW of Li for stars between late-F and early-M type in stellar system with ages $\lesssim 150 - 200$ Myr is an excellent empirical method for the estimation of the stellar ages. In the context of this work, the utility is that, given a fixed young cluster age, it allows us to discriminate between the (young) stars that are likely members from those that belong to the field.

1.6 The Surface Gravity

In principle, knowing the star mass and radius (in solar units), the surface gravity could be derived directly as

$$g = \frac{g_{\odot} M_*}{R_*^2}, \quad (1.17)$$

or logarithmically

$$\log g = \log M_* - 2 \log R_* + 4.437 \quad (1.18)$$

where $g_{\odot}$ is the gravity of the Sun. A direct method to determine this quantity is given by the spectroscopic measurements, where the main advantage is the independence from the object distance.

As described briefly in section 1.4.1, during the phase of PMS also the surface gravity evolves with the time since a star is contracted and the radius decreases moving on the ZAMS (i.e., $g \propto R_*^{-2}$). Therefore, for a fixed mass, a star in MS will have higher gravity than a star in PMS due to its smaller radius. In the same way, the PMS (and hence MS) stars will have a surface gravity higher than giant stars (i.e., stars evolved beyond the MS phase). Indeed, after the end of the hydrogen fusion and the formation of helium core, the radiation pressure is stopped and the gravitational attraction causes the core to contract, converting gravitational potential energy into thermal energy. The increasing of the core temperature is high enough to begin the burning of hydrogen in a shell around the core, producing a high radiation pressure that leads the outer layers of the stars to expand. This expansion leads to a decrease of the effective temperature. The star enters in the giant phase in which it increases its radius and consequently decreases the gravity. Therefore, the surface gravity combined with the effective temperature is a useful diagnostic to separate the stars in a young OCs, composed principally by PMS and MS stars, from the contamination given by the giant field stars.

Chapter 2

Formation and Evolution of Star Clusters

Almost all stars form in clusters (e.g., Tutukov 1978; Lada et al. 1984; Baumgardt & Kroupa 2007; McKee & Ostriker 2007) although only a little portion of them can be found in these systems at older age (Lada & Lada 2003; Piskunov et al. 2006). The debate on the initial conditions of star clusters, such as the level of the substructure, the density of stars, the presence of mass segregation, is still open. These systems are at first heavily embedded in their parent molecular clouds and only about 10% of them evolve to become bound OCs. This suggests that after 5 - 10 Myr they are dispersed into the field. Indeed, the comparison between the observed OCs with those expected given the EC sample indicates that clusters undergo to an “infant mortality” (Miller & Scalo 1978; Adams & Myers 2001; Lada & Lada 2003), and only a small fraction of ECs is able to survive to the early dynamical phases and gas expulsion. Therefore, the majority of OCs is unbound from the beginning or internal and external mechanisms and the subsequent evolution lead to early destruction and dissolution (e.g., Lada & Lada 2003; Piskunov et al. 2006). Conversely, the small fraction of the remaining OCs can survive for several Gyr (Friel 1995). In this context, it is crucial to have an overall view of the models describing the cluster formation and evolution.

2.1 Star and Cluster Formation

Interstellar gas is structured into clouds which have a wide range of masses, from sub-stellar ($\sim 10^{-4} M_{\odot}$) to giant aggregates ($\sim 10^7 M_{\odot}$), with a typical GMC mass of $\sim 10^5 M_{\odot}$ (e.g., Elmegreen et al. 2000; Elmegreen 2007) and with very different sizes (e.g., Blitz 1993; Elmegreen 1993). The star clusters form from GMCs, which are created from the interstellar medium through several physical processes, such as spiral density waves, supernova explosion, and thermal/gravitational instabilities (e.g., Elmegreen 1993). In the very early phase of their lifetime, these GMCs are

gravitationally bound objects and they are stable against the collapse thanks to the internal turbulent pressure. However, the gas rapidly dissipates energy through the motions of the internal supersonic turbulent flows and this marks the beginning of the gravitational collapse of these clouds (Jeans 1902), which are fragmented. In few million years the gas is converted into molecular clumps and many dense molecular cores. The cloud of molecular gas typically has an initial mass of $\gtrsim 500 M_{\odot}$ and in the early phases should be compressed in a small volume (characteristically $\sim 1 \text{ pc}^3$). The timescale of the collapse is the free-fall time, which is defined as

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho}} \quad (2.1)$$

where ρ is the gas density. The densest regions tend to collapse and form stars first, therefore the newborn stars reflect the structure of the parent cloud. When the molecular cores become gravitationally unstable, they collapse. The surrounding material falls down the core potential which gains mass until its density and temperature reach the necessary values to dissociate and ionize most of the hydrogen in the gas. Now the core found a new configuration of hydrostatic equilibrium and a proto-star is created. Each core can produce one or more proto-stellar objects (see Krumholz 2014, for a review) with different masses and sizes.

2.1.1 Models of Cluster Formation

Two main models are proposed to explain the star formation in clusters. The first one is the monolithic collapse scenario, for which a top-down star formation from the collapse of a massive star-forming cloud (e.g., McKee & Tan 2003; Krumholz et al. 2005, 2009) is expected. The stars form in clusters with high mass ($M_d \gtrsim 10^5 - 10^6 M_{\odot}$) and with high density ($\rho_d \gtrsim 10^3 - 10^4$ stars per pc^3). In this scenario, clusters are formed rapidly (mean age spread of $\sim 3 \text{ Myr}$) from a massive GMC, which forms several proto-stellar cores at the same time and in a confined volume through efficient cooling processes (e.g., Kroupa et al. 2001; Banerjee & Kroupa 2014). Therefore, the stars belonging to the cluster are formed in a single episode of starburst. Moreover, the model predicts a signature of primordial mass segregation, where the more massive stars tend to be formed in the central cluster zones. Then, the subsequent phases of evolution lead to an expansion of the system.

In the second model, stars form in a broad and smooth distribution of surface densities. The clusters form via competitive accretion (e.g., Bonnell et al. 2003) and the star formation occurs in a hierarchically structured way (e.g., Bressert et al. 2010). This means that the distribution of densities is non-uniform and the areas with greater dimensions and smaller densities contain the denser sub-areas (Elmegreen et al. 2006; Bastian et al. 2007). In this scenario, the hierarchical fragmentation of the parent cloud produces several small clusters which can merge to create a more massive stellar system (Bonnell et al. 2003; Offner et al. 2008;

Smith et al. 2009). This model predicts that only a small fraction of young stellar objects forms in high dense clusters.

Independently from the models proposed for the formation, after the birth of first cluster stars, the system enters in the phase of embedded cluster (EC). The ECs are the youngest stellar systems known and they are often invisible at optical wavelengths. On the contrary, they can be well observed in the infrared band (see Lada & Lada 2003, for a review). Table 2.1 resumes the main characteristics of the formation models.

Table 2.1: Models, fundamental quantities, and expectations for cluster formation.

Model	Key ingredients	Predictions
Monolithic collapse	Collapse of massive GMC, single episode of starburst	Cluster forms rapidly, formation of high density and massive clusters, primordial mass segregation
Hierarchical collapse	Fragmentation of parent cloud, stars form in hierarchical way	Cluster forms via competitive accretion, formation of several small clusters, merging produces massive cluster

2.2 Cluster Evolution

In this section, I will discuss how clusters evolve and in particular what are the mechanisms leading to their dispersion in the field. I will start describing the simple analytical model proposed by Hills (1980), then I will enter in more details in the other models based on more sophisticated N-body simulations. Two main models are proposed to understand the early cluster phases and the subsequent dynamical evolution. The first model is the so-called “residual gas expulsion” scenario, which is based on the stellar feedback from high mass stars and the expulsion of the primordial cloud gas. Instead, the second one is based on the interaction between the cluster members and on the external tidal shocks while the gas dissolution and the feedback of high mass stars are not relevant. Finally, I will give a brief overview regarding the observations that support these models.

2.2.1 The Hills Model (1980)

When the surrounding gas is removed, the star formation process is stopped. Typically, this takes place $\sim 5 - 10$ Myr after the cluster formation. This gas is the entity that held the cluster bound, and after its dissolution the dynamical state of the system is changed. At this moment, the star cluster is finally and completely formed and the dynamical response to the removal of the remaining parent gas determines whether the system remains bound or it is completely disrupted.

Two fundamental physical parameters determine the state and the evolution of a newborn stellar system: the star formation efficiency ϵ (i.e., the fraction of gas converted into stars) and the timescale of the gas dispersion, t_{gd} . The efficiency of star formation is defined as the ratio between the stellar mass and the total cluster mass M (stars and gas)

$$\epsilon = \frac{M_{star}}{M_{star} + M_{gas}}. \quad (2.2)$$

and observationally it was found that it can reach a maximum value of $\sim 30\%$ (Lada 1999; Lada & Lada 2003) and only rarely it exceeds this value.

The stars in a cluster respond to the variation produced by the gas removal. Hills (1980) proposed a simple model. If the system of gas and stars is virialized, the kinetic energy T and the potential energy U are related by the virial theorem as

$$-2T = U \quad (2.3)$$

and both T and U scale with the total mass of the system, M , as $T \propto M$ and $U \propto M^2$. When the gas is removed, the total mass is reduced to ϵM . Therefore, the kinetic energy after the gas removal is $T' = \epsilon T$ and, if there is not a preferential direction of the gas expulsion, the new potential energy is $U' = \epsilon^2 U$. The total energy of the new system configuration is

$$\begin{aligned} E = T' + U' &= \epsilon T + \epsilon^2 U = \epsilon(T + \epsilon U) = \epsilon(1 - 2\epsilon)T = \\ &= \epsilon(1 - 2\epsilon) \left(-\frac{U}{2} \right) = \epsilon \left(\epsilon - \frac{1}{2} \right) U. \end{aligned} \quad (2.4)$$

Theoretically, if $\epsilon > 0.5$ the total energy E is negative and the system is bound. In order to find a new configuration of equilibrium, the system expands at a larger radius and the stars left behind after gas expulsion violently relax to the new potential. Instead, if the mass removed through the gas expulsion is more than half initial mass, the cluster is found in an unbound state.

In this context, t_{gd} plays a crucial role in the determination of the state of stellar systems. Indeed, the comparison between t_{gd} and the crossing time, t_{cr} , determines the dynamical regimes of the gas removal, that could be rapid or adiabatic if $t_{gd} \ll t_{cr}$ or $t_{gd} \gg t_{cr}$, respectively. On the one hand, if the expulsion of gas is rapid (t_{gd} lower than t_{cr}), the stars will not change their velocity and position since the time for the system to find a new configuration of equilibrium is too short. On the other

hand, if the gas removal takes place slowly compared to the dynamical time, the system remains in virial equilibrium all the times and it expands smoothly. Indeed, meanwhile the gas is slowly expelled from the cluster potential well, simultaneously the system has the necessary time to re-establish its virial equilibrium.

In any case, this is only a simple approximation of the real processes that involve stars and gas in the early phases. Infact, several aspects make the general theory more complex. Primarily, the kinetic energy is not distributed in uniformly among the stars. In the condition of rapid mass loss, this means that stars with a velocity higher than their average speed could escape from the system at the moment when gas is removed, although ϵ is greater than 0.5. Viceversa, the stars with a lower velocity could be still in bound state also if the reduction of the total mass is significant, i.e., $\epsilon < 0.5$, because the time to transfer the energy from high velocity escaping stars to the lower velocity ones is too short.

The second point is that the cluster system initially might not be in virial equilibrium. Typically, in young systems, the stars are in subvirial state compared to the gas (i.e., they have a lower velocity dispersion, Krumholz 2014), thus their kinetic energy is lower than that expected at the virial equilibrium and it is more complicated to unbind them from cluster potential well. In the case of fast gas removal, to unbind the system the star formation efficiency would have to be lower than the values described previously.

Finally, if a cluster undergoes to an adiabatic mass loss and its outer regions expand rapidly, then the stars that lie in these regions will be easily stripped by the tidal gravitational field of the Galaxy. The system might be completely destroyed if the expansion proceeds so far that leads to a drastic decrease of the mean cluster density. As a consequence, the clusters will be completely disrupted. Therefore, it is not totally true that a cluster with a slow gas expulsion always remains in virial equilibrium (e.g., Krumholz 2014).

The Hills model is a simple way to explain the gas expulsion and the eventual cluster disruption. After that, several other models are proposed using detailed N-body simulations and observations. In the following sections I will describe them.

2.2.2 Residual Gas Expulsion Scenario

As described above, after the cluster birth, it is quite complex to explain its evolution, especially in the early phases. In the “residual gas expulsion” scenario, several authors proposed that gas dissipation through the feedback from high-mass stars plays a fundamental role in the star system evolution (e.g., Tutukov 1978; Goodwin 1997; Bastian & Goodwin 2006; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007; Proszkow & Adams 2009), as in the Hills (1980) model. The process of gas dissolution is mainly due to the formation of stars massive and luminous enough to inject a considerable amount of energy in their parent cloud through radiation pressure, proto-stellar jets, stellar winds, and supernovae explosions. These effects

modify the cloud completely and regulate the properties of the emerging cluster. After the gas dissolution the emerging cluster is expected to be in a supervirial state, which means that it is unbound and its stars rapidly disperse in the Galactic field.

The importance of gas expulsion was investigated through N-body simulations, which show that bound systems will be dispersed even with $\epsilon \approx 30\%$, but the timescale of gas dispersion is also important. Infact, if the gas is removed slowly and adiabatically, even clusters with $\epsilon \sim 10\%$ can remain bound (Kroupa & Boily 2002; Boily & Kroupa 2003a,b; Baumgardt & Kroupa 2007). Instead, if the gas expulsion is fast only clusters with star formation efficiency higher than 30% are able to survive and remain bound (Lada et al. 1984; Bastian & Goodwin 2006; Goodwin & Bastian 2006).

Immediately after the star feedback sweeps out the gas, the cluster potential changes and stars with a velocity greater than the new escape velocity tend to run away from the cluster. If the gas is removed instantaneously, the cluster can be modeled as if it was initially out of virial equilibrium. In order to find the new virial equilibrium, the cluster undergoes to violent relaxation. In figure 2.1 (from Goodwin & Bastian 2006) is shown the fraction of stellar mass loss with time due to the escape of stars from the cluster potential for different values of the effective

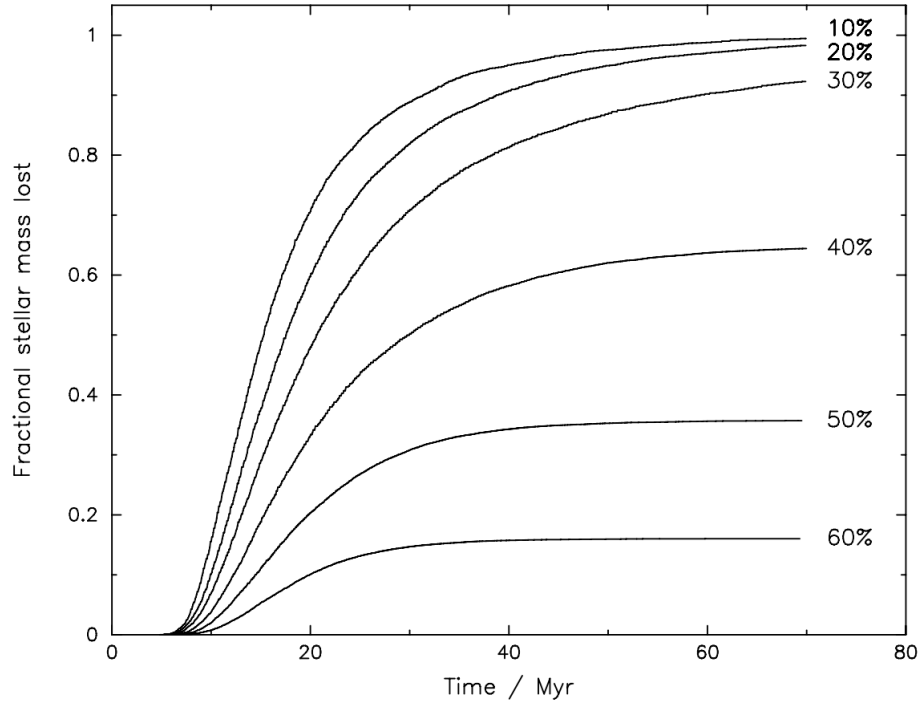


Figure 2.1: Fraction of stellar mass lost with time due to star expulsion (from Goodwin & Bastian 2006). Different values of effective star formation efficiency are shown.

star formation efficiency, ϵ_e , which parametrizes how far out of virial equilibrium the cluster is after gas expulsion. They defined the star formation efficiency as effective, as they have assumed that initially (i.e., before the gas expulsion) the stars and gas are in virial equilibrium. They defined the total (i.e., gas plus stars) initial virial ratio as $Q = T/|U|$, where T is the kinetic energy, and U the potential energy. A system in virial equilibrium has $Q = 0.5$. After the dispersion of the gas, the virial ratio of the stars is $Q_* = \epsilon T/\epsilon^2 |U| = (1/\epsilon) Q$ (since the mass after the gas dispersion is $M_* = \epsilon M$). The effective star formation efficiency is derived from the virial ratio of the stars as $\epsilon_e = 1/2 Q_*$. If the stars and gas are virialized before the gas expulsion, the ϵ_e is equivalent to the ϵ . A cluster with an effective star formation efficiency ϵ_e which is in virial equilibrium before the gas dispersion will have a stellar velocity dispersion that is $\sqrt{1/\epsilon_e}$ too large to be virialized after the instantaneous gas lost. They found that the lower ϵ_e is the farther out of virial equilibrium the system is¹. They found that clusters with $\epsilon_e < 30\%$ become completely unbound in few tens of Myr, while the ones with $\epsilon_e > 30\%$ can become bound systems, or at least they leave a bound core. In any case, also systems with effective efficiency less than 50% may lose a high fraction of their stellar mass until the first ~ 40 Myr. These escaping stars are the main signature of the cluster violent relaxation.

In another work, Baumgardt & Kroupa (2007) showed that star clusters expand after the gas expulsion and the amount of expansion depends on the velocity of the process. If the gas expulsion is rapid, the cluster stars are driven towards the outer regions. This might lead to an overestimate of the cluster dimension because now these stars are unbound objects not physically associated with the cluster, but they are still close to the stellar system and they might be indistinguishable from the real members. Also, they argued that clusters which are able to survive to the gas dissolution as bound systems must have formed in a smaller region and with high central densities respect to the present.

Another important point in these models is the behavior of the ratio between the real mass and that expected at the virial equilibrium. Goodwin & Bastian (2006) calculated the ratio between M_{dyn} and the true cluster mass after gas removal through the stellar feedback. They derived the dynamical mass using the velocity dispersion and the radius of the simulated clusters (see equation 1.6 in section 1.2.1), while the true mass is obtained through a comparison between the observed simulated luminosity and the mass-luminosity ratio from a single stellar population model. In figure 2.2 (from Goodwin & Bastian 2006) is reported the variation with the time of the dynamical-mass-to-true-mass ratio for several values of effective star formation efficiency. It is found that in the first 10 - 20 Myr after the gas expulsion, the dynamical mass may be overestimated, especially in clusters with $\epsilon_e < 50\%$.

¹The parameter ϵ_e is a direct measure of ϵ only under the assumption that stars are initially in virial equilibrium with the gas. Infact, if this is not true, in particular cases it might have values that exceed 100% (i.e., clusters would contract after the rapid gas dispersion). However, Goodwin & Bastian (2006) showed in their simulations that evidence indicates that ϵ_e is less than 100%.

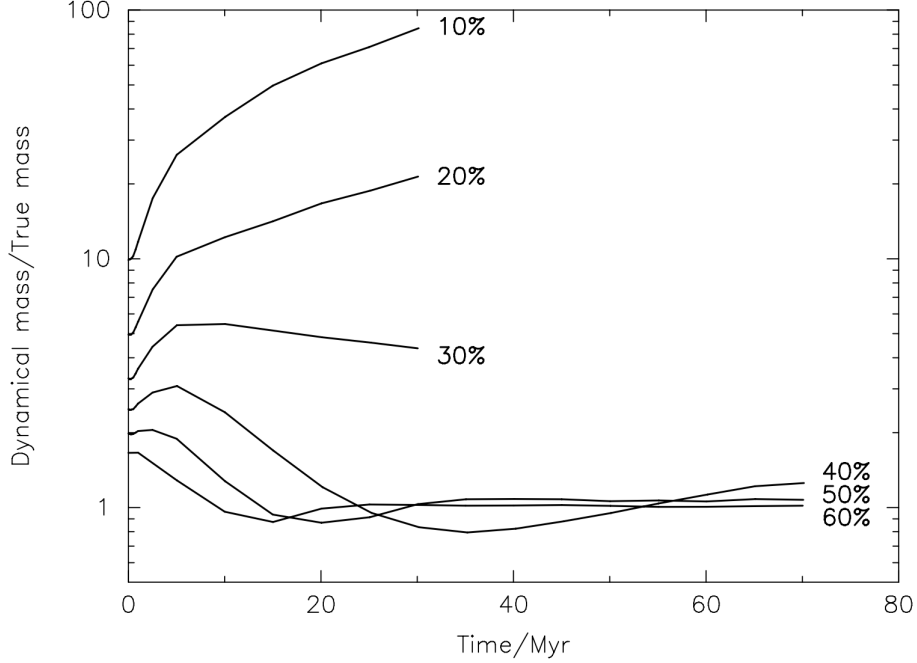


Figure 2.2: Evolution of the ratio of dynamical mass to true observed mass with the time after gas expulsion (from Goodwin & Bastian 2006). Several values of ϵ_e are shown. The zero point in time is the moment of the gas expulsion, namely ~ 5 Myr after cluster formation.

This is due to the cluster expansion after the gas expulsion and this is reflected in the determination of the cluster velocity dispersion. Infact, the measure of this quantity might be affected by the presence of the escaping stars with high velocity, which in the first 20 Myr may be still associated to the cluster, as shown in Baumgardt & Kroupa (2007). This leads to an overestimate of cluster velocity dispersion that reflects the mass estimate calculated under the assumption of the virial equilibrium ($M_{dyn} \propto \sigma_{1D}^2$). Figure 2.2 shows that stars in clusters with $\epsilon_e > 50\%$ rapidly found a new configuration of equilibrium and the two estimates of mass are in agreement at a cluster age of 15 - 20 Myr. This also reflects the low fraction of escaping stars in systems with high star formation. Instead, in clusters with $\epsilon_e \sim 40\%$ the dynamical mass is greater than the true mass at least up to ~ 30 Myr, while between 30 and 40 Myr the total mass is underestimated by the dynamical one. The two values are in agreement only at ~ 50 Myr. In the case of ϵ_e lower than 40%, the simulation stops the mass ratio evolution at ~ 30 Myr because the star evaporation has reduced the total mass and only few star members are still close to the center. Goodwin & Bastian (2006) have interpreted these results as an indication of the gas expulsion and the subsequent violent relaxation, confirming the idea of the cluster infant mortality (e.g., Lada & Lada 2003).

In these models also the dynamical state of the stars at the time of gas expulsion is relevant for the cluster survival. Simulations show that if a star system is

subvirial before the gas is dispersed, it can form a bound cluster and survive to the destructive effects of gas expulsion also if its star formation efficiency is lower than 30%. Viceversa, if the star system is supervirial then even clusters with $\epsilon \sim 50\%$ can be destroyed (Goodwin 2009).

2.2.3 Models without Stellar Feedback

Another models suggested by several authors propose that the dynamical evolution and dissipation of clusters may be the combination of several internal and external processes, such as two-body interactions and encounters with the external gas (e.g., Bastian 2011; Kruijssen et al. 2011, 2012; Parker & Meyer 2012; Parker & Dale 2013, 2015; Parker & Wright 2016), which reduce the cluster mass and can perturb the system leading it to a complete dissolution. In these models the effect of gas expulsion and stellar feedback is negligible and other factors are considered to explain the system evolution. One contribution to the cluster disruption is given by the loss of mass due to the stellar evolution, which removes the massive stars during the early phases. The process is time-dependent and after the first 10 Myr, all the clusters will have lost $\sim 30\%$ of the initial mass (Lamers et al. 2005). This process leads to modify the system potential well and to a further mass-loss through the stars with velocity higher than the escape one (Lamers et al. 2010). However, the mechanism of mass-loss due to the evolution of stars is taken into account also in the residual gas expulsion scenario and it gives only a limited contribution to the systems disruption, especially for the more massive ones.

In these models the main mechanism that leads to the cluster evolution and dissolution is the stellar-dynamical evaporation. Cluster members suffer of many wide (and rarely close) encounters with the other members. The potential and kinetic energy are continuously rearranged among the stars of the cluster (*two-body relaxation*, e.g., Lee & Goodman 1995). Given the energy equipartition in the cluster potential (Spitzer 1987), after many two-body encounters, the less massive stars gain kinetic energy and move to larger radii. Thus, these stars increase the velocity and they might become unbound (kinetic plus potential energy greater than zero). This happens when these low-mass stars are thrown away from the cluster due to their new high velocity and/or when they cross the Jacobi radius (i.e., the radius that splits the region where stars are bound from the region in which the tidal fields are able to strip the stars from the cluster (e.g., Portegies Zwart et al. 2010)). Conversely, the more massive stars gain potential energy and go towards the cluster center. The described phenomenon is the mass segregation, where the distribution of the mean stellar mass decreases with the cluster radius.

In the simulations of these models, stellar feedback and gas dispersion are not fundamental for the cluster dissolution. In particular, Parker & Dale (2013) simulated the formation and evolution of star clusters with the influence of stellar feedbacks and without them. They did not identify general differences in evolu-

tion between the different sets of simulations. Also, they examined the structure of clusters using the Q -parameter (Cartwright & Whitworth 2004; Cartwright 2009), which is a tool to distinguish between a smooth radial density gradient or a multi-scale subclustering. This parameter is given by the ratio between $\bar{m}$ and $\bar{s}$, where $\bar{m}$ is the mean edge length of the minimal spanning tree and $\bar{s}$ is the mean distance between the members. Characterizing substructure in clusters is important since a high level of subclusters facilitates the dynamical mass segregation in young clusters (e.g., Allison et al. 2010). When $Q < 0.8$ the clusters are substructured, while with $Q > 0.8$ clusters have a large radial density gradient and they are centrally concentrated. All the simulated clusters are initially substructured and they found

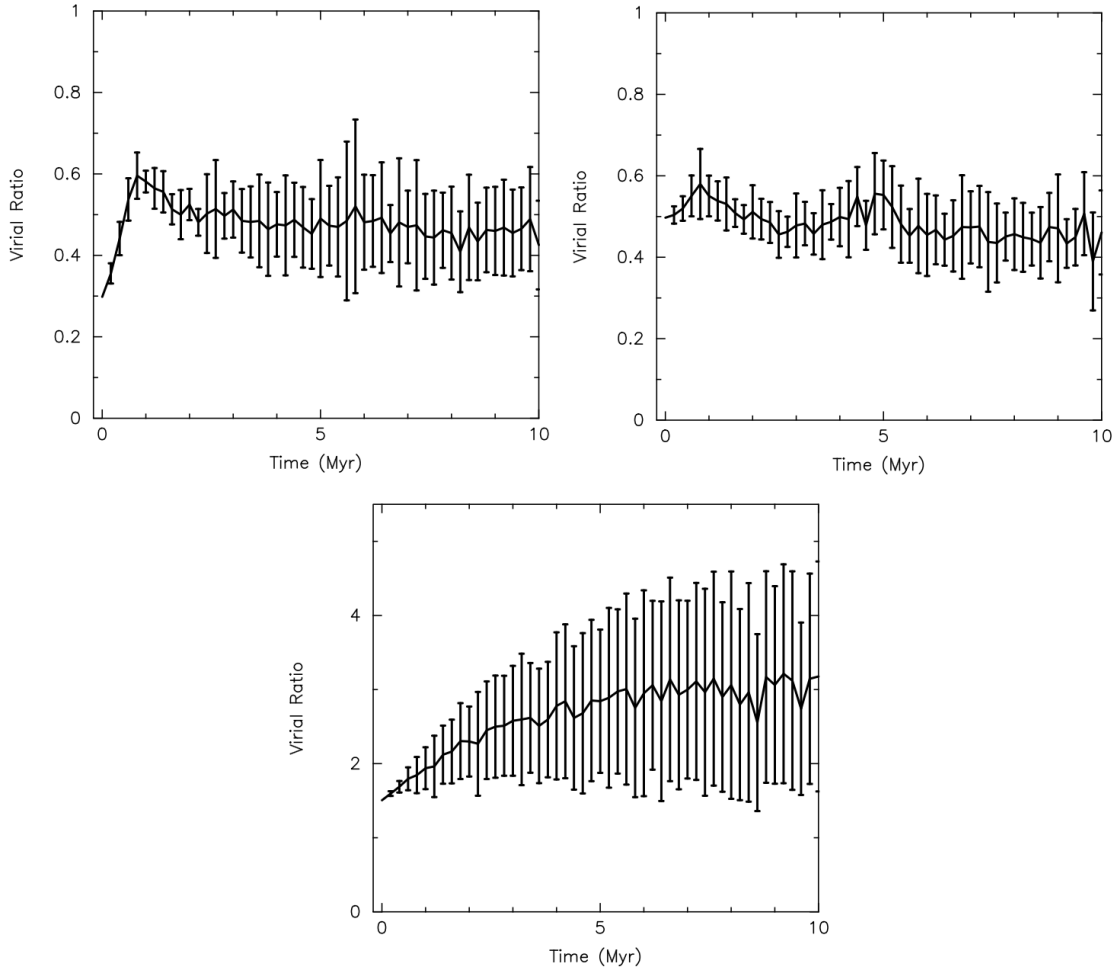


Figure 2.3: The evolution over time of the average of virial ratio for three simulations in Parker & Wright (2016), with 1σ uncertainties. The upper left plot shows a simulation in which cluster is initially subvirial (virial ratio = 0.3). The upper right plot represents a simulated cluster which is initially in virial equilibrium (virial ratio equal to 0.5). Lastly, the bottom plot shows a simulation that starts supervirial (virial ratio equal to 1.5). In these three simulation the clusters initially have the same substructured distribution.

that clusters for which stellar feedback is considered tend to lose the substructure more slowly than those without feedback.

Other simulations performed by Kruijssen et al. (2012) showed that also the density of cluster environments plays a key role in the process that leads to the system dissolution. Infact, they have suggested that in dense regions the young stellar systems are disrupted by the effect of tidal shocks given by the surrounding gas (e.g., Lamers & Gieles 2006; Elmegreen & Hunter 2010). This is the “cruel cradle effect”, in which the disruption of young clusters is given by their environment. Instead in these simulations the gas expulsion plays the same role of the tidal shocks only in star-forming regions with low ambient gas densities.

Furthermore, Parker & Wright (2016) performed N-body simulations of the cluster evolution assuming a wide range of initial conditions to estimate the variation of the radial velocity dispersion over time. They suggested that the observed velocity dispersion is not a good diagnostic for the cluster mass or virial state of the system and that it is inflated with respect to virial expectations in the early part of a cluster life. Figure 2.3 (from Parker & Wright (2016)) shows the evolution of the average virial ratio (i.e., ratio between kinetic and potential energy or, from the velocity dispersion analysis, the ratio between observed velocity dispersion and that expected at the virial equilibrium) over the time for a cluster with same number of stars, radius, and structure, but different initial dynamical state. The cluster is initially in subvirial, virial equilibrium, and supervirial state in the upper left, upper right, and bottom panel, respectively. The simulation that starts subvirial likely undergoes in a slightly supervirial phase within the first 3 Myr and then it reaches

Table 2.2: Models, fundamental quantities, and expectations for cluster evolution proposed in literature.

Model	Key ingredients	Main physical processes involved	Predictions
Hills model	ϵ, t_{gd} gas and stars in virial equilibrium	Gas expulsion	Cluster expansion
Residual gas expulsion	ϵ, t_{gd} , initial dynamical state, gas and stars in virial equilibrium	Star feedback, gas expulsion, stars expulsion, cluster expansion	Supervirial state after gas expulsion
Two-body interactions and external tidal encounters	ϵ , 2-body encounters, initial dynamical state, external tidal shocks, cluster density	Stellar evaporation, mass segregation, cluster expansion	Dynamical state depends on the initial state

the virial equilibrium and fluctuates around this value. The same fluctuations close to the virial equilibrium are present in the case of initial virial equilibrium. Finally, cluster that starts supervirial remains supervirial within the errors for the entire simulation. From these results, Parker & Wright (2016) argued that finding a velocity dispersion in excess of the virial value does not necessarily mean that the cluster is in a supervirial state, but actually it might be in virial equilibrium, especially in clusters that are in subvirial phase or in virial equilibrium at the beginning. This is in contrast with the residual gas expulsion scenario, in which clusters are expected to be in supervirial state after the rapid gas expulsion. In Table 2.2 a summary of the evolutionary models is presented.

2.2.4 Observations

In the last years, few results have been already achieved. A number of studies derived the properties of clusters and compared the model predictions with observations (e.g., Cartwright & Whitworth 2004; Bastian & Goodwin 2006; Parker et al. 2012; Wright et al. 2014). In particular, Cartwright & Whitworth (2004) analyzed the structure of several young star clusters and they found that such systems show both a smooth large-scale radial density gradient and multiscale subclustering. Bastian & Goodwin (2006) studied the surface brightness profiles of massive young clusters and they found an excess of light at large radii. This is in agreement with the simulations of the effects of gas expulsion, that produce the same excess due to stars escaping during a period of violent relaxation. The rapid gas expulsion should also be the reason for which the virial mass estimates are wrong for several tens of Myr. They suggested that these results are an indication that gas expulsion is a crucial phase in cluster evolution. Wright et al. (2014) studied the massive OB association Cygnus OB2 using the substructure and mass segregation as indicators of dynamical evolution. They found that this low-density association is dynamically young and it has several physical substructures. They concluded that it is a region very close to its initial conditions. The presence of very high mass stars ($\sim 100 M_{\odot}$) suggests that these objects can also form in low-density environments. This is in contrast with the prediction that all the stars form in dense clusters, especially the high-mass ones.

In other works the cluster dynamical properties are studied using the radial velocity of their star components (e.g., Cottaar et al. 2012a; Sacco et al. 2015, 2017). In particular, several kinematic studies have been already obtained from the observations of OCs with age smaller than 100 Myr, such as Chamaeleon I, ρ Oph and Gamma Velorum, where multiple kinematic populations (Jeffries et al. 2014; Sacco et al. 2015; Mapelli et al. 2015) have been discovered, improving the knowledge of origin and evolution of OCs. In particular, Jeffries et al. (2014) studied the Gamma Velorum system which is composed of two distinct clusters. The velocity dispersion of the first cluster is consistent with virial equilibrium, while the second

one is supervirial. Sacco et al. (2015) discovered that the second cluster is much more extended than what has been considered in Jeffries et al. (2014), and this population could originate from either the same region of the first cluster and it could have expanded on a wide region after the gas expulsion (confirmed by N-body simulations of Mapelli et al. (2015)), or in a low-density, diffuse and wide environment around the cluster in virial equilibrium. Also, in young clusters discrepancies between the kinematic properties of the pre-stellar cores and PMS stars formed in the same environments (Rigliaco et al. 2016; Sacco et al. 2017) have been discovered. Rigliaco et al. (2016) studied the L1688 star-forming region in the ρ Ophiuchi molecular cloud complex. They found that the members of this region are in virial equilibrium and they are bound to the remnant gas. They also found that an instantaneous removal of gas will leave the stars in a supervirial state, causing them to expand and disperse into the Galactic field, as expected by the residual gas expulsion scenario. Sacco et al. (2017) found that young cluster Chamaeleon I formed in a low-density environment, in virial equilibrium or a supervirial state, and highly substructured, as suggested by N-body simulations (Parker et al. 2014). Moreover, they support the scenario in which young clusters form from the merging of smaller subsystems.

On the other hand, different authors studied the dynamic of several clusters in the Galaxy and the Magellanic clouds (Mengel & Tacconi-Garman 2007; Bressert et al. 2010; Rochau et al. 2010; Bastian 2011; Hénault-Brunet et al. 2012; Clarkson et al. 2012; Cottaar et al. 2012a; Wright et al. 2016) with multi-epoch high-resolution spectroscopy and they found that the effect of gas expulsion is not significantly important. Notably, Bressert et al. (2010) performed a study of the surface density of several young stellar objects in nearby star-forming regions and they found that $< 26\%$ of stars are formed in dense environments where their surroundings may affect their evolution. Cottaar et al. (2012a) found that the young massive cluster Westerlund I is subvirial, implying that it is bound. Therefore, this is in contrast with the residual gas expulsion scenario, for which a cluster with age of ~ 5 Myr should be out of virial equilibrium because of a recent expulsion of gas, while Westerlund I has survived as a bound system at its gas expulsion. Wright et al. (2016) studied the OB association Cygnus OB2 using the proper motions of the cluster stars. They suggested that this massive association was born with physical and kinematic substructure, which is still there. This result is in contradiction with the idea that the OB associations are the expanded remnants of star clusters disrupted by gas expulsion. Finally, Bastian (2011) suggested that these results indicate that the gas expulsion on these young clusters has not affected them and that the role of infant mortality in cluster populations have been overestimated.

2.3 Open Questions and Requirements

As described in the previous section, understanding the origin and the evolution of star clusters is one of the main debate in the astrophysical field. The summary of

scenarios proposed in the literature and the several observations performed in the past indicate that no consensus has been reached yet. Several questions are still open and require a step forward in terms of theory and observations.

- What are the initial conditions for star cluster formation. Literature works show that stars might form either in massive and mass segregated cluster or in hierarchically structured environments. It is not still completely clear if there are several mechanisms that work on the monolithic collapse of a massive cloud or clusters are formed through gradually merging of smaller systems.
- How the cluster environments affect the star formation, namely if the parameters that characterize these ambients, such as temperature, pressure, density, and content of gas and stars, have an impact on the star formation and the resulting cluster. These conditions either might have an impact on the forming stars and determining their final properties, or each star might form without any influence of the environment. Currently, exactly what determines the properties of an OC and its stars is not fully clear.
- What are the effects of stellar feedback and stellar interactions and, consequently, the timescales of star formation and cluster evolution. Through these processes, stars release energy into their companions and environment and modify the conditions that regulate a potential subsequent star formation and cluster survival. Therefore, understanding the timescales of these effects and what are the dominant processes that drive the early phases of cluster evolution and lead to their dissolution are a key point. Also, it is fundamental to understand how and why several clusters are able to survive for several Gyr. Indeed, important questions are why only a small fraction of clusters survive as a bound system after the early stage of evolution and what are the processes leading to their dissolution and to the formation of a long-lived system.

All these questions are fundamental. As described in the previous section, several models are proposed to answer to these issues. Since different scenarios lead to a different cluster structure and kinematics, together with hydrodynamic and N-body simulations, observations of large and homogeneous samples of OCs are needed. This allows us to limit the errors which often affect the correct interpretation of the data and to probe the evolutionary models proposed in the literature. For these reasons, it is necessary to acquire detailed informations with high precision of the kinematic properties of unbiased populations in star clusters covering a wide range of properties, such as age, distance, density and total mass of clusters. Moreover, the structural properties of OCs, such as mass segregation, level of sub-structure and density, should be determined with a large statistical significance in order to be compared with theoretical models.

Now we just entered in the era of kinematic thanks to the advent of the *Gaia* space mission and a variety of ground-based complementary surveys. The European Space Agency (ESA) mission *Gaia* (Perryman et al. 2001; de Bruijne 2012; Gaia Collaboration et al. 2016a,b, 2018c) provides the astrometric parameters (i.e., parallaxes and proper motions) and the positions of $\sim 2 \times 10^9$ stars. In order to complement *Gaia* data, large high-resolution spectroscopic surveys are necessary to derive chemistry and parameters of the stars and to provide radial velocity informations with a high accuracy, which means a level of precision on the radial velocity less than 0.5 km s^{-1} . Such accuracy allows us to resolve the internal cluster kinematics and tests the theoretical models from an observational point of view. A fundamental contribution is given by the *Gaia*-ESO Survey (Gilmore et al. 2012; Randich et al. 2013), described here in the following Chapter. With the combination of data from *Gaia* and this survey, it is possible to obtain a large set of observables (i.e., positions, distances, masses, ages, radial velocities, stellar parameters, metallicity, and other membership indicators).

To date, all the observational studies described in section 2.2.4 focus on very young clusters, i.e., with an age range between 1 and 20 Myr, and only few are performed on clusters with old age. Therefore, the study of old clusters is necessary to have a full overview of the processes that lead the cluster evolution and, eventually, the cluster disruption. So, it is necessary to extend these kinds of studies covering all the fundamental physical cluster parameters, such as the cluster age and the total mass. Therefore, in this work I analyzed the kinematic and dynamical properties of several open clusters spanning a range of age from 20 Myr up to 3.5 Gyr, using the *Gaia*-ESO Survey data.

Chapter 3

Data and Methods

In the last few years, several large ground-based spectroscopic surveys have been developed observing the main components of the MW. Among these surveys, a fundamental contribution is given by the *Gaia*-ESO Survey (GES), which has performed detailed and homogeneous observations of a very large sample of stars of the Southern sky. The products of this survey allow us to investigate the open questions described in section 2.3.

In this Chapter, I will first briefly describe the *Gaia*-ESO Survey and will illustrate the observing strategy, in particular for OCs. Then, I will present the main data products of this survey; finally, I will describe the main methods and techniques used in this Ph.D. work to study the kinematic properties and the dynamical state of OCs with the GES data.

3.1 The *Gaia*-ESO Survey

The *Gaia*-ESO Survey (Gilmore et al. 2012; Randich et al. 2013) is a large public spectroscopic survey carried out with the Fibre Large Array Multi Element Spectrograph (FLAMES, Pasquini et al. 2002) instrument on the Very Large Telescope (VLT), which is a telescope facility operated by the European Southern Observatory (ESO) on Cerro Paranal in the Atacama Desert of Northern Chile. *Gaia*-ESO is so far the only spectroscopic survey carried out in an 8-*m* class telescope. Hence it reaches much fainter magnitude than the other surveys (e.g., APOGEE Majewski et al. 2017). The survey started in December 2011 and observations have been completed in January 2018 for a total of 340 nights. The main aim of GES is to understand the formation and evolution of the different Galactic components. GES has targeted $\sim 10^5$ stars, which cover all the major components of the Galaxy, with a particular focus on open clusters. Indeed, the survey observed 65 OCs distributed across the Galactic thin disc and covering all accessible cluster ages and masses. Figure 3.1 shows the age distribution of the clusters observed by GES.

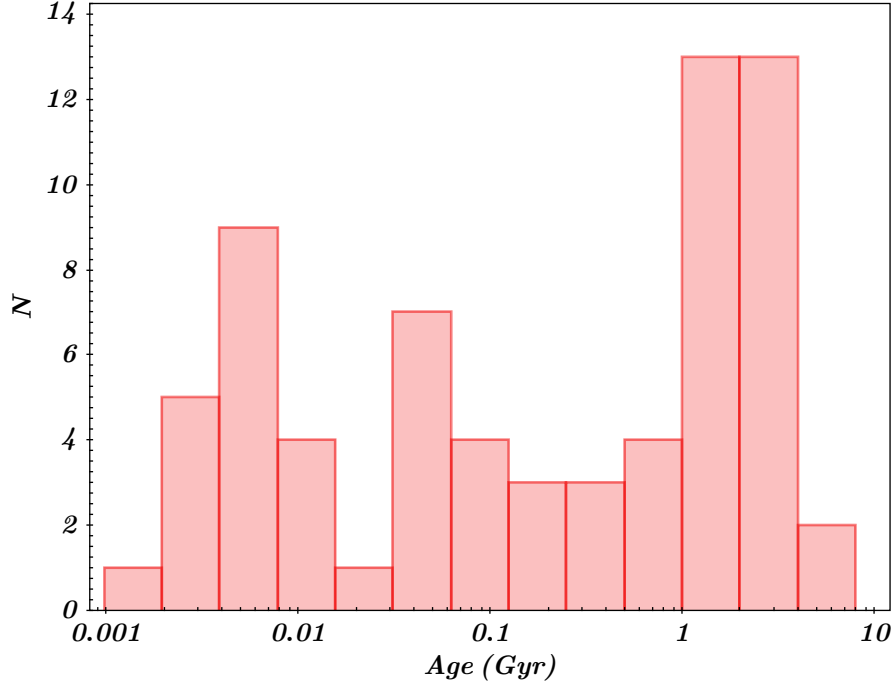


Figure 3.1: Age distribution of the clusters observed by GES.

3.1.1 Instrument: FLAMES

FLAMES is a multi-object instrument with a field of view (FoV) of 25 arcmins in diameter. It feeds two different spectrographs, GIRAFFE and UVES, covering the whole visual spectral range and it has a fiber positioner (OzPoz). GES made use of both the intermediate and high-resolution spectrographs, GIRAFFE and UVES, respectively.

UVES is the high-resolution spectrograph (with a resolving power of $R = \frac{\lambda}{\Delta\lambda} \simeq 47000$ when it is used in fiber mode) and it allows the simultaneous observation of 7 stars and one fiber on the sky. Three setups are available, with central wavelengths of 5200 (U520), 5800 (U580), and 8600 Å (U860), and each setup has a spectral range of 2000 Å. In the context of GES, it is used to observe stars in the magnitude range $9 < V < 16.5$, and in particular UVES 520 and UVES 580 are used to observe the hot and cool stars, respectively.

Instead, in the framework of GES GIRAFFE is used in MEDUSA mode obtaining medium resolution spectra (R between ~ 11000 and ~ 38000 , depending on the setup) and each grating covers a fraction of the entire visible range (3700 - 9570 Å). Using the MEDUSA fibre system feeding, it is possible to allocate simultaneously 132 targets, including the sky fibres. In the GES observations $\sim 10^5$ stars are observed in the magnitude range $11 < V < 19$. GIRAFFE has several setups that are used both in the observation of MW and OCs. In the context of OC observations, these setups have a large number of spectral features which are useful

to derive the radial velocities and characteristics of the stars, such as temperature, gravity, metallicity, elemental abundances, and rotational velocity. In table 3.1 the setups of UVES and GIRAFFE used in the context of GES observations of OCs are shown together with the information about the central wavelength, the spectral range, and the resolving power.

Table 3.1: Setups of UVES and GIRAFFE used in GES.

Spectrograph	Setup	Central λ [Å]	Spectral band [Å]	R
UVES	U520	5200	2000	47000
UVES	U580	5800	2000	47000
GIRAFFE	HR03	4124	168	31400
GIRAFFE	HR04	4297	205	24000
GIRAFFE	HR05A	4471	247	20250
GIRAFFE	HR06	4656	222	24300
GIRAFFE	HR09B	5258	213	31750
GIRAFFE	HR14A	6515	394	18000
GIRAFFE	HR15N	6650	320	19200

3.1.2 Cluster Sample

The GES observing strategy has been designed to survey the bulge and the thick and thin discs. Since the work presented in this thesis is focused on OCs, I describe below the observing strategy for these objects.

The clusters are selected in order to provide further insights on how they form, evolve and eventually dissolve using a large, unbiased samples of members; to use them as templates for stellar evolution at different masses, ages and metallicities; and to perform a detailed study of the properties and evolution of the disc of MW. Those goals require gathering a sample of clusters spanning a wide range of ages (from a few Myr to several Gyr) and positions in the Galaxy.

A dedicated team has selected the OCs from several catalogs (e.g., Dias et al. 2002), and from the WEBDA database¹. The selected clusters have good photometry in near-infrared (using the Two Micron All Sky Survey (2MASS) photometry, Skrutskie et al. 2006) and/or optical bands. The cluster selection is optimized to fine-sample the age-[Fe/H]-Galactocentric distance-mass parameter space. The clusters selected in the final sample are divided in two categories: the young OCs, with age less than 100 Myr, and the old OCs, with age greater than 100 Myr. In figure 3.2 the distance from the Sun versus age of the clusters observed by GES is shown. The lack of young clusters in regions far from the Sun is mainly due to

¹<http://www.univie.ac.at/webda>

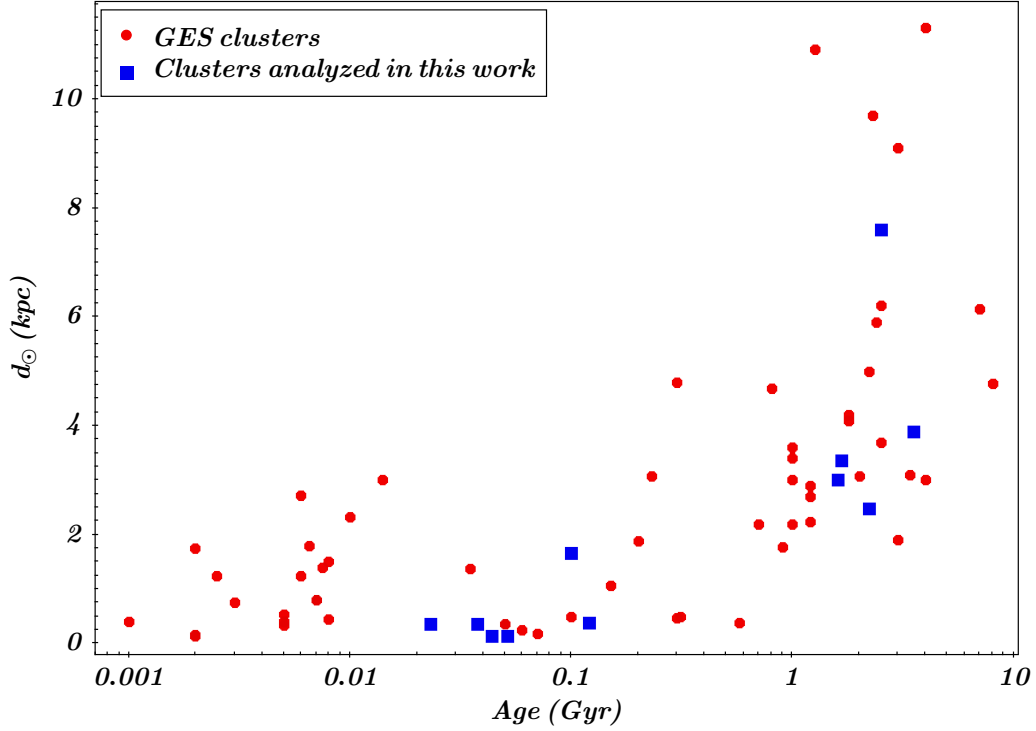


Figure 3.2: Distance from the Sun versus age of the clusters observed by GES. The red points are the clusters observed by GES, while the blue squares are the clusters studied in this work.

the magnitude limits of the observations because at large distances it is easier to observe stars with low absolute magnitude. Indeed, the typical PMS stars in young clusters at large distances have a high absolute magnitude, and given the magnitude limit of GES observations, it is not possible to observe them.

3.1.3 Open Cluster Target Selection and Observing Strategy

The target stars are selected with different criteria for UVES and GIRAFFE. UVES is used mainly to derive the cluster chemical pattern (Spina et al. 2014b,a, 2017), while GIRAFFE is used to observe an unbiased sample of cluster members to study cluster dynamics and stellar evolution. Therefore, based on the information available in the literature, the UVES fibres are assigned to stars that are secure or very likely members. Instead, the targets observed with GIRAFFE have been selected in an unbiased way, down to $V \sim 19$, from a strip around the cluster sequence in the CMDs. This sequence is defined based on known members from the literature, using all the available photometric catalogs (both in optical and infrared) and kinematic information when available. The strip is chosen so to include the majority of the known candidates of all relevant colors and magnitudes. In figure 3.3 two examples

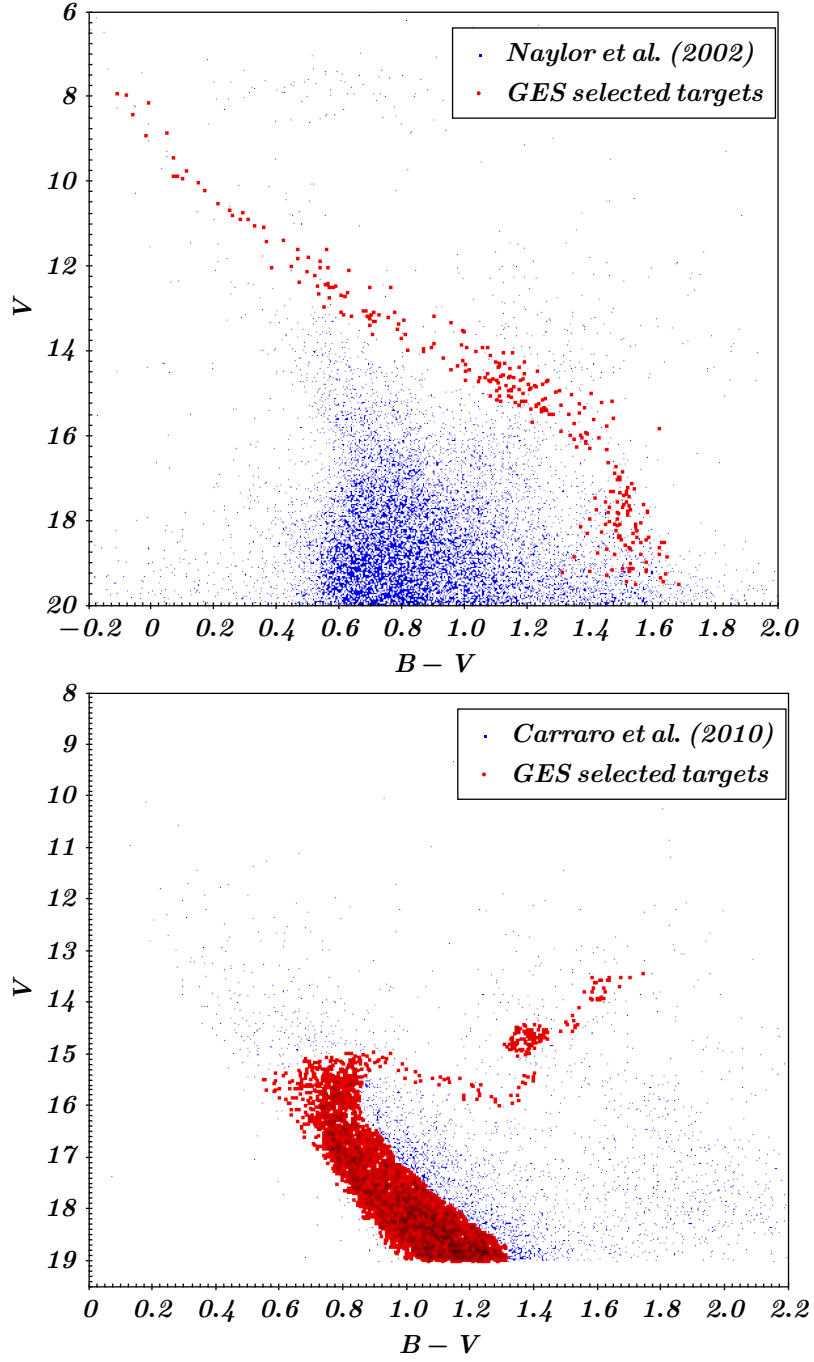


Figure 3.3: The target selections for a young (age < 100 Myr) and old (age > 100 Myr) OCs. *Upper panel:* the target selection of the OC NGC 2547 (age ~ 40 Myr). The small blue points mark the stars in the parent catalog of Naylor et al. (2002), while the big red ones are the stars selected as targets by GES. *Bottom panel:* target selection of the OC Trumpler 20 (age ~ 1.6 Gyr). The symbols are the same of NGC 2547. The selection is based on the parent catalog of Carraro et al. (2010).

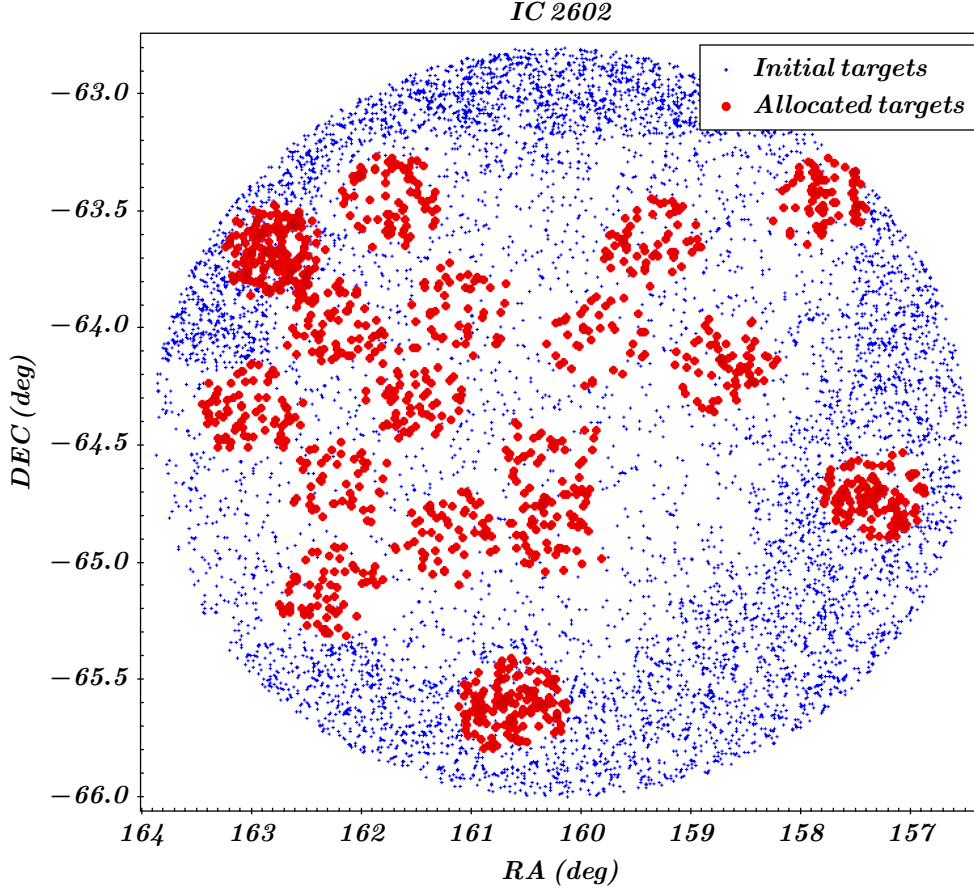


Figure 3.4: Spatial distribution of the initial selected targets (small blue crosses) and the final allocated targets (red points) for the cluster IC 2602.

of target selection for a young cluster (NGC 2547) and an old one (Trumpler 20) are shown. Both the selection in CMDs and in the sky need to be inclusive. However, it should be noted that this inclusive strategy implies that the final samples will include a large number of foreground and background contaminants.

Moreover, especially for close-by clusters, even with the significant amount of observing time dedicated to each cluster, it is not possible to cover the whole area occupied by the targets selected in this first step. As described in the following sections, this must be taken into account when estimating the total cluster mass. For example, figure 3.4 shows the initial selected targets (small blue crosses) and the final allocated targets (red points) for cluster IC 2602, which is close to the Sun.

Generally, if a cluster is closer than ~ 1500 pc, almost the whole population is targeted. In cluster at larger distances, the observed stars lie principally in the upper (P)MS and, in the case of old clusters, RGB phase and red clump (RC).

The GES fields are observed in the so-called Observing Blocks (OBs) typically of either 30 minutes or 1 hour of duration; the OBs comprise two science exposures

of 10 or 25 minutes interspersed by a short calibration lamp exposure in order to perform the wavelength calibration. The OBs may be repeated from two to eight times depending on the magnitude of the targets.

In the ESO archive, observational data for several clusters are also available. These data were re-analyzed within GES as complementary data.

3.1.4 GES Workflow

The data flow of GES is divided among 19 Working Groups (WGs), from WG0 to WG18. Each WG has a specific task. In the work-flow, a few WGs select the initial samples of stellar objects that are targeted by GES, while other WGs work on the reduction and analysis of the data. In particular, the cluster target selection is performed by WG1 and WG4.

The pipeline reduction of the GIRAFFE raw spectra and RV determination are performed at Cambridge Astronomy Survey Unit (CASU) - Institute of Astronomy, while for the UVES spectra are carried out at INAF - Osservatorio Astrofisico di Arcetri (OAA). The data reduction is described in Jeffries et al. (2014) and Sacco et al. (2014) for GIRAFFE and UVES data, respectively. After the reduction, wavelength calibrated spectra are released for the analysis.

The spectrum analysis is distributed among several WGs, depending on the type of stars. In particular, WG10 and WG11 focus on the analysis of the normal F-, G-, and K-type stars observed with GIRAFFE and UVES, respectively, while WG12 analyzes the cool PMS stars observed with both UVES and GIRAFFE. They produce a number of data products, among which effective temperatures, surface gravities, elemental abundances, and equivalent widths (EWs). Furthermore, WG12

Table 3.2: Available data from GES archive and their application during this work. Each product has an associated error.

Data	Unit	Applications within this work
T_{eff}	K	membership/stellar masses
$\log g$		membership
γ		membership
EW(Li)	$m\text{\AA}$	membership
[Fe/H]		membership
$v \sin i$	km s^{-1}	kinematic study
RV	km s^{-1}	kinematic study

Notes. Data from GES: T_{eff} is the effective temperature; $\log g$ is the surface gravity; γ is the gravity index; EW(Li) is the equivalent width of the lithium line at 6708 Å; [Fe/H] is the metallicity; $v \sin i$ is the projected rotational velocity; RV is the radial velocity.

derives also the activity indicators and mass accretion rates. Within these WGs several nodes participate to the spectrum analysis and derive the data products. These products delivered by the nodes are combined to produce the recommended set of measurements provided by the various WGs, which in turn are homogenized with each other to produce the final recommended values and errors. The uniform set of derived data is periodically released to all the members of the GES consortium via a science archive².

Table 3.2 shows the data available in the GES archive used in this work and their main applications, which will be explained in the next section.

3.2 Methods

My work started with the analysis of the data products. Specifically, with the data listed in table 3.2, I performed an analysis of the kinematic properties and dynamical state of several OCs. In this section, I will describe the main methods used. In particular, depending on the cluster age, I used the spectroscopic information provided by GES in order to identify cluster members in each cluster. Then, using several techniques, I derived the main characteristics of these clusters, such as their total masses and radii.

3.2.1 Spectroscopic Members Selection in Young OCs

As described in section 3.1.3, the inclusive selection strategy adopted by GES also implies a degree of contamination by field stars among the initial selected targets in each cluster. In clusters younger than 100 Myr it is possible to exclude these contaminants using the parameters derived by the GES consortium. This has been done as follows.

Starting from the initial sample of observed targets, I excluded the stars that are secure non-members of the clusters through three independent spectroscopic criteria. These criteria are based on the surface gravity, the equivalent width of the lithium line, and the star metallicity. However, this analysis excludes the obvious non-members, thus a few contaminant field stars may be still present within the sample of final selected candidates.

- The main sources of contamination for a nearby young cluster are the background giants. Indeed, given their distance, several of these objects may have an apparent magnitude that is the same of the cluster members; hence these background giants may lie in the same CMD region occupied by the cluster sequence. As described in section 1.4, in clusters with age less than 100 Myr the members are PMS stars. In section 1.6 it is explained how gravity changes

²The GES science archive is run by the Royal Observatory of Edinburgh. More information on the archive are available at their website: ges.roe.ac.uk

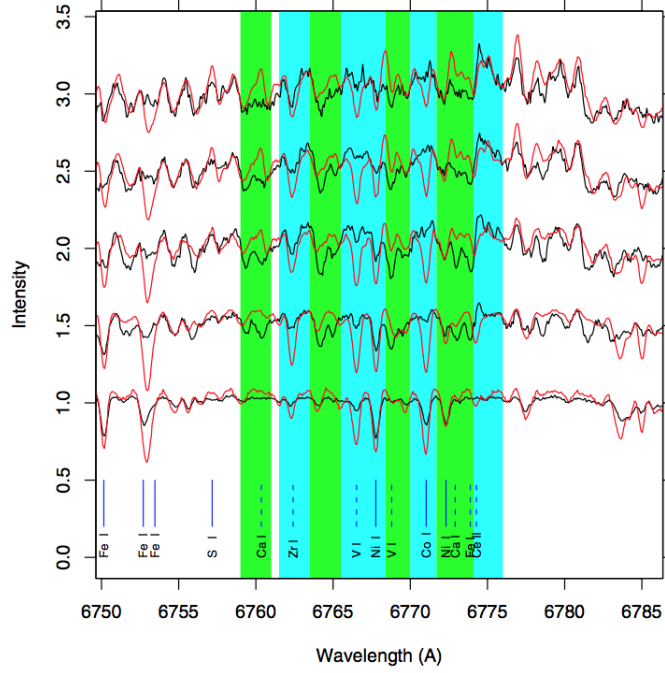


Figure 3.5: Spectra of MS (black) and giants (red) stars with different temperatures in the wavelength range 6750 - 6780 Å, used to define the γ gravity-sensitive index (from Damiani et al. 2014). The solid blue segments indicate the lines well-identified, while the dashed blue segments indicate lines for which identification is less certain. The cyan and green bands show the ranges used to sample low- g and high- g lines, respectively. They derived γ from the flux ratio between low- g lines and contrasting high- g features nearby.

as a star evolves. Given equation 1.17, the background giants will have lower gravity than the cluster members. Therefore, the gravity indicators allow us to separate these contaminant stars from the candidate members. In the context of this work, for the GIRAFFE stars I used the gravity index γ (Damiani et al. 2014) since its measurements are available for a larger number of GIRAFFE spectra than the measurement of the surface gravity, $\log g$. On the other hand, for the UVES stars I used the $\log g$, since for these targets γ is not derived.

The γ index is an efficient gravity indicator for the GIRAFFE targets when it is combined with the effective temperature of the stars. It is an empirical index and it is sensitive to stellar gravity over a wide range of spectral types. It allows a good separation between the low-gravity giants and the higher gravity members of young OC for spectral types later than G. Damiani et al. (2014) have derived this empirical index in particular ranges of the spectrum where gravity sensitive features are present (see figure 3.5).

Figure 3.6 (from Damiani et al. (2014)) shows the γ index plotted against τ , which is an index sensitive to temperature, for the stars observed with

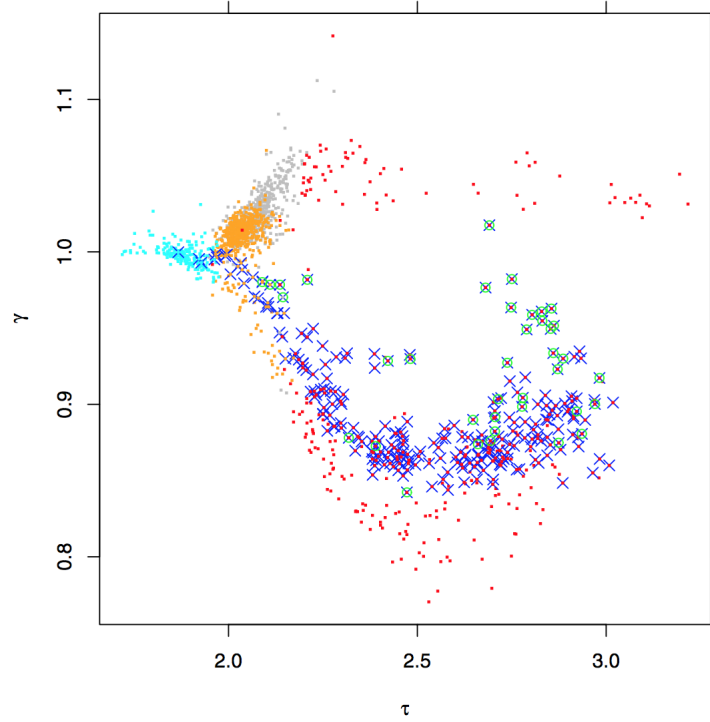


Figure 3.6: Gravity index γ versus temperature index τ for all the types of stars observed with GIRAFFE in the γ Velorum cluster, adapted from Damiani et al. (2014). The cyan dots are A to early-G stars, red dots are late-K and M stars, grey dots are giants while orange dots are intermediate-type stars with no reddening (mostly G, K stars). The blue crosses are the bona-fide cluster members derived for γ Velorum, which are selected by the combination of at least two indicators among X-ray emission, EW(Li), and RV. The stars with H α emission are the green circles.

GIRAFFE in the γ Velorum cluster (5 - 10 Myr, Jeffries et al. 2009b). From this figure, the separation between the low-gravity giant stars (grey dots) and higher-gravity stars for the full range of temperature is well clear. Particularly, the plot shows that the cluster members (blue crosses), which are mainly in the PMS phase, are quite well separated from the higher-gravity MS stars (the cyan, red, orange, and grey points under the sequence defined by the blue crosses).

In the context of this work, I considered as giants all the GIRAFFE targets within the region which has approximately T_{eff} lower than 5400 K and γ higher than 0.98, within a 1σ error bar. As described above, for UVES targets the gravity index is not defined and we use the surface gravity: I considered as giants the stars with $\log g$ lower than 3.75 dex. In order to check the consistency between using γ or $\log g$, I show in figure 3.7 the comparison between these two parameters for cluster IC 2602: it is clear that the selection of the giants is basically the same whether I consider targets with $\gamma > 0.98$

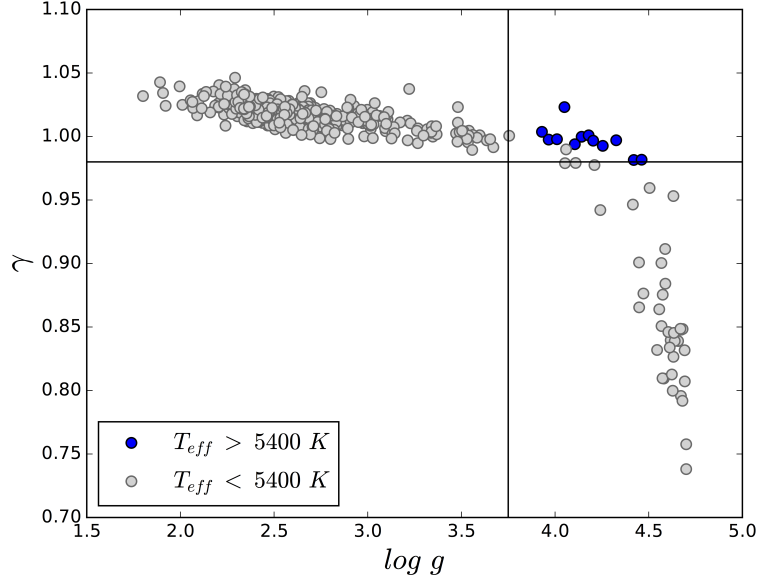


Figure 3.7: Gravity index (γ) as a function of the surface gravity ($\log g$) for IC 2602. The blue dots are the targets with an effective temperature greater than 5400 K, while the gray dots are those with a $T_{\text{eff}} < 5400$ K. The solid lines delimit the regions in which a target is considered a giant star based on its γ index (above the horizontal black line) and on its $\log g$ value (to the left of the vertical black line).

and $T_{\text{eff}} < 5400$ K or targets with $\log g < 3.75$. All the targets identified as giants with γ and T_{eff} are indeed distinctly below the value of $\log g = 3.75$.

- The second source of contamination in the target sample of young clusters are the foreground dwarfs. In order to exclude these stars from the final sample of candidate spectroscopic members, I used the $\text{EW}(\text{Li})$ at 6708 Å. The EW of an absorption line is defined as the width, in wavelength units, of a rectangular strip of spectrum having the same area as the absorption line and it is given by the integral

$$\text{EW} = \int \frac{F_c - F_\lambda}{F_c} d\lambda, \quad (3.1)$$

where F_c is the flux of the continuum normalized at 1 and F_λ is the stellar flux at the specific wavelength λ . It is a measure of the strength of the absorption line. For weak lines, an approximately linear relation between the EW value of a line and the abundance of the correspondent element responsible of the transition is expected, hence the line strength increases with increasing abundances.

As described in section 1.5, lithium starts being depleted during the PMS phase depending on the star mass (e.g., Soderblom 2010). In particular, the $\text{EW}(\text{Li})$ can be used as a youth indicator in a specific range of temperature

for stars with age between 20 and 50 Myr, that is the age range considered for the sample of young OCs analyzed in this work. The stars with a high value of $EW(\text{Li})$ and a stellar temperature between 4000 K and 6000 K can be identified as candidate cluster members. Stars with $T_{\text{eff}} < 4000$ K in this particular age range have already burned all their lithium, while above 6000 K lithium is preserved even in much older stars. Furthermore, above 6000 K the Li I 6708 Å line becomes very weak and difficult to measure.

The progression of the Li depletion in OCs is shown in figure 3.8. The figure presents the $EW(\text{Li})$ versus the effective temperature for the members of two young OCs (age between 40 and 50 Myr, IC 2602 and IC 2391, Randich et al. 2001), one intermediate OC (age ~ 125 Gyr, Pleiades, Bouvier et al. 2018), and one old OC (age ~ 625 Gyr, Hyades, Cummings et al. 2017). From this figure, it is clear how the $EW(\text{Li})$ is a very useful youth indicator in star clusters.

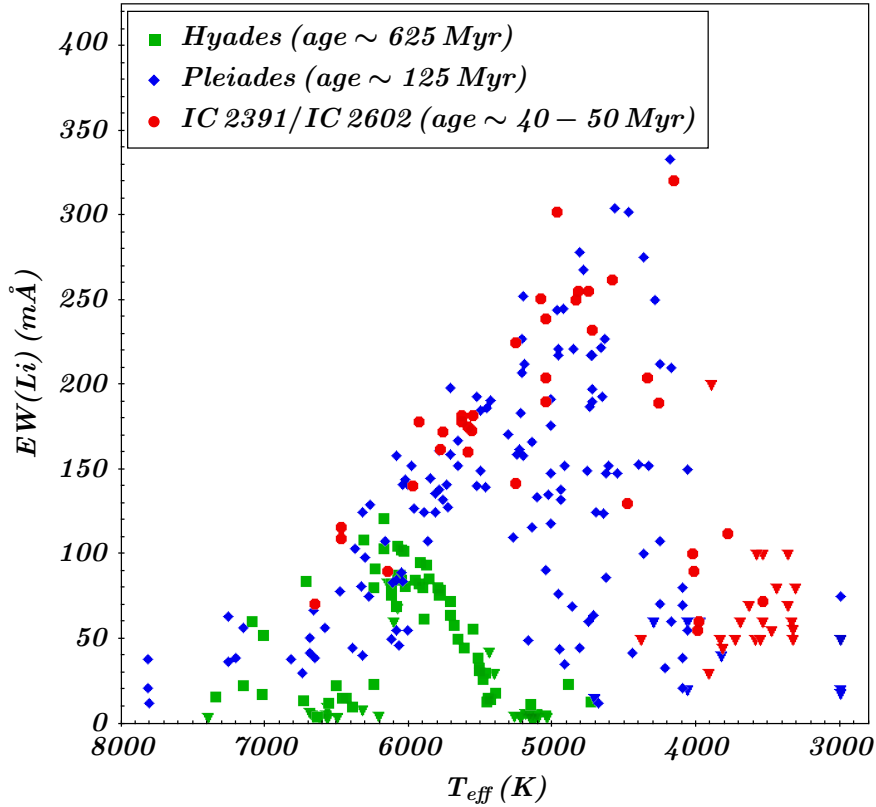


Figure 3.8: Equivalent width of Li I line versus star effective temperature for the members of four OCs with different age. The red points displayed the IC2391/IC2602 clusters (age $\sim 40 - 50$ Myr), the blue diamonds displayed the Pleiades cluster (age ~ 125 Myr), while the green squares displayed the Hyades cluster (age ~ 625 Myr). In each cluster the triangles identify the upper limits. Data are from Randich et al. (2001), Bouvier et al. (2018), and Cummings et al. (2017) for IC2391/IC2602, Pleiades, and Hyades, respectively.

Therefore, in this work I used the $\text{EW}(\text{Li})$ combined with T_{eff} to exclude the dwarf non-members from the sample of stars remaining from the first selection step. I identified the secure non-members using a threshold between 4000 K and 6000 K, that was defined using previous observations available in the literature of the young clusters analyzed in this work. A star with an $\text{EW}(\text{Li})$ above the boundary threshold will have an age between 20 and 50 Myr.

- Finally, the last step in the determination of spectroscopic candidate members is to exclude all the stars with a high subsolar metallicity, i.e., $[\text{Fe}/\text{H}] < -0.5$ dex. As reported in a recent study using the GES data of several young regions (Spina et al. 2017), the OCs analyzed in my work have a close to solar or slightly sub-solar metallicity with a small dispersion.

3.2.2 Kinematic Analysis

3.2.2.1 Uncertainties in Radial Velocities

In this work I used RVs to study the cluster kinematic. In GES, for the stars observed with GIRAFFE, the RVs are determined by CASU and are provided among the data products. In this context, Jackson et al. (2015) empirically determined the precision of the RV, which is critical to resolving the cluster kinematic. Specifically, they derived the uncertainties and their underlying distribution of probability as a function of the signal-to-noise ratio (S/N , mean ratio per pixel of the spectrum obtained during the extraction process), T_{eff} , and $v \sin i$ by comparing repeated measurements of the RV for the same star in GES. They identified two classes of measurement uncertainties: (i) the short-term repeat observations, where the RV uncertainty is empirically derived using the repeated observations of the same star within an OB; (ii) the long-term repeat observations, in which the uncertainties are estimated by the comparison of the mean values of RV of the same target in two different OBs. In the former case, the noise in the spectra and intrinsic errors in the reduction process are the primary causes of uncertainties and errors due to the wavelength calibration are expected to be small, since the exposure for this calibration is between the two scientific exposure within the same OB. In the latter case, also the external uncertainties in the wavelength calibration due to several technical and ambient factors should be considered as contributors of the final RV uncertainties. The RV uncertainties have a strong dependence both on S/N and $v \sin i$, thus the empirical formula must take into account them. In order to find the underlying normalized distribution of measurement uncertainties, the approach is to divide E_{RV} by function of target, signal, and properties of the spectrograph. The RV precision for short-term repeats scales as

$$S_{\text{RV},0} = B \frac{(1 + ([v \sin i]/C)^2)^{3/4}}{S/N}, \quad (3.2)$$

where $C \approx 0.895 c/R_\lambda$, R_λ is the spectrograph resolving power, c is the speed of light and B is a constant determined empirically which depends on the temperature of the star. For long-term repeats, Jackson et al. (2015) take into account also the independent contribution of the variations in the wavelength calibration. An empirically determined constant is added in quadrature to the short-term uncertainty, therefore

$$S_{\text{RV}} = \sqrt{A^2 + S_{\text{RV},0}^2}. \quad (3.3)$$

The constant A ($\sim 0.25 \text{ km s}^{-1}$) is the best RV precision which can be obtained for a spectrum with large S/N and low $v \sin i$. Therefore, with equations 3.2 and 3.3 it is possible to derive the empirical uncertainty on RVs for GIRAFFE targets. In table 3.3 are shown the values of the constants A , B , and C depending on the temperature of the target. It should be noted that the value of the constant B is limited to the temperature between 3200 K and 7200 K. This is due to the low member statistics in GES observations outside this temperature range.

Table 3.3: Values of constants for the empirical derivation of uncertainties on RV for the setup HR15N.

Constant (km s^{-1})	Temperature range (K)	
A	/	0.25 ± 0.02
C	/	15.8
B	3200 - 4000	3.9 ± 0.1
B	4000 - 4800	4.4 ± 0.2
B	4800 - 5600	4.9 ± 0.1
B	5600 - 6400	7.8 ± 0.3
B	6400 - 7200	10.3 ± 1.1

3.2.2.2 Radial Velocity Distribution of Star Clusters

Using the RVs and their empirical uncertainties derived following Jackson et al. (2015), I determined the intrinsic RV dispersion of clusters observed with GES, σ_c , that is a fundamental quantity to constrain the dynamical state of an OC. In the determination of this quantity, the errors in the RVs and the presence of binary stars must be considered. Infact, in a binary system the orbital motion introduced by a companion offsets the individual RV measurement of the primary star from the motion of the center of mass of the system. When the binaries cannot be detected and they are considered as single stars, they add to the dispersion on the measurement of σ_c . Therefore, the velocities induced by binary motions may mask the small velocity dispersion ($< 1 \text{ km s}^{-1}$) expected in OCs (e.g., Geller

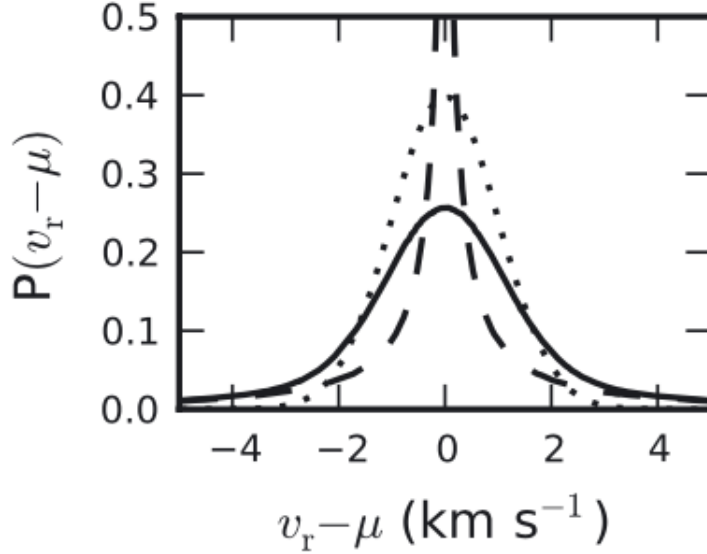


Figure 3.9: Probability distribution function for RV offset from the mean velocity (figure from Cottaar et al. (2012b)). The quantity $v_r - \mu$ is the offset of each RV from the mean cluster velocity. The three curves are the velocities draw from a Gaussian distribution with RV dispersion of 1 km s^{-1} (dotted line), the distribution of velocity offsets due to the orbital motions of the binaries (dashed line), and the RV distribution with dispersion of 1 km s^{-1} and a fraction of binaries of 100% (solid line).

et al. 2008, 2010), resulting in an inflated RV dispersion. I modeled the RV cluster distribution using a maximum likelihood technique developed by Cottaar et al. (2012b)³, where they determined the intrinsic RV distribution using a single epoch of RV data. Specifically, this technique fits the observed cluster RV distribution with a model that assumes a Gaussian intrinsic RV distribution which is broadened by the orbital motions of unresolved binary systems and by the uncertainties in the RV measurements. The distribution of the RV errors and the binary distribution are defined in Jackson et al. (2015) and Cottaar et al. (2012b), respectively. Single stars and the centers of mass of binaries are assumed to share the same intrinsic RV distribution. Figure 3.9 (from Cottaar et al. (2012b)) shows the effect of the binary motions on the probability distribution function in a single epoch dataset of RVs. The aim of the method developed by Cottaar et al. (2012b) is to find the characteristics of the intrinsic distribution (i.e., the dotted line in figure 3.9) knowing the properties of the binary distribution and the distribution of the RV uncertainties.

The likelihood of a star observed radial velocity, v_i , given its RV uncertainty

³Available online at <https://github.com/MichielCottaar/velbin>

($S_{RV,i}$, estimated using the equation 3.3) and an intrinsic RV distribution, is

$$\mathcal{L}_i(v_i) = (1 - f_{\text{bin}}) \cdot \mathcal{L}_{\text{sing}}(v_i, S_{RV,i}) + f_{\text{bin}} \cdot \mathcal{L}_{\text{bin}}(v_i, S_{RV,i}) \quad (3.4)$$

where f_{bin} is the binary fraction in a cluster, $\mathcal{L}_{\text{sing}}$ is the likelihood of single stars and $\mathcal{L}_{\text{bin}}$ is the likelihood of binary stars. Equation 3.4 is calculated for every star since the result is different and it depends mainly on the error measurement. The best-fitting model is found by varying the free parameters that describe the model of the intrinsic RV distribution over a grid of possible values and maximizing the summed logarithmic likelihood for all stars.

In order to calculate the likelihood of binary stars, it was necessary to adopt some assumptions on their properties. Since in many clusters the stars are mainly solar-type, I assumed that the properties of binary are those of the observed solar-type binaries in the solar neighborhood. Specifically, three binary parameters must be assumed: the period distribution, the secondary to primary mass ratio (q), and the binary eccentricities. The distribution of the binary periods is a log-normal with a mean of 5.03 and dispersion of 2.28 in $\log_{10}$ days (Raghavan et al. 2010). Instead, q is described by a power-law in the form $\frac{dN}{dq} \sim q^{0.25}$ for $0.1 < q < 1$ (Reggiani & Meyer 2013). Finally, the eccentricities have a flat distribution ($f(e)$) between 0 and the maximum value e_{max} defined as

$$e_{\text{max}} = \frac{1}{2} \left[0.95 + \tanh \left(0.6 \log_{10} \frac{P}{\text{days}} - 1.7 \right) \right] \quad (3.5)$$

where P is the binary period in days (from Parker & Goodwin 2009).

As described in section 3.1.3, the inclusive strategy of GES observations implies a presence of contamination by field stars. In clusters with age less than 100 Myr the majority of them are excluded following the method described in section 3.2.1, while in old clusters this is not possible. Therefore, using the GES data it is necessary to perform the fit of RV distribution considering the presence of two distinct populations: the cluster and the Galactic field. The two components are modeled with two Gaussian distributions. In the model the properties of field populations are free parameters without boundaries. An important assumption is that the stars belong either to the cluster or to the field and that the fraction of field stars is $f_{\text{field}} = 1 - f_{\text{clus}}$. The likelihood of observing a given RV is given by

$$\mathcal{L}_i = f_{\text{clus}} \cdot \mathcal{L}_{\text{clus},i} + (1 - f_{\text{clus}}) \cdot \mathcal{L}_{\text{field},i} \quad (3.6)$$

where $\mathcal{L}_{\text{clus}}$ and $\mathcal{L}_{\text{field}}$ are the likelihood calculated using equation 3.4. In the fitting model there are 5 free parameters: the central RV of the cluster, v_c , and field, v_f , the intrinsic velocity dispersion of cluster, σ_c , and field, σ_f , and the fraction of stars that belong to the cluster, $f_{\star, \text{clus}}$. The best-fit is given by the values of these parameters that maximize the summed logarithmic likelihood. Instead, in this work I assumed that the binary fraction is a fixed parameter.

A subsequent fundamental step is to estimate the probability of a star to belong to the cluster. Starting from the assumption of the adopted model, the probability of a cluster member, $p_c(v_r)$, to have $RV = v_r$ and the probability of a field star to have the same RV , $p_f(v_r)$, given the set of best-fit parameters can be derived as

$$p_{c,i}(v_r) = f_{clus} \frac{\mathcal{L}_{clus,i}}{\mathcal{L}_i} \quad p_{f,i}(v_r) = (1 - f_{clus}) \frac{\mathcal{L}_{field,i}}{\mathcal{L}_i} \quad (3.7)$$

where the terms are those defined in equation 3.6. Therefore, starting from these functions, the probability of a star to be a cluster member is given by

$$p_{cl,i}(v_r) = \frac{p_{c,i}(v_r)}{p_{c,i}(v_r) + p_{f,i}(v_r)}. \quad (3.8)$$

3.2.3 Cluster Mass and Radii Determination

The total mass and the half-mass radius of a cluster are fundamental quantities to determine the cluster dynamical state. The first step in the derivation of these properties is to calculate the mass of each star. Depending on the cluster age, two methods are proposed.

In young clusters ($t_{age} < 100$ Myr), after the selection of the spectroscopic candidate members described in section 3.2.1, the mass of each of them is derived by interpolating the PMS evolutionary tracks developed by Tognelli et al. (2011) at the positions in the HR diagram. In order to determine the star position in HRD, the effective temperature and bolometric luminosity, L_{bol} , of the stars are necessary. The first one is the T_{eff} measured from the GES spectra. The second one is derived using the literature magnitudes. The luminosity is estimated from the V magnitude (or the J magnitude when the former is not available). Using the reddening values ($E(B - V)$) available in the literature, the initial magnitude is corrected for extinction following the law of Savage & Mathis (1979). The extinction depends on the properties of the interstellar medium (ISM) and its effect strongly increases at shorter wavelengths. The correction for a specific passband x is given by $m_{0,x} = m_x - A_x$, where m_x is the apparent magnitude and A_x is the total extinction. In V and J band the A_V and A_J are given by

$$A_V = 3.12 E(B - V) \quad A_J = 0.87 E(B - V) \quad (3.9)$$

where the coefficient 3.12 and 0.87 are commonly written as R_V and R_J , respectively. The absolute magnitude M_x is derived using the classical formula

$$M_x = m_{0,x} + 5 - 5 \log_{10} d \quad (3.10)$$

where d is the distance of the cluster (in parsec). To derive the bolometric magnitude M_{bol} , a bolometric correction (in this work BC_V or BC_J , i.e., the correction that must be made to the absolute magnitude in a given band of an object in order

to convert it to its bolometric magnitude) is derived by interpolating the relations given in table A5 of Kenyon & Hartmann (1995) at the stellar effective temperature, since it depends on this quantity. Then, it is applied to the absolute star magnitude by

$$M_{bol} = M_x + BC_x. \quad (3.11)$$

Finally, adopting the cluster distance and a solar bolometric magnitude of $M_{\odot} = 4.74$, the bolometric magnitude is converted into L_{bol} using the formula

$$\frac{L_{bol}}{L_{\odot}} = 10^{-[(M_{bol}-4.74)/2.5]}. \quad (3.12)$$

In old clusters ($t_{age} \geq 100$ Myr) the estimate of the masses is based on the CMDs and the isochrones of Bressan et al. (2012). Since in the MS phase the trend in the isochrone of both magnitude and color index is monotonic, knowing the magnitude of each star, it is possible to derive the mass given the magnitude-mass relation defined by the model. The PARSEC isochrone is retrieved using the cluster age and cluster metallicity from the literature. The absolute magnitude (V) and the color index (B – V or V – I) defined by this isochrone are modified to the apparent values using the cluster distance and the reddening, that are retrieved from literature works, as well. Then, for the stars in MS phase the mass is derived with a linear interpolation of the stars apparent magnitude in the magnitude-mass relation defined by this isochrone. In these clusters also stars in post-MS phase are present, mainly in RC (see section 3.1.3). For these objects the assumption is that their mass is the same one of the stars at TO point.

After the determination of the individual masses, the total mass of the cluster (M_{tot}) is determined as follows. The method can be divided in several steps.

- The stars within the GES magnitude range are considered and the corresponding mass (M_{obs}) is obtained by adding up all star masses in the sample. Two methods are proposed to derive this quantity: (i) considering only the stars with a probability of being a member greater than 0.8, and (ii) considering all stars and weighing the mass for their corresponding p_{cl} .
- The following step is to divide M_{obs} by the level of completeness of the observations. This factor takes into account the fraction of cluster members within the magnitude range and within the area covered by the observations that have not been observed for technical reasons, e.g., the impossibility of allocating the fibers. This is due to the high number of candidate members in the area of the observations and/or conflicts with fiber allocation (see for example the figure 3.4). In this work, the level of completeness within the observed magnitude range is calculated by dividing the number of the observed stars by the number of stars selected as initial candidate targets in GES (section 3.1.3) and located within a circular region, with the assumptions that

this region contains the whole cluster and that the initial sample of targets is complete. In young OCs a unique level of completeness is derived, while in old OCs there are a level of completeness for stars in MS phase and another one for stars in post-MS phases (i.e., SGB, RGB, and RC stars), because the targets observed in these two areas of the CMDs have different times of phase evolution. Indeed, in OCs the phases of post-MS, such as RC phase, are really rapid respect to the MS phase, therefore, in most cases, only several stars lie in these regions of the CMD and the observation of the majority of the likely members selected as targets is possible. For this reason the level of completeness is different from that derived for the stars in MS. Therefore, in the case of old OCs, the corrected M_{obs} is derived as the mass of the stars below the TO point corrected by the MS completeness.

- After this, I multiplied M_{obs} (corrected for the completeness) by a factor of 1.25, which takes into account the presence of binaries, under the assumption of a 50% binary fraction and a mass ratio q with a flat distribution.
- The last step is to multiply this corrected M_{obs} by another important factor that takes into account the fraction of the cluster mass in stars outside the magnitude range of GES observations. This factor is calculated analytically, using the assumption that the mass function of the clusters follows a multi-power-law behavior described in Kroupa (2001) (see section 1.2.2) between $0.01 M_{\odot}$ and the mass of the most massive cluster star. However, as shown in figure 1.3, this is only an approximation of the real PDMF, especially in clusters with age greater than 100 Myr. Therefore, the total cluster mass derived using this mass function is an upper limit of the real value, since in the low mass regime the cluster mass might be overestimated. Indeed, an assumption is that in the low-mass region (mass $\lesssim 0.2 - 0.3 M_{\odot}$) the dispersion of cluster members due to the evolution of the system is negligible.

Depending on cluster age, a different mass extrapolation is performed. In young OCs several high-mass stars are still present in MS since the star evolution is at the early phases. However, the upper magnitude limit of GES does not allow the observations of these very massive stars as well as the stars with a magnitude under the fainter GES magnitude limit. Therefore, the total mass outside the GES magnitude range is extrapolated in the low-mass regime (between $0.01 M_{\odot}$ and the lower mass star observed by GES) and in the high-mass one (between the highest mass star observed by GES and the most massive star retrieved by the literature). In old OCs the members have had enough time to evolve and high-mass stars are already in the post-MS phases and the GES magnitude limits include them. Therefore, in these clusters the high-mass population is observed by GES and only the cluster mass in the low mass regime is extrapolated.

In order to find M_{tot} , in both cases the extrapolated cluster masses are added

to the M_{obs} . As described above, in old clusters several stars are outside the MS phase (particularly in the RC), which are not taken into account in the derivation of M_{obs} . Therefore, the mass observed in the post-MS phases (i.e., the total mass of stars observed in the SGB, RGB, and RC), which is corrected for the post-MS completeness and the presence of binaries, is simply added to M_{tot} .

To study the dynamical properties of the clusters, I also estimated the half-mass radius (r_{hm}). The r_{hm} is defined as the radius that contains half of the observed mass. This radius is critically dependent on the presence of mass segregation in the clusters. Indeed, r_{hm} decreases with an increasing level of mass segregation. While in old clusters the GES observations are able to include all the high-mass stars of the system, in young OCs the GES magnitude range does not allow the observation of very bright (and massive) stars, as described previously. Therefore, in these systems it is difficult to account for the presence of mass segregation only with the GES data. Recently, several young clusters have been investigated by Gaia Collaboration et al. (2017), who used the Tycho-*Gaia* Astrometric Solution (TGAS) subset of the first *Gaia* data release (DR1, Gaia Collaboration et al. 2016b,a), and by Gaia Collaboration et al. (2018a), who used the second *Gaia* data release (DR2, Gaia Collaboration et al. 2018d), to derive cluster membership, mean parallaxes, and proper motion values. In this work I used the data provided by G17. In particular, in the TGAS sample there are most of the brightest stars of each cluster and the observations are spatially complete. Using the stars identified as members by G17 within the same circular regions assumed in GES observation plus the cluster members present in the literature outside the Gaia magnitude range (stars with $V \lesssim 6$, very high-mass stars), when they are available, it is possible to correctly take into account the presence of mass segregation in young clusters observed with GES. In these OCs the r_{hm} is defined as the radius that contains half of the mass given by the sum of masses of TGAS and literature stars.

Chapter 4

Young Open Clusters

In this Chapter, I will show the results obtained for a sample of four young OCs using the Gaia-ESO Survey products and the methods described in the previous Chapter. I studied the young open clusters IC 2602, IC 2391, IC 4665, and NGC 2547, which are composed principally by PMS stars. At the end of this Chapter, I will discuss the implication of the results on the models of early cluster dissipation. The results of this part of Ph.D. work are described in Bravi et al. (2018).

4.1 Sample of Clusters

The four clusters have similar ages (from ~ 20 Myr to ~ 50 Myr) and different distances. IC 2602 and IC 2391 are among the closest clusters to the Sun (distance ~ 150 pc), while the other two clusters are more distant (~ 365 pc). Given the uniform magnitude limit for the observations of clusters in GES, stars with different mass limits in the different clusters are reached (see the next section). The cluster properties are summarized in Table 4.1, where distances, ages, and reddening values are from Randich et al. (2018). Each cluster has been subject to a variety of studies carried out to identify the stellar population based on combinations of X-ray data (e.g., Prosser 1993; Randich et al. 1995; Patten & Simon 1996; Martin & Montes 1997; Jeffries & Tolley 1998), optical photometry (e.g., Prosser et al. 1996; Jeffries et al. 2004), and optical spectroscopy (e.g., Randich et al. 1997; Stauffer et al. 1997; Barrado y Navascués et al. 1999; Jeffries et al. 2000; Jeffries & Oliveira 2005; Platais et al. 2007; Manzi et al. 2008; Jeffries et al. 2009a); many high- and low-mass cluster members have been identified using the position in the HR diagram, presence of the lithium absorption line at 6708 Å, and RVs. These studies show that the number of previously known spectroscopically confirmed members in the four clusters range from 40 in IC 4665 to 75 in NGC 2547. In the case of NGC 2547, Sacco et al. (2015) found a secondary population that is kinematically distinct from the main cluster population.

Table 4.1: Properties of young clusters.

Cluster	RA (J2000)	DEC (J2000)	Distance (pc)	Age (Myr)	E(B-V)
IC 2602	10h 40m 48s	-64d 24m 00s	$148.0^{+7.3}_{-6.1}$	$43.7^{+4.3}_{-3.9}$	0.068 ± 0.025
IC 2391	08h 40m 32s	-53d 02m 00s	$146.0^{+7.1}_{-6.1}$	$51.3^{+5.0}_{-4.5}$	0.088 ± 0.027
IC 4665	17h 46m 18s	+05d 43m 00s	$366.0^{+46.8}_{-37.9}$	$23.2^{+3.5}_{-3.1}$	0.226 ± 0.080
NGC 2547	08h 10m 00s	-49d 12m 00s	$364.0^{+46.8}_{-37.9}$	$37.7^{+5.7}_{-4.8}$	0.080 ± 0.024

4.2 Data and Allocated Targets

For these four young clusters I used the data from the fourth internal data release (GESviDR4). In this release the values of $v \sin i$ are not available and, therefore, I used the measurements given by WG12. In a number of cases, the recommended values of EW(Li) and T_{eff} from the final homogenization process were not provided. In some of these cases we use the EW(Li) and T_{eff} derived by the nodes of WG12. This choice is justified by the fact that the values measured by different nodes are in agreement, within the errors, with those recommended by WG12, when they are

Table 4.2: Number of targets observed in the four clusters.

Name	Setup	Number stars	Number T_{eff}	Number γ index	Number $\log g$	Number EW(Li)	Number RV
IC2602	HR15N	1528	1483	1481	729	1374	1528
	U 580	42	42	-	42	25	41
	U 520	7	7	-	7	-	6
	Tot.	1577	1532	1481	778	1399	1575
IC2391	HR15N	403	385	378	180	386	402
	U 580	20	20	-	20	13	20
	U 520	8	8	-	8	-	7
	Tot.	431	413	378	208	399	429
IC4665	HR15N	545	527	520	258	503	546
	U 580	22	21	-	21	19	21
	U 520	-	-	-	-	-	-
	Tot.	567	548	520	279	522	567
NGC2547	HR15N	450	399	383	149	385	450
	U 580	5	5	-	5	3	5
	U 520	19	18	-	18	-	13
	Tot.	474	422	383	172	388	468

Notes. The table shows the number of targets with available values of the different recommended stellar parameters (in the case of EW(Li) or T_{eff} also from the nodes).

available.

As described in 3.1.3, in each cluster a list of initial targets is created. Then, the targets are allocated depending on their priority. In the case of IC 2602 ESO archival data have also been retrieved and analyzed. In order to be consistent with the *Gaia*-ESO selection method, I considered only the archive data for stars that are in the strip of the CMD used for the GES selection. Table 4.2 summarizes the number of targets observed in each cluster. I list the number of stars observed with the different GIRAFFE and UVES setups, as well as the number of targets for which stellar parameters were derived.

In figures 4.1, 4.2, and 4.3 I show the spatial distribution of the stars selected as initial candidate members by GES (small blue crosses) and the stars effectively allocated in the observations (red points) for IC 2391, IC 4665, and NGC 2547, respectively (for cluster IC 2602 the figure is shown in section 3.1.3). The allocated targets of IC 4665 and NGC 2547 are uniformly distributed in the whole area of cluster. Instead, for IC 2602 and IC 2391, the stars observed by GES cover only a section of the cluster area. This is related to the closer distance of these two clusters, that does not allow to observe a large fraction of the initial selected targets uniformly, also using several OBs. This must be taken into account in the derivation of the observation completeness, that is described in the next section.

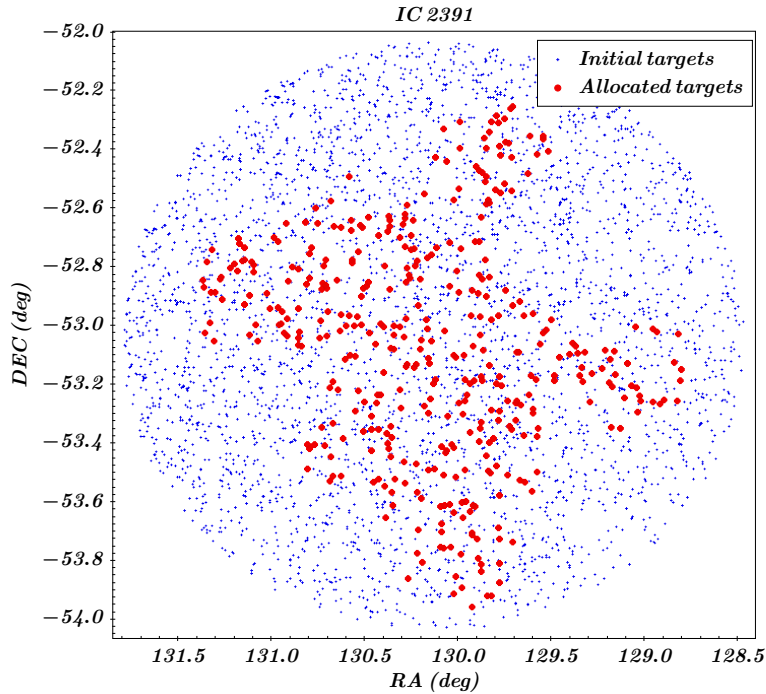


Figure 4.1: Spatial distribution of GES initial targets and allocated stars in cluster IC 2391. The small blue crosses are the initial candidate targets, while the red points are the stars effectively observed by GES.

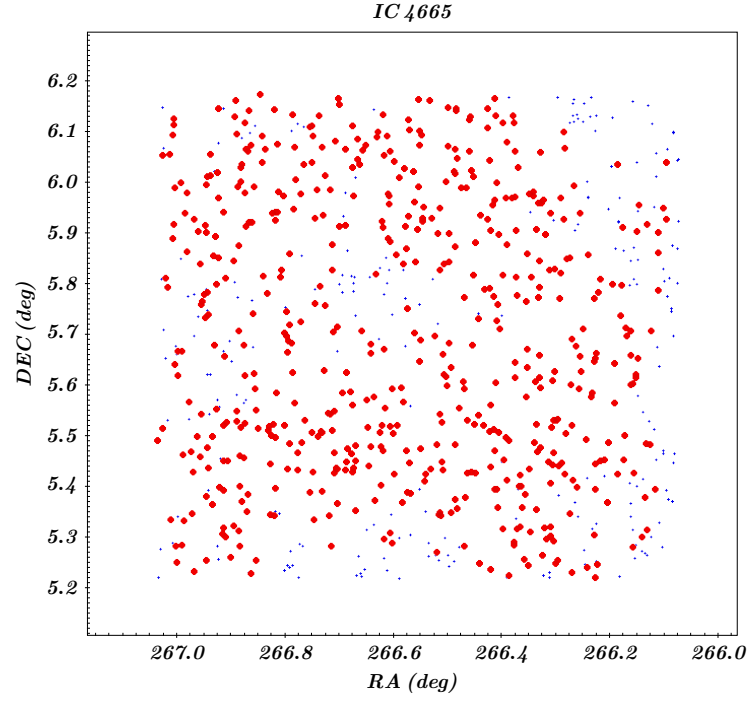


Figure 4.2: Spatial distribution of GES initial targets and allocated stars in cluster IC 4665. The symbols are the same of the figure 4.1.

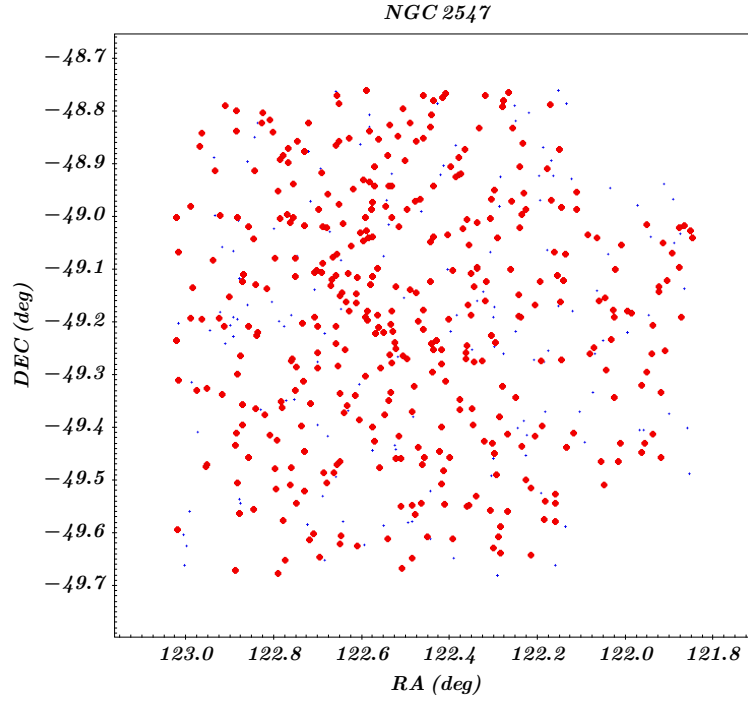


Figure 4.3: Spatial distribution of GES initial targets and allocated stars in cluster NGC 2547. The symbols are the same of the figure 4.1.

4.2.1 Completeness

As discussed in section 3.1.3, the initial targets were selected in order to be complete within the magnitude range of GES and within the area that contains all the stars selected as initial candidate targets, which is defined by the radius R_{GES} . Following the method described in section 3.2.3, I obtained a $\sim 25\%$ level of completeness for IC 2602 and IC 2391, while for IC 4665 and NGC 2547 I derived a mean level of completeness of $\sim 65\%$ and $\sim 75\%$, respectively. The level of completeness of IC 2602 and IC 2391 is much lower because only a part of the area of the sky including the initial candidate targets has been observed (see figures 3.4 and 4.1), as described previously. Figure 4.4 shows the level of completeness in bin of J magnitude of each cluster. The magnitude limits of completeness depend on the cluster. In table 4.3 I list the magnitude limit used to derive the completeness, the radius R_{GES} in parsec, and the level of completeness obtained in each cluster.

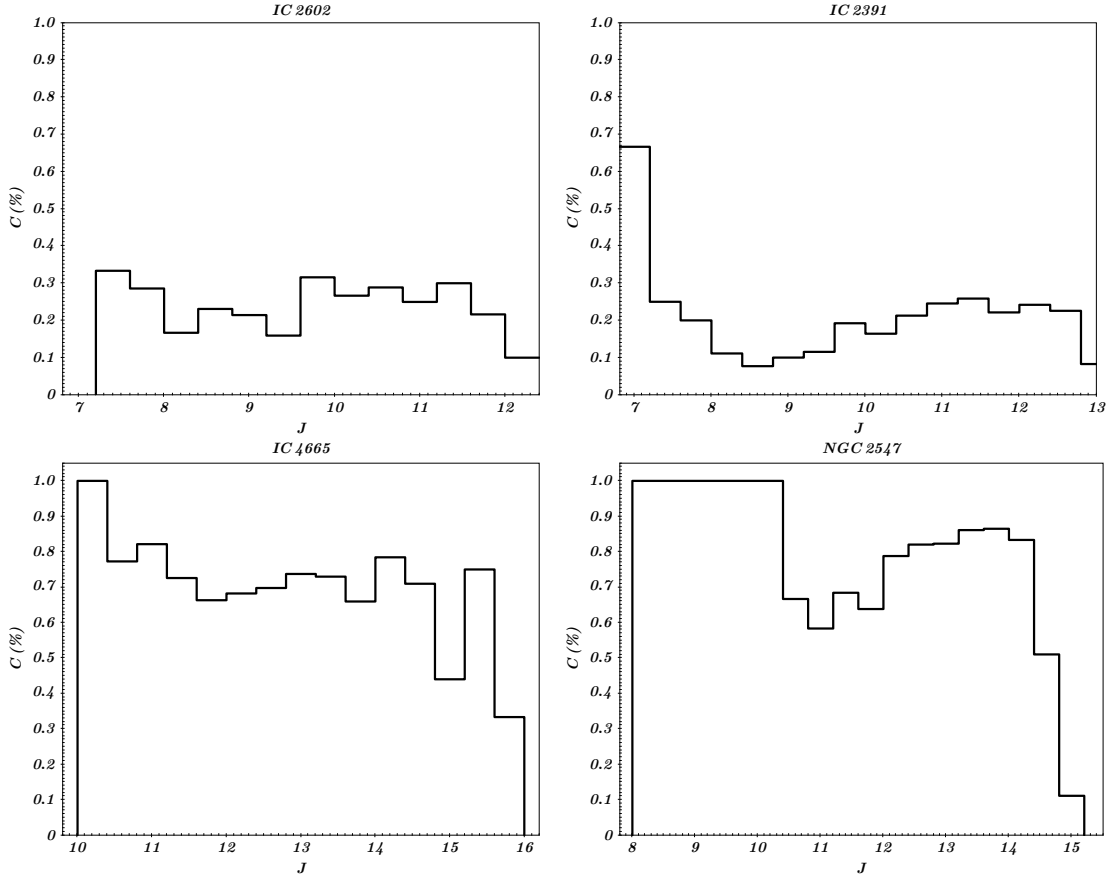


Figure 4.4: Completeness of GES observations in each cluster. The upper left plots show the completeness of IC 2602, while the right one the completeness of IC 2391. The bottom plots display the completeness of IC 4665 (left) and NGC 2547 (right). The magnitude limits depend on the cluster.

Table 4.3: J magnitude range, radius of GES observations, and completeness of the four clusters.

Cluster	J Magnitude range completeness	R _{GES} (pc)	Completeness (%)
IC 2602	6.8 – 12.0	4.13	~ 25
IC 2391	7.0 – 12.8	2.55	~ 25
IC 4665	10.0 – 16.0	4.47	~ 65
NGC 2547	8.0 – 15.5	3.18	~ 75

4.3 Selection of Spectroscopic Candidates

Starting from the initial sample of observed cluster targets, I was able to exclude stars that do not belong to the clusters. As described in section 3.2.1, I used three independent spectroscopic criteria based on the gravity index γ (or $\log g$ for

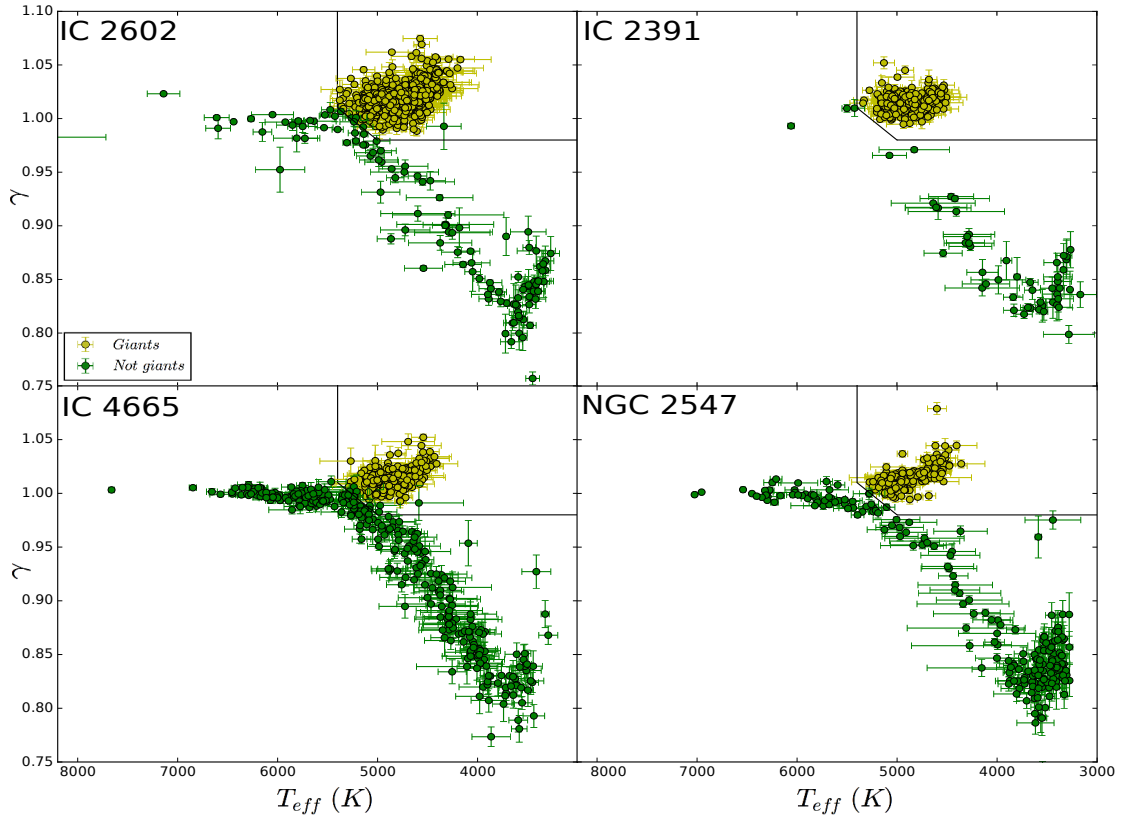


Figure 4.5: Gravity index γ as a function of the stellar effective temperature T_{eff} for the stars observed with GIRAFFE. The yellow filled dots are the stars identified as giants, while the remaining stars are shown as green filled dots. The black line indicates the threshold used to separate the giants and the non-giants.

UVES spectra), the $\text{EW}(\text{Li})$, and the metallicity $[\text{Fe}/\text{H}]$. All stars where any of the first two parameters or the effective temperature were not measured have been excluded. I retained stars without the metallicity measurement since very few stars were discarded on the basis of this parameter.

As a first step, I excluded from the sample of candidate members the background giants using the gravity indicators. Figure 4.5 shows γ as a function of the effective temperature for the GIRAFFE stars. I considered as giants all the stars within the region defined by the black line. From this figure the separation between the high gravity PMS stars of these young clusters and the low gravity background giants is evident.

Then, I used the $\text{EW}(\text{Li})$ to exclude dwarf non-members from the sample of stars remaining from the first selection step. In figure 4.6 I show the $\text{EW}(\text{Li})$ as a function

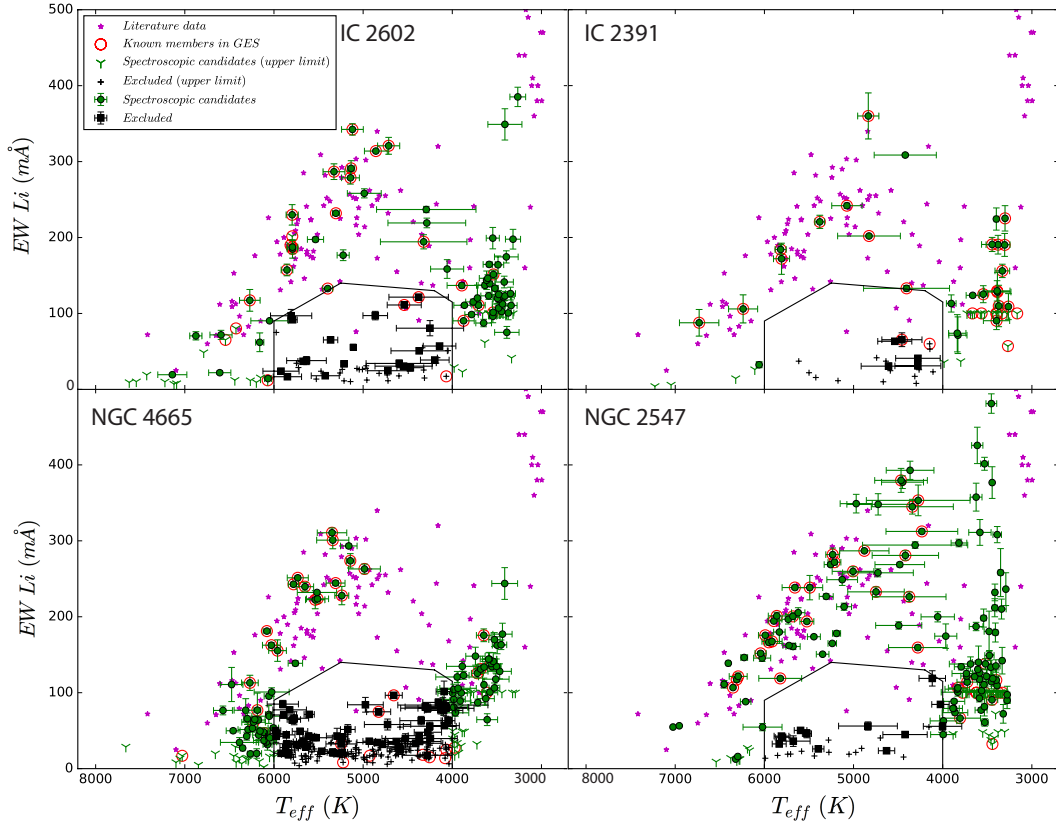


Figure 4.6: Equivalent width of the lithium line as a function of T_{eff} . The purple stars are the known members of the four clusters used to trace the lower envelope of the bulk of cluster spectroscopic candidates (solid line), as given in the literature. The open red circles show the members of each cluster that were reported in the literature and observed again by GES. The green symbols mark the stars selected as spectroscopic candidates. The stars excluded by the lithium criterion are shown in black. We also highlight the sources with an estimate of $\text{EW}(\text{Li})$ (dots and squares) or only an upper limit (arrows and crosses).

of T_{eff} for the four clusters. As described in section 3.2.1, I classified as secure non-members all the stars below the threshold indicated with a continuous black line between 4000 K and 6000 K (identified by the black symbols in figure 4.6). All the other stars are selected as candidate members (green symbols). As mentioned, the threshold was defined using previous observations of these four clusters available in the literature (Martin & Montes 1997; Randich et al. 1997, 2001; Jeffries et al. 2003; Jeffries & Oliveira 2005; Jeffries et al. 2009a), that are displayed with the purple stars in the plots.

As last step, I excluded targets with a measured $[\text{Fe}/\text{H}] < -0.5$ dex that would be incompatible with the nearly solar metallicity of these clusters (Spina et al. 2017).

To summarize, I retained from the criteria 101, 53, 121, and 187 stars for IC 2602, IC 2391, IC 4665, and NGC 2547, respectively. I defined these stars as “spectroscopic candidates”. Given the different target selection strategy used for UVES targets, I also considered as spectroscopic candidate UVES stars without T_{eff} , γ , RVs and/or EW(Li) that are known members from the literature.

4.4 Kinematic Analysis

Using the stars selected as spectroscopic candidates from the analysis in the previous section, I studied the kinematic properties of the cluster sample. I calculated the empirical errors on RV of the GIRAFFE stars with the method described in section 3.2.2.1 and then I derived the intrinsic RV dispersion, σ_c , for each cluster. The maximum likelihood technique is described in section 3.2.2.2. As mentioned, the analysis in section 4.3 excludes the obvious non-members and the sample of spectroscopic candidates will not be entirely clean of contaminating field stars. Hence, I modeled the RV distribution with two Gaussian distribution, one for the cluster population and one for the field, while in the case of NGC 2547 I performed the fit with three distinct populations to take into account the presence of the population *B* of young stars in the Vela OB2 associations found by Sacco et al. (2015).

Since the uncertainties on the RV measurements have been empirically calculated only for the GIRAFFE targets, I excluded the UVES targets from the fits. For all clusters, I modeled only the stars with RV within the range $-90 \leq \text{RV} \leq 90$ km s⁻¹.

Finally, starting from the assumptions of the models, using the RVs of the spectroscopic candidates and equation 3.8, I estimated the probability p_{cl} that each of these spectroscopic candidates is a true member. In each cluster I found many new high-probability members and confirmed many of those known in the literature. New high-probability members are extended across the whole area covered by GES observations, suggesting that these clusters could be more extended than previously thought.

4.4.1 Effect of Binary Systems

As described in Chapter 3, the maximum likelihood technique developed by Cottaar et al. (2012b) allows us to consider the effects of non-single stars on the RV dispersion. The presence of a high number of unresolved binaries in the sample leads to an inflated RV dispersion. How the binary motions affect the RV dispersion depends on the cluster characteristics and the binary population properties (e.g., Kouwenhoven & de Grijs 2008), and this could introduce uncertainties in the estimate of the dynamical mass using the equation 1.6 (e.g., Seleznev et al. 2017). In particular, Kouwenhoven & de Grijs (2008) found that binaries are really relevant in clusters with low stellar density (~ 0.1 stars pc^{-3}), since the binary orbital motions dominate the velocity dispersion. In clusters with density between 0.1 and 10^7 stars pc^{-3} the effect of the binaries in the cluster velocity dispersion is still important and the amount of such effect depends on the properties of binary population. Finally, they found that in high dense clusters ($\gtrsim 10^7$ stars pc^{-3}) the velocity dispersion is large and the contribution on it of the binaries is not relevant.

Table 4.4: Best parameters from the fits of the RV distributions.

Cluster	f_{bin} (%)	v_c (km s^{-1})	σ_c (km s^{-1})
IC 2602	0.0	17.63 ± 0.19	0.80 ± 0.47
IC 2602	0.2	17.65 ± 0.18	0.75 ± 0.40
IC 2602	0.5	17.63 ± 0.16	0.60 ± 0.20
IC 2602	0.8	17.60 ± 0.16	0.45 ± 0.20
IC 2602	1.0	17.58 ± 0.16	0.33 ± 0.29
IC 2391	0.0	14.85 ± 0.17	0.67 ± 0.18
IC 2391	0.2	15.04 ± 0.19	0.65 ± 0.19
IC 2391	0.5	14.98 ± 0.17	0.53 ± 0.17
IC 2391	0.8	15.02 ± 0.18	0.43 ± 0.18
IC 2391	1.0	14.95 ± 0.20	0.33 ± 0.24
IC 4665	0.0	-13.65 ± 0.18	-
IC 4665	0.2	-13.83 ± 0.16	-
IC 4665	0.5	-13.64 ± 0.21	< 0.5
IC 4665	0.8	-13.69 ± 0.21	-
IC 4665	1.0	-13.72 ± 0.17	-
NGC 2547	0.0	12.54 ± 0.11	0.87 ± 0.11
NGC 2547	0.2	12.79 ± 0.10	0.79 ± 0.11
NGC 2547	0.5	12.80 ± 0.09	0.63 ± 0.09
NGC 2547	0.8	12.81 ± 0.09	0.51 ± 0.11
NGC 2547	1.0	12.77 ± 0.09	0.37 ± 0.13

However, using the method described in section 3.2.2.2, the presence of the binaries in the RV distribution can be taken into account hence deriving the intrinsic RV distribution. I performed several fits for each cluster, with the fraction of the binaries (f_{bin}) fixed at several different values: 0, 0.2, 0.5, 0.8, and 1.0. Table 4.4 shows the results of the fits for all the clusters, where the central velocity v_c and the intrinsic velocity dispersion σ_c for the different values of f_{bin} are reported. In the table the effects of the binaries on the velocity distribution are clearly shown. Indeed, the value of the derived intrinsic RV dispersion decreases with an increasing level of f_{bin} since the contribution of the binary systems to the RV distribution becomes more important when the fraction is large. Moreover, one can note that the intrinsic velocity dispersion obtained without binaries is on average a factor ~ 2 greater than that estimated with a binary fraction of 100%. Therefore, this is a confirmation of the importance of binary systems in the cluster velocity distribution. Furthermore, this discrepancy is consistent with the theoretical results obtained by

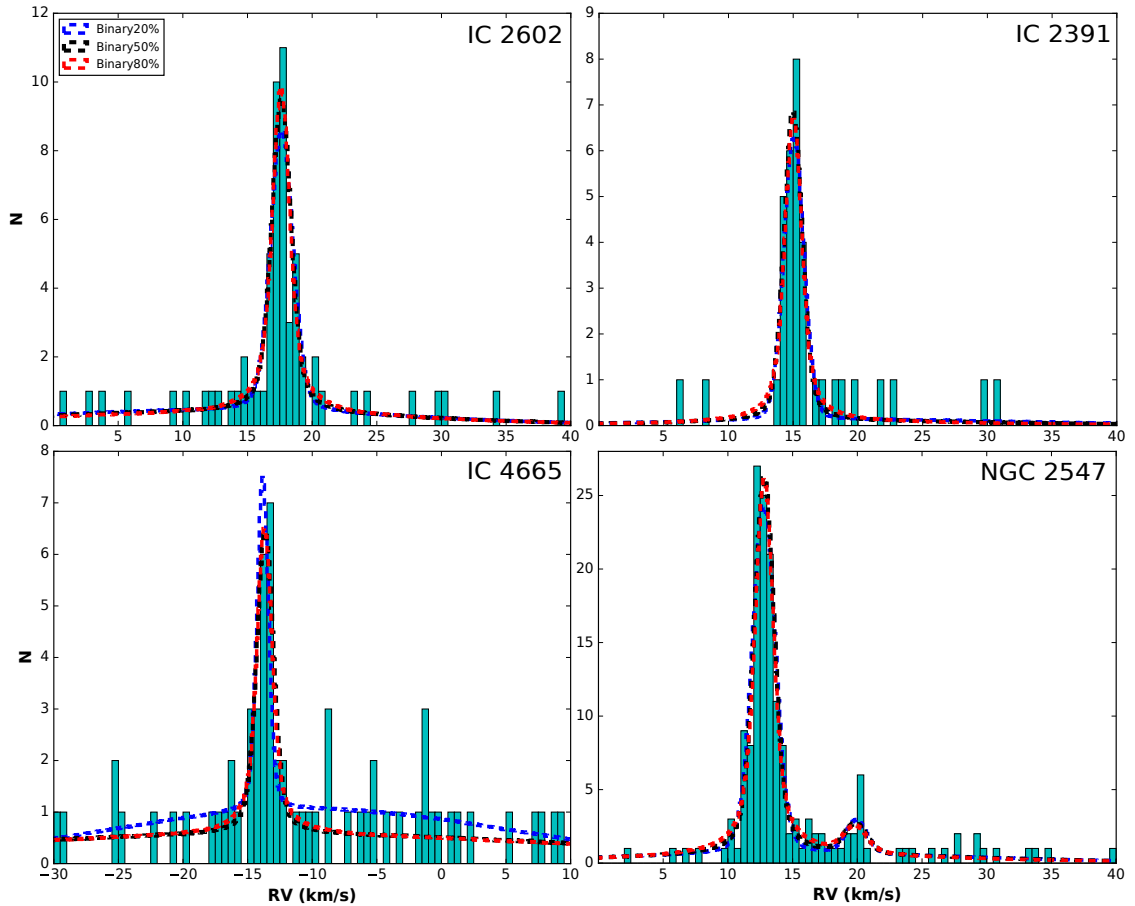


Figure 4.7: Radial velocity distribution of the sample of young clusters. The blue, black, and red dashed lines represent the fits performed by setting the binary fraction to 0.2, 0.5, and 0.8, respectively.

Kouwenhoven & de Grijs (2008) for OCs with a stellar density typical of the systems studied in this work, which have a density between 0.1 and 10^7 stars pc^{-3} , and with the typical velocity dispersions derived in this section.

In the context of this work, the results obtained for f_{bin} of 0 and 1.0 are extreme cases that are not probable in a real cluster, while a more realistic value of the fraction of binaries is between 0.2 and 0.8. Furthermore, the results in table 4.4 show that both v_c and σ_c derived for a binary fraction of 0.2 and 0.8 are within the error bounds of the best values obtained for a fraction of 0.5 (within 1σ for IC 2602 and IC 2391 and $\sim 2\sigma$ for NGC 2547). Finally, several works (e.g., Raghavan et al. 2010; Jeffries et al. 2014) found that f_{bin} of the observed solar-type binaries in the solar neighborhood is $\sim 46\%$; since I assumed that the properties of binary are the same of this kind of stars, I adopted the results obtained with a binary fraction set to 0.5 as the best values for the rest of the subsequent analysis. However, multi-

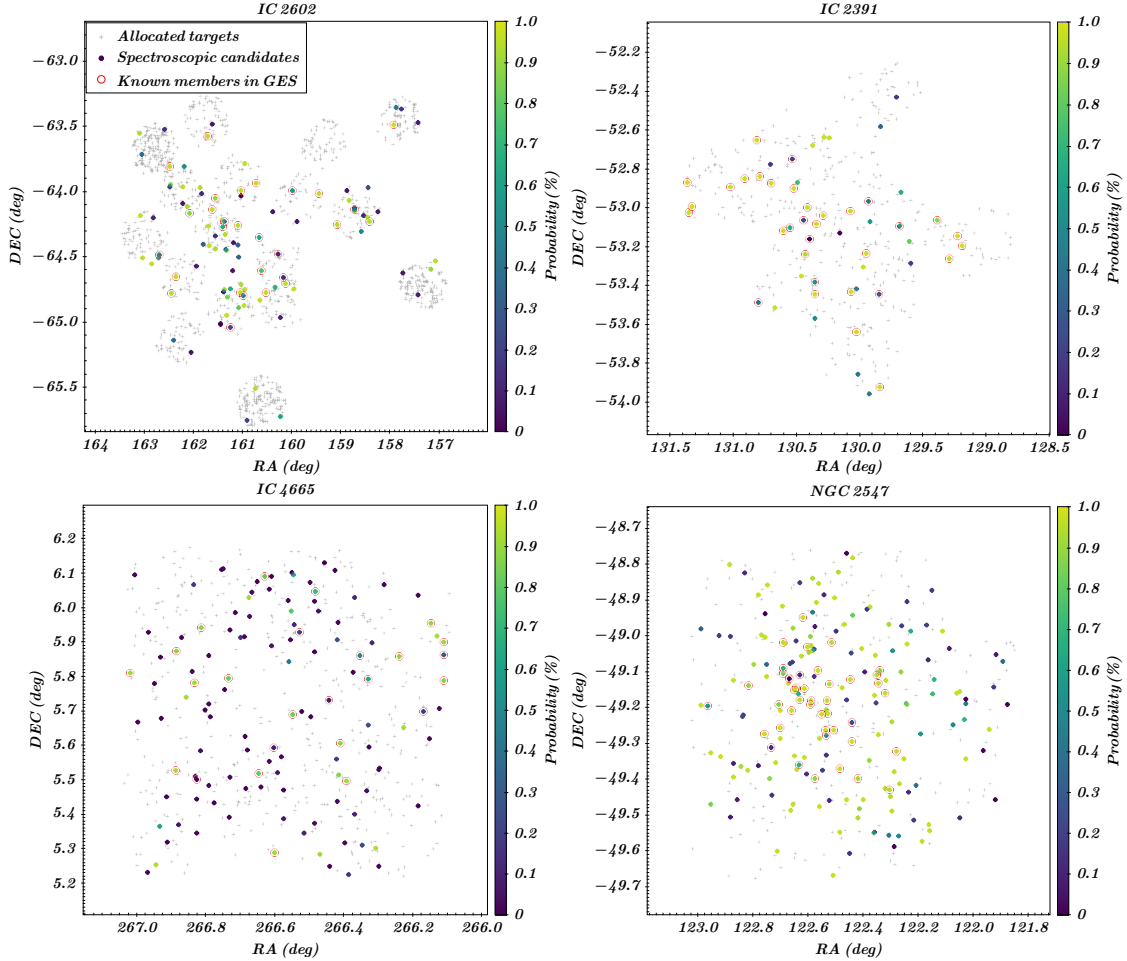


Figure 4.8: Spatial distribution of allocated targets (grey crosses), known members from the literature (red circles), and candidate members weighted for the corresponding probability (colored dots) in the four clusters.

epoch observations will be needed to determine the real fraction of binaries in these clusters.

Since the intrinsic RV dispersion for IC4665 is too low to be resolved with the GES data, I was able only to estimate an upper limit of $\sim 0.5 \text{ km s}^{-1}$, which is slightly larger than the typical error of the RV measurements ($\sim 0.3 \text{ km s}^{-1}$). The central RV estimates are in agreement with the values found by previous works for IC 2602 and IC 2391 (Marsden et al. 2009), for IC 4665 (Jeffries et al. 2009a), and for NGC 2547 (Sacco et al. 2015). In figure 4.7 the RV distributions and the fits obtained with f_{bin} fixed to 0.2, 0.5, and 0.8 of each cluster are shown.

Figure 4.8 shows the spatial distributions of the spectroscopic candidates weighted for their corresponding probability, using the results obtained with a binary fraction fixed to 50%, where the known members in literature are highlighted with the red circles.

4.4.2 Assumptions on Binary Properties and Robustness of Fits

The model assumes that the properties of binaries are distributed as for solar mass stars in the solar neighborhood. However, as discussed by Burgasser et al. (2007); Raghavan et al. (2010) and Duchêne & Kraus (2013), binary properties probably change as a function of the stellar mass or may depend on the dynamical evolution of the star-forming region where they have been formed (e.g., Marks et al. 2011). Therefore, I performed several tests in order to investigate how the results depend on the assumed binary properties. Specifically, I calculated the best fit values assuming *a*) a mean binary period a factor of five lower and higher than that found for solar mass stars by Raghavan et al. (2010); *b*) a distribution of eccentricities in the form $f(e) \sim e^2$ between 0 and e_{max} , instead of a flat distribution; and *c*) a flat distribution for the mass ratio q rather than the power law defined by Reggiani & Meyer (2013). In the case of mass ratio q , for the test I used the flat distribution since it is strongly supported by observational evidence (e.g., Mermilliod & Mayor 1999; Patience et al. 2002; Bender & Simon 2008; Duchêne & Kraus 2013, for a review). Other distributions have been proposed in the literature, for example the random pairing distribution, where the lowest mass is randomly drawn from the

Table 4.5: Robustness of the fits assuming different conditions of the binary properties.

Cluster	σ_c (km s^{-1})	$\sigma_{\log P = 4.33 \text{ days}}$ (km s^{-1})	$\sigma_{\log P = 5.73 \text{ days}}$ (km s^{-1})	$\sigma_{f(e) \sim e^2}$ (km s^{-1})	$\sigma_{\frac{dN}{dq} = \text{flat}}$ (km s^{-1})
IC 2602	0.60 ± 0.20	0.61 ± 0.22	0.60 ± 0.21	0.62 ± 0.21	0.62 ± 0.24
IC 2391	0.53 ± 0.17	0.51 ± 0.16	0.53 ± 0.18	0.49 ± 0.16	0.54 ± 0.17
NGC 2547	0.63 ± 0.09	0.62 ± 0.09	0.61 ± 0.09	0.64 ± 0.09	0.66 ± 0.10

mass distribution (e.g., Kroupa 1995). However, the random pairing distribution has been ruled out both theoretically and observationally (Kouwenhoven et al. 2005, 2007a,b; Kobulnicky & Fryer 2007; Metchev et al. 2008; Kouwenhoven et al. 2009). The results of these tests, reported in table 4.5, show that the assumptions of the binary properties adopted in this work do not strongly affect the final results. This is evident from figure 4.9, where for the three clusters the different intrinsic velocity dispersions with the 1σ errors are plotted. In each cluster the values obtained from the fits with different binary properties are in good agreement. Since I estimated an upper limit on the σ_c of IC 4665, I did not consider this cluster in these tests.

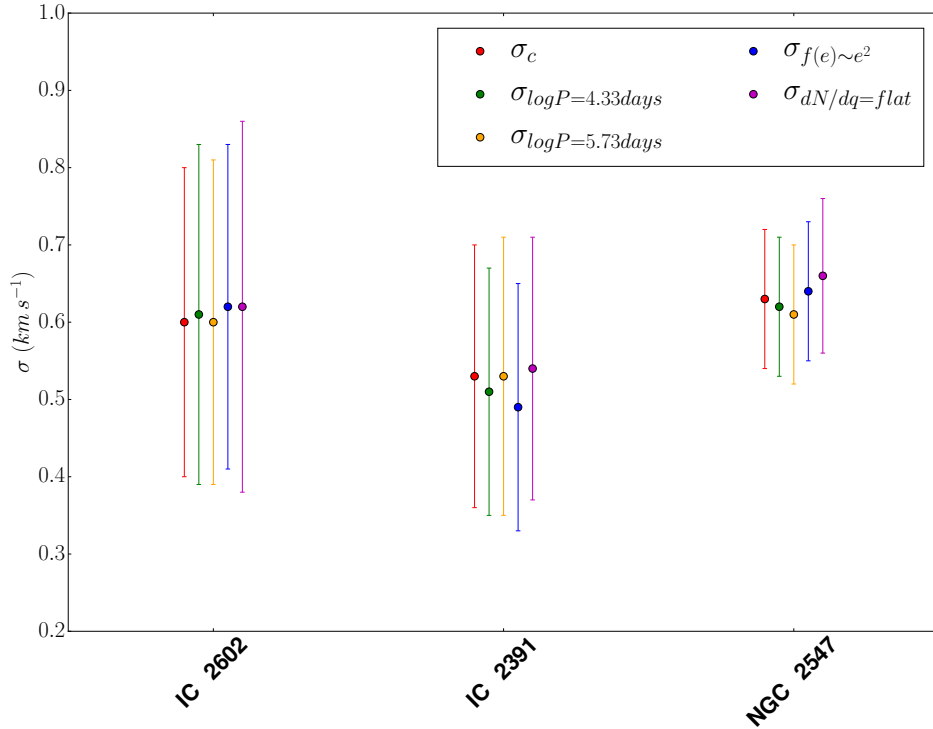


Figure 4.9: Radial velocity distribution of the sample of young clusters. The blue, black, and red dashed lines represent the fits performed by setting the binary fraction to 0.2, 0.5, and 0.8, respectively.

4.5 Velocity Dispersion from TGAS Data¹

The clusters studied in this work have been investigated by Gaia Collaboration et al. (2017) (hereafter G17), who used the Tycho-*Gaia* Astrometric Solution (TGAS) subset of the first *Gaia* data release (DR1, Gaia Collaboration et al. 2016a,b) to derive cluster memberships, mean parallaxes, and proper motion values.

¹This part of work has been performed mainly by the PhD student Eleonora Zari and the group based in Leiden, and it is a part of the published paper “*The Gaia-ESO Survey: a kinematical and dynamical study of four young open clusters*”, Bravi L., Zari E., et al. 2018, A&A, 615, 37.

There is not much overlap between the TGAS (stars brighter than about magnitude $V = 11.5$) and GES samples. On the one hand, this can be considered a limitation (e.g., we have RVs for the GES stars, but we lack astrometry, and vice versa); on the other hand, it can also be seen as an opportunity to derive certain cluster properties in an independent way. We focus on the velocity dispersion of the four clusters, and on the comparison of the values obtained using the two samples.

To derive the velocity dispersion using the TGAS data, we apply the maximum likelihood procedure described in Lindegren et al. (2000) (hereafter L00), in particular in their Appendix A.4, to the stars selected as members by G17². Assuming that all the stars in a moving group share the same space velocity with a low isotropic internal velocity dispersion, L00 determine the group centroid space motion, the internal velocity dispersion, and the individual parallaxes for all members. The observables used by L00 are parallaxes and proper motions, which are modeled as random variables with a probability density function (PDF) that depends on the model parameters: the cluster centroid space motion v_0 , the velocity dispersion σ_v , and the n parallaxes of the n stars ϖ . They also assume that the observations are independent and unbiased.

The likelihood function is the product of the single PDFs of all the stars. The method requires that the model provide a statistically corrected description of the data. In particular, it must be applied to actual members of the cluster or to the sources whose space motion agrees with the model. Outliers can be detected by computing a suitable goodness of fit statistic for each star in the solution. Lindegren et al. (2000) named this quantity g_i for each star with index i (with $i = 1, \dots, n$), and find that g_i approximately follows a χ^2 distribution. Therefore, for a given significance level, the star should be considered a kinematic outlier if $g_i > g_{lim}$. For example, a 1% significance level requires $g_{lim} \sim 14$. The outlier rejection procedure is iterative: at each step the star with the highest g_i is rejected from the sample. A new solution is then computed, including new g_i values. The process is repeated until all $g_i < g_{lim}$. Unfortunately, the internal velocity dispersion σ_v is strongly underestimated by this method. The bias in the σ_v estimate is probably related to the fact that an isotropic velocity dispersion is assumed for the cluster, while in practice only one component of this velocity can be measured astrometrically, i.e., the one perpendicular to the plane containing the line of sight and the centroid velocity vector (called $\eta_{\perp,i}$ by L00). Lindegren et al. (2000) deal with the problem by using the proper motion residuals to compute the peculiar velocity components ($\eta_{\perp,i}$) and their observational uncertainties. They then compute an estimate of $\sigma_{\perp}$, and hence of σ_v , assuming isotropic dispersion. They test the method using Monte Carlo simulations, and conclude that $\sigma_{\perp}$ is in practice an unbiased estimate of σ_v .

We applied the likelihood maximization procedure described above first considering all the stars identified as members by G17, then restricting the samples to the

²The python implementation of the procedure is available at: <https://github.com/eleonorazari/KinematicModelling>.

Table 4.6: Velocity dispersion estimates obtained with the maximum likelihood procedure described in the text using the Nelder–Mead method, except those indicated by an asterisk (where the Newton Conjugate Gradient method was employed). The quoted errors are obtained using the Cramér–Rao inequality.

	IC 2602	IC 2391	IC 4665	NGC 2547
N_i	66	43	16	34
σ_v [km s ^{−1}]	0.48 ± 0.04	0.59 ± 0.06	0.18 ± 0.04	0.43 ± 0.08
N_f	63	42	15	34
σ_v [km s ^{−1}]	0.20 ± 0.02	0.43 ± 0.05	0.03 ± 0.04	0.43 ± 0.08
$\sigma_\perp$ [km s ^{−1}]	0.32 ± 0.02	0.42 ± 0.05	0.10 ± 0.02	0.60 ± 0.10
$N_{r < R_{\text{GES},i}}$	38	22	10	17
σ_v [km s ^{−1}]	0.18 ± 0.02	0.20 ± 0.04	0.05 ± 0.03	0.24 ± 0.08 (*)
$N_{r < R_{\text{GES},f}}$	37	22	10	17
σ_v [km s ^{−1}]	0.16 ± 0.02	0.20 ± 0.04	0.05 ± 0.03	0.24 ± 0.08 (*)
$\sigma_\perp$ [km s ^{−1}]	0.24 ± 0.02	0.30 ± 0.05	0.13 ± 0.03	0.40 ± 0.10

Notes. The first row lists the initial number of stars, from G17. The second row gives the values of σ_v estimated using the stars from the first row. The third row gives the number of stars remaining after the exclusion procedure, and the fourth and fifth rows give σ_v and $\sigma_\perp$. The second half of the table is the same as the first half, except for the initial number of stars. Row six lists the number of stars within the radii from the cluster center given in table 4.14.

areas defined by the radii (R_{GES}) shown in table 4.8. We derived the centroid space velocity for the four clusters, and then we computed $\sigma_\perp$. The results are listed in table 4.6, together with their statistical errors³.

The estimated values for the velocity dispersion of the clusters analyzed in this study depend strongly on the number of stars considered. For example, the velocity dispersion of IC 2602 changes from ~ 0.48 km s^{−1} to ~ 0.20 km s^{−1} after the exclusion of only three stars. A similar trend can also be observed for the other clusters. Furthermore, changing the likelihood maximization method (see table 4.7) causes the velocity dispersion estimates to change slightly as well. For these reasons, the results given in table 4.6 and 4.7 needs to be interpreted with care. In particular, the errors in tables 4.6 and 4.7 correspond to the statistical errors, and do not take into account any systematic effect. A tentative estimate of the accuracy of the velocity dispersions obtained can be computed using half the difference between the velocity dispersion values obtained with the two different methods, considering the same number of stars (i.e., N_i and $N_{r < R_{\text{GES},i}}$). In this way, we obtain systematic errors between ~ 0.01 km s^{−1} and ~ 0.1 km s^{−1}, depending on the cluster.

³In practice, to maximize the likelihood we used the Nelder–Mead and Newton–CG methods, both supported by the `scipy.optimize.minimize` function.

Table 4.7: Same as table 4.6, but using the Newton Conjugate Gradient maximization method.

	IC 2602	IC 2391	IC 4665	NGC 2547
N_i	66	43	16	34
σ_c [km s ⁻¹]	0.38 ± 0.03	0.34 ± 0.04	0.20 ± 0.05	0.40 ± 0.07
N_f	59	40	15	34
σ_c [km s ⁻¹]	0.12 ± 0.02	0.10 ± 0.02	0.02 ± 0.06	0.40 ± 0.07
$\sigma_\perp$ [km s ⁻¹]	0.25 ± 0.02	0.18 ± 0.02	0.11 ± 0.02	0.60 ± 0.10
$N_{r < R_{\text{GES},i}}$	38	22	10	17
σ_c [km s ⁻¹]	0.25 ± 0.03	0.28 ± 0.05	0.16 ± 0.05	0.24 ± 0.08
$N_{r < R_{\text{GES},f}}$	37	22	10	17
σ_c [km s ⁻¹]	0.15 ± 0.02	0.28 ± 0.04	0.16 ± 0.03	0.24 ± 0.08
$\sigma_\perp$ [km s ⁻¹]	0.25 ± 0.02	0.30 ± 0.05	0.12 ± 0.02	0.37 ± 0.09

4.6 Total Mass and Radii

As described in the previous Chapter, the analysis of the dynamics of clusters requires an estimation of their total mass and their half-mass radius. In section 3.2.3, I described the method to derive these quantities in young clusters. Figure 4.10 shows the HR diagram for each cluster, color-coded by membership probability. In this figure the PMS tracks (Tognelli et al. 2011) are shown in order to derive the star mass (black and red lines, where for the red ones the mass is reported). Also, the isochrones at 20 (magenta line) and 50 Myr (blue line) are shown, that are the limits of the age range of these four clusters. One can note that high-probability spectroscopic candidates tend to be closer to the cluster sequence than low-probability ones. This validates that the adopted approach works.

Once I evaluated the mass of the spectroscopic candidates, I estimated the total mass of the cluster (M_{tot}) following the method described in section 3.2.3. As mentioned, I considered two different approaches to derive this quantity: using the spectroscopic candidates with p_{cl} greater than 0.8, and using all spectroscopic candidates weighted by their corresponding p_{cl} . Then, I corrected these quantities for the cluster completeness listed in table 4.3 and the presence of binaries. Lastly, I extrapolated the cluster mass outside the GES magnitude range (see table 4.3 for magnitude range of each cluster). Table 4.8 shows the total masses derived for the four clusters. The total masses found with the different samples agree within a factor of ~ 1.5 . I adopted $M_{\text{tot},w}$ for the subsequent dynamical analysis.

Finally, I also need an estimate of the half-mass radius (r_{hm}). Using the method described at the end of Chapter 3, I derived this radius for each cluster. The r_{hm} of the four clusters are listed in Table 4.8.

In the tables 4.10, 4.11, 4.12, and 4.13 the properties of the spectroscopic can-

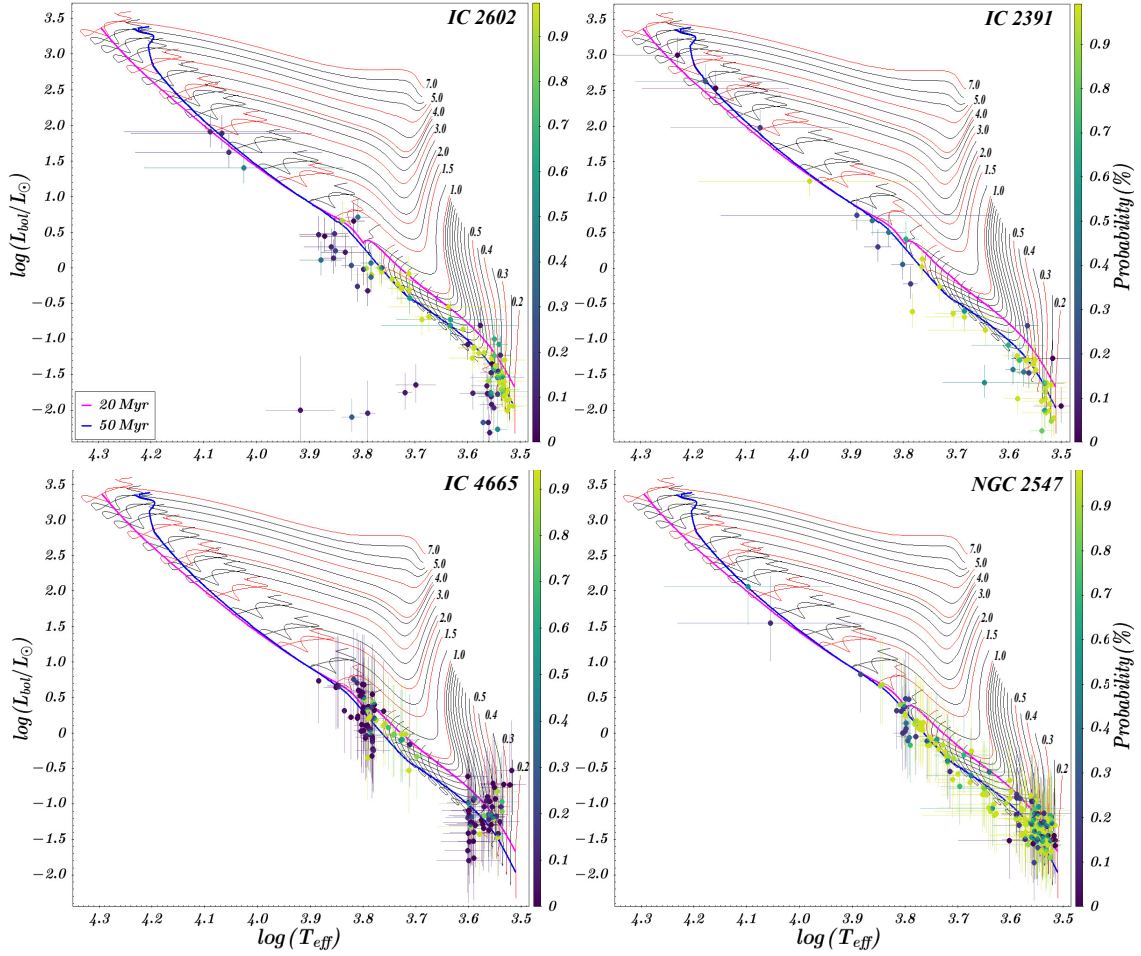


Figure 4.10: Hertzsprung–Russell diagram of the sample of clusters. The colored filled dots represent GES targets retained after the procedure of cleaning from the obvious contaminants. The spectroscopic candidates color-coded depending on the probability of belonging to the cluster (scale at right). The magenta and blue lines are the isochrones at 20 and 50 Myr, respectively, and the black and red lines are the PMS evolutionary tracks (Tognelli et al. 2011).

didates selected in section 4.3 are summarized for the OC IC 2602, IC 2391, IC 4665, and NGC 2547, respectively. In the tables also the derived properties using the GES data are listed, such as the logarithm of the bolometric luminosity, $\log(L_{bol}/L_{\odot})$, the probability of each star, p_{cl} , and the single mass of the stars, $M_{\star}$. In the table of NGC 2547, I listed both the probability for a star to belong to the population A ($p_{cl,A}$), and that for the same star to belong to the population B ($p_{cl,B}$). The letters “U” and “G” in the fourth column indicate the stars observed with UVES and GIRAFFE, respectively, while the letter “K” in the twelfth column indicates the stars reported in literature and observed again by GES. In the $\log g$ and $\text{EW}(\text{Li})$ columns the errors are not listed in several stars. This means that the value reported is an upper limit.

Table 4.8: Total mass calculated with the two different approaches and half-mass radius of the four clusters.

Cluster	$M_{\text{tot},0.8}$ ($M_{\odot}$)	$M_{\text{tot},w}$ ($M_{\odot}$)	r_{hm} (pc)
IC 2602	~ 173	~ 244	~ 1.56
IC 2391	~ 111	~ 151	~ 0.98
IC 4665	~ 78	~ 96	~ 1.19
NGC 2547	~ 176	~ 201	~ 0.80

Notes. $M_{\text{tot},0.8}$ and $M_{\text{tot},w}$ indicate the total masses calculated using the sample of spectroscopic candidates with probability to be a member greater than 0.8 and using all spectroscopic candidates weighted by p_{cl} , respectively.

4.6.1 Total Cluster Mass from TGAS Data

Following the same method for young OCs described in section 3.2.3, I derived the total cluster masses, $M_{\text{tot,TGAS}}$, using the stars identified as members by G17 within the area defined by R_{GES} , which are shown in table 4.9. In this case, I have assumed a level of completeness of 100% since TGAS is assumed to be complete. In table 4.9 are also reported the total masses derived using the sample of GES spectroscopic candidates considering both only the stars with a probability of being a member greater than 0.8 and considering all stars in which the masses are weighted for their corresponding p_{cl} . The total masses found with the different samples agree within a factor of ~ 1.8 . In particular, the results show a good correspondence between the masses estimated through the spectroscopic candidates weighted by p_{cl} ($M_{\text{tot},w}$) and those calculated with the TGAS sample ($M_{\text{tot,TGAS}}$) within the GES region. This validates the results of this work since the masses are estimated starting from almost independent star samples (only a tiny fraction of them are in common).

Table 4.9: Total mass of the four young clusters calculated with the GES and TGAS sample.

Cluster	R_{GES} (pc)	$M_{\text{tot},0.8}$ ($M_{\odot}$)	$M_{\text{tot},w}$ ($M_{\odot}$)	$M_{\text{tot,TGAS}}$ ($M_{\odot}$)
IC 2602	4.13	~ 173	~ 244	~ 229
IC 2391	2.55	~ 111	~ 151	~ 126
IC 4665	4.47	~ 78	~ 96	~ 144
NGC 2547	3.18	~ 176	~ 201	~ 216

Table 4.10: Properties of spectroscopic candidates of IC 2602.

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log ($L_{\text{bol}}/L_{\odot}$)	Known members	P_{cl} (%)	M _* (M _{$\odot$})
10281886-6431375	157.07	-64.52	G	3318 ± 48	17.32 ± 0.50	0.85	-	100.0	-0.26	-1.84		0.96	~ 0.26
10284372-6435392	157.18	-64.59	U	6875 ± 68	19.02 ± 0.56	-	4.37 ± 0.03	70.5 ± 5.4	0.00	0.65		0.90	~ 1.50
10294476-6447131	157.43	-64.78	G	3592 ± 87	34.22 ± 0.30	0.81	-	100.0	-0.23	-1.80		0.08	~ 0.38
10294687-6328143	157.44	-63.47	G	3886 ± 97	0.50 ± 0.28	0.83	4.54 ± 0.13	23.1	-0.16	-1.75		0.08	~ 0.30
10305964-6437156	157.74	-63.66	G	5223 ± 67	-2.70 ± 0.30	0.98	-	176.7 ± 7.1	0.06	-1.74		0.07	~ 0.35
10310811-6321493	157.78	-63.36	G	3493 ± 49	9.08 ± 0.35	0.84	-	120.0 ± 7.2	-0.25	-1.77		0.19	~ 0.37
10313087-6321203	157.87	-63.35	G	3602 ± 94	13.68 ± 0.28	0.82	-	146.3 ± 4.7	-0.23	-1.75		0.42	~ 0.41
10314490-6329221	157.93	-63.48	U	6544 ± 137	-	0.82	4.00	65.2	-0.09	0.65	K	1.00	~ 1.45
10330081-6409181	158.25	-64.15	G	6264 ± 27	-1.59 ± 0.25	0.99	4.14	11.7	0.25	-0.02		0.07	~ 1.19
10334181-6413457	158.42	-64.22	G	5305 ± 39	17.07 ± 0.25	0.97	4.21 ± 0.01	232.0 ± 1.4	-0.10	-0.29	K	0.96	~ 0.90
10334842-6358099	158.45	-63.96	G	6608 ± 124	10.14 ± 1.78	1.00	4.17 ± 0.18	22.0 ± 2.3	-0.10	0.03		0.25	~ 1.21
10335200-6411257	158.46	-64.19	G	3371 ± 62	17.93 ± 0.48	0.86	-	100.7 ± 9.0	-0.26	-1.76		0.96	~ 0.30
10341190-6410471	158.54	-64.17	G	7140 ± 163	64.97 ± 0.36	1.02	4.05	19.3 ± 1.7	-0.13	0.13		0.10	~ 1.40
10342277-6418095	158.59	-64.30	G	3422 ± 89	20.95 ± 0.33	0.84	4.60 ± 0.18	121.8 ± 5.1	-0.26	-1.52		0.48	~ 0.35
10345408-6408452	158.72	-64.14	G	4057 ± 185	18.64 ± 0.25	0.86	4.44 ± 0.14	158.5 ± 12.3	-0.05	-0.86		0.93	~ 0.72
10345416-6407241	158.72	-64.12	G	3659 ± 109	48.66 ± 0.28	0.79	4.67 ± 0.04	100.0	-0.24	-1.65		0.06	~ 0.42
10345587-6407385	158.73	-64.13	U	3471 ± 60	20.05 ± 0.39	0.80	4.69 ± 1.00	100.0	-0.24	-1.07	K	0.63	~ 0.37
10345649-6408023	158.73	-64.13	U	11272 ± 2000	66.65 ± 0.40	0.80	4.48 ± 1.00	-	-	1.61		0.14	~ 2.60
10351999-6404021	158.83	-64.06	G	3401 ± 42	18.58 ± 0.31	0.83	4.61 ± 0.18	100.0	-0.26	-1.65		0.94	~ 0.34
10353025-6359152	158.87	-63.98	G	4987 ± 190	-9.86 ± 0.60	0.96	-	258.2 ± 6.0	-	-1.63		0.06	~ 0.40
10361825-6414564	159.07	-64.24	G	3705 ± 74	18.44 ± 0.25	0.82	-	110.9 ± 2.9	-0.19	-1.18	K	0.95	~ 0.56
10374942-6400505	159.45	-64.01	G	3893 ± 164	17.67 ± 0.26	0.83	-	136.9 ± 3.4	-0.15	-1.26	K	0.97	~ 0.55
10393502-6413486	159.89	-64.23	G	3979 ± 56	-6.53 ± 0.26	0.85	4.56	29.2	-0.10	-1.07		0.06	~ 0.61
10394942-6444250	159.95	-64.74	G	3430 ± 75	17.57 ± 0.28	0.84	-	100.0	-0.25	-1.46		0.97	~ 0.35
10395597-6359300	159.98	-63.99	G	5120 ± 122	14.94 ± 0.28	0.87	-	342.3 ± 7.5	-	-0.42	K	0.57	~ 0.85
10403019-6442169	160.12	-64.70	G	3873 ± 119	17.73 ± 0.25	0.84	-	90.3 ± 1.8	-0.13	-1.12	K	0.97	~ 0.60
10404211-6439116	160.17	-64.65	U	12250 ± 2000	29.70 ± 0.40	-	4.48 ± 1.00	-	-	1.90	K	0.12	~ 3.00
10405531-6457543	160.23	-64.96	G	3590 ± 69	2.93 ± 0.34	0.85	-	100.0	-0.21	-1.46		0.10	~ 0.47
10405564-6543083	160.23	-65.71	U	4285 ± 43	20.04 ± 0.33	0.89	-	219.2 ± 6.3	-0.03	-0.72		0.62	~ 0.76
10410641-6428279	160.27	-64.47	U	11641 ± 2000	30.53 ± 0.40	-	4.06 ± 1.00	-	-	1.88	K	0.11	~ 2.90
10412390-6443564	160.34	-64.73	G	3409 ± 190	24.03 ± 3.55	0.87	-	349.0 ± 20.6	-0.21	-1.73		0.68	~ 0.34
10413334-6409173	160.38	-64.15	G	3635 ± 24	-6.62 ± 0.71	0.82	-	61.9	-	-2.16		0.06	~ 0.31
10420708-6446079	160.52	-64.76	G	5397 ± 55	17.41 ± 0.25	0.98	4.05 ± 0.17	132.8 ± 1.4	0.01	-0.22	K	0.97	~ 0.92
10422815-6436128	160.61	-64.60	G	3538 ± 42	15.71 ± 0.30	0.81	4.62 ± 0.17	151.4 ± 5.5	-0.22	-1.23	K	0.75	~ 0.45
10423472-6449492	160.64	-64.83	G	3479 ± 69	17.58 ± 0.35	0.82	4.63 ± 0.13	107.2 ± 6.6	-0.25	-1.50		0.97	~ 0.40
10424171-6421047	160.67	-64.35	U	5814 ± 73	15.10 ± 0.56	-	4.35	190.0	-	-	K	0.65	~ 1.10
10425608-6355510	160.73	-63.93	G	5135 ± 40	18.06 ± 0.26	0.98	-	291.1 ± 10.0	-0.02	-0.30	K	0.96	~ 0.87
10430024-6530179	160.75	-65.50	G	5534 ± 90	16.70 ± 0.25	0.99	-	197.4 ± 2.9	0.02	-0.15	K	0.94	~ 0.95
10433789-6544597	160.90	-65.74	U	7092 ± 142	9.78 ± 0.56	-	4.03	7.8	-	0.23		0.21	~ 1.50
10434875-6346481	160.95	-63.78	U	3335 ± 57	17.51 ± 0.52	0.84	4.67 ± 0.10	41.5	-0.28	-1.71		0.96	~ 0.27
10435021-6445022	160.95	-64.75	G	3394 ± 132	17.57 ± 0.37	0.84	4.66 ± 0.12	174.5 ± 8.0	-0.28	-1.59		0.97	~ 0.33
10435316-6452006	160.97	-64.86	G	3783 ± 75	17.46 ± 0.26	0.83	-	98.6 ± 2.6	-0.16	-1.19		0.97	~ 0.57
10435700-6447397	160.98	-64.79	U	6070 ± 121	21.95 ± 0.56	-	3.79	12.0	-0.04	0.06	K	0.39	~ 1.10
10440681-6359351	161.02	-63.99	U	5792 ± 60	17.45 ± 0.56	-	4.46 ± 0.09	185.0 ± 12.1	0.02	-0.05	K	0.96	~ 1.00
10440827-6401435	161.03	-64.02	U	7623 ± 279	0.62 ± 0.40	-	4.09	9.3	-0.19	0.46		0.08	~ 1.60
10440829-6442183	161.03	-64.70	G	3522 ± 37	18.66 ± 0.27	0.84	-	133.2 ± 3.7	-0.25	-1.37		0.93	~ 0.44
10440835-6401440	161.03	-64.02	U	7427 ± 348	-486.56 ± 0.56	-	4.07	19.2	-0.17	0.44		-	-
10441394-6446273	161.05	-64.77	G	5142 ± 100	17.34 ± 0.29	0.97	-	278.6 ± 8.2	-	-0.08	K	0.97	~ 1.10
10441890-6453211	161.07	-64.88	G	3591 ± 87	19.33 ± 0.30	0.83	-	123.2 ± 4.7	-0.23	-1.77		0.80	~ 0.42
10442124-6430068	161.08	-64.50	G	3489 ± 178	12.17 ± 1.29	0.89	-	100.0	-0.22	-1.54		0.35	~ 0.40
10442256-6415301	161.09	-64.25	U	5854 ± 65	17.49 ± 0.56	-	4.50 ± 0.08	157.3 ± 7.7	0.02	-0.00	K	0.96	~ 1.05
10442417-6424337	161.10	-64.40	U	3718 ± 19	11.79 ± 0.39	0.79	-	120.3 ± 17.1	-	-2.17		0.29	~ 0.25
10444403-6423219	161.18	-64.38	G	3615 ± 28	-19.31 ± 0.46	0.82	-	143.7 ± 12.2	-	-2.31		0.07	~ 0.22

Table 4.10 – *Continue*

CNAME	RA (°)	DEC (°)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{bol} / L _⊙)	Known members	p _d (%)	M _* (M _⊙)
10445010-6436059	161.20	-64.60	G	3580 ± 80	42.63 ± 0.50	0.79	4.62 ± 0.14	100.0	-0.22	-1.91		0.06	~ 0.37
10445962-6502191	161.24	-65.03	U	5795 ± 62	25.27 ± 0.56	-	4.39	201.6	0.07	0.00	K	0.22	~ 1.05
10450182-6444398	161.25	-64.74	G	3545 ± 73	12.84 ± 2.16	0.73	4.70	193.2 ± 14.1	-0.14	-1.41		0.67	~ 0.46
10451506-6448220	161.31	-64.80	G	3436 ± 115	19.33 ± 0.55	0.83	4.63 ± 0.12	112.5 ± 9.7	-0.26	-1.70		0.85	~ 0.35
10451743-6456434	161.32	-64.94	G	3410 ± 106	17.80 ± 0.32	0.84	4.63 ± 0.15	123.0 ± 6.1	-0.25	-1.48		0.97	~ 0.34
10451854-6426540	161.32	-64.44	G	3461 ± 81	17.04 ± 0.45	0.83	-	100.0	-0.26	-1.60		0.96	~ 0.38
10452228-6426201	161.34	-64.43	G	6438 ± 15	27.85 ± 0.25	0.99	4.32	12.2	0.18	-0.26		0.15	~ 1.20
10452558-6419430	161.35	-64.32	G	3392 ± 69	16.80 ± 0.47	0.83	4.65 ± 0.11	100.0	-0.26	-1.79		0.95	~ 0.31
10452826-6413450	161.36	-64.22	U	6426 ± 148	21.95 ± 0.56	-	3.98	80.3	-0.09	0.71	K	0.39	~ 1.40
10452984-6444543	161.37	-64.74	G	3265 ± 88	16.48 ± 0.76	0.87	-	385.2 ± 12.7	-0.26	-1.93		0.93	~ 0.22
10453159-6445466	161.38	-64.76	G	3648 ± 88	42.40 ± 0.28	0.80	4.58 ± 0.17	87.4 ± 4.9	-0.21	-1.76		0.06	~ 0.44
10453719-6416088	161.40	-64.26	G	3541 ± 40	15.38 ± 0.27	0.84	-	101.4 ± 2.7	-0.24	-0.99	K	0.66	~ 0.44
10453903-6413029	161.41	-64.21	G	3388 ± 136	16.95 ± 0.39	0.69	-	75.1 ± 7.8	-1.28	-1.28		0.96	~ 0.31
10454789-6500411	161.44	-65.01	U	7223 ± 37	-27.20 ± 0.40	-	3.95	10.1	-0.27	0.29		0.10	~ 1.50
10454944-6500491	161.45	-65.01	G	3579 ± 59	91.16 ± 0.27	0.81	-	139.1 ± 3.5	-0.23	-1.34		-	-
10461304-6426079	161.55	-64.43	G	3388 ± 151	18.76 ± 0.75	0.84	4.68 ± 0.07	100.0	-0.27	-1.79		0.93	~ 0.31
10461326-6420195	161.55	-64.33	G	3544 ± 42	5.60 ± 0.39	0.79	4.67 ± 0.07	96.2 ± 8.4	-0.22	-1.96		0.12	~ 0.38
10461480-6402570	161.56	-64.04	U	5796 ± 68	19.05 ± 0.56	-	4.38	229.9 ± 13.4	-	-	K	0.90	~ 1.00
10462776-6329003	161.61	-63.48	G	8258 ± 541	39.00 ± 1.72	0.98	-	46.0	-	-1.99		0.07	~ 2.00
10462898-6407577	161.62	-64.13	U	6271 ± 115	17.83 ± 0.56	-	3.94	117.3 ± 14.3	-	-	K	0.96	~ 1.20
10464405-6424504	161.68	-64.41	G	3347 ± 56	17.37 ± 0.40	0.85	-	126.2 ± 8.4	-0.28	-1.85		0.97	~ 0.27
10464781-6415459	161.69	-64.26	G	3319 ± 84	17.51 ± 0.76	0.86	-	197.8 ± 13.0	-0.23	-1.94		0.96	~ 0.26
10465181-6334157	161.71	-63.57	G	4857 ± 128	18.16 ± 0.25	0.95	4.63 ± 0.07	313.8 ± 2.0	-0.06	-0.72	K	0.96	~ 0.77
10471270-6424109	161.80	-64.40	G	6594 ± 124	23.37 ± 0.61	0.99	-	71.8 ± 6.0	0.63	-2.09		0.30	~ 1.30
10471901-6400463	161.82	-64.01	G	3480 ± 63	30.05 ± 0.59	0.87	-	118.5 ± 8.1	-0.24	-1.44		0.12	~ 0.40
10472668-6357592	161.86	-63.96	G	3479 ± 74	16.63 ± 0.29	0.83	4.61 ± 0.19	125.0 ± 5.3	-0.23	-1.53		0.94	~ 0.40
10474712-6434113	161.94	-64.56	U	6159 ± 45	-1.95 ± 0.56	-	4.26 ± 0.05	62.0 ± 12.3	0.15	-0.31		0.07	~ 1.19
10481093-6513390	162.04	-65.22	U	6788 ± 313	-9.84 ± 0.56	-	3.99	48.6	-0.05	0.21		0.06	~ 1.30
10481856-6409537	162.07	-64.16	U	5793 ± 60	19.19 ± 0.56	-	4.39	187.3 ± 8.8	-	-	K	0.88	~ 1.00
10483152-6406465	162.13	-64.11	G	3863 ± 118	16.51 ± 0.25	0.84	-	110.8 ± 2.0	-0.16	-1.11		0.92	~ 0.60
10484452-6348240	162.18	-63.80	G	3486 ± 63	14.30 ± 0.58	0.84	-	164.1 ± 11.6	-0.22	-2.26		0.50	~ 0.21
10485165-6357419	162.21	-63.96	G	3340 ± 67	17.14 ± 0.44	0.86	-	110.5 ± 10.8	-0.24	-2.00		0.96	~ 0.27
10485180-6405150	162.21	-64.08	G	3765 ± 84	57.56 ± 0.27	0.82	-	115.2 ± 3.7	-0.17	-0.80		0.06	~ 0.62
10492624-6439000	162.35	-64.65	G	4321 ± 485	17.31 ± 0.26	0.90	-	194.3 ± 9.3	-0.01	-0.54	K	0.97	~ 0.88
10493613-6508024	162.40	-65.13	U	7544 ± 301	12.95 ± 0.56	-	4.08	10.3	-0.08	0.10		0.37	~ 1.60
10494839-6446284	162.45	-64.77	U	5327 ± 123	18.04 ± 0.56	-	4.34 ± 0.30	286.7 ± 10.3	-0.12	-0.28	K	0.96	~ 0.92
10495006-6356304	162.45	-63.94	G	3634 ± 76	18.98 ± 0.26	0.80	4.57 ± 0.18	137.1 ± 3.3	-0.21	-1.58		0.88	~ 0.45
10495515-6357402	162.47	-63.96	U	7121 ± 185	-40.18 ± 0.40	-	3.98	7.0	-0.14	0.47		0.14	~ 1.50
10495685-6348191	162.48	-63.80	G	4713 ± 124	18.12 ± 0.56	-	4.46	320.8 ± 11.1	-0.03	-0.68	K	0.96	~ 0.75
10502171-6331129	162.59	-63.52	G	3446 ± 68	29.71 ± 1.36	0.75	4.70	102.6 ± 7.4	-0.27	-1.22		0.13	~ 0.36
10504603-6428460	162.69	-64.47	U	10576 ± 2000	21.17 ± 0.40	-	4.08 ± 1.00	-	-	1.40	K	0.46	~ 2.30
10504991-6430131	162.70	-64.50	G	4291 ± 557	14.96 ± 0.28	0.91	-	236.9 ± 4.1	-0.03	-0.80		0.57	~ 0.70
10511789-6411527	162.82	-64.19	G	6150 ± 93	3.55 ± 0.52	0.98	-	15.5	-0.09	-2.04		0.10	~ 1.20
10512455-6433055	162.85	-64.55	G	6049 ± 209	17.94 ± 0.26	1.00	3.92 ± 0.01	90.3 ± 1.0	-0.12	-0.09		0.97	~ 1.10
10520652-6430162	163.02	-64.50	G	3417 ± 102	17.50 ± 0.35	0.83	4.69 ± 0.05	141.4 ± 7.7	-0.26	-1.70		0.97	~ 0.34
10521047-6342542	163.04	-63.71	U	6066 ± 39	22.44 ± 0.56	-	4.12 ± 0.07	14.2	0.387	-0.12		0.35	~ 1.15
10521826-6410521	163.07	-64.18	U	3586 ± 68	17.39 ± 0.26	0.81	-	164.6 ± 3.1	-0.22	-1.26		0.97	~ 0.50
10522362-6332566	163.09	-63.54	U	6197 ± 51	18.80 ± 0.56	-	4.07 ± 0.05	9.3	0.154	-0.00		0.93	~ 1.20

Table 4.11: Properties of spectroscopic candidates of IC 2391.

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T_{eff} (K)	RV (km s^{-1})	γ	$\log g$ (dex)	EW(Li) ($m\text{\AA}$)	[Fe/H] (dex)	$\log(L_{\text{bol}}/L_{\odot})$	Known members	p_{cl} (%)	$M_{\star}$ ($M_{\odot}$)
08364573-5311329	129.19	-53.19	G	3263 $\pm$ 13	15.43 $\pm$ 0.55	0.87	-	108.9 $\pm$ 17.1	-	-2.11	K	0.98	~ 0.21
08365498-5308342	129.22	-53.14	U	5379 $\pm$ 54	15.21 $\pm$ 0.56	-	4.46 $\pm$ 0.04	220.6 $\pm$ 8.7	-0.07	-0.26	K	0.98	~ 0.91
08371059-5315334	129.29	-53.25	U	9500 $\pm$ 2000	13.87 $\pm$ 0.40	-	3.77 $\pm$ 1.00	-	-	1.22	K	0.96	~ 2.10
08373280-5303334	129.38	-53.05	G	3305 $\pm$ 15	16.74 $\pm$ 0.37	0.86	-	190.2 $\pm$ 15.1	-	-2.14	K	0.89	~ 0.24
08382349-5316545	129.59	-53.28	G	3644 $\pm$ 81	30.80 $\pm$ 0.30	0.83	-	100.0	-0.21	-1.47		0.19	~ 0.48
08382671-5310072	129.61	-53.16	G	3439 $\pm$ 75	17.31 $\pm$ 0.48	0.82	4.67 $\pm$ 0.10	100.0	-0.28	-2.28		0.82	~ 0.30
08384138-5255039	129.67	-52.91	G	3984 $\pm$ 274	18.73 $\pm$ 0.45	0.84	-	35.5	-0.16	-1.07		0.66	~ 0.61
08384269-5305160	129.67	-53.08	G	6059 $\pm$ 30	15.90 $\pm$ 0.26	0.99	4.21 $\pm$ 0.05	32.4 $\pm$ 3.9	0.16	-0.61		0.97	~ 1.05
08384480-5305253	129.68	-53.09	U	11814 $\pm$ 2000	30.92 $\pm$ 0.40	-	3.98 $\pm$ 1.00	-	-	1.97	K	0.19	~ 3.00
08385073-5225382	129.71	-52.42	U	7047 $\pm$ 183	33.09 $\pm$ 0.56	-	4.06	5.9	-0.08	0.30		0.17	~ 1.40
08392060-5234475	129.83	-52.57	U	6322 $\pm$ 135	0.19 $\pm$ 0.56	-	3.87	14.4	-0.03	0.05		0.33	~ 1.10
08392258-5355056	129.84	-53.91	G	5075 $\pm$ 170	15.36 $\pm$ 0.25	0.96	-	241.8 $\pm$ 3.4	-	-0.63	K	0.98	~ 0.78
08392384-5326231	129.84	-53.43	U	1500 $\pm$ 2000	25.65 $\pm$ 0.40	-	4.00 $\pm$ 1.00	-	-	2.62	K	0.28	~ 4.50
08394141-5304035	129.92	-53.06	G	3398 $\pm$ 23	19.73 $\pm$ 0.40	0.82	-	224.3 $\pm$ 14.6	-	-2.00		0.57	~ 0.30
08394203-5357189	129.92	-53.95	G	3904 $\pm$ 54	6.37 $\pm$ 0.83	0.86	-	113.1 $\pm$ 11.3	-0.07	-1.42		0.44	~ 0.51
08394304-5257510	129.92	-52.96	U	6732 $\pm$ 221	22.08 $\pm$ 0.56	-	4.09	87.7 $\pm$ 17.5	-0.05	0.50	K	0.42	~ 1.35
08394843-5313583	129.95	-53.23	G	3334 $\pm$ 17	14.56 $\pm$ 0.50	0.85	-	100.0	-	-2.00	K	0.98	~ 0.26
08395367-5318036	129.97	-53.30	G	3837 $\pm$ 97	14.52 $\pm$ 0.25	0.83	-	73.8 $\pm$ 24.5	-0.13	-1.23		0.98	~ 0.56
08400303-5351064	130.01	-53.85	U	7228 $\pm$ 291	-15.17 $\pm$ 0.56	-	4.06	4.1	-0.14	0.67		0.42	~ 1.50
08400623-5324475	130.02	-53.41	G	3728 $\pm$ 82	21.85 $\pm$ 0.26	0.81	4.54 $\pm$ 0.19	100.0	-0.17	-1.45		0.43	~ 0.49
08400624-5338069	130.02	-53.63	U	5808 $\pm$ 90	15.40 $\pm$ 0.56	-	4.35	172.0 $\pm$ 20.5	-0.05	0.12	K	0.98	~ 1.15
08401609-5325476	130.06	-53.42	G	3268 $\pm$ 12	15.18 $\pm$ 0.57	0.84	-	57.0	-	-2.10	K	0.98	~ 0.22
08401746-5300554	130.07	-53.01	U	14330 $\pm$ 2000	-179.95 $\pm$ 0.56	-	4.02 $\pm$ 1.00	-	-	2.53	K	1.00	~ 4.30
08403748-5307427	130.15	-53.12	G	3280 $\pm$ 255	46.75 $\pm$ 0.31	0.79	4.78 $\pm$ 0.02	100.0	-0.27	-1.26		-	~ 0.53
08405752-5238207	130.23	-52.63	G	3689 $\pm$ 75	14.22 $\pm$ 0.26	0.82	-	100.0	-0.19	-1.30		0.98	~ 0.44
08410820-5238056	130.28	-52.63	G	3530 $\pm$ 39	15.26 $\pm$ 0.31	0.81	4.60 $\pm$ 0.20	100.0	-0.25	-1.42		0.99	~ 0.24
08410934-5302130	130.28	-53.03	G	3301 $\pm$ 13	15.05 $\pm$ 0.63	0.87	-	225.2 $\pm$ 16.7	-	-1.63	K	0.98	~ 0.24
08412223-5304468	130.34	-53.07	G	3371 $\pm$ 43	15.18 $\pm$ 0.41	0.84	4.63 $\pm$ 0.15	109.8 $\pm$ 27.2	-0.26	-1.60	K	0.98	~ 0.30
08412526-5333573	130.35	-53.56	G	4420 $\pm$ 348	8.47 $\pm$ 0.26	0.92	-	308.5 $\pm$ 2.1	0.01	-1.60		0.52	~ 0.55
08412588-5322415	130.35	-53.37	U	4835 $\pm$ 119	20.10 $\pm$ 0.40	-	4.47	360.0 $\pm$ 30.3	-0.06	-0.60	K	0.54	~ 0.78
08412598-5326349	130.35	-53.44	G	3331 $\pm$ 82	14.40 $\pm$ 0.43	0.87	-	156.0 $\pm$ 8.8	-0.28	-1.90	K	0.98	~ 0.26
08412998-5240379	130.37	-52.67	G	3829 $\pm$ 101	15.20 $\pm$ 0.26	0.82	4.54 $\pm$ 0.17	71.3 $\pm$ 24.1	-0.15	-1.83		0.99	~ 0.38
08413595-5309268	130.39	-53.15	G	3165 $\pm$ 162	47.15	0.83	4.79 $\pm$ 0.01	100.0	-0.24	-1.93	K	-	-
08413967-5259340	130.41	-52.99	G	4406 $\pm$ 482	15.89 $\pm$ 0.28	0.91	-	133.0 $\pm$ 3.7	-0.01	-0.86	K	0.97	~ 0.68
08414395-5314068	130.43	-53.23	G	3391 $\pm$ 138	13.64 $\pm$ 0.36	0.84	4.66 $\pm$ 0.09	100.0	-0.25	-1.73	K	0.95	~ 0.32
08414659-5303449	130.44	-53.06	U	7731 $\pm$ 2000	51.37 $\pm$ 0.56	-	3.90 $\pm$ 1.00	-	-	0.74	K	0.22	~ 1.60
08415154-5320597	130.46	-53.34	G	3578 $\pm$ 59	14.55 $\pm$ 0.26	0.82	-	100.0	-0.22	-1.35		0.98	~ 0.48
08415760-5251531	130.49	-52.86	G	3798 $\pm$ 28	18.08 $\pm$ 0.52	0.85	-	36.9	-	-1.29		0.72	~ 0.54
08420492-5253539	130.52	-52.89	G	3545 $\pm$ 46	14.29 $\pm$ 0.42	0.82	-	125.3 $\pm$ 11.2	-0.24	-1.28	K	0.98	~ 0.46
08420879-5244496	130.53	-52.74	G	3666 $\pm$ 79	29.86 $\pm$ 0.26	0.84	-	100.0	-0.19	-0.80	K	0.20	~ 0.53
08421230-5306038	130.55	-53.10	U	6239 $\pm$ 163	10.82 $\pm$ 0.40	-	3.98-	105.9 $\pm$ 18.5	-0.09	0.41	K	0.66	~ 1.21
08422538-5306501	130.60	-53.11	U	16958 $\pm$ 2000	-	-	4.00 $\pm$ 1.00	-	-	2.99	K	1.00	~ 5.50
08424099-5330359	130.67	-53.50	G	3663 $\pm$ 73	14.74 $\pm$ 0.26	0.82	-	123.8 $\pm$ 2.4	-0.19	-1.28	K	0.99	~ 0.52
08424903-5252157	130.70	-52.87	G	3396 $\pm$ 147	15.59 $\pm$ 0.66	0.83	4.73 $\pm$ 0.01	90.4 $\pm$ 11.7	-0.26	-1.60	K	0.98	~ 0.33
08424965-5246269	130.70	-52.77	U	6108 $\pm$ 85	46.91 $\pm$ 0.56	-	4.19	26.2	-0.21	-0.21		0.18	~ 0.97
08431058-5250134	130.79	-52.83	G	3564 $\pm$ 56	14.79 $\pm$ 0.26	0.82	-	100.0	-0.23	-1.31	K	0.99	~ 0.47
08431303-5329082	130.80	-53.48	G	3400 $\pm$ 130	22.58 $\pm$ 0.37	0.86	-	100.0	-0.27	-1.61	K	0.40	~ 0.33
08431548-5238493	130.81	-52.64	G	3379 $\pm$ 134	15.19 $\pm$ 0.60	0.82	4.84 $\pm$ 0.13	190.5 $\pm$ 12.3	-0.26	-1.66	K	0.98	~ 0.31
08433841-5250551	130.91	-52.84	G	3390 $\pm$ 144	14.12 $\pm$ 0.57	0.85	4.65 $\pm$ 0.11	129.7 $\pm$ 13.4	-0.25	-1.83	K	0.98	~ 0.32
08440521-5253171	131.02	-52.88	U	5818 $\pm$ 62	14.09 $\pm$ 0.56	-	4.31 $\pm$ 0.09	184.2 $\pm$ 6.3	0.02	0.01	K	0.98	~ 1.05
08451883-5259257	131.32	-52.99	G	3386 $\pm$ 151	14.58 $\pm$ 0.52	0.83	4.79 $\pm$ 0.07	128.1 $\pm$ 25.8	-0.26	-2.03	K	0.98	~ 0.28
08452470-5301226	131.35	-53.02	G	3446 $\pm$ 118	14.14 $\pm$ 0.35	0.84	4.62 $\pm$ 0.15	190.8 $\pm$ 9.3	-0.23	-1.86	K	0.98	~ 0.35
08452692-5252020	131.36	-52.86	G	4827 $\pm$ 351	15.84 $\pm$ 0.25	0.97	-	201.9 $\pm$ 1.7	-0.02	-0.68	K	0.97	~ 0.75

Table 4.12: Properties of spectroscopic candidates of IC 4665.

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log ($L_{bol}/L_{\odot}$)	Known members	p_{cl} (%)	M _* (M _{$\odot$})
17442695+0554052	266.11	5.90	U	5340 $\pm$ 180	-13.66 $\pm$ 0.56	-	4.34 $\pm$ 0.25	300.9 $\pm$ 11.4	-0.01	-0.01	K	0.91	$\sim$ 1.10
17442698+0551456	266.11	5.86	G	3646 $\pm$ 82	-16.10 $\pm$ 0.58	0.82	-	175.6 $\pm$ 8.4	-0.19	-1.15	K	0.29	$\sim$ 0.54
17442711+0547196	266.11	5.78	U	5537 $\pm$ 108	-13.09 $\pm$ 0.56	-	4.40 $\pm$ 0.09	222.4 $\pm$ 11.9	0.01	-0.03	K	0.87	$\sim$ 1.00
17443019+0542317	266.12	5.70	G	3925 $\pm$ 50	-29.10 $\pm$ 0.39	0.87	-	80.1	-0.01	-1.26	-	0.02	$\sim$ 0.55
17443184+0550508	266.13	5.91	G	3945 $\pm$ 240	-13.55 $\pm$ 0.33	0.81	4.51 $\pm$ 0.07	120.7 $\pm$ 7.3	-0.15	-1.31	-	0.93	$\sim$ 0.52
17443565+0557208	266.14	5.95	U	6108 $\pm$ 45	-14.12 $\pm$ 0.56	-	3.80 $\pm$ 0.02	46.8 $\pm$ 6.8	-0.29	0.00	K	0.89	$\sim$ 1.10
17443667+0537161	266.15	5.62	G	6291 $\pm$ 112	1.32 $\pm$ 0.55	1.00	3.89	51.5 $\pm$ 6.9	-0.01	0.49	-	0.02	$\sim$ 1.30
17444099+0541558	266.17	5.69	U	7029 $\pm$ 142	-17.28 $\pm$ 0.56	-	4.12	16.9	-0.12	0.64	K	0.18	$\sim$ 1.48
17444501+0525346	266.18	5.42	U	6388 $\pm$ 72	-30.17 $\pm$ 0.56	-	3.85 $\pm$ 0.02	14.1	-0.13	0.52	-	0.02	$\sim$ 1.35
17444501+0602115	266.18	6.03	G	3624 $\pm$ 96	-31.28 $\pm$ 0.36	0.82	-	92.2 $\pm$ 8.6	-0.21	-0.96	-	0.02	$\sim$ 0.51
17445460+0539152	266.22	5.65	G	6163 $\pm$ 49	-13.47 $\pm$ 0.31	1.00	3.86 $\pm$ 0.04	9.6	-0.07	0.20	-	0.93	$\sim$ 1.19
17445810+0551329	266.24	5.85	G	5511 $\pm$ 124	-13.18 $\pm$ 0.27	0.99	4.48 $\pm$ 0.03	223.6 $\pm$ 5.5	-0.04	-0.00	K	0.89	$\sim$ 1.04
17450816+0604037	266.28	6.06	G	6084 $\pm$ 114	37.44 $\pm$ 0.29	0.99	4.10 $\pm$ 0.10	35.0 $\pm$ 5.5	-0.16	-0.03	-	0.01	$\sim$ 1.05
17451152+0532052	266.29	5.53	G	3714 $\pm$ 76	-1.09 $\pm$ 0.28	0.81	4.57 $\pm$ 0.16	86.9 $\pm$ 4.6	-0.19	-1.04	-	0.03	$\sim$ 0.60
17451204+0531523	266.30	5.53	U	3900 $\pm$ 70	-1.22 $\pm$ 0.27	0.82	4.64 $\pm$ 0.01	30.0	-0.12	-0.94	-	0.03	$\sim$ 0.67
17451225+0514597	266.30	5.24	G	6432 $\pm$ 125	-31.53 $\pm$ 0.56	-	3.99 $\pm$ 0.11	28.6	-0.34	0.60	-	0.02	$\sim$ 1.38
17451435+0518116	266.30	5.30	G	5161 $\pm$ 93	-13.86 $\pm$ 0.27	0.95	-	293.2 $\pm$ 2.5	-	-0.53	-	0.93	$\sim$ 0.82
17451670+0535564	266.31	5.89	G	3643 $\pm$ 82	-8.86 $\pm$ 0.34	0.81	4.56 $\pm$ 0.19	133.7 $\pm$ 7.6	-0.21	-1.21	-	0.12	$\sim$ 0.52
17451905+0535491	266.32	5.59	G	3606 $\pm$ 82	32.88 $\pm$ 0.33	0.82	-	100.0	-0.26	-1.29	-	0.01	$\sim$ 0.51
17451940+0547401	266.33	5.79	G	5309 $\pm$ 106	-12.63 $\pm$ 0.30	0.99	4.46 $\pm$ 0.09	244.3 $\pm$ 3.1	-0.05	-0.09	K	0.63	$\sim$ 1.01
17451961+0539392	266.33	5.66	G	3527 $\pm$ 60	-16.30 $\pm$ 0.35	0.85	-	106.3 $\pm$ 6.5	-0.23	-1.17	-	0.25	$\sim$ 0.44
17452041+0528130	266.33	5.47	G	3979 $\pm$ 239	-4.33 $\pm$ 0.95	0.81	4.59 $\pm$ 0.06	34.6	-0.35	-1.80	-	0.04	$\sim$ 0.40
17452363+0518410	266.34	5.31	G	6111 $\pm$ 117	-10.97 $\pm$ 0.27	0.99	4.05 $\pm$ 0.11	37.1 $\pm$ 3.3	-0.08	0.03	-	0.23	$\sim$ 1.05
17452508+0551388	266.35	5.86	G	5349 $\pm$ 165	-12.35 $\pm$ 0.29	0.99	4.41 $\pm$ 0.17	310.6 $\pm$ 6.3	-0.04	-0.09	K	0.48	$\sim$ 0.99
17452869+0524053	266.36	5.40	G	6049 $\pm$ 135	-8.68 $\pm$ 0.28	0.99	4.07 $\pm$ 0.18	15.8	-0.32	-0.12	-	0.11	$\sim$ 0.98
17452906+0601462	266.37	6.02	U	6475 $\pm$ 127	-8.83 $\pm$ 0.56	-	4.01	110.8 $\pm$ 22.5	-0.06	0.70	-	0.12	$\sim$ 1.42
17453005+0548490	266.37	5.81	G	3761 $\pm$ 102	25.31 $\pm$ 0.32	0.83	-	100.0	-0.17	-1.22	-	0.01	$\sim$ 0.56
17453297+0513313	266.38	5.22	G	6025 $\pm$ 196	-9.88 $\pm$ 0.30	1.00	4.05 $\pm$ 0.01	100.9 $\pm$ 5.5	0.10	-0.24	-	0.16	$\sim$ 0.95
17453451+0529538	266.39	5.49	G	3613 $\pm$ 64	-13.95 $\pm$ 0.32	0.82	-	100.0	-0.21	-1.15	K	0.92	$\sim$ 0.52
17453550+0519023	266.39	5.31	U	6314 $\pm$ 135	0.82 $\pm$ 0.56	-	3.87	13.2	-0.04	0.56	-	0.02	$\sim$ 1.35
17453881+0536232	266.41	5.60	U	6270 $\pm$ 93	-13.30 $\pm$ 0.56	-	3.92	113.0 $\pm$ 10.0	-0.03	0.47	K	0.90	$\sim$ 1.30
17453967+0530530	266.41	5.51	G	3512 $\pm$ 148	-13.29 $\pm$ 0.88	0.83	-	117.8 $\pm$ 8.1	-0.14	-0.82	-	0.87	$\sim$ 0.40
17454034+0557260	266.41	5.95	G	3984 $\pm$ 185	-32.48 $\pm$ 0.37	0.85	4.44 $\pm$ 0.20	104.2 $\pm$ 7.0	-0.11	-1.41	-	0.01	$\sim$ 0.50
17454087+0526223	266.42	5.43	G	6362 $\pm$ 56	-1.47 $\pm$ 0.28	0.99	-	6.6	-0.17	0.02	-	0.03	$\sim$ 1.05
17454102+0554235	266.42	5.90	G	3927 $\pm$ 131	-11.31 $\pm$ 0.31	0.85	-	20.9	-0.07	-1.17	-	0.27	$\sim$ 0.57
17454123+0533444	266.42	5.56	G	6572 $\pm$ 106	-10.41 $\pm$ 0.44	0.99	4.1	76.6 $\pm$ 5.8	-0.03	0.75	-	0.19	$\sim$ 1.45
17454235+0606281	266.42	6.10	G	3935 $\pm$ 204	-38.76 $\pm$ 0.45	0.84	-	105.8 $\pm$ 11.7	-0.17	-1.25	-	0.01	$\sim$ 0.56
17454623+0514595	266.44	5.24	G	6657 $\pm$ 54	8.79 $\pm$ 0.49	1.00	4.27	19.8	0.01	0.22	-	0.01	$\sim$ 1.30
17454646+0543549	266.44	5.73	G	3681 $\pm$ 75	-20.75 $\pm$ 0.30	0.83	-	131.1 $\pm$ 5.7	-0.19	-0.95	K	0.07	$\sim$ 0.56
17454987+0607516	266.45	6.13	G	3965 $\pm$ 150	-76.60 $\pm$ 0.39	0.87	-	73.5 $\pm$ 4.5	-0.28	-1.15	-	0.01	$\sim$ 0.59
17455281+0517052	266.47	5.28	G	6175 $\pm$ 75	-13.45 $\pm$ 0.33	1.00	3.92 $\pm$ 0.06	64.0 $\pm$ 3.0	-0.10	-0.34	-	0.92	$\sim$ 0.91
17455394+0559234	266.47	5.98	G	3887 $\pm$ 176	-5.16 $\pm$ 0.39	0.80	4.59 $\pm$ 0.06	134.7 $\pm$ 6.5	-0.14	-1.39	-	0.05	$\sim$ 0.50
17455598+0602542	266.48	6.04	G	5653 $\pm$ 97	-14.64 $\pm$ 0.32	0.99	4.49 $\pm$ 0.13	239.6 $\pm$ 5.6	0.01	0.07	K	0.71	$\sim$ 1.10
17455673+0552240	266.48	5.87	G	3995 $\pm$ 157	11.00 $\pm$ 0.31	0.84	4.51 $\pm$ 0.07	39.6	-0.26	-0.61	-	0.01	$\sim$ 0.79
17455679+0522334	266.48	5.37	G	5760 $\pm$ 81	-24.73 $\pm$ 0.32	1.00	-	138.7 $\pm$ 3.2	-	0.30	-	0.04	$\sim$ 1.21
17455679+0601044	266.48	6.01	U	6284 $\pm$ 75	-35.36 $\pm$ 0.56	-	4.15 $\pm$ 0.01	13.6	0.16	0.68	-	0.01	$\sim$ 1.40
17455931+0541010	266.49	5.68	G	3899 $\pm$ 112	-44.91 $\pm$ 0.43	0.82	4.58 $\pm$ 0.08	99.7 $\pm$ 7.8	-0.08	-1.52	-	0.01	$\sim$ 0.46
17455975+0604227	266.49	6.07	G	3293 $\pm$ 95	-78.39 $\pm$ 0.43	0.86	-	100.0	-	-0.52	-	0.03	$\sim$ 0.25
17460389+0520444	266.51	5.34	G	6215 $\pm$ 67	-19.50 $\pm$ 0.30	0.99	4.15	64.8 $\pm$ 3.6	0.27	-0.03	-	0.09	$\sim$ 1.05
17460577+0541546	266.52	5.69	G	3723 $\pm$ 68	-109.31 $\pm$ 1.35	0.81	4.53 $\pm$ 0.16	32.4	-0.20	-1.33	-	-	-
17460709+0555486	266.52	5.93	G	6079 $\pm$ 42	-16.80 $\pm$ 0.32	0.99	4.43 $\pm$ 0.06	181.1 $\pm$ 1.6	0.09	0.35	K	0.20	$\sim$ 1.20
17461081+0557072	266.54	5.95	G	3452 $\pm$ 63	-8.83 $\pm$ 0.26	0.82	4.60 $\pm$ 0.19	163.1 $\pm$ 6.3	-0.25	-1.03	-	0.12	$\sim$ 0.37
17461159+0605417	266.54	6.09	G	3437 $\pm$ 107	-15.90 $\pm$ 1.82	0.79	4.70 $\pm$ 0.04	177.1 $\pm$ 14.4	-0.23	-0.96	-	0.68	$\sim$ 0.35

Table 4.12 – Continue

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{hot} / L _⊙)	Known members	p _{cl} (%)	M _* (M _⊙)
17461198+0541258	266.54	5.69	G	4985 ± 178	-14.40 ± 0.30	0.98	-	262.9 ± 6.4	-0.01	-0.33	K	0.82	~ 0.90
17461267+0606091	266.55	6.10	G	6171 ± 67	17.44 ± 0.27	0.99	4.02 ± 0.19	44.2 ± 6.0	-0.31	0.37		0.01	~ 1.26
17461292+0559296	266.55	5.99	G	3443 ± 91	-14.65 ± 0.51	0.83	-	100.0	-0.22	-1.10		0.79	~ 0.36
17461351+0554301	266.55	5.90	G	3608 ± 116	-29.71 ± 0.35	0.85	-	64.5 ± 7.8	-0.24	-1.14		0.02	~ 0.51
17461438+0550362	266.55	5.84	G	3873 ± 61	-12.22 ± 0.29	0.82	4.56 ± 0.09	122.9 ± 5.2	-0.20	-0.91		0.43	~ 0.68
17461523+0601186	266.56	6.02	G	3944 ± 183	7.69 ± 0.51	0.86	-	33.7	-0.07	-1.28		0.01	~ 0.55
17461801+0523216	266.57	5.38	G	3468 ± 130	-5.875 ± 0.45	0.82	-	128.1 ± 9.9	-0.25	-1.24		0.06	~ 0.38
17461845+0528170	266.57	5.47	U	6058 ± 37	-36.51 ± 0.56	-	4.15 ± 0.05	71.3 ± 11.7	0.09	0.54		0.01	~ 1.33
17461964+0534066	266.58	5.56	U	7055 ± 131	-26.96 ± 0.56	-	4.1	13.1	-0.05	0.66		0.03	~ 1.48
17462261+0531159	266.59	5.52	G	6847 ± 36	-25.26 ± 3.64	1.00	4.22	4.8	-0.09	0.31		0.06	~ 1.35
17462473+0517214	266.60	5.28	U	5960 ± 99	-13.63 ± 0.56	-	4.37	155.4 ± 14.1	0.00	0.17	K	0.91	~ 1.15
17462477+0535381	266.60	5.59	G	5143 ± 43	-7.25 ± 0.55	0.98	-	273.6 ± 9.4	-0.09	-0.16	K	0.08	~ 0.99
17462645+0535236	266.61	5.88	G	6156 ± 110	-6.38 ± 0.28	1.00	3.99 ± 0.12	49.5 ± 2.2	-0.08	0.06		0.06	~ 1.05
17462680+0605304	266.61	6.09	G	3582 ± 77	10.67 ± 0.37	0.78	4.70 ± 0.01	144.2 ± 8.9	-0.24	-1.18		0.01	~ 0.49
17462804+0533207	266.61	5.55	G	6056 ± 53	-0.96 ± 0.37	1.00	4.09 ± 0.14	95.4 ± 3.1	0.04	-0.08		0.03	~ 1.02
17462833+0603129	266.61	6.05	G	6298 ± 41	-40.70 ± 0.27	1.00	-	65.8 ± 7.5	0.18	0.36		0.01	~ 1.27
17463149+0605280	266.63	6.09	G	6029 ± 100	-14.52 ± 0.42	0.99	4.2	162.5 ± 3.2	0.02	0.43	K	0.81	~ 1.28
17463397+0528512	266.64	5.48	G	6241 ± 53	-62.56 ± 0.30	1.00	4.00	53.2 ± 5.2	-0.27	-0.07		0.01	~ 1.03
17463553+0531076	266.64	5.51	G	3718 ± 67	-14.48 ± 0.33	0.81	4.53 ± 0.20	125.6 ± 6.2	-0.19	-1.16	K	0.80	~ 0.57
17463638+0604294	266.65	6.07	G	3972 ± 211	-49.42 ± 0.47	0.84	4.46 ± 0.14	44.6	-0.10	-1.52		0.01	~ 0.48
17464015+0602453	266.66	6.04	G	3593 ± 93	0.52 ± 0.33	0.78	4.66 ± 0.07	144.2 ± 8.3	-0.24	-1.03		0.02	~ 0.49
17464182+0558289	266.67	5.97	G	3995 ± 173	-3.21 ± 0.40	0.85	4.46 ± 0.15	100.0	0.01	-1.65		0.04	~ 0.42
17464228+0601506	266.67	6.03	G	3796 ± 80	-13.48 ± 0.37	0.82	-	49.8	-0.17	-1.42		0.92	~ 0.50
17464332+0535140	266.68	5.58	G	3984 ± 157	31.49 ± 0.30	0.87	-	80.8 ± 4.2	-0.22	-0.98		0.01	~ 0.66
17464426+0528335	266.68	5.47	G	6451 ± 36	9.15 ± 0.31	0.99	-	16.6	0.07	0.23		0.01	~ 1.27
17464511+0537339	266.68	5.62	G	6001 ± 125	18.70 ± 0.25	0.99	4.20 ± 0.06	20.8	0.17	0.31		0.01	~ 1.19
17464549+0554555	266.68	5.91	G	3540 ± 45	-79.11 ± 0.77	0.84	-	141.2 ± 11.6	-0.27	-0.92		0.01	~ 0.43
17464824+0554522	266.70	5.91	G	3996 ± 164	-17.75 ± 0.34	0.84	4.49 ± 0.10	99.4 ± 6.1	-0.23	-1.19		0.15	~ 0.58
17465203+0559079	266.71	5.98	G	6114 ± 71	17.02 ± 0.26	1.00	3.87 ± 0.05	1.9	-0.31	0.05		0.01	~ 1.05
17465546+0556081	266.73	5.93	G	3912 ± 115	-57.80 ± 0.34	0.83	4.52 ± 0.15	89.0 ± 5.0	-0.18	-1.26		0.01	~ 0.55
17465562+0530294	266.73	5.50	G	3864 ± 191	-0.14 ± 0.78	0.77	4.70 ± 0.15	48.7	-0.18	-1.29		0.02	~ 0.54
17465585+0523343	266.73	5.39	G	6351 ± 24	-54.09 ± 0.26	1.00	3.98	27.0 ± 1.3	0.08	0.11		0.01	~ 1.16
17465642+0547446	266.73	5.79	G	3973 ± 222	-14.39 ± 0.28	0.84	4.45 ± 0.16	27.6	0.01	-0.99	K	0.82	~ 0.65
17465904+0545448	266.74	5.76	G	3323 ± 40	-46.78 ± 0.42	0.88	-	100.0	-0.25	-0.73		0.01	~ 0.27
17470039+0606443	266.75	6.11	G	3740 ± 108	-74.45 ± 0.93	0.80	4.58 ± 0.15	148.1 ± 11.8	-0.20	-1.28		0.01	~ 0.53
17470103+0606402	266.75	6.11	G	6306 ± 25	-37.78 ± 0.25	0.99	4.16	42.7 ± 5.2	0.10	0.29		0.01	~ 1.27
17470638+0526026	266.77	5.43	U	6386 ± 214	7.71 ± 0.56	-	4.07 ± 0.25	34.5 ± 6.4	-0.01	0.58		0.01	~ 1.37
17470932+0541020	266.78	5.68	G	3888 ± 42	-32.54 ± 0.46	0.83	-	48.7	0.30	-1.75		0.01	~ 0.32
17470994+0551383	266.79	5.86	G	3527 ± 63	-38.95 ± 0.40	0.83	-	169.9 ± 9.2	-0.27	-1.17		0.01	~ 0.44
17470996+0543141	266.79	5.72	G	3644 ± 19	-31.90 ± 0.33	0.82	-	110.4 ± 8.8	-	-1.37		0.01	~ 0.50
17470997+0529064	266.79	5.48	G	3664 ± 124	-25.33 ± 0.32	0.82	4.56 ± 0.19	100.0	-0.21	-0.89		0.03	~ 0.54
17471253+0542149	266.80	5.70	G	3412 ± 144	169.82 ± 2.51	0.92	-	243.8 ± 20.9	-0.27	-0.72		-	-
17471544+0556358	266.81	5.94	G	5733 ± 118	-13.27 ± 0.71	0.99	4.42	251.3 ± 2.7	0.06	0.13	K	0.88	~ 1.15
17471599+0535094	266.81	5.58	G	7661 ± 26	-1.50 ± 0.01	1.00	-	28.7	-	0.73		0.03	~ 1.60
17471834+0530062	266.82	5.50	G	6228 ± 132	-45.88 ± 0.37	1.00	3.97 ± 0.16	61.1 ± 1.6	-0.18	0.10	K	0.01	~ 1.10
17471842+0526438	266.82	5.44	G	6007 ± 58	13.32 ± 0.25	0.99	4.05 ± 0.01	53.6 ± 3.3	0.21	-0.40		0.01	~ 1.28
17471868+0520485	266.82	5.34	G	6072 ± 50	2.14 ± 0.27	0.99	4.18 ± 0.08	31.6 ± 7.3	0.14	-0.32		0.02	~ 0.92
17471950+0530414	266.83	5.51	G	3496 ± 54	-22.15 ± 0.47	0.81	4.66 ± 0.10	162.5 ± 11.2	-0.25	-1.41		0.05	~ 0.41
17472001+0546537	266.83	5.78	G	3564 ± 52	-13.37 ± 0.29	0.81	-	138.5 ± 5.5	-0.21	-1.20	K	0.92	~ 0.47
17472070+0604000	266.83	6.06	G	6001 ± 124	-17.11 ± 0.27	0.99	4.04 ± 0.16	15.6	-0.23	0.20		0.18	~ 1.13
17472159+0548584	266.83	5.81	G	6457 ± 77	10.43 ± 0.83	1.00	4.07 ± 0.03	49.9 ± 2.6	-0.22	0.20		0.01	~ 1.20
17472613+0544284	266.85	5.74	G	3504 ± 46	-13.58 ± 0.41	0.84	-	134.6 ± 9.8	-0.22	-1.47		0.92	~ 0.42
17472923+0554503	266.87	5.91	G	3972 ± 202	-37.10 ± 0.32	0.85	-	17.6	0.03	-1.08		0.01	~ 0.60
17473104+0522166	266.87	5.37	G	6052 ± 194	-5.49 ± 0.25	0.99	4.19 ± 0.00	69.05 ± 1.5	0.03	-0.05	K	0.05	~ 1.05
17473252+0552316	266.88	5.87	U	6186 ± 38	-14.25 ± 0.56	-	4.28 ± 0.02	77.0 ± 22.6	0.14	0.33		0.88	~ 1.27

Table 4.12 – *Continue*

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s $^{-1}$)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L_{bol} / $L_{\odot}$)	Known members	p_{cl} (%)	M _* (M $_{\odot}$)
17473331+0531460	266.88	5.52	G	5781 $\pm$ 58	-13.53 $\pm$ 0.36	0.98	4.38	242.8 $\pm$ 2.7	0.11	0.10	K	0.92	$\sim$ 1.11
17473922+0519144	266.91	5.32	G	6047 $\pm$ 66	7.34 $\pm$ 0.26	0.99	4.15 $\pm$ 0.01	40.6 $\pm$ 1.6	-0.01	-0.22		0.01	$\sim$ 1.05
17473947+0527101	266.91	5.45	G	6289 $\pm$ 112	5.00 $\pm$ 0.26	0.99	4.13 $\pm$ 0.17	11.3	-0.04	0.03		0.01	$\sim$ 1.18
17474322+0540474	266.93	5.67	U	7099 $\pm$ 162	21.08 $\pm$ 0.56	-	4.03	8.2	-0.13	0.64		0.01	$\sim$ 1.48
17474362+0551253	266.93	5.85	G	6265 $\pm$ 33	-57.91 $\pm$ 0.27	0.99	4.11	19.5 $\pm$ 1.5	-0.28	0.34		0.01	$\sim$ 1.27
17474403+0521592	266.93	5.36	G	5517 $\pm$ 220	-12.68 $\pm$ 0.25	0.99	4.11 $\pm$ 0.15	232.0 $\pm$ 1.6	0.11	-0.02		0.63	$\sim$ 1.02
17474709+0515204	266.94	5.25	G	6113 $\pm$ 46	-13.72 $\pm$ 0.25	0.99	4.09 $\pm$ 0.12	47.9 $\pm$ 1.1	-0.05	0.23		0.94	$\sim$ 1.20
17474798+0546505	266.94	5.78	G	3578 $\pm$ 87	24.79 $\pm$ 0.26	0.83	-	100.8 $\pm$ 3.4	-0.23	-0.71		0.01	$\sim$ 0.45
17475221+0555454	266.96	5.92	G	3983 $\pm$ 128	-69.32 $\pm$ 0.37	0.84	4.50 $\pm$ 0.09	91.2 $\pm$ 4.8	-0.28	-1.09		0.01	$\sim$ 0.60
17475250+0513595	266.96	5.23	U	6317 $\pm$ 131	-35.54 $\pm$ 0.56	-	3.88	76.9 $\pm$ 15.2	-0.01	0.68		0.01	$\sim$ 1.40
17475954+0540044	266.99	5.66	G	3554 $\pm$ 101	-33.84 $\pm$ 0.28	0.80	4.60 $\pm$ 0.16	134.3 $\pm$ 4.7	-0.26	-0.76		0.01	$\sim$ 0.43
17480166+0605412	267.00	6.09	G	6193 $\pm$ 54	-36.66 $\pm$ 0.27	1.00	3.84 $\pm$ 0.05	19.9 $\pm$ 6.2	-0.09	0.10	K	0.01	$\sim$ 1.19
17480498+0548421	267.02	5.81	U	5239 $\pm$ 78	-13.63 $\pm$ 0.56	-	4.52	227.9 $\pm$ 12.1	-0.05	-0.01		0.91	$\sim$ 1.15

Table 4.13: Properties of spectroscopic candidates of NGC 2547.

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{bol} /L _⊙)	Known members	P _{d,A} (%)	P _{d,B} (%)	M _* (M _⊙)
08073009-4911229	121.87	-49.18	G	3606 ± 24	505.01 ± 2.38	0.83	-	130.6 ± 11.4	-	-1.55	-	-	-	~ 0.45
08073463-4904107	121.89	-49.06	G	4365 ± 267	60.05 ± 2.28	0.96	-	392.9 ± 12.0	-0.15	-0.55	-	0.38	0.04	~ 0.87
08073999-4903023	121.91	-49.05	G	3530 ± 43	20.51 ± 0.29	0.86	-	401.5 ± 8.5	-0.23	-1.13	-	0.08	0.71	~ 0.44
08074077-4927238	121.91	-49.45	G	3540 ± 28	402.70 ± 1.49	0.83	-	198.3 ± 11.9	-	-1.49	-	-	-	~ 0.44
08074194-4908306	121.92	-49.14	G	3563 ± 50	8.11 ± 0.59	0.79	4.68 ± 0.06	102.7 ± 11.8	-0.25	-1.51	-	0.17	< 0.01	~ 0.68
08074609-4915345	121.94	-49.25	G	3994 ± 140	13.12 ± 0.26	0.85	4.46 ± 0.15	44.9 ± 2.9	0.02	-0.91	-	0.98	< 0.01	~ 0.44
08075151-4919093	121.96	-49.31	G	3453 ± 65	469.32 ± 0.59	0.84	-	114.6 ± 9.5	-0.25	-1.45	-	-	-	~ 0.37
08080644-4920336	122.02	-49.34	G	3415 ± 26	12.82 ± 0.47	0.83	-	211.9 ± 11.9	-	-1.50	-	0.98	< 0.01	~ 0.34
08080667-4911212	122.02	-49.18	U	6189 ± 93	63.03 ± 0.56	-	4.09 ± 0.05	27.1	0.10	-0.06	-	0.42	0.05	~ 1.11
08080675-4910331	122.02	-49.17	G	3291 ± 12	468.03 ± 5.05	0.66	-	236.4 ± 21.6	-	-1.44	-	-	-	~ 0.24
08080817-4913590	122.03	-49.23	G	6166 ± 39	10.32 ± 0.27	0.99	3.87 ± 0.01	23.9	0.15	-0.17	-	0.70	< 0.01	~ 1.10
08081164-4909164	122.04	-49.15	G	3332 ± 20	13.33 ± 0.97	0.84	-	142.2 ± 17.5	-	-1.66	-	0.96	< 0.01	~ 0.26
08081196-4930268	122.04	-49.50	G	3342 ± 21	19.03 ± 0.42	0.86	-	585.8 ± 42.5	-	-1.51	-	0.13	0.64	~ 0.27
08081455-4909326	122.06	-49.15	G	3479 ± 122	12.38 ± 0.42	0.81	-	100.0	-0.25	-1.32	-	0.97	< 0.01	~ 0.39
08081758-4914493	122.07	-49.24	G	3432 ± 59	16.76 ± 0.40	0.85	-	534.3 ± 34.7	-0.25	-1.25	-	0.49	0.06	~ 0.35
08082095-4902029	122.08	-49.03	G	3612 ± 63	20.05 ± 0.27	0.84	-	425.6 ± 23.9	-0.21	-0.96	-	0.07	0.76	~ 0.50
08082690-4859131	122.11	-48.98	G	4481 ± 278	12.96 ± 0.25	0.93	-	268.7 ± 2.9	-0.04	-0.76	-	0.98	< 0.01	~ 0.70
08083389-4907176	122.14	-49.12	G	4970 ± 180	10.05 ± 0.57	0.95	-	349.0 ± 12.2	-	-0.75	-	0.70	< 0.01	~ 0.74
08083560-4904333	122.14	-49.16	G	3329 ± 50	15.56 ± 0.78	0.86	-	100.0	-0.27	-1.21	-	0.73	0.02	~ 0.67
08083609-4852238	122.15	-48.87	G	3836 ± 37	7.70 ± 0.32	0.84	-	104.7 ± 4.0	-0.17	-0.91	-	0.17	< 0.01	~ 0.67
08083830-4932320	122.15	-49.54	G	3625 ± 76	11.99 ± 0.31	0.82	-	187.2 ± 5.5	-0.21	-1.23	-	0.96	< 0.01	~ 0.52
08083843-4931303	122.16	-49.52	G	3431 ± 60	12.26 ± 0.47	0.83	-	100.0	-0.27	-1.50	-	0.97	< 0.01	~ 0.35
08083910-4904025	122.16	-49.06	G	3582 ± 125	19.09 ± 0.29	0.85	-	311.1 ± 16.9	-0.22	-1.38	-	0.12	0.65	~ 0.47
08084089-4858085	122.17	-48.96	G	6275 ± 31	-0.85 ± 0.26	1.00	4.00	12.3	-0.05	0.06	-	0.20	< 0.01	~ 1.05
08084459-4934202	122.18	-49.57	G	4724 ± 350	12.08 ± 0.36	0.95	-	348.0 ± 14.0	-0.02	-0.25	-	0.97	< 0.01	~ 1.05
08084618-4916240	122.19	-49.27	G	3519 ± 39	16.20 ± 0.28	0.80	4.68 ± 0.04	100.0	-0.22	-1.29	-	0.56	0.04	~ 0.43
08084975-4924561	122.20	-49.41	G	6283 ± 53	6.57 ± 0.28	1.00	3.86 ± 0.06	12.6	-0.24	0.13	-	0.39	< 0.01	~ 1.19
08085197-4930499	122.21	-49.51	G	3872 ± 119	-9.05 ± 0.26	0.82	4.55 ± 0.16	88.6 ± 2.6	-0.16	-0.86	-	0.17	< 0.01	~ 0.69
08085448-4859096	122.22	-48.98	G	3343 ± 68	7.721 ± 1.94	0.88	-	100.0	-0.27	-1.16	-	0.68	< 0.01	~ 0.28
08085677-4926054	122.23	-49.43	G	3733 ± 161	39.66 ± 0.33	0.82	4.36 ± 0.10	125.3 ± 6.5	-0.27	-1.49	-	0.13	0.02	~ 0.48
08085758-4911261	122.23	-49.19	G	3475 ± 51	12.07 ± 0.30	0.81	4.67 ± 0.07	149.1 ± 6.5	-0.22	-1.48	-	0.97	< 0.01	~ 0.40
08085779-4901171	122.24	-49.02	G	3725 ± 99	12.49 ± 0.31	0.82	-	100.0	-0.19	-1.39	-	0.98	< 0.01	~ 0.50
08085790-4854189	122.24	-48.90	U	6376 ± 108	21.68 ± 0.56	-	4.24 ± 0.09	13.9	0.27	-2.32	-	0.16	0.39	~ 1.18
08085856-4911171	122.24	-49.18	G	3408 ± 26	15.31 ± 0.36	0.82	-	179.3 ± 12.5	-	-1.65	-	0.69	0.02	~ 0.33
08090022-4920332	122.25	-49.34	G	5127 ± 172	12.61 ± 0.26	0.96	-	248.9 ± 7.5	-	-0.65	-	0.98	< 0.01	~ 0.77
08090250-4858172	122.25	-48.97	G	5732 ± 71	23.51 ± 0.26	0.99	4.56 ± 0.10	196.7 ± 6.2	0.04	-0.11	-	0.19	0.09	~ 1.00
08090287-4906022	122.26	-49.10	G	6451 ± 17	14.34 ± 0.29	0.99	4.22	111.1 ± 5.0	0.07	0.39	-	0.89	< 0.01	~ 1.27
08090470-4924396	122.26	-49.41	G	3549 ± 41	13.55 ± 0.36	0.81	-	100.0	-0.23	-1.28	-	0.97	< 0.01	~ 0.46
08090471-4933274	122.26	-49.55	G	3519 ± 42	16.61 ± 0.29	0.85	-	100.0	-0.22	-1.04	-	0.51	0.05	~ 0.42
08090720-4919144	122.28	-49.32	G	4747 ± 316	12.31 ± 0.26	0.95	-	232.8 ± 6.4	0.05	-0.69	-	0.96	< 0.01	~ 0.53
08090869-4935130	122.28	-49.58	G	3277 ± 34	95.26 ± 1.94	0.85	4.62 ± 0.19	89.9 ± 10.8	-0.18	-1.58	-	0.93	< 0.01	~ 0.28
08090911-4922405	122.28	-49.37	G	3368 ± 49	12.20 ± 0.41	0.83	4.61 ± 0.19	100.0	-0.25	-1.20	-	0.95	< 0.01	~ 0.87
08091025-4902250	122.29	-49.04	G	4308 ± 589	16.25 ± 0.30	0.87	-	294.4 ± 4.2	-0.06	-1.05	-	0.92	< 0.01	~ 0.84
08091082-4929167	122.29	-49.48	G	3648 ± 75	11.88 ± 0.27	0.82	-	100.0	-0.19	-1.22	-	0.96	< 0.01	~ 0.53
08091111-4914183	122.29	-49.23	G	3352 ± 79	11.43 ± 0.56	0.84	-	100.0	-0.27	-1.21	-	0.94	< 0.01	~ 0.28
08091194-4926542	122.29	-49.44	G	3556 ± 164	14.13 ± 0.47	0.82	-	100.0	-0.12	-1.51	-	0.93	< 0.01	~ 0.44
08091307-4925401	122.30	-49.42	G	5234 ± 77	13.87 ± 0.33	0.98	4.52	281.9 ± 8.6	-0.08	-0.41	-	0.95	< 0.01	~ 0.87
08091332-4857599	122.30	-48.96	G	5105 ± 83	11.43 ± 0.26	0.98	3.84 ± 0.11	213.2 ± 4.6	0.01	-0.36	-	0.92	< 0.01	~ 0.84
08091385-4933181	122.30	-49.55	G	3414 ± 22	17.33 ± 0.32	0.87	-	232.1 ± 11.0	-	-1.30	-	0.43	0.10	~ 0.34
08091645-4907239	122.31	-49.12	G	3528 ± 38	12.55 ± 0.32	0.85	-	60.9 ± 4.9	-0.29	-1.17	-	0.98	< 0.01	~ 0.43
08091657-4909309	122.31	-49.15	G	4340 ± 459	11.87 ± 0.26	0.89	-	344.9 ± 9.6	-0.06	-1.10	-	0.96	< 0.01	~ 0.62
08091713-4925277	122.32	-49.42	G	3616 ± 185	12.85 ± 1.24	0.78	4.75 ± 0.15	100.0	-0.20	-1.51	-	0.96	< 0.01	~ 0.52
08092131-4905431	122.33	-49.09	G	3829 ± 106	12.60 ± 0.30	0.83	-	106.3 ± 4.3	-0.16	-1.21	-	0.98	< 0.01	~ 0.56

Table 4.13 – *Continue*

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{bol} / L _⊙)	Known members	p _{d,A} (%)	p _{d,B} (%)	M _* (M _⊙)
08092131-4905540	122.33	-49.09	G	3569 ± 67	10.65 ± 0.27	0.83	-	77.1 ± 3.1	-0.24	-1.06		0.76	< 0.01	~ 0.47
08092276-4916309	122.34	-49.27	G	5306 ± 78	12.82 ± 0.27	0.98	4.43 ± 0.15	226.8 ± 3.4	-0.07	-0.26		0.98	< 0.01	~ 0.90
08092293-4907575	122.34	-49.13	G	6293 ± 100	13.16 ± 0.27	0.99	4.49 ± 0.18	121.5 ± 4.5	0.01	-0.23	K	0.98	< 0.01	~ 1.20
08092438-4906282	122.35	-49.10	G	3725 ± 114	11.88 ± 0.28	0.82	-	114.0 ± 3.2	-0.20	-0.29	K	0.96	< 0.01	~ 0.53
08092475-4911138	122.35	-49.18	G	3587 ± 31	18.50 ± 1.30	0.95	-	117.8 ± 13.6	-	-1.82		0.21	0.50	~ 0.39
08092574-4903156	122.35	-49.05	G	3406 ± 33	13.25 ± 1.11	0.81	-	72.3	-	-1.67		0.96	< 0.01	~ 0.33
08092586-4932443	122.35	-49.54	G	3624 ± 65	20.15 ± 0.38	0.84	-	357.5 ± 18.3	-0.21	-0.96		0.08	0.74	~ 0.51
08092592-4906585	122.35	-49.16	G	3346 ± 39	12.06 ± 0.69	0.82	4.73 ± 0.01	100.0	-0.17	-1.32		0.97	< 0.01	~ 0.27
08092678-4932554	122.36	-49.54	G	3792 ± 76	11.80 ± 0.28	0.82	-	134.2 ± 4.2	-0.17	-1.06		0.95	< 0.01	~ 0.62
08093010-4850777	122.37	-48.91	G	3388 ± 47	13.35 ± 0.64	0.83	4.63 ± 0.16	100.0	-0.27	-1.27		0.97	< 0.01	~ 0.31
08093053-4920443	122.37	-49.34	G	7024 ± 13	14.23 ± 0.24	0.99	-	54.8 ± 1.4	-0.07	0.66		0.90	< 0.01	~ 1.49
08093277-4855312	122.38	-48.92	G	3625 ± 20	26.57 ± 0.33	0.80	-	100.0	-	-1.46		0.16	0.04	~ 0.47
08093443-4906027	122.39	-49.10	G	3279 ± 12	20.44 ± 0.53	0.88	-	687.6 ± 22.9	-	-1.51		0.08	0.71	~ 0.23
08093593-4927191	122.39	-49.45	G	3991 ± 149	12.48 ± 0.25	0.88	-	62.9 ± 2.1	-0.05	-0.66		0.98	< 0.01	~ 0.78
08093744-4902028	122.40	-49.03	G	3551 ± 47	12.20 ± 0.66	0.79	4.68 ± 0.03	48.0	-0.22	-1.31		0.97	< 0.01	~ 0.46
08093925-4928494	122.41	-49.48	G	3687 ± 237	14.89 ± 0.92	0.83	4.46 ± 0.19	137.8 ± 9.4	-0.14	-1.57		0.89	< 0.01	~ 0.45
08094053-4930204	122.41	-49.50	G	3437 ± 64	14.12 ± 0.45	0.82	4.62 ± 0.18	118.7 ± 10.1	-0.25	-1.47		0.93	< 0.01	~ 0.36
08094083-4923503	122.42	-49.39	G	5658 ± 143	11.26 ± 0.69	0.99	4.42	238.5 ± 2.5	0.04	-0.17	K	0.93	< 0.01	~ 0.95
08094507-4856307	122.43	-48.94	G	6025 ± 96	14.87 ± 0.52	1.00	-	145.6 ± 4.5	-0.02	0.16		0.82	0.01	~ 1.10
08094510-4846520	122.43	-48.78	G	3782 ± 467	13.54 ± 0.57	0.83	4.47 ± 0.12	100.0	-0.23	-1.08		0.97	< 0.01	~ 0.61
08094556-4917365	122.43	-49.29	G	4274 ± 581	12.50 ± 0.57	0.85	-	353.3 ± 20.2	-0.01	-1.15	K	0.97	< 0.01	~ 0.61
08094610-4914270	122.44	-49.24	U	7650 ± 50	18.27 ± 0.56	-	4.1 ± 0.2	-	-0.00	0.82	K	0.25	0.39	~ 1.65
08094673-4902546	122.44	-49.04	G	3532 ± 29	18.42 ± 1.44	0.85	-	81.7 ± 12.3	-	-1.61		0.23	0.48	~ 0.42
08094684-4907198	122.44	-49.12	G	5893 ± 65	12.12 ± 0.26	0.99	4.04 ± 0.01	194.4 ± 1.3	0.05	0.04	K	0.97	< 0.01	~ 1.03
08094807-4936237	122.45	-49.60	G	5189 ± 44	29.20 ± 0.27	0.98	4.03 ± 0.01	178.1 ± 3.4	0.03	-0.54		0.03	0.14	~ 0.83
08095021-4927232	122.45	-49.45	G	3654 ± 135	12.46 ± 0.32	0.81	4.57 ± 0.16	100.0	-0.19	-1.45		0.98	< 0.01	~ 0.48
08095046-4846112	122.46	-48.76	G	3305 ± 16	47.4 ± 1.58	0.83	-	48.5	-	-1.49		-	-	-
08095071-4910383	122.46	-49.17	G	6020 ± 218	7.07 ± 0.25	1.00	3.92 ± 0.11	54.7 ± 4.7	-0.33	-0.04		0.17	< 0.01	~ 1.10
08095212-4857590	122.46	-48.96	G	3311 ± 14	13.51 ± 0.39	0.83	-	100.0	-	-1.52		0.97	< 0.01	~ 0.25
08095429-4908418	122.47	-49.14	G	3453 ± 101	13.10 ± 0.38	0.84	-	100.0	-0.24	-1.47		0.98	< 0.01	~ 0.37
08095640-4932446	122.48	-49.54	G	3460 ± 34	12.48 ± 0.62	0.83	-	133.6 ± 16.6	-	-1.55		0.97	< 0.01	~ 0.37
08095644-4922109	122.48	-49.36	G	4278 ± 328	12.32 ± 0.26	0.90	-	159.5 ± 3.3	-0.01	-1.00	K	0.97	< 0.01	~ 0.64
08095786-4849182	122.49	-48.82	G	5257 ± 71	13.98 ± 0.27	0.98	-	268.7 ± 2.6	0.04	-0.33		0.94	< 0.01	~ 0.90
08095940-4859111	122.49	-48.98	G	5238 ± 47	29.72 ± 0.25	0.98	4.50 ± 0.02	164.9 ± 2.11	0.05	-0.39		0.13	0.03	~ 0.87
08100063-4853392	122.50	-48.89	G	3449 ± 51	12.96 ± 0.31	0.84	-	100.0	-0.23	-1.39		0.98	< 0.01	~ 0.36
08100180-4915454	122.50	-49.26	G	3777 ± 183	13.32 ± 0.31	0.81	-	100.0	-0.19	-1.42	K	0.97	< 0.01	~ 0.49
08100204-4939564	122.50	-49.66	G	4450 ± 235	12.59 ± 0.30	0.94	-	377.3 ± 8.3	0.01	-0.82		0.98	< 0.01	~ 0.70
08100380-4901071	122.51	-49.01	G	5914 ± 113	13.92 ± 0.40	0.99	4.39	167.5 ± 1.9	-0.01	0.13	K	0.95	< 0.01	~ 1.10
08100542-4907585	122.52	-49.13	G	3329 ± 35	11.84 ± 1.67	0.81	4.81 ± 0.06	100.0	-0.27	-1.23	K	0.95	< 0.01	~ 0.26
08100575-4927298	122.52	-49.45	G	3883 ± 107	34.65 ± 0.27	0.82	4.59 ± 0.10	45.5	-0.21	-1.14		0.12	0.02	~ 0.58
08100708-4912597	122.52	-49.21	G	3398 ± 25	12.80 ± 0.46	0.83	-	116.6 ± 13.5	-	-1.49	K	0.98	< 0.01	~ 0.33
08100749-4910447	122.53	-49.17	G	4233 ± 402	11.97 ± 0.30	0.88	-	312.4 ± 2.7	-0.04	-1.13	K	0.96	< 0.01	~ 0.61
08100785-4916357	122.53	-49.27	U	12524 ± 2000	8.40 ± 0.40	-	3.95 ± 1.0	-	-	2.05	K	0.51	< 0.01	~ 3.01
08100810-4912157	122.53	-49.20	G	5346 ± 70	13.89 ± 0.25	0.98	4.49 ± 0.08	150.7 ± 1.6	-0.16	-0.16		0.95	< 0.01	~ 0.94
08100826-4910565	122.53	-49.33	G	6309 ± 22	30.70 ± 0.25	0.99	4.17	10.9	0.05	0.02	K	0.13	0.02	~ 1.18
08100893-4915413	122.53	-49.26	G	4418 ± 372	13.47 ± 0.25	0.91	-	280.8 ± 6.1	-0.01	-0.86		0.97	< 0.01	~ 0.70
08101006-4853042	122.54	-48.88	G	3876 ± 62	33.34 ± 0.25	0.83	4.56 ± 0.12	79.3 ± 2.2	-0.18	-0.91		0.12	0.02	~ 0.68
08101165-4922274	122.54	-49.37	G	6298 ± 14	23.22 ± 0.25	0.99	4.36	16.0 ± 1.4	0.14	-0.47		0.20	0.10	~ 1.22
08101223-4913056	122.55	-49.21	G	6042 ± 62	12.94 ± 0.26	0.99	4.02 ± 0.04	151.8 ± 2.5	0.04	0.12	K	0.98	< 0.01	~ 1.14
08101374-4917112	122.55	-49.28	G	3535 ± 82	12.21 ± 0.37	0.82	-	100.0	-0.20	-1.33		0.97	< 0.01	~ 0.45
08101431-4928268	122.55	-49.47	G	3594 ± 20	12.49 ± 0.55	0.80	-	100.0	-	-1.42		0.97	< 0.01	~ 0.47
08101502-4851129	122.56	-48.85	G	3641 ± 74	12.70 ± 0.26	0.83	-	121.1 ± 3.0	-0.20	-0.88		0.98	< 0.01	~ 0.51
08101546-4905487	122.56	-49.09	G	5822 ± 240	13.13 ± 0.25	0.98	4.17 ± 0.03	118.8 ± 2.5	0.04	-0.16	K	0.98	< 0.01	~ 1.01
08101697-4854194	122.57	-48.90	G	5678 ± 79	12.14 ± 0.27	0.98	4.24 ± 0.15	160.8 ± 4.0	0.03	-0.16		0.97	< 0.01	~ 0.98
08101799-4923503	122.57	-49.39	G	5214 ± 72	14.40 ± 0.25	0.98	4.51	271.9 ± 2.9	-0.07	-0.33	K	0.87	< 0.01	~ 0.87

Table 4.13 – *Continue*

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{bol} / L _⊙)	Known members	p _{d,A} (%)	p _{d,B} (%)	M _* (M _⊙)
08101811-4858252	122.57	-48.97	G	3445 ± 13	20.46 ± 0.25	0.86	-	376.7 ± 20.8	-	-1.25		0.08	0.72	~ 0.36
08101836-4906461	122.57	-49.11	G	6321 ± 12	25.56 ± 0.25	1.00	4.07	12.6 ± 1.0	0.17	0.36		0.17	0.05	~ 1.23
08101842-4902145	122.57	-49.03	G	3817 ± 87	2.46 ± 0.25	0.87	-	297.2 ± 5.0	-0.19	-0.60		0.25	< 0.01	~ 0.66
08101987-4856000	122.58	-48.93	G	4726 ± 396	17.29 ± 0.25	0.95	-	257.9 ± 5.2	-0.01	-0.60		0.43	0.09	~ 0.76
08102002-4850165	122.58	-48.83	G	3378 ± 98	11.29 ± 1.11	0.83	-	48.1	-0.28	-1.57		0.94	< 0.01	~ 0.31
08102029-4902254	122.58	-49.04	G	3537 ± 44	13.71 ± 0.37	0.86	-	110.6 ± 7.3	-0.22	-1.45		0.96	< 0.01	~ 0.44
08102103-4910448	122.58	-49.17	G	3520 ± 16	12.59 ± 0.28	0.82	-	138.0 ± 6.8	-	-1.38	K	0.98	< 0.01	~ 0.43
08102150-4901339	122.58	-49.02	G	3730 ± 66	12.31 ± 0.26	0.82	-	122.0 ± 3.8	-0.21	-1.25		0.97	< 0.01	~ 0.55
08102171-4900068	122.59	-49.00	G	3350 ± 26	12.65 ± 5.21	0.86	-	258.2 ± 31.6	-0.23	-1.75	K	0.87	0.03	~ 0.27
08102210-4911230	122.59	-49.18	G	3618 ± 60	13.31 ± 0.29	0.83	-	100.0	-	-1.35		0.97	< 0.01	~ 0.50
08102311-4902454	122.59	-49.04	G	3736 ± 8	14.17 ± 0.25	0.84	-	100.0	-	-1.45		0.91	< 0.01	~ 0.49
08102486-4901495	122.60	-49.03	G	5950 ± 46	13.40 ± 0.27	0.99	4.01 ± 2.24	166.4 ± 3.6	0.01	0.06	K	0.97	< 0.01	~ 1.07
08102529-4923024	122.60	-49.38	G	3499 ± 83	29.09 ± 0.28	0.82	4.64 ± 0.13	100.0	-0.26	-1.27		0.14	0.03	~ 0.41
08102704-4908487	122.61	-49.14	G	5523 ± 78	12.60 ± 0.25	0.99	-	193.9 ± 2.7	-0.03	-1.14	K	0.98	< 0.01	~ 0.96
08102741-4920196	122.61	-49.33	G	3405 ± 21	12.23 ± 0.32	0.83	-	100.0	-0.32	-1.45		0.97	< 0.01	~ 0.32
08102854-4856518	122.61	-48.94	G	5860 ± 95	12.38 ± 0.29	0.99	4.36 ± 0.02	201.1 ± 4.8	0.04	0.08	K	0.97	< 0.01	~ 1.03
08103001-4903218	122.62	-49.05	G	3390 ± 25	13.65 ± 0.49	0.87	-	109.5 ± 12.3	-	-1.47		0.96	< 0.01	~ 0.32
08103088-4910443	122.62	-49.17	G	3805 ± 228	13.45 ± 0.49	0.81	4.47 ± 0.11	66.5 ± 6.7	-0.18	-1.44	K	0.97	< 0.01	~ 0.51
08103100-4851071	122.62	-48.85	G	3830 ± 185	-5.63 ± 0.30	0.82	4.34 ± 0.09	100.7 ± 5.2	-0.10	-1.29		0.18	< 0.01	~ 0.54
08103144-4906301	122.63	-49.10	U	11358 ± 2000	29.30 ± 0.40	-	4.60 ± 1.0	-	-	-	K	0.14	0.03	~ 2.40
08103186-4921296	122.63	-49.35	G	4467 ± 295	15.31 ± 0.32	0.94	-	379.6 ± 15.8	-0.02	-0.77	K	0.68	0.02	~ 0.70
08103259-4909436	122.63	-49.16	G	3545 ± 101	9.86 ± 0.24	0.73	4.68	100.0	-0.22	-1.52		0.64	< 0.01	~ 0.44
08103397-4922186	122.64	-49.37	G	3533 ± 41	12.92 ± 0.32	0.82	-	100.0	-0.22	-1.47		0.98	< 0.01	~ 0.44
08103432-4900496	122.64	-49.01	G	6540 ± 21	-9.51 ± 0.26	1.00	4.10	9.1	-0.24	0.31		0.18	< 0.01	~ 1.24
08103470-4908400	122.64	-49.14	G	5879 ± 76	13.35 ± 0.29	0.99	4.06 ± 0.02	175.6 ± 1.7	0.05	0.17	K	0.97	< 0.01	~ 1.10
08103572-4909008	122.64	-49.15	G	4375 ± 412	13.61 ± 0.25	0.90	-	226.3 ± 6.3	-0.01	-1.05	K	0.96	< 0.01	~ 0.63
08103582-4920054	122.64	-49.33	G	3420 ± 47	12.76 ± 0.35	0.83	-	135.2 ± 8.2	-0.27	-1.42		0.98	< 0.01	~ 0.33
08103676-4858389	122.65	-48.97	G	3403 ± 30	11.32 ± 0.41	0.86	-	40.5	-	-1.69		0.92	< 0.01	~ 0.34
08103735-4928104	122.65	-49.46	G	3459 ± 64	12.21 ± 0.37	0.83	-	100.0	-0.33	-1.33		0.97	< 0.01	~ 0.37
08103764-4904185	122.65	-49.07	G	3643 ± 8	-9.41 ± 0.25	0.82	-	100.0	-0.22	-1.27		0.18	< 0.01	~ 0.52
08103812-4912285	122.65	-49.20	G	5005 ± 233	13.41 ± 0.25	0.97	-	259.8 ± 6.1	-0.01	-0.57		0.97	< 0.01	~ 0.79
08103930-4929046	122.66	-49.48	G	3965 ± 123	12.95 ± 0.25	0.87	-	174.5 ± 16.1	-0.04	-0.82		0.98	< 0.01	~ 0.73
08103983-4904377	122.66	-49.07	G	6209 ± 59	-0.74 ± 0.25	1.01	3.69 ± 0.15	88.23 ± 1.7	-0.20	0.47		0.20	< 0.01	~ 1.22
08104061-4907056	122.66	-49.11	G	3375 ± 47	47.75 ± 0.47	0.85	-	100.0	-0.27	-1.44	K	-	-	-
08104108-4907525	122.67	-49.13	G	3357 ± 67	12.49 ± 0.40	0.84	-	100.0	-0.27	-1.20		0.98	< 0.01	~ 0.28
08104335-4901152	122.68	-49.02	G	4493 ± 258	13.07 ± 0.25	0.93	-	188.5 ± 4.8	-0.00	-0.86		0.98	< 0.01	~ 0.69
08104546-4901068	122.68	-49.01	G	6310 ± 20	11.79 ± 0.25	0.99	4.19	117.4 ± 3.1	-0.04	0.27	K	0.95	< 0.01	~ 1.23
08104554-4905204	122.68	-49.08	G	4878 ± 276	10.20 ± 0.25	0.97	-	286.8 ± 2.1	0.01	-0.30	K	0.68	< 0.01	~ 0.95
08104570-4906171	122.69	-49.10	G	3623 ± 64	11.05 ± 0.28	0.83	-	100.0	-0.24	-1.12	K	0.85	< 0.01	~ 0.53
08104618-4855013	122.69	-48.91	G	3340 ± 52	12.70 ± 0.62	0.83	4.70 ± 0.09	210.2 ± 13.1	-0.26	-1.49		0.97	< 0.01	~ 0.26
08104793-4917078	122.69	-49.28	G	3862 ± 143	12.88 ± 0.27	0.83	-	73.8 ± 3.1	-0.15	-1.19		0.98	< 0.01	~ 0.57
08104831-4912292	122.70	-49.20	G	3276 ± 9	13.32 ± 0.40	0.82	-	97.3 ± 11.2	-	-1.30		0.97	< 0.01	~ 0.23
08104835-4915249	122.70	-49.25	G	3446 ± 64	13.33 ± 0.42	0.84	-	90.7 ± 6.7	-0.22	-1.39	K	0.97	< 0.01	~ 0.36
08104984-4911258	122.70	-49.19	G	6351 ± 14	11.09 ± 0.28	0.99	4.29	106.8 ± 1.7	-0.15	0.39	K	0.86	< 0.01	~ 1.24
08105058-4935573	122.71	-49.59	U	5832 ± 64	12.13 ± 0.56	-	4.4	179.9 ± 14.9	-0.00	0.03		0.97	< 0.01	~ 1.05
08105210-4921138	122.71	-49.35	G	3587 ± 9	12.64 ± 0.26	0.83	-	92.7 ± 4.8	-	-1.22		0.98	< 0.01	~ 0.49
08105523-4926365	122.73	-49.44	G	3320 ± 19	27.62 ± 0.41	0.82	-	72.2 ± 12.3	-	-1.26		0.15	0.03	~ 0.26
08105610-4918399	122.73	-49.31	G	3442 ± 278	41.09 ± 2.10	0.97	-	32.5	-0.18	-1.13	K	0.13	0.02	~ 0.36
08105720-4923478	122.73	-49.39	G	3351 ± 51	11.05 ± 0.48	0.84	-	100.0	-0.25	-1.41		0.88	< 0.01	~ 0.28
08105940-4851272	122.74	-48.85	G	3482 ± 30	12.74 ± 0.50	0.85	-	44.1	-	-1.65		0.98	< 0.01	~ 0.38
08110007-4904413	122.75	-49.07	G	3621 ± 77	5.65 ± 0.32	0.79	4.64 ± 0.08	100.0	-0.22	-1.28		0.35	< 0.01	~ 0.52
08110009-4906442	122.75	-49.11	G	5732 ± 68	12.07 ± 0.25	0.99	4.19 ± 0.19	162.1 ± 1.75	0.01	-0.17		0.97	< 0.01	~ 0.99
08110139-4900089	122.75	-49.00	G	5444 ± 72	13.03 ± 0.26	0.99	4.57 ± 0.06	173.7 ± 1.81	-0.04	-0.22		0.98	< 0.01	~ 0.95
08110155-4856150	122.75	-48.93	G	5999 ± 586	91.33 ± 0.40	0.86	-	44.8	-0.18	-1.51		-	-	-
08110234-4916249	122.75	-49.27	G	5680 ± 73	13.15 ± 0.27	0.99	-	200.5 ± 4.2	-0.01	-0.07	K	0.98	< 0.01	~ 1.00

Table 4.13 – *Continue*

CNAME	RA ($^{\circ}$)	DEC ($^{\circ}$)	Inst.	T _{eff} (K)	RV (km s ⁻¹)	γ	log g (dex)	EW(Li) (mÅ)	[Fe/H] (dex)	log (L _{bol} / L _⊙)	Known members	p _{d,A} (%)	p _{d,B} (%)	M _* (M _⊙)
08110496-4859465	122.77	-48.99	G	3543 ± 43	12.43 ± 0.34	0.84	-	100.0	-0.23	-1.46		0.98	< 0.01	~ 0.44
08110722-4853061	122.78	-48.88	G	3578 ± 42	12.77 ± 0.29	0.84	-	100.0	-0.23	-0.95		0.98	< 0.01	~ 0.46
08110759-4921423	122.78	-49.36	G	3598 ± 69	19.90 ± 0.31	0.84	-	140.0 ± 21.3	-0.21	-1.21		0.07	0.76	~ 0.55
08111134-4904442	122.79	-49.07	G	6954 ± 13	14.11 ± 0.24	1.00	-	56.4 ± 1.2	0.04	0.67		0.92	< 0.01	~ 1.49
08111579-4908139	122.81	-49.13	G	3527 ± 87	11.08 ± 0.47	0.86	-	100.0	-0.21	-1.32	K	0.89	< 0.01	~ 0.44
08111669-4922290	122.81	-49.37	G	3393 ± 25	12.36 ± 0.74	0.86	-	100.0	-	-1.56		0.97	< 0.01	~ 0.33
08111885-4849246	122.82	-48.82	G	3458 ± 116	33.77 ± 0.54	0.85	-	37.7	-0.26	-1.52		0.12	0.02	~ 0.37
08112074-4913100	122.83	-49.21	G	6404 ± 22	27.55 ± 0.26	0.99	4.29	138.8 ± 1.7	0.28	0.30		0.15	0.04	~ 1.22
08112121-4913280	122.83	-49.22	G	6226 ± 38	53.66 ± 0.26	0.99	4.38	146.3 ± 3.3	0.25	-0.10		0.29	0.03	~ 1.08
08112213-4921470	122.84	-49.36	G	4055 ± 186	14.15 ± 0.26	0.88	-	199.9 ± 6.6	-0.08	-0.99		0.92	< 0.01	~ 0.64
08112560-4927206	122.85	-49.45	G	3454 ± 60	19.62 ± 0.33	0.88	-	480.8 ± 12.8	-0.24	-1.49		0.08	0.74	~ 0.37
08112887-4923364	122.87	-49.39	G	3704 ± 99	12.10 ± 0.29	0.80	4.56 ± 0.01	100.0	-0.21	-1.28		0.97	< 0.01	~ 0.53
08112894-4921190	122.87	-49.35	G	3388 ± 47	20.01 ± 0.57	0.87	-	308.1 ± 10.6	-0.27	-1.31		0.08	0.73	~ 0.31
08112917-4907229	122.87	-49.12	G	3470 ± 58	13.14 ± 0.42	0.83	-	100.0	-0.22	-1.49		0.97	< 0.01	~ 0.38
08113168-4900035	122.88	-49.00	G	3582 ± 79	-8.73 ± 0.35	0.80	4.61 ± 0.14	100.0	-0.24	-1.52		0.17	< 0.01	~ 0.46
08113190-4930135	122.88	-49.50	G	3479 ± 55	20.04 ± 0.34	0.85	-	180.7 ± 26.7	-0.24	-1.29		0.07	0.75	~ 0.39
08113238-4848010	122.88	-48.80	G	3572 ± 63	12.34 ± 0.31	0.84	-	100.0	-0.23	-1.29		0.97	< 0.01	~ 0.47
08114045-4920115	122.91	-49.33	G	3884 ± 106	13.26 ± 0.28	0.84	-	79.3 ± 3.1	-0.08	-1.20		0.97	< 0.01	~ 0.57
08114140-4859550	122.92	-48.99	G	3584 ± 81	24.15 ± 0.28	0.81	-	126.2 ± 4.6	-0.23	-1.13		0.18	0.07	~ 0.49
08114859-4928089	122.95	-49.46	G	3452 ± 28	15.48 ± 4.16	0.82	-	129.3	-	-1.52		0.85	0.05	~ 0.37
08114867-4919306	122.95	-49.32	G	3739 ± 89	12.66 ± 0.29	0.85	-	100.0	-0.19	-1.19		0.98	< 0.01	~ 0.56
08115134-4911410	122.96	-49.19	G	5490 ± 144	16.25 ± 0.42	0.98	-	238.3 ± 16.1	0.01	-0.09	K	0.55	0.04	~ 0.97
08115737-4911322	122.98	-49.19	G	5620 ± 74	13.09 ± 0.28	0.99	-	205.4 ± 6.5	0.01	-0.08		0.98	< 0.01	~ 0.98
08115745-4858503	122.98	-48.98	G	3509 ± 64	17.99 ± 0.35	0.86	-	121.6 ± 8.6	-0.26	-1.41		0.32	0.24	~ 0.43

4.7 Discussion

4.7.1 GES versus TGAS Velocity Dispersion

In this section, I compared the velocity dispersion obtained from the GES (see section 3.2.2.2) and TGAS data (see section 4.5). I decided to use the values of $\sigma_{\perp}$ estimated from the sample of G17 within the radius R_{GES} (last row of Table 4.6) with an error given by the sum of statistical error and systematic error ($\sim 0.1 \text{ km s}^{-1}$). In figure 4.11 I show, for each of the four clusters, the spatial distribution of the members selected by G17 from the TGAS catalogue and the spectroscopic candidates selected by GES. The G17 members of IC 2602 and IC 2391 within R_{GES} are uniformly distributed in the whole area of GES observations. Instead,

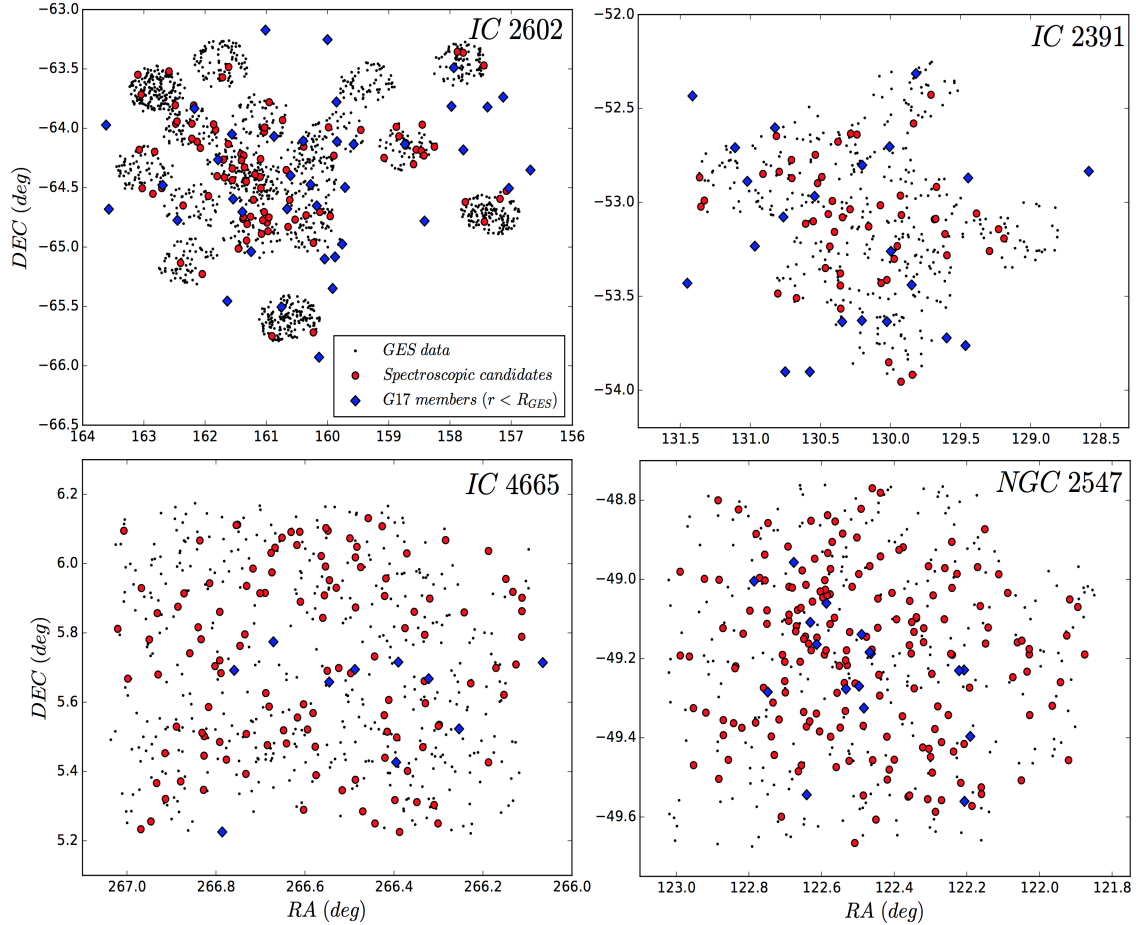


Figure 4.11: Spatial distribution of GES and TGAS stars in the four clusters. The black points are the stars observed with GES and the red filled dots are the spectroscopic candidates selected in section 4.3. The blue diamonds are the stars selected as members by G17 within the radius R_{GES} . The stars identified by red dots and blue diamonds are those used to derive the velocity dispersions in the GES and TGAS sample, respectively.

for IC 4665 and NGC 2547, the TGAS members seem to cover only a section of the cluster area. This may be related to the greater distance of these clusters; the membership selection in G17 is based on position, parallaxes, and proper motions, so it is strongly affected by distance.

The velocity dispersions derived from the GES data (see table 4.14) are higher than those derived from the TGAS data but consistent within 2σ . Furthermore, I stress that the typical error uncertainty on proper motions in DR1 (Gaia Collaboration et al. 2016a) is $\sim 1 \text{ mas yr}^{-1}$, which corresponds to about $0.7 - 1.7 \text{ km s}^{-1}$ at the distance of the four clusters studied in this thesis. Therefore, we are pushing the *Gaia* data to their limit of precision, and their systematic errors need to be better investigated.

However, all four clusters analyzed in this work show the same trend, i.e., TGAS dispersions are lower than those of GES. The origin of this discrepancy could have two explanations. The first is the presence of asymmetries in the system (e.g., Baumgardt & Makino 2003; Baumgardt & Kroupa 2007). To derive the velocity dispersions in GES I used the radial velocity of stars, while in TGAS we used the velocity perpendicular to the plane containing the line of sight. Several N-body simulations show that anisotropy in the velocity could be present and it depends on the cluster initial conditions, its evolution history, and tidal effects (e.g., Vesperini et al. 2014; Tiongco et al. 2016, see the last section for a brief discussion about the anisotropy). In either case, it is unlikely that all clusters show the same trend of asymmetry. The second is the energy equipartition. After the relaxation, a cluster tends to evolve towards the energy equipartition where the more massive stars settle on the center of cluster and cede kinetic energy to the less massive ones. In this case, the velocity dispersion is related to the mass m of stars as $\sigma(m) \propto m^{-0.5}$. So, I expect that the more massive stars are dynamically colder (i.e., have a lower velocity dispersion). The four clusters in this work might already be relaxed (relaxation times $10 - 30 \text{ Myr}$) and I found that the median mass of GES samples is lower than that of TGAS samples by a factor between ~ 2.5 and ~ 4 , depending on the cluster. Therefore, I expect differences in velocity dispersions between a factor ~ 1.6 and ~ 2 , which is about what I found. I recall that the presence of energy equipartition in star clusters is still very debated. Spera et al. (2016) and Parker et al. (2016) noted that energy equipartition might not occur even after many two-body relaxation timescales.

Finally, I point out that G17 found members up to 15 pc from the cluster center and outside R_{GES} . It is not clear whether these distant stars are actual cluster members, unbound escaping stars, or field stars with kinematic properties consistent with the cluster, but if I calculate the total mass of the cluster and the half-mass radius using the full G17 sample, I find similar virial velocity dispersions σ_{vir} , and therefore the conclusions on young OCs would not change.

These are still preliminary results and more data with better accuracy are needed. The second data release of *Gaia* (DR2) include parallaxes and proper

motions of low-mass population of these clusters. Thus, I will be able to investigate this discrepancy more thoroughly. Therefore, in the next section I will discuss only the results obtained with GES data.

4.7.2 Effect of Feedback on the Cluster Dissipation Mechanism

The aim is to probe the dynamical state of these 20 – 50 Myr clusters in order to investigate the mechanism leading to cluster dispersion. In particular, determining if they are “supervirial” or “subvirial” is critically important. In Chapter 2 I described the models for the cluster evolution. According to the “residual gas expulsion” scenario (e.g., Kroupa et al. 2001; Goodwin & Bastian 2006), young clusters become supervirial after feedback from massive stars sweeps out the gas that did not form stars. Otherwise, according to other models, the gas dispersion does not affect the virial ratio of the cluster and the dynamical interactions in the denser regions of a cluster drive the dynamical evolution (e.g., Kruijssen et al. 2012; Parker & Wright 2016).

It is possible to understand whether a cluster is supervirial by comparing the measured one-dimensional velocity dispersion σ_c with the value derived analytically (σ_{vir}) from the cluster properties under the assumption of virial equilibrium, which is given by the equation

$$\sigma_{vir} = \sqrt{\frac{M_{tot} G}{\eta r_{hm}}}, \quad (4.1)$$

where r_{hm} is the half-mass radius, G is the gravitational constant, η is a dimensionless factor which depends on the cluster density profile and is ≈ 9.75 for a Plummer sphere profile, and M_{tot} is the cluster mass. In Table 4.14 I list the velocity dispersion derived from the GES RVs (see section 4.4) and from equation 4.1. Also, the half-mass radii and the total masses are shown.

The observed velocity dispersions are higher than the values calculated by assuming virial equilibrium by about a factor two, leading to the conclusion that three out of four clusters (except IC 4665, which has an upper limit on the velocity

Table 4.14: Properties of the four clusters.

Cluster	M_{tot} ($M_\odot$)	r_{hm} (pc)	σ_c (km s ⁻¹)	σ_{vir} (km s ⁻¹)	M_{dyn} ($M_\odot$)
IC 2602	~ 244	~ 1.56	0.60 ± 0.20	~ 0.26	~ 1275
IC 2391	~ 151	~ 0.98	0.53 ± 0.17	~ 0.26	~ 485
IC 4665	~ 96	~ 1.37	< 0.5	~ 0.19	-
NGC 2547	~ 201	~ 0.80	0.63 ± 0.09	~ 0.33	~ 720

dispersion) are supervirial. Figure 4.12 shows the intrinsic velocity dispersion obtained from the GES data versus that derived analytically at the virial equilibrium. The dashed blue line is the 1:1 relation. I can rule out that this conclusion is due to errors on the estimates of the velocity dispersion σ_{vir} . In particular, uncertainties on the mass are lower than a factor 1.5, as shown in table 4.8. The half-mass radius r_{hm} could be underestimated in case of mass segregation because it was calculated using the more massive stars in the sample, but a larger r_{hm} implies a smaller σ_{vir} , so it supports the conclusion on the virial ratio of the clusters. Finally, Elson et al. (1987) and Fleck et al. (2005) found that deviation of the density profile from a Plummer sphere can lead to a value of η that is lower by a factor 2. However, considering that $\sigma_{vir} \propto \eta^{-1/2}$ this deviation cannot explain a discrepancy of a factor two.

The result that these three clusters are in supervirial state is evident also comparing the total mass obtained using the GES data and the dynamical mass, M_{dyn} (listed in the last column of table 4.14), derived using the inverse of equation 4.1, which is the mass expected at the virial equilibrium for a cluster with a velocity dispersion equal to σ_c . In each cluster M_{dyn} is at least a factor 3.2 greater than M_{tot} , and it is unlikely that the estimates of the total mass are wrong by such a factor, given the GES target selection strategy (i.e., inside the GES magnitude range

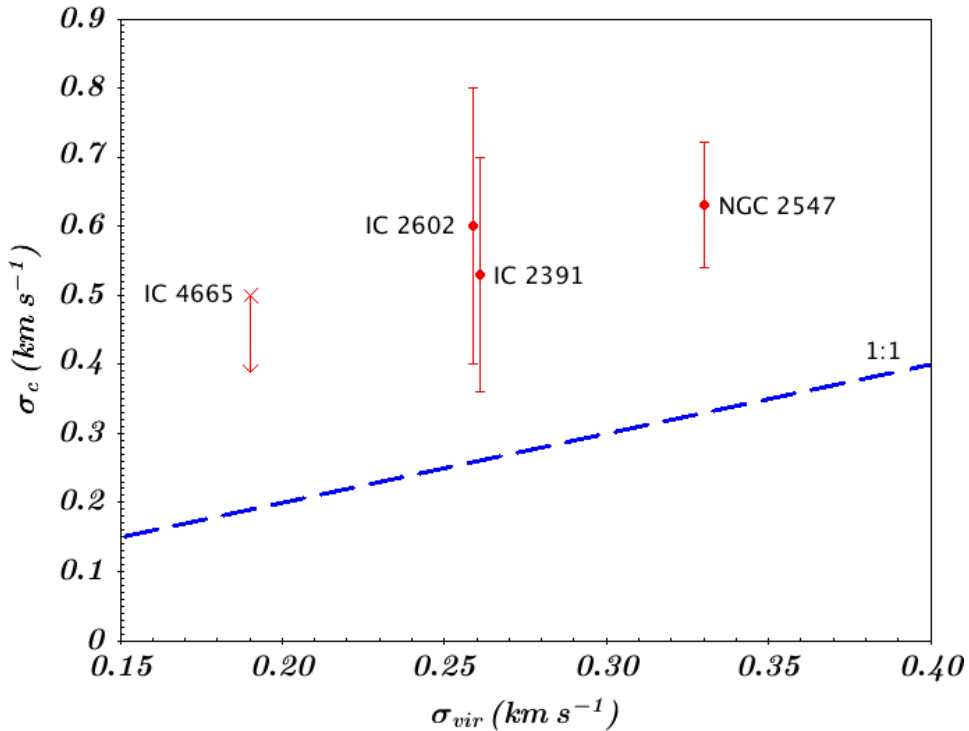


Figure 4.12: Intrinsic velocity dispersion derived from the GES data versus the velocity dispersion obtained under the assumption of the virial equilibrium. The dashed blue line represents the 1:1 relation.

almost all the cluster members should be observed). This is an additional evidence that the three clusters are supervirial.

The presence of clusters in a supervirial state after gas expulsion has been predicted by several N-body simulations (e.g., Bastian & Goodwin 2006; Baumgardt & Kroupa 2007) supporting the residual gas expulsion scenario. In particular, Baumgardt & Kroupa (2007) suggest that after the gas that did not form stars is swept out, clusters expand so the virial dispersion decreases and the virial ratio increases. They then return in a virial state only after the unbound stars are dispersed, which should occur after about 20 – 40 crossing times. If I calculate the crossing time as σ_c/r_{hm} , the clusters studied in this thesis have a dynamical age of about 20 – 30 crossing times; therefore, the results are in good agreement with these simulations. However, one can note that the crossing time used to track the cluster evolution in the simulations is calculated at cluster formation. I do not know the initial crossing time of these four clusters, but it is likely shorter than the current one, so the evolution of these clusters could be slower than observed in the simulations.

Parker & Wright (2016) performed N-body simulations of the cluster evolution assuming an initial spatial distribution that better resembles the hierarchical structure observed in young star forming region and investigated whether the ratio σ_c/σ_{vir} can be used to trace the dynamical state of a cluster. They found that clusters that are initially subvirial or are in global virial equilibrium but subvirial on local scale relax to virial equilibrium after 25 – 50 crossing times. However, the measured ratio σ_c/σ_{vir} would lead to the conclusions that they are supervirial. This apparent inconsistency arises because clusters are never fully relaxed but keep an imprint of early non-equilibrium even after several crossing times.

4.7.2.1 Anisotropy in the Velocity Distribution

The comparison between the observed and the virial velocity dispersions assumes that the velocity distribution is isotropic. However, star clusters usually have an anisotropic velocity. Several works show that a cluster which is initially isotropic and isolated, develops an outer radial anisotropy moving on with age (e.g., Takahashi 1995, 1996; Spurzem & Aarseth 1996), given that the stars with radial orbits dominate the orbit distribution in the halo (due to the two-body relaxation in the center). Instead, for a cluster in a tidal field, the radial anisotropy is suppressed during the evolution by the tidal stripping of stars preferentially on radial orbits, and this leads to a tangentially anisotropic velocity distribution in the outer parts (e.g., Takahashi & Lee 2000; Baumgardt & Makino 2003; Hurley & Shara 2012). As a cluster evolves and loses a relevant fraction of its mass, the velocity dispersion returns to an isotropic configuration at all distances from the center (e.g., Giersz & Heggie 1997; Tiongco et al. 2016). Vesperini et al. (2014) and Tiongco et al. (2016) also show that if a star cluster undergoes an early violent relaxation phase, it will develop an isotropic core and it will have an anisotropic radial velocity distribution that increases with the distance from the center (if the cluster is isolated). Instead,

if it is in an external tidal field, the outer regions show an isotropic or a tangentially anisotropic velocity distribution. If the velocity distributions of the clusters analyzed in this work are like in the first case (isolated cluster), the assumption of isotropic velocity might be confirmed, at least in their central parts.

An anisotropic velocity distribution in a cluster may introduce an uncertainty on the estimates of velocity dispersion if this is derived only using the RVs of the cluster members. In particular, the presence of anisotropy is crucial in the study of cluster dynamical state. In this work, I used only the RVs and I assumed the isotropy velocity hypothesis, therefore the effects due to the presence of an anisotropic velocity distribution may be taken into account using the proper motions of the second *Gaia* data release. I will investigate this cluster characteristic in more detail in the near future.

Chapter 5

Old Open Clusters

In this chapter, I will show the results obtained for a sample of seven old OCs (i.e., age greater than 100 Myr) using the Gaia-ESO Survey products and the methods described in Chapter 3. The main goals of this part of thesis are the investigation of how the Galactic gravitational field or encounters with other GMCs affect the cluster evolution and dissipation, and how clusters are able to survive for several Gyr. Therefore, using the obtained results in this chapter, I will discuss the implication on the models describing the cluster dynamical evolution on long timescales.

5.1 Sample of Clusters

The clusters at ages greater than 100 Myr are interesting since systems with such ages should be already in a virialized state. Indeed, their lifetime is well greater than the relaxation time (equation 1.9), that typically is of the order of ~ 100 Myr. The effects of stellar evaporation acting on these clusters occur on very long timescales and the cluster disruption is driven only by either the external gravitational fields or tidal interactions (e.g., Baumgardt & Makino 2003). Thus, such clusters are expected to be in virial equilibrium. Furthermore, as described in Chapter 2, a cluster with age $\gtrsim 100$ Myr survived to the embedded cluster phase (first 10 Myr) and early evolution, where the majority of star systems are rapidly disrupted by the effects of parent gas expulsion and/or internal two-body interactions ($\sim 10 - 100$ Myr). These clusters enters in another phase in which they should start to be affected by the tidal effects due to Galactic fields or encounters with GMCs, which lead to their disruption ($\sim 100 - 300$ Myr; e.g., Portegies Zwart et al. 1998; Lamers et al. 2005; Portegies Zwart et al. 2010, and reference therein). Hence, clusters at these ages are expected to be already disrupted by these effects. However, at ages of several Gyr, some clusters have been able to survive also at this last dynamical phase.

Therefore, I chose a sample of seven clusters which have ages ranging from ~ 100 Myr to ~ 3.5 Gyr to perform a kinematic and dynamical analysis. Since the mean

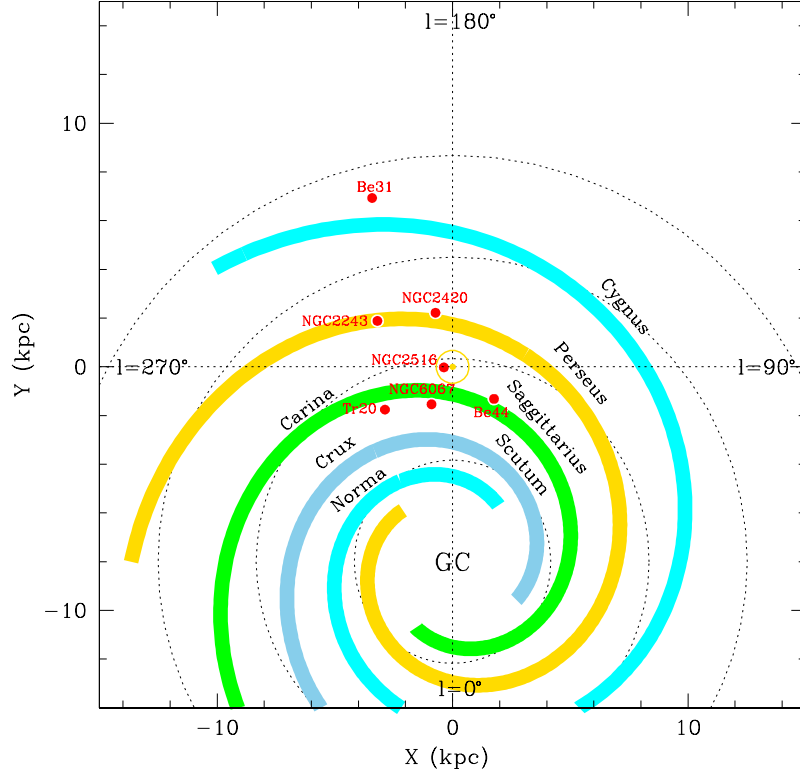


Figure 5.1: Distribution of the seven old OCs studied in this thesis (red points) projected onto the Galactic plane. The location of Galactic center is indicated in figure with GC. The yellow symbol at the center marks the position of the Sun (distance Sun - Galaxy center = 8 kpc), while the colored stripes indicate the approximate position of the different Galaxy spiral arms (Vallée 2005).

age of clusters which are able to survive to the early phases of evolution is ~ 300 Myr (table 1.1), I selected two clusters likely virialized with an age of ~ 100 Myr, in order to test the possible influence of first tidal effects, and other five clusters with age greater than 1 Gyr, in order to check the present dynamical state of long-lived clusters and to compare it with the theoretical models of evolution. Their distances span the range between ~ 387 pc (NGC 2516) and ~ 7760 pc (Berkeley 31). Also the projection of these clusters in the plane of Galaxy are rather various: Berkeley 44 is located in the first quadrant of the Galactic plane; NGC 2516, NGC 6067, and Trumpler 20 are in the fourth quadrant; NGC 2243, NGC 2420 and Berkeley 31 are in the third one (see figure 5.1). The cluster properties are listed in Table 5.1, where distances, ages, and reddening values come from several works, while the metallicities are taken from Magrini et al. (2018). The radius R_{GES} defines the cluster area in the sky considered for the kinematic and dynamical analysis and it is supposed to contain all the cluster members.

Table 5.1: Cluster properties.

Cluster	RA (J2000)	DEC (J2000)	Distance (kpc)	R_{GES} (pc)	Age (Gyr)	E(B-V)	[Fe/H]
Berkeley 31 ^[1]	06h 57m 37s	08d 18m 20s	7.76 ± 0.40	~ 10.5	2.60 ± 0.30	0.14 ± 0.05	-0.20 ± 0.06
Berkeley 44 ^[2]	19h 17m 18s	19d 32m 27s	2.20 ± 0.20	~ 4.7	1.60 ± 0.30	1.06 ± 0.04	$+0.27 \pm 0.06$
NGC 2243 ^[3]	06h 29m 34s	-31d 17m 00s	3.90 ± 0.30	~ 14.3	3.50 ± 0.50	0.06 ± 0.02	-0.38 ± 0.04
NGC 2420 ^{[4],[5],[6]}	07h 38m 23s	21d 34m 24s	2.48 ± 0.15	~ 7.8	2.20 ± 0.30	0.05 ± 0.01	-0.13 ± 0.04
NGC 2516 ^[7]	07h 58m 04s	-60d 45m 11s	0.39 ± 0.05	~ 5.1	0.12 ± 0.01	0.10 ± 0.06	-0.06 ± 0.05
NGC 6067 ^[8]	16h 13m 11s	-54d 13m 06s	1.78 ± 0.12	~ 9.0	0.10 ± 0.05	0.35 ± 0.04	$+0.20 \pm 0.08$
Trumpler 20 ^[9]	12h 39m 32s	-60d 37m 36s	3.37 ± 0.30	~ 12.3	1.66 ± 0.20	0.32 ± 0.07	$+0.15 \pm 0.07$

Notes. References of age, distance, and color excess are give in square brackets after the cluster name in the first column: [1] Cignoni et al. (2011); [2] Jacobson et al. (2016); [3] Bragaglia & Tosi (2006); [4] Salaris et al. (2004); [5] Sharma et al. (2006); [6] Anthony-Twarog et al. (2006); [7] Randich et al. (2018); [8] Alonso-Santiago et al. (2017); [9] Donati et al. (2014). In the particular case of Berkeley 31, the cluster is concentrated in the central part of the FLAMES field since it is very distant from the Sun (~ 7.8 kpc). Therefore, on the basis of the work of Cignoni et al. (2011), who found an half-mass radius of 2.85 arcmin, I selected from the initial target table the stars within a radius of 5.7 arcmin.

5.2 Data and Allocated Targets

The analysis of these seven clusters has been performed using the data from the fifth internal data release (GESviDR5). As described in Chapter 3, the initial targets are selected in order to define an unbiased sample of members (with GIRAFFE) and to derive the chemical pattern (with UVES). The target stars in this sample of old clusters are selected in the CMDs using the optical (B, V, and I band) and 2MASS photometry within a strip around the cluster sequence defined by the known members in literature, and in these seven OCs the stars lie principally in upper MS, SGB, and RC (see section 3.1.3) given their ages. In each cluster I excluded from the kinematical and dynamical analysis the fast rotators (i.e., all the stars with projected rotational velocity, $v \sin i$, greater than 50 km s^{-1}) because the error on the RV is not well determined. In the derivation of completeness and total mass, I considered these stars as if they had not been observed.

In the case of NGC 2243 and Trumpler 20, ESO archival data are also present. I considered only the archival stars that are included in the initial sample of targets selected by GES and that have defined values of B, V, and I magnitude. Table 5.2 shows the number of observed targets in each cluster with different instrument setups.

Table 5.2: Number of targets observed in the seven old clusters.

Setup	Berkeley 31	Berkeley 44	NGC 2243	NGC 2420	NGC 2516	NGC 6067	Trumpler 20
HR15N	225	64	672	520	66	326	462
HR9B	-	-	-	-	-	298	639
U 580	8	7	27	31	35	17	42
U 520	-	-	-	-	13	10	-
Tot.	233	71	699	551	712	651	1143

5.3 Completeness

In order to derive the total cluster mass, I need to estimate the level of completeness to take into account the stars that have not been observed by GES. As discussed in section 3.2.3, in old clusters several targets lie in post-MS phases in the CMDs, principally in RC and in small number in SGB and RGB. Depending on the cluster, only few stars are found in these CMD regions since the evolution of these phases is really rapid. Therefore, following the procedure described in section 3.2.3, I derived two separate levels of completeness, one for the stars in the post-MS phase and one for stars that lie under the TO in the CMD (i.e., in the MS phase). These levels of completeness are derived within the circular regions defined by R_{GES} , that are supposed to contain the whole cluster. In the nearest cluster NGC 2516 I considered a unique total level of completeness (total completeness of 77.2 %) since stars in post-MS phase are not observed because of the combination of the brightest magnitude limit of GES observations and the cluster distance. This issue is also discussed in the section of cluster parameters. For each cluster, the levels of completeness for the MS and post-MS phases are reported in table 5.3, as well the total observation completeness that is derived as the ratio between the total number of the observed stars and the total number of stars selected as initial candidate targets in GES. In order to derive an estimate of the completeness error, in these clusters I calculated the level of completeness for bins of V magnitude and I estimated the standard deviation from the mean value. As a result, I estimated a mean error of the level of completeness of $\sim 10\%$ for the whole cluster sample.

Table 5.3: Radius of observations and completeness for stars in MS and post-MS phase of the seven clusters.

Cluster	R_{GES} (pc)	MS completeness (%)	Post-MS completeness (%)	Total completeness (%)
Berkeley 31	~ 10.5	91.0	95.8	92.8
Berkeley 44	~ 4.7	29.4	47.8	31.3
NGC 2243	~ 14.3	77.1	84.8	78.8
NGC 2420	~ 7.8	78.7	74.5	78.0
NGC 2516	~ 5.1	-	-	77.2
NGC 6067	~ 9.0	14.8	68.6	15.4
Trumpler 20	~ 12.3	21.0	57.7	24.6

5.4 Kinematic Analysis

In old OCs, the initial target selection is less affected by contaminant stars (e.g., by background giants) and the methods used to identify contaminant stars discussed in the section 3.2.1 cannot be applied. For this reason, I used the whole observed star sample to determine the kinematic properties, assuming the presence of a cluster and a field population.

For the kinematic analysis I used only the stars for which the uncertainties on RVs are calculated with the empirical method described in section 3.2.2.1, using the formula developed by Jackson et al. (2015). This formula is developed only for the GIRAFFE targets observed with three gratings, HR10, HR15N, and HR21, and in this work it is applied to the stars observed by HR15N. Therefore, I excluded also the UVES targets from the fits. I used the maximum likelihood technique described in section 3.2.2.2. In order to take into account the presence of the field stars, I added a second broader Gaussian distribution to the model, with the field parameters (i.e., the central velocity and the velocity dispersion of the field stars) free to vary. For all clusters, I fixed the fraction of binaries, f_{bin} , at 0.5. Finally, I modeled only the stars with RVs within the range $-150 \leq \text{RV} \leq 150 \text{ km s}^{-1}$. Table 5.4 shows the results of the fits. The results for mean RV are in agreement within the errors with the values found in several literature works.

Figure 5.2 and 5.3 show the radial velocity distributions of the seven clusters obtained with f_{bin} fixed to 50%. From these plots it can be noted that the presence of field star components is particularly evident in NGC 6067, in which the cluster component is only a small percentage of the total sample ($\sim 12\%$). This leads to an uncertain determination of the velocity dispersion since it is difficult to clearly distinguish the cluster stars from the field ones. Indeed, the errors on parameters

Table 5.4: Best parameters from the fits of the RV distributions with a binary fraction fixed at 50%.

Cluster	v_c (km s ⁻¹)	σ_c (km s ⁻¹)	$f_{*,\text{clus}}$ (%)	v_f (km s ⁻¹)	σ_f (km s ⁻¹)
Berkeley 31	56.58 ± 0.24	0.79 ± 0.23	0.35 ± 0.06	56.37 ± 3.37	26.54 ± 2.49
Berkeley 44	-8.77 ± 0.23	0.55 ± 0.21	0.34 ± 0.07	7.96 ± 5.36	30.21 ± 3.88
NGC 2243	59.59 ± 0.06	0.55 ± 0.08	0.79 ± 0.03	51.04 ± 3.82	30.93 ± 2.80
NGC 2420	74.60 ± 0.06	0.59 ± 0.05	0.73 ± 0.03	30.86 ± 3.84	30.39 ± 2.71
NGC 2516	23.85 ± 0.07	0.82 ± 0.06	0.68 ± 0.03	22.66 ± 3.62	36.54 ± 3.05
NGC 6067	-38.35 ± 0.62	1.59 ± 0.44	0.12 ± 0.04	-33.24 ± 2.18	28.44 ± 1.75
Trumpler 20	-39.72 ± 0.22	1.09 ± 0.24	0.25 ± 0.03	-16.97 ± 1.78	25.23 ± 1.46

Notes. Column 1 reports the name of the cluster. Columns 2 and 3 are the central velocity and intrinsic velocity dispersion of cluster, respectively. Column 4 is the fraction of stars that belong to the cluster. Columns 5 and 6 are the central velocity and velocity dispersion of the field stars.

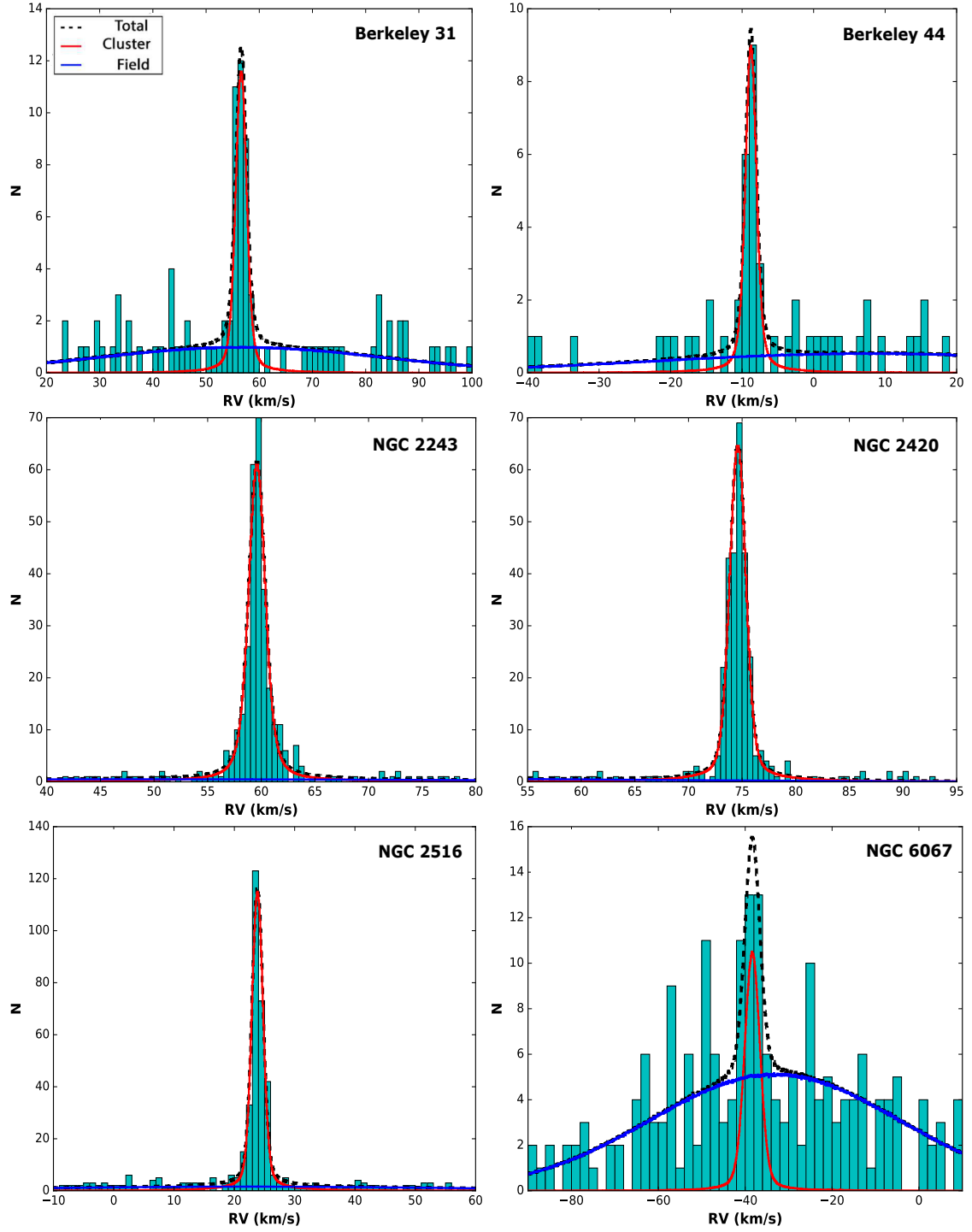


Figure 5.2: Radial velocity distributions of Berkeley 31, Berkeley 44, NGC 2243, NGC 2420, NGC 2516, and NGC 6067. The blue line is the field component while the red one is the cluster component. The black dashed line represents the sum of the two distinct components. The binary fraction is fixed to 0.5.

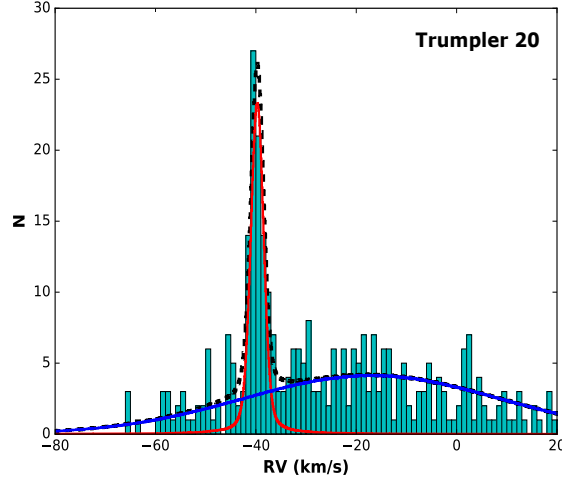


Figure 5.3: Radial velocity distribution of Trumpler 20. The lines are the same of the figure 5.2.

are large and they must be properly taken into account in the further analysis.

Once the intrinsic RV dispersion and central velocity (with the related errors) have been determined in each cluster, I estimated the probability of each star to belong to the clusters using equation 3.8 and considering also all the stars which had been excluded from the fits. In figures 5.4, 5.5, and 5.6 the spatial distribution of the stars used to perform the subsequent analysis (last row of table 5.2) are shown. Each target is weighted by the corresponding probability. In each cluster, the high probability candidate members are concentrated mainly in the central zone. However, as in the case of young clusters (see section 4.4), also several stars with p_{cl} greater than 0.9 are found in the outer regions of GES observations.

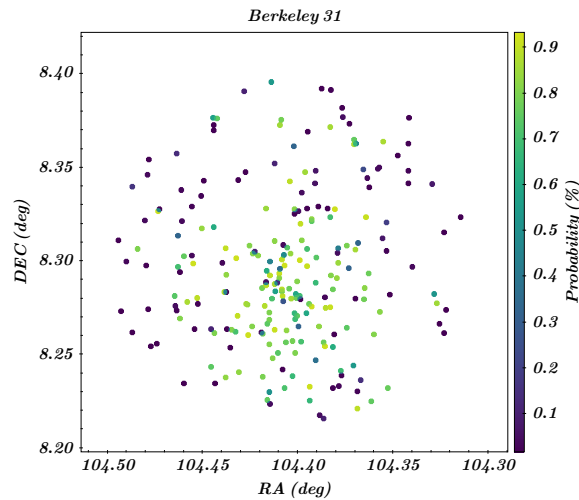


Figure 5.4: Spatial distributions of allocated targets weighted for the corresponding probability (colored dots) in cluster Berkeley 31.

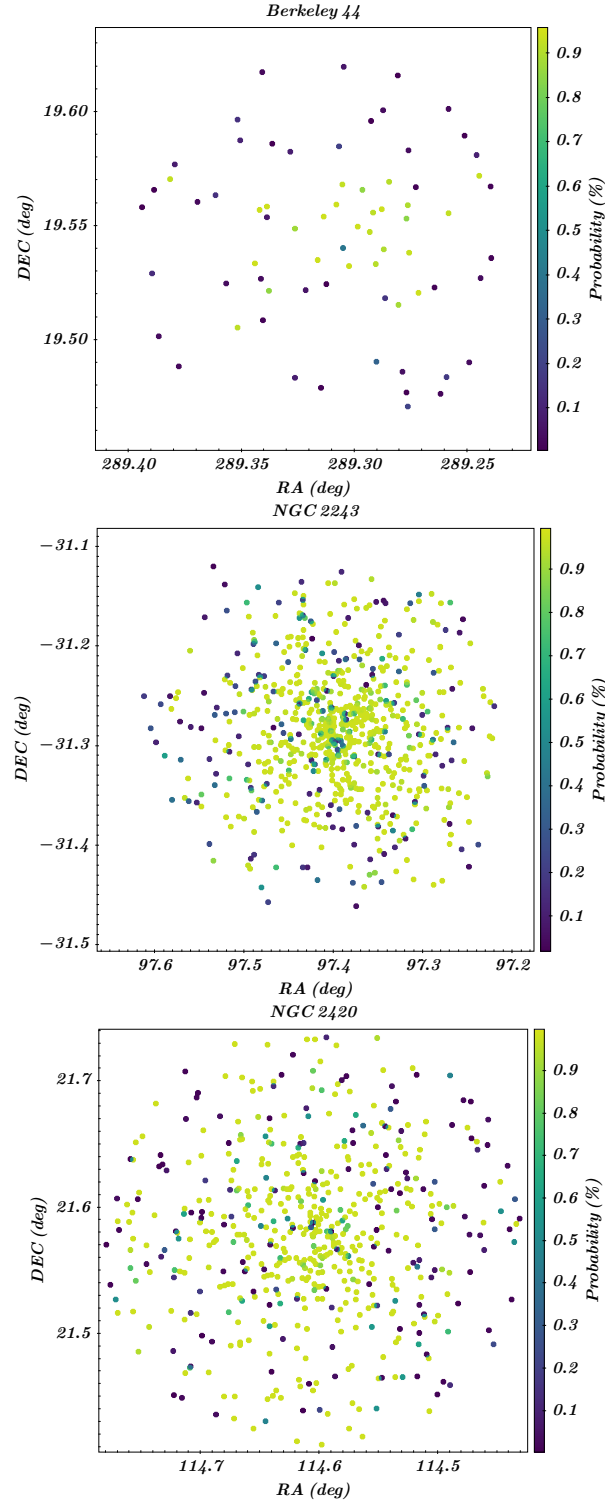


Figure 5.5: Spatial distributions of allocated targets weighted for the corresponding probability (colored dots) in clusters Berkeley 44, NGC 2243, and NGC 2420.

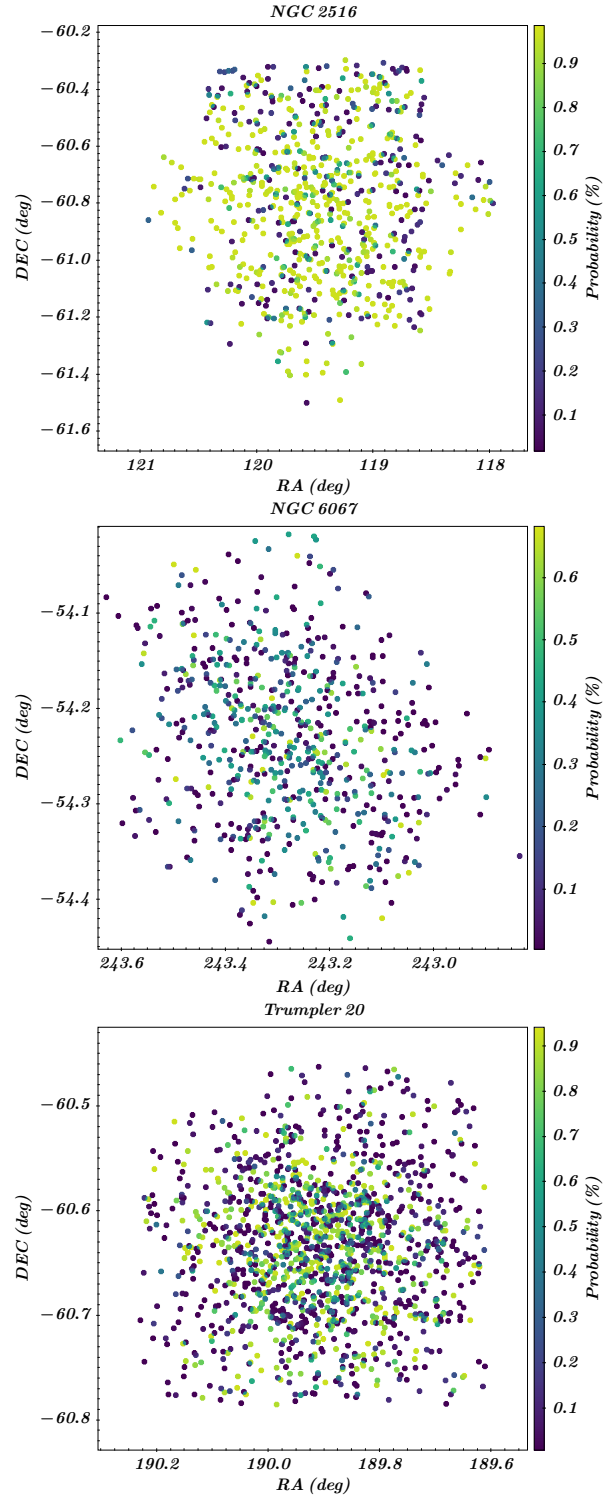


Figure 5.6: Spatial distributions of allocated targets weighted for the corresponding probability (colored dots) in clusters NGC 2516, NGC 6067, and Trumpler 20.

5.4.1 The Effects of Binaries on Velocity Dispersion

As described in the previous Chapters, the cluster velocity dispersion is inflated by the orbital motions of unresolved binaries. With the method developed by Cottaar et al. (2012b), the broadening of RV distribution due to the binaries is taken into account. As in the case of young clusters, I performed the fit of the RV distributions also using different values of f_{bin} (i.e., 0, 0.2, 0.8, and 1.0) for all the clusters. Table 5.5 shows the results obtained for the different fraction of binaries. The derived velocity σ_c obtained with a binary fraction fixed to 0 are on average a factor ~ 1.9 greater than those with f_{bin} fixed to 100%, which corresponds to a variation in the dynamical mass (equation 1.6) of a factor ~ 3.6 . For the clusters studied in this work, which have a typical density between 0.1 and 10^7 stars pc^{-3} , this result is in agreement with the expectations about the effects of binaries on the velocity dispersion and mass determination obtained by Kouwenhoven & de Grijs (2008).

Table 5.5: Central velocity and velocity dispersions obtained with fraction of binaries fixed to 0%, 20%, 80%, and 100% for the sample of old clusters.

Cluster	f_{bin} (%)	v_c (km s^{-1})	σ_c (km s^{-1})
Berkeley 31	0.0	56.59 ± 0.25	0.99 ± 0.25
	0.2	56.61 ± 0.23	0.87 ± 0.23
	0.8	56.61 ± 0.24	0.66 ± 0.25
	1.0	56.66 ± 0.26	0.52 ± 0.35
Berkeley 44	0.0	-8.75 ± 0.21	0.60 ± 0.19
	0.2	-8.75 ± 0.22	0.58 ± 0.20
	0.8	-8.77 ± 0.26	0.47 ± 0.24
	1.0	-8.80 ± 0.28	0.39 ± 0.28
NGC 2243	0.0	59.61 ± 0.07	0.87 ± 0.08
	0.2	59.62 ± 0.07	0.73 ± 0.09
	0.8	59.58 ± 0.06	0.35 ± 0.10
	1.0	59.57 ± 0.06	0.28 ± 0.14
NGC 2420	0.0	74.58 ± 0.06	0.74 ± 0.05
	0.2	74.61 ± 0.06	0.66 ± 0.05
	0.8	74.60 ± 0.06	0.50 ± 0.06
	1.0	74.62 ± 0.06	0.38 ± 0.09
NGC 2516	0.0	23.89 ± 0.07	0.99 ± 0.06
	0.2	23.83 ± 0.07	0.95 ± 0.06
	0.8	23.83 ± 0.07	0.65 ± 0.08
	1.0	23.80 ± 0.06	0.45 ± 0.10
NGC 6067	0.0	-38.23 ± 0.57	1.76 ± 0.44
	0.2	-38.87 ± 0.67	1.68 ± 0.43
	0.8	-38.31 ± 0.65	1.50 ± 0.46
	1.0	-38.28 ± 0.67	1.43 ± 0.48
Trumpler 20	0.0	-39.59 ± 0.21	1.30 ± 0.21
	0.2	-39.67 ± 0.21	1.20 ± 0.22
	0.8	-39.78 ± 0.22	0.93 ± 0.24
	1.0	-39.82 ± 0.21	0.82 ± 0.24

As in the case of young OCs, I adopted the results obtained with a f_{bin} fixed to 0.5 for the subsequent analysis because (i) f_{bin} fixed to 0 and 1.0 are extreme values for a real cluster, (ii) σ_c derived for f_{bin} of 0.2 and 0.8 are in agreement with the best value obtained for a fraction of binaries of 0.5, and (iii) f_{bin} of the observed solar-type binaries in the solar neighborhood is $\sim 46\%$ (e.g., Raghavan et al. 2010).

5.5 Cluster Parameters

5.5.1 Star Masses

Starting from the literature values of cluster parameters listed in Table 5.1, I derived the single star masses using the CMDs and the PARSEC evolutionary models (Bresan et al. 2012), as described in section 3.2.3 for the case of old clusters. Figures 5.7 and 5.8 show the V vs. B – V or the V vs. V – I CMDs used in order to derive masses. The stars are color-coded by their membership probability p_{cl} , while the red lines are the isochrones corresponding to the cluster parameters listed in Table

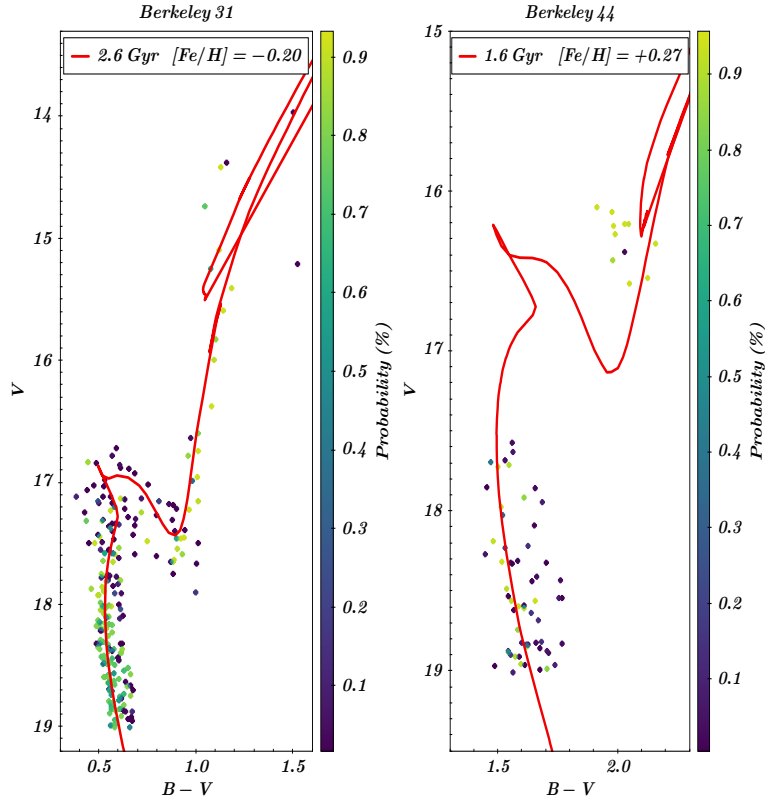


Figure 5.7: The V versus B – V CMD for Berkeley 31 and Berkeley 44. The red line is the isochrone corresponding to the cluster parameters listed in Table 5.1. Each star is weighted by its membership probability p_{cl} .

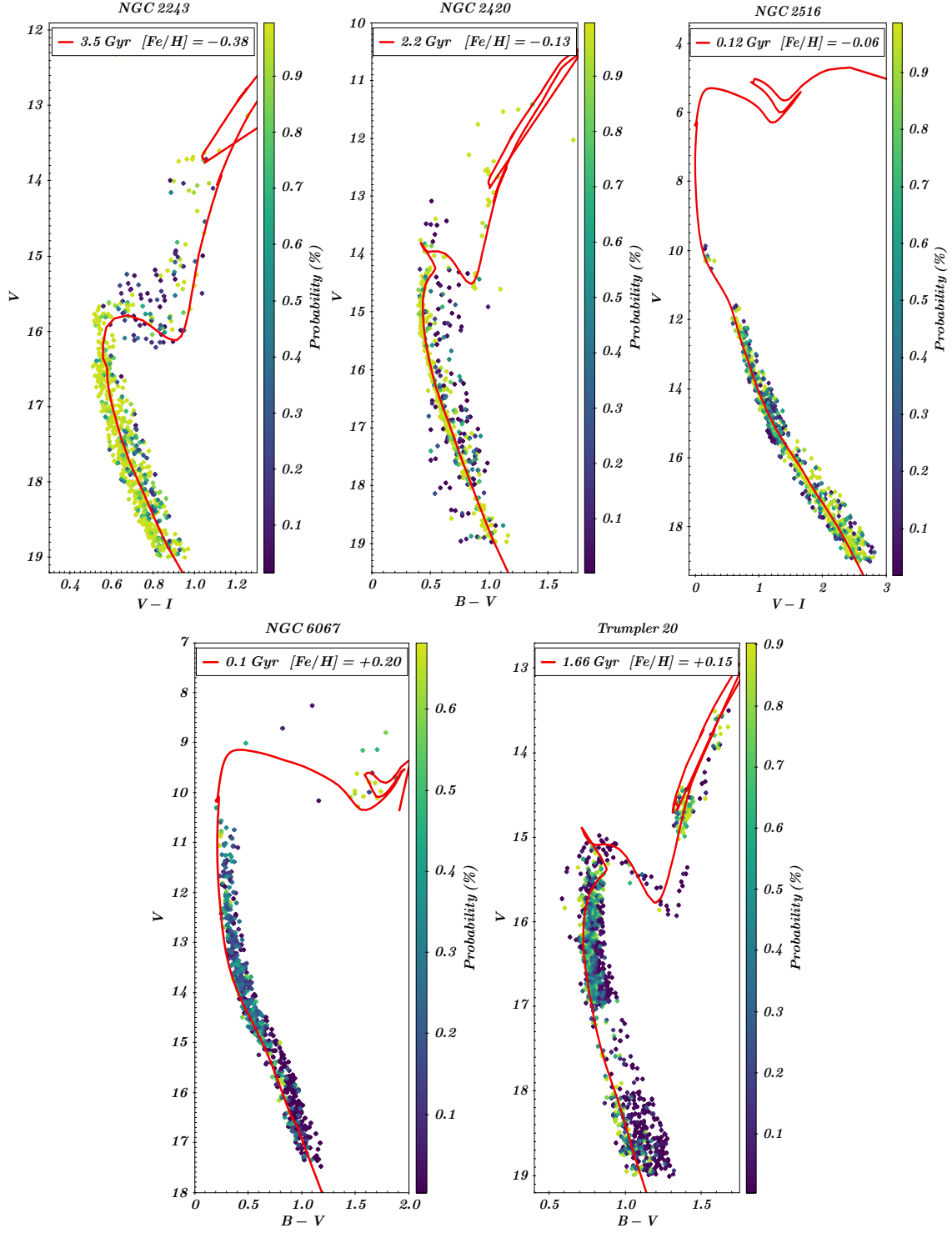


Figure 5.8: As figure 5.7 but for clusters NGC 2243, NGC 2420, NGC 2516, NGC 6067, and Trumpler 20.

5.1. As in the case of young OCs (see chapter 4), in each cluster the stars selected as target with high-probability tend to be closer to the cluster sequence defined by the isochrone than low-probability ones. Furthermore, in the RC of all clusters, the majority of the stars have high probability to belong to the cluster. This is a further confirmation of the quality both of the data and method. The CMDs are shown in figure 5.7 and 5.8, where the stars are weighted by the corresponding probability.

5.5.2 Total Cluster Mass and Cluster Radius

In each cluster, it is necessary to estimate the M_{tot} and r_{hm} to investigate their dynamical state. Using the stellar masses determined as described in the previous section, within the magnitude range of GES observations, I obtained the total cluster mass following the method described in section 3.2.3. I derived the observed mass using both all the stars weighted by their corresponding p_{cl} and the stars with p_{cl} greater than 0.8, which are corrected for the presence of binaries and for the completeness in MS and post-MS phases (values in table 5.3). Lastly, I extrapolated the cluster mass expected outside the GES magnitude range. In the particular case of NGC 2516, I needed to extrapolate also the cluster mass in the upper MS, i.e., between the most massive star observed by GES and the star mass at the TO point, as done for the sample of young OCs in Chapter 4. Infact, the brightest magnitude limit of GES observations does not allow the observation of the most massive stars that lie at the cluster TO and in the post-MS phases. Moreover, in this cluster I did not consider the very few stars in the RGB and RC phases found in literature since their contribution to the total mass is negligible.

The total cluster mass and the mass of a star at the TO, M_{TO} , are reported in table 5.6. In the case of NGC 6067, it was not possible to derive $M_{\text{tot},0.8}$ since this cluster has not targets with $p_{cl} > 0.8$. This is due to the high level of field contamination that does not allow to determine members with high probability. As in the case of young OCs, I adopted $M_{\text{tot},w}$ for the subsequent dynamical analysis.

In order to derive an estimate of the error on the total masses, I derived the sum of observed and extrapolated mass (without considering the completeness) again by varying the cluster parameters (i.e., age, metallicity, distance, and reddening) within their error ranges (table 5.1). I considered the standard deviation of the resulting values as error on the summed mass. Then, I propagated this latter error and the error on the completeness (see the end of section 5.3) in order to derive the error on total mass M_{tot} . Furthermore, in order to derive the cluster mass outside the GES magnitude range, I assumed a Kroupa MF (Kroupa 2001). While in young OCs this MF is an excellent approximation of the present-day MF given that young systems did not have time to evolve and lose members, the present-day mass function of old clusters may show a deficit of stars in the low mass regime as the cluster ages, as explained in section 1.2.2. Therefore, as a caveat, the estimates of the total mass reported in this work should be taken as an upper limit, since as a result of

Table 5.6: Derived masses of the seven old open clusters.

Cluster	M_{TO} ($M_{\odot}$)	$M_{\text{tot,w}}$ ($M_{\odot}$)	$M_{\text{tot,0.8}}$ ($M_{\odot}$)	r_{hm} (pc)
Berkeley 31	1.4	1587 ± 175	963 ± 105	~ 5.5
Berkeley 44	1.7	1118 ± 140	1023 ± 125	~ 1.3
NGC 2243	1.2	4441 ± 450	4210 ± 430	~ 4.4
NGC 2420	1.5	2354 ± 240	2189 ± 225	~ 3.0
NGC 2516	4.4	3342 ± 635	2297 ± 570	~ 2.1
NGC 6067	4.7	7083 ± 750	-	~ 2.7
Trumpler 20	1.7	12067 ± 1110	7594 ± 710	~ 4.2

dynamical evolution, significant fractions of the low-mass content may have been lost to the field.

Regarding the half-mass radius, I used for old OCs the method described in section 3.2.3. At age older than 100 Myr the MS turn-off lies in the magnitude range of GES observations for six out of seven clusters. Instead, as described above, in the case of NGC 2516 several massive stars are outside the observations, given the combination of GES magnitude range and proximity of this cluster. In the case of presence of mass segregation, the half-mass radius might be overestimated, while this not happens in the case of the other six clusters in which the whole members sample is observed. For this reason, in NGC 2516 it was necessary to apply the same method used for the sample of young OCs, i.e., to consider the stars identified as members by Gaia Collaboration et al. (2018b) (with the data of the *Gaia* data release 2, DR2) within the R_{GES} and with magnitude over the upper limit of GES observations. I assumed that these stars have a probability to belong to the cluster of 100%. In this case, the r_{hm} is the radius that contains half of the mass given by the sum of GES masses and the mass of stars in Gaia Collaboration et al. (2018b). However, considering the whole *Gaia* sample, this cluster seems to be more extended than previously thought, as described previously. Therefore, the r_{hm} derived could be only a lower limit for NGC 2516. The r_{hm} for the seven clusters are shown in table 5.6.

5.6 Preliminary Discussion on Cluster Evolution

As explained in the previous chapters, the aim of this work is to study the dynamical state of several OCs spanning a wide range of ages using homogeneous datasets. In particular, determining if they are or not in virial equilibrium is fundamental, since this may allow questioning the different scenarios proposed for their survival. Following the approach adopted on young OCs, I used the velocity dispersions obtained with the GES data (σ_c) and that expected at the virial equilibrium (σ_{vir}),

which is derived analytically using the equation 4.1. In this work, the errors on the virial velocity dispersion are obtained by propagating only the error on M_{tot} (derived in the previous section). However, other sources of error, which I did not take into account in this work, may be present: (i) if the observed mass distribution is different from the real total mass distribution, due to some effects of mass segregation, the estimate of r_{hm} might be either smaller or larger; (ii) if the cluster density is not described by a Plummer density profile, the value of η can be lower. Both these effects can lead to a different value of σ_{vir} . In table 5.7 I list the velocity dispersion derived from the GES RVs and σ_{vir} , as well as the total mass and half-mass radius of each cluster.

The virial velocity dispersions as a function of the velocity dispersions obtained with GES data are shown in figure 5.9. The dashed blue line is the 1:1 relation. Six out of seven clusters follow the 1:1 relation, indicating that they are in virial equilibrium. In these six clusters the intrinsic velocity dispersions obtained with the GES data and the virial velocity dispersions are in agreement within 1.25σ . This confirms the models that predict that the small number of OCs, which were able to survive at the first early evolution and gas expulsion, are in equilibrium (although a real final equilibrium state does not exist for a cluster, since self-gravitating systems are unstable) and they can survive as bound systems also for several Gyr (e.g., Portegies Zwart et al. 1998; Baumgardt & Makino 2003; Lamers et al. 2005; Bastian et al. 2005).

Instead, for Berkeley 31 the two values of the velocity dispersion are in agreement only within 2σ . This discrepancy may be due to a high fraction of binaries. Infact, the fraction of binaries is expected to decrease with decreasing the stellar mass, hence in high-mass stars (O and B stars) the binary fraction is much higher than the fraction in low-mass ones (e.g., Mason et al. 2009). Although in old clusters high-mass stars are no longer present, the stars observed by GES in Berkeley 31 are the brightest stars of the system because of combination of the cluster distance and magnitude limit of observations; therefore, in order to test this prediction, I

Table 5.7: Velocity dispersions and properties of old clusters in the sample.

Cluster	M_{tot} ($M_{\odot}$)	r_{hm} (pc)	σ_c (km s^{-1})	σ_{vir} (km s^{-1})
Berkeley 31	1587 ± 175	~ 5.5	0.79 ± 0.23	0.36 ± 0.02
Berkeley 44	1118 ± 140	~ 1.3	0.55 ± 0.21	0.61 ± 0.04
NGC 2243	4441 ± 450	~ 4.4	0.55 ± 0.08	0.66 ± 0.03
NGC 2420	2354 ± 240	~ 3.0	0.59 ± 0.05	0.59 ± 0.03
NGC 2516	3342 ± 635	~ 2.1	0.82 ± 0.06	0.84 ± 0.08
NGC 6067	7083 ± 750	~ 2.7	1.59 ± 0.44	1.09 ± 0.06
Trumpler 20	12067 ± 1110	~ 4.2	1.09 ± 0.24	1.13 ± 0.05

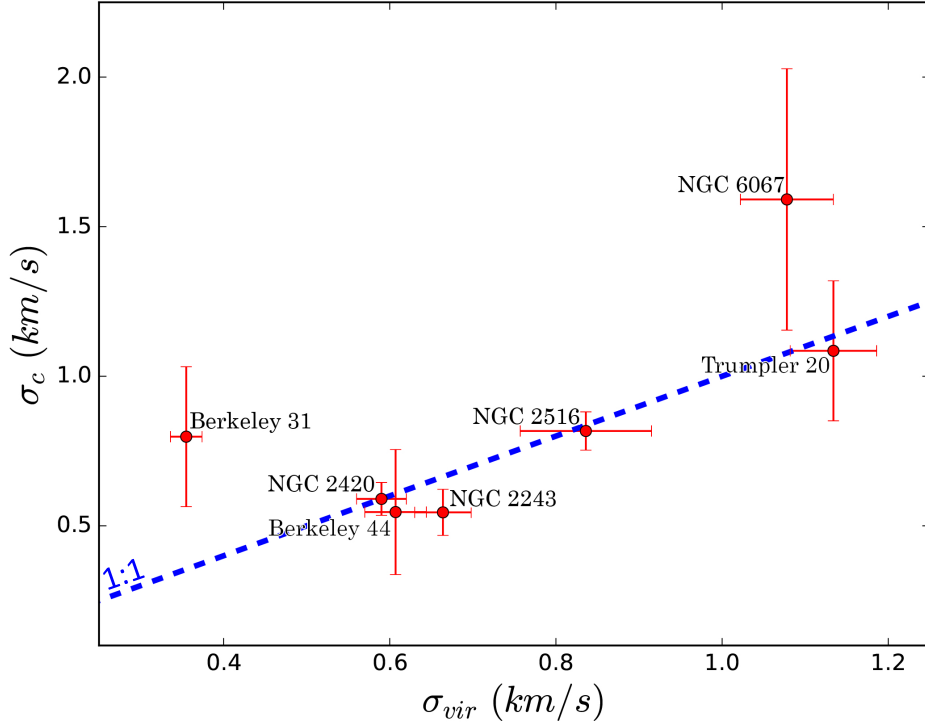


Figure 5.9: Comparison between the cluster radial velocity dispersions obtained with the GES data, σ_c , and the velocity dispersions derived under the assumption of the virial equilibrium. The dashed blu line represents the 1:1 relation.

performed the same procedure described in the previous sections but with a binary fraction fixed at 0.8. The results are listed in Table 5.8 and show that the velocity dispersions of Berkeley 31 are consistent between them within a 1.2σ with this fraction of binaries. This is clear from figure 5.10, where I plot in blue the velocity dispersions of Berkeley 31 obtained with a binary fraction fixed at 0.8. This indicates that in this cluster the fraction of binary population could be higher than 50%. However, given that the stellar mass at the TO point is only $1.4 M_\odot$, a binary fraction of 80% is likely too high for stars with such mass in OCs. Further investigations will be needed in order to prove this result.

Table 5.8: Properties of Berkeley 31 obtained using a binary fraction of 0.8.

Cluster	M_{tot} ($M_\odot$)	r_{hm} (pc)	σ_c (km s^{-1})	σ_{vir} (km s^{-1})
Berkeley 31	1618 ± 179	~ 5.6	0.66 ± 0.25	0.36 ± 0.02

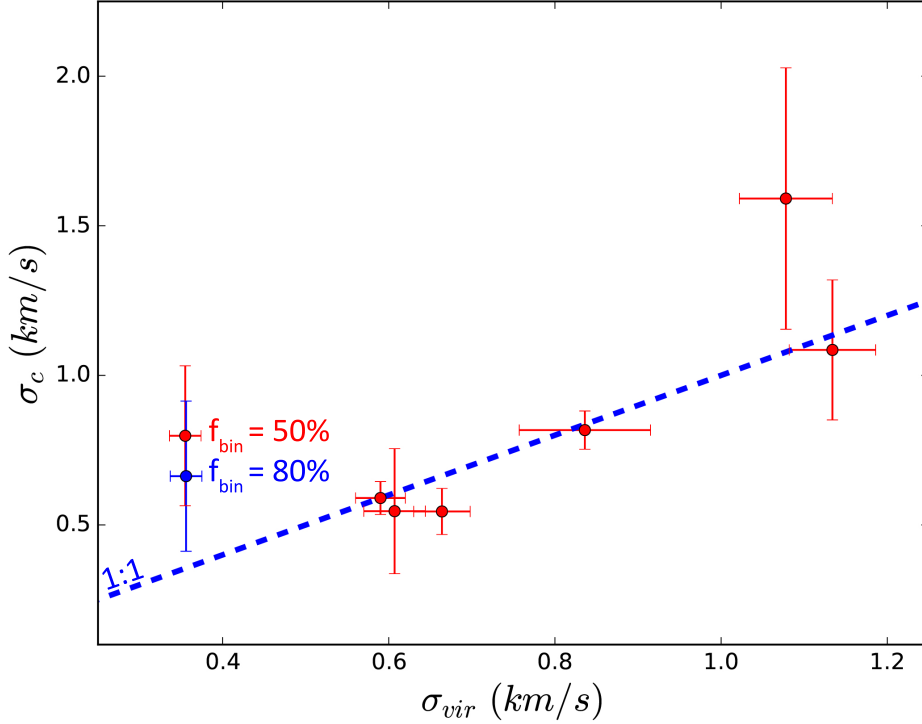


Figure 5.10: Comparison between velocity dispersions obtained with f_{bin} fixed at 0.5 (in red) and 0.8 (in blue) for OC Berkeley 31. The velocity dispersions of the other clusters are the same of the figure 5.9.

The seven old OCs analyzed in this thesis likely started their evolution with a higher number of members, which then dispersed in the field. A possible theoretical scenario that can be tested with the observational results of this work is the model proposed by O’Leary et al. (2014), that describes the internal cluster evolution. All gravitationally bound clusters expand and, as they get older, they are likely tidally disrupted either by passing molecular clouds or the gravitational potential of the Galaxy. Their internal evolution may follow two different evolutionary paths. On the one hand, in clusters with a large initial population the core collapses while the external parts expand. The core collapse is due to the effects of both two-body relaxation and stellar evaporation, which move energy from the central to the external part of clusters, leading to the mass segregation (e.g., Makino 1996; Portegies Zwart et al. 2010). On the other hand, in smaller clusters binary heating prevents the core collapse and in this case clusters expand until the moment of tidal disruption. O’Leary et al. (2014) found that the path followed by a cluster depends on the initial number members N and on the initial virial radius r_{vir} . In particular, they found a “collapse line” in the $r_{vir} - N$ plane (see figure 1 and 6 in O’Leary et al. (2014)) by N -body simulations. This is the line defined by the systems for

which the MS lifetime of their most massive stars is equal to the time required by these same stars to move towards the center of the cluster via dynamical friction. A cluster undergoes core collapse only if it lies above this line, that is defined by the following equation:

$$r_{coll} = 2 \left(\frac{6.9 + \ln N_4}{6.9 \sqrt{N_4}} \right)^{2/3} \text{ pc}, \quad (5.1)$$

where $N_4 \equiv N/10^4$. However, as a cluster evolves, it changes both the number of members and its virial radius due to several effects. With the present-day N and r_{vir} , they predicted the cluster evolution using another fundamental property, the cluster age, t_{age} . If a cluster is located below the collapse line, the system globally expands until the tidal disruption. For cluster above the collapse line, they defined a theoretical “relative age”, t_1 , in order to compare it with t_{age} . This relative age is defined as the time necessary for a cluster to reach the present-day N and r_{vir} starting from the collapse line, and it is given by the equation

$$t_1 \approx 30 \left(\frac{r_{vir}}{r_{coll}} \right)^{3.3} \text{ Myr}, \quad (5.2)$$

where r_{coll} is the cluster virial radius that defines the collapse line in equation 5.1 and r_{vir} is the present-day virial radius. When $t_{age} > t_1$ clusters have started their evolution below the collapse line, hence they will globally expand and will never undergo to core collapse. Only clusters with $t_{age} < t_1$ can experience the core collapse.

I applied this theoretical method to the old clusters analyzed in this part of work. Starting from the cluster properties obtained in the previous sections, I extrapolated the present-day total number of members N (using the Kroupa mass function defined in section 1.2.2 between $0.1 M_\odot$ and the mass expected at the TO) and I derived the present-day r_{vir} (using the equation 1.1). In table 5.9 I reported the derived properties of each cluster, as well as the cluster ages, while in figure 5.11 I plot in the $r_{vir} - N$ space the seven old OCs studied in this work.

Only one cluster (Berkeley 31) lies below the collapse line, while another cluster (Berkeley 44) is exactly on this line. Therefore, these clusters are expected to globally expand until they begin to be tidally disrupted by the outer gravitational fields. In Berkeley 44, the spatial distribution (top panel of 5.5) and table 5.2 show that this cluster has a low number of observed members. This may indicate that the majority of its members are already lost in the field and the cluster might be unbound, despite the comparison between the intrinsic velocity dispersion and virial dispersion indicates that it is in equilibrium. Furthermore, in the model of O’Leary et al. (2014), the core collapse is not expected due to the heating by binaries. This supports the idea that a high fraction of binaries could be present in Berkeley 31. Hence, this system could be already in an unbound state, as also indicated from the comparison between σ_c and σ_{vir} , from which I found that this cluster is slightly

supervirial. This cluster was able to survive until its actual age probably because it is located in the outer region of the Galaxy, as shown in figure 5.1, where the interactions with GMCs or the effects of tidal field are less frequent and important. Although all the results seem to confirm the expansion and the future disruption of these clusters, their positions are really near r_{coll} and more investigations are necessary to determine their accurate position in the $r_{vir} - N$ plane.

Instead, five out of seven clusters are above the collapse line. NGC 2420 and NGC 6067 have a $t_1 \approx 360$ Myr and $t_1 \approx 40$ Myr, respectively, that are lower than their ages ($t_{age} \sim 2.20$ Gyr and ~ 100 Myr, respectively). Following the model proposed by O’Leary et al. (2014), this indicates that these clusters started their evolution below r_{coll} and will never experience a core collapse. Therefore, they will expand for their entire life.

In the other three clusters (NGC 2243, NGC 2516, and Trumpler 20) the cluster ages are less than the derived relative ages t_1 . Therefore, all these clusters will have a core collapse, while the external members will expand and disperse in the field. In particular, NGC 2243 has t_1 that is ~ 8.6 Gyr, well greater than its t_{age} . Bergbusch & Blake (1996) found in this OC that its bright stars are more concentrated than the faint ones, suggesting that mass segregation has occurred. Therefore, this cluster probably has already undergone core collapse and this may be an explanation of the large concentration in the inner part of this system of high probability candidate members, as shown in the middle panel of figure 5.5. Also, NGC 2516 and Trumpler 20 have relative ages that are higher than their t_{age} , and following O’Leary et al. (2014), these clusters will experience the core collapse, if they have not done already.

However, all these results are still uncertain and the discussion on the comparison of the observed data with this model is open. Indeed, it is difficult to explain how clusters without core collapse are able to survive for such a long time. In this model, several sources of error should be considered. In particular, the present-day N may be overestimated, since the MF models predict that several low-mass mem-

Table 5.9: Derived properties for the seven old open clusters.

Cluster	t_{age} (Gyr)	N	r_{vir} (pc)	t_1 (Gyr)
Berkeley 31	2.60 ± 0.30	~ 4000	1.8 ± 1.1	~ 0.02
Berkeley 44	1.60 ± 0.30	~ 2700	2.7 ± 2.0	~ 0.03
NGC 2243	3.50 ± 0.50	~ 11700	10.3 ± 3.2	~ 8.63
NGC 2420	2.20 ± 0.30	~ 5800	4.9 ± 1.0	~ 0.36
NGC 2516	0.12 ± 0.01	~ 6700	3.7 ± 0.9	~ 0.15
NGC 6067	0.10 ± 0.05	~ 14000	2.0 ± 1.1	~ 0.04
Trumpler 20	1.66 ± 0.20	~ 29200	6.6 ± 3.3	~ 5.20

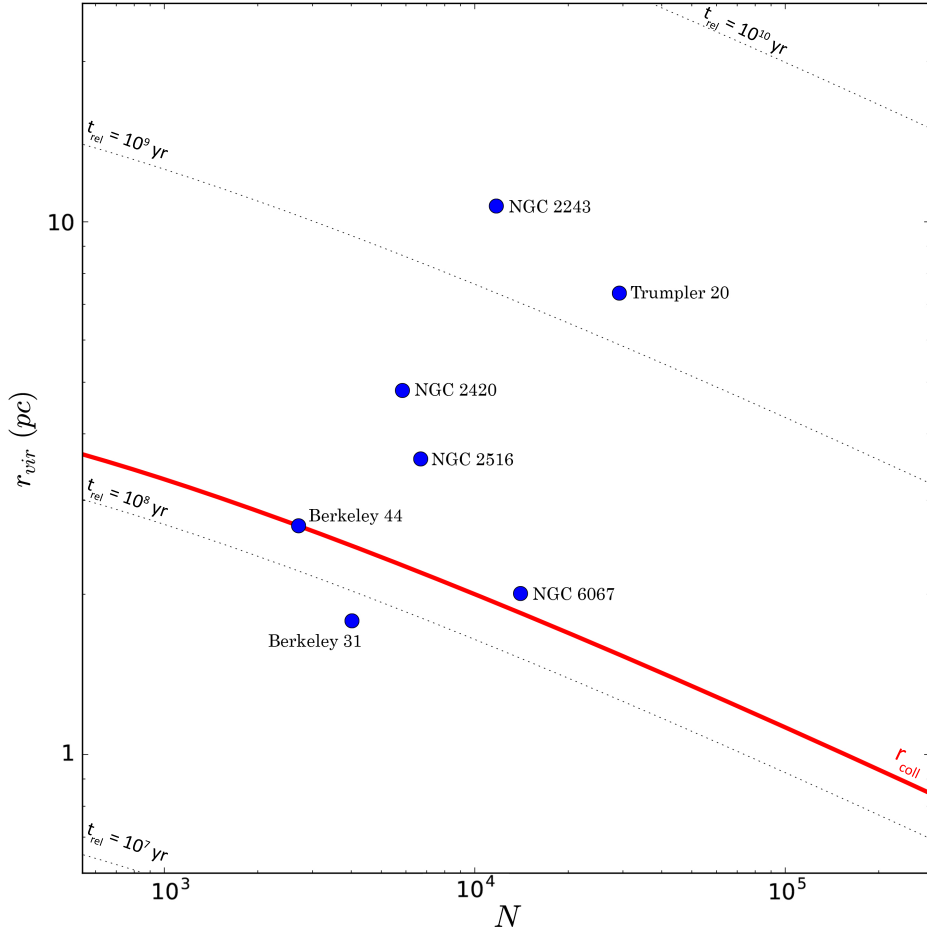


Figure 5.11: Distribution of the seven old open clusters in the $r_{vir} - N$ plane. The red solid line is the collapse line defined by equation 5.1, while the dotted black lines from the bottom to the top are the relaxation time t_{rel} at 10^7 , 10^8 , 10^9 , and 10^{10} years, respectively.

bers are lost as the cluster evolves. Hence, the extrapolated value of N in table 5.9 should be considered as an upper limit. As a consequence, also the estimates of both the total cluster mass and virial radius might be affected by this effect. Moreover, the evolution in clusters with age of several Gyr may have been more turbulent. Indeed, this model is difficult to apply in old clusters which began with a much higher number of members N and are now or have been disrupting by some tidal interactions, such as tidal streams. The original locations of such clusters in the $r_{vir} - N$ space are thus uncertain, as are their fates. Therefore, deep investigations will be needed to improve the uncertainties that act on the fundamental model parameters. Further detailed analysis will be required to confirm the past, the present and the future evolution of these OCs.

5.6.1 Anisotropic Velocity Distribution

As in the case of young clusters, the results presented in the previous section are based on the assumption of isotropic velocity distribution. As described in the section 4.7.2.1, star clusters develop a radial anisotropic velocity distribution as they evolve (e.g., Takahashi & Lee 2000; Baumgardt & Makino 2003; Tiongco et al. 2016; Vesperini et al. 2014). However, if they are in advanced stages of evolution, such as the clusters with ages of the order of Gyrs analyzed in this work, and they have lost a relevant fraction of initial mass as a result of the two-body relaxation, the systems evolve again towards a global isotropic velocity distribution. Nevertheless, within the sample analyzed in this work, the clusters might also have suffered of the disturbing external potential which has may induce other effects of anisotropy, especially in the outer regions. A detailed study of the eventual existence of anisotropies in velocity distribution may reassess the results presented in the clusters analyzed in this work. Therefore, the presence of some kind of anisotropy in velocity and the connection between the kinematic properties and the dynamical evolution of these old clusters will be investigated using the proper motions of the second *Gaia* data release.

Chapter 6

Summary and Conclusions

Origin and evolution of open clusters are fundamental topics in the study of star formation and Galaxy evolution. A key point is the comparison between the observational data and the proposed models for cluster evolution. Therefore, the study of kinematic properties and dynamical state of OCs spanning a wide range of properties, such as age, is crucial to test and call into question the models proposed for their evolution and dissipation. To date, this kind of study has been carried out only for a few OCs, and previous investigations are performed with data, methods, techniques, and procedures for the analysis independent of each other. This has led to inconsistencies between the analysis and results in the different works. The work presented in this thesis aims at studying a sample of OCs using spectroscopic parameters, such as radial velocities, that are obtained homogeneously from the GES spectra. Moreover, the same methods for a sample of OCs are used to derive the kinematic properties and to perform the dynamical analysis, allowing uniform results. Also, the data of the first *Gaia* data release have been used for a small part of this work.

My Ph.D. work was divided in two main parts. In the first one, I studied a sample of young clusters, that means clusters with ages less than 100 Myr. Instead, in the second part of work, I analyzed a sample of open clusters with age between 100 Myr and several Gyr.

The four open clusters studied in the first part of the work have age between 20 and 50 Myr (Chapter 4). Using the gravity index, the lithium equivalent width, and the metallicity, I derived a sample of spectroscopic candidate members in each cluster. Then, using a maximum likelihood technique (Cottaar et al. 2012b), with the radial velocities of the stars selected as spectroscopic candidates and taking into account the broadening due both to the uncertainties on radial velocities and to the orbital motions of unresolved binary systems, I derived the cluster intrinsic velocity dispersion and membership probabilities for each one of them. The results are based on the assumption that the cluster binary fraction is fixed to 50%. This value is confirmed by several works, which show that f_{bin} is $\sim 46\%$ for the observed solar-type binaries in the solar neighborhood, which are the kind of binary stars taken

into consideration in this work. Photometry from the literature and the effective temperature from GES spectra were used to estimate stellar masses and the total mass of each cluster after correcting for the presence of binaries and completeness of GES observations. Furthermore, a group based in Leiden independently derived the intrinsic velocity dispersion of the clusters from the astrometric parameters of cluster members in the TGAS catalogue, which I compared with those derived from radial velocities. On the basis of this analysis, I obtained the following main results.

- In each cluster I found many new high-probability members and confirmed many of those known in the literature. New high-probability members are extended across the whole area covered by GES observations (section 4.4).
- The velocity dispersion measured with GES data is about a factor two higher than that calculated by assuming virial equilibrium given the masses of the clusters and the spatial distribution of their members. This result indicates that clusters are in supervirial state and two explanations are proposed. The residual gas expulsion scenario (e.g., Kroupa et al. 2001; Goodwin & Bastian 2006) suggests that clusters became unbound after the feedback from massive stars swept out the gas that did not form stars. While a second scenario suggests that the observed velocity dispersion could be higher than the virial dispersion because most stellar systems do not fully relax, even after 20 – 30 crossing times, as shown in the N-body simulations of Parker & Wright (2016). These results rely on the assumption of isotropic velocity. Several theoretical works (e.g., Takahashi & Lee 2000; Baumgardt & Makino 2003; Vesperini et al. 2014; Tiongco et al. 2016) show that star clusters usually have an anisotropic velocity distribution. However, clusters that undergo an early phase of violent relaxation, such as those in this work, develop an isotropic core and an anisotropic radial velocity distribution by moving outwards. This supports the assumption of isotropic velocity distribution, at least in the inner cluster regions. In any case, the eventual presence of anisotropy in velocity distribution will have to be investigated with the astrometric parameters of the second *Gaia* data release.
- The velocity dispersion measured from the RVs is higher than that estimated from TGAS data. Given the masses of the stars in the GES and the TGAS sample, this discrepancy would suggest that the system is relaxed and in a state of energy equipartition. However, given the limited numbers of cluster members in the TGAS sample and the error on astrometric parameters, we are not able to draw a firm conclusion. Significant progresses are possible with the second *Gaia* data release.

This first part of work was published in a paper in *Astronomy & Astrophysics* with the title: “*The Gaia-ESO Survey: a kinematical and dynamical study of four young open clusters*”, Bravi L., et al. 2018, *A&A*, 615, 37.

For the second part of my work, I selected a sample of seven open clusters with age between 100 Myr and 3.5 Gyr (Chapter 5). Following the same maximum likelihood method used for the young open clusters, I derived the cluster intrinsic velocity dispersion and membership probabilities. Using the photometry from the literature, I estimated the mass of each star and the total mass of each cluster (corrected for the presence of binaries and completeness). The main preliminary results can be summarized as follows.

- Comparing the velocity dispersions obtained by the GES data with those derived under the assumption of virial equilibrium, I found that for six out of seven clusters the virial velocity dispersions and the velocity dispersions obtained through the GES data are in agreement, therefore clusters are in virial equilibrium. This is what expected in the evolutionary models, that predict that open clusters that were able to survive at the first early evolutionary stages and to the gas expulsion are in equilibrium and they can also survive for several Gyr. Results are based on the assumption of isotropy of velocity distribution since clusters in an advanced stage of evolution and with a large fraction of initial mass lost by two-body interactions evolve towards a global isotropic velocity distribution unless they have suffered of external tidal interactions, which may induce other effects of anisotropy in the outer regions. This possibility will be tested with the astrometric parameters of the second *Gaia* data release.
- In the open cluster Berkeley 31 the observed and virial velocity dispersions are in agreement only within 2σ . In this cluster, the fraction of binaries adopted may be too low, since its observed stars are the most massive and it is expected that high-mass objects have a higher binary fraction with respect the less massive ones. If I use a binary fraction fixed at 80% the two velocity dispersions are in agreement. However, further investigations are necessary to check this result.
- Starting from the data obtained with the kinematic analysis, I tested the model for the internal cluster evolution proposed by O’Leary et al. (2014). This model predicts that the evolution may follow two paths: a core collapse or the expansion of the whole system until the moment of tidal disruption. The two paths depend both on the number of the initial stellar members N and the initial virial radius r_{vir} , and a “collapse line” divides them. In order to test the evolutionary status of real clusters using this model, they defined a theoretical “relative age” t_1 , which is compared with the actual age of a cluster, t_{age} . The present-day position of a star system in the $r_{vir} - N$ plane and the comparison between its t_1 and t_{age} determine if such a cluster will experience a core collapse. Therefore, using the present-day virial radius and present-day total number of members, I found that four out seven clusters will

never undergo core collapse due to the binary heating and they will expand until the tidal disruption, because they are located either below the collapse line in the $r_{vir} - N$ plane or they have a relative age t_1 bigger than the actual cluster age, thus they started in a region where the core collapse is not expected. Therefore, an open question still open is to understand how these clusters were able to survive so long if they did not have a core collapse. Instead, in other three clusters, I found that the external members will expand while the central parts undergo to interior contraction and the clusters will experience a core collapse. In any case, the dynamical evolution in such old clusters may have been more complex. Indeed, the fate of clusters predicted by this model could be more uncertain if clusters have started with a much higher number of members N and at the present time (or in the past) they are already disrupting by some tidal interactions. Therefore, these results are still preliminary, since several both theoretical and observational uncertainties shall be deeply investigated to improve the agreement between observations and model.

This second part of Ph.D. work was presented at the conference “*Cool Stars 20*” in Boston, Massachusetts, and it will be submitted soon for publications in the *Astronomy & Astrophysics*.

During my Ph.D. work, I have been involved in the analysis of spectra of the fifth internal data release (GESviDR5). In particular, using a set of pipelines developed in IDL by Elena Franciosini in Arcetri, I derived the equivalent width of the lithium line of targets in several clusters observed by GES.

Future Perspective

The future steps on this kind of work will be to perform the same dynamical analysis in several more clusters with a different range of properties. In particular, it will be important to study these properties also in embedded clusters, and to increase the number of both young clusters (i.e., age between 10 and 100 Myr) and old clusters, especially systems with age greater than 3.5 Gyr. In this context, in addition to the clusters observed by GES, a significant contribution will be given by future wide-field, multi-object, high-resolution spectrographs that will be operative in the next years (e.g., MOONS, 4MOST, WEAVE).

Specifically, MOONS (Cirasuolo et al. 2011) is a multi-objects spectrograph at the VLT, with a FoV of 25 arcmin in diameter. It will use simultaneously 1000 fibers and will provide RVs, metallicities, and chemical abundances for several million of stars, complementing the GES. The big advantage of this spectrograph will be its capability of observing in the near-IR. This will allow performing a kinematic and dynamical study on clusters in embedded phase or still partially obscured by the primordial gas (i.e., clusters with age between 1 and 5 Myr). Therefore, it will be possible to study the processes that lead to the early cluster disruption

just before the gas expulsion. Moreover, several clusters in the heavily-obscured regions of the Bulge may be observed and interactions with the Galactic field may be investigated.

The 4MOST (de Jong 2011) is a multi-object spectrograph mounted at 4-meter VISTA telescope, in Chile. It will obtain 2400 spectra simultaneously with two low-resolution and one high-resolution spectrographs ($R \sim 4000 - 20000$). In the context of future work, the main advantage is the big FoV (2.5 degree of diameter), which may allow a kinematic analysis covering a wide cluster area and analyze also the member stars farther from the center. This will confirm if OCs (in particular those investigated in this work) are more extended than previously thought. The same kind of analysis can be performed in the Northern sky using the future wide-field survey facility WEAVE (Dalton et al. 2012) at the William Herschel Telescope, that will be similar to the 4MOST facility (but with a FoV of 2 degree of diameter).

Furthermore, a fundamental complementary contribution is given by the *Gaia* space mission. In this Ph.D. work, data from the first release has been used for the sample of four young clusters, to perform a preliminary kinematic analysis using the astrometric parameters (i.e., mean parallax and proper motions). As explained above, the obtained results are uncertain, especially given the errors on the astrometric data. The data of the second data release of this mission (April 2018) improved the number of observed sources and the uncertainties on parallaxes and proper motions. Indeed, it obtained the astrometric parameters for ~ 1.3 billion sources with an uncertainty in the proper motion components of 0.05, 0.2, and 1.2 mas yr $^{-1}$ for sources with $G < 14$ mag, $G = 17$ mag, and $G = 20$ mag, respectively (Lindgren et al. 2018). This will allow a better determination of membership and cluster distance. Using these higher quality data, it will be possible to derive independently the intrinsic velocity dispersion of clusters and perform a direct comparison with the results of GES. The proper motions can be used not only for membership determination but also for cluster orbit reconstruction, allowing to treat clusters as objects moving through the disk, rather than systems fixed to a given Galactocentric radius. This allows to understand how the cluster evolution has been influenced in the past by possible tidal effects, due either to the disk or the gravitational potential. Finally, using the combination of *Gaia* data with high-quality ground-based spectroscopy, such as GES and in future MOONS and 4MOST, it will be possible to study the kinematics of a larger sample of open clusters in a six-dimensional space.

List of publications

Here, I list the publications produced as first author and as co-authors during the three years of PhD work.

- “*The Gaia-ESO Survey: a kinematical and dynamical study of four young open clusters*”, **Bravi L.**, et al. 2018, A&A, 615, 37;
- “*The Gaia-ESO Survey: open clusters in Gaia-DR1 . A way forward to stellar age calibration*”, Randich, S., Tognelli, E., Jackson, R., Jeffries, R. D., Degl’Innocenti, S., Pancino, E., Re Fiorentin, P., Spagna, A., Sacco, G. G., Bragaglia, A., Magrini, L., Prada Moroni, P. G., Alfaro, E., Franciosini, E., Morbidelli, L., Roccatagliata, V., Bouy, H., **Bravi, L.**, et al. 2018, A&A, 612, 99;
- “*The Gaia-ESO Survey: Structural and dynamical properties of the young cluster Chamaeleon I*”, Sacco, G. G., Spina, L., Randich, S., Palla, F., Parker, R. J., Jeffries, R. D., Jackson, R., Meyer, M. R., Mapelli, M., Lanzafame, A. C., Bonito, R., Damiani, F., Franciosini, E., Frasca, A., Klutsch, A., Prisin-zano, L., Tognelli, E., Degl’Innocenti, S., Prada Moroni, P. G., Alfaro, E. J., Micela, G., Prusti, T., Barrado, D., Biazzo, K., Bouy, H., **Bravi, L.**, et al. 2017, A&A, 601, 97;
- “*The Gaia-ESO Survey: the present-day radial metallicity distribution of the Galactic disc probed by pre-main-sequence clusters*”, Spina, L., Randich, S., Magrini, L., Jeffries, R. D., Friel, E. D., Sacco, G. G., Pancino, E., Bonito, R., **Bravi, L.**, et al. 2017, A&A, 601, 70;
- “*The Gaia-ESO Survey: kinematical and dynamical study of four young open clusters*”, **Bravi L.** 2017, MmSAI, 88, 830;
- “*Kinematics of young star clusters with the Gaia-ESO Survey*”, Sacco, G. G., Randich, S., **Bravi, L.**, Jeffries, R., Rigliaco, E., 2017, MmSAI, 88, 660;

Bibliography

- Adams, F. C. & Myers, P. C. 2001, *ApJ*, 553, 744
- Allison, R. J., Goodwin, S. P., Parker, R. J., Portegies Zwart, S. F., & de Grijs, R. 2010, *MNRAS*, 407, 1098
- Alonso-Santiago, J., Negueruela, I., Marco, A., et al. 2017, *MNRAS*, 469, 1330
- Anthony-Twarog, B. J., Tanner, D., Cracraft, M., & Twarog, B. A. 2006, *AJ*, 131, 461
- Banerjee, S. & Kroupa, P. 2014, *ApJ*, 787, 158
- Barrado y Navascués, D., Stauffer, J. R., Bouvier, J., & Martín, E. L. 2001, *ApJ*, 546, 1006
- Barrado y Navascués, D., Stauffer, J. R., & Patten, B. M. 1999, *ApJL*, 522, L53
- Basri, G., Marcy, G. W., & Graham, J. R. 1996, *ApJ*, 458, 600
- Bastian, N. 2011, in *Stellar Clusters and Associations: A RIA Workshop on Gaia*, 85–97
- Bastian, N., Covey, K. R., & Meyer, M. R. 2010, *ARA&A*, 48, 339
- Bastian, N., Ercolano, B., Gieles, M., et al. 2007, *MNRAS*, 379, 1302
- Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, *A&A*, 431, 905
- Bastian, N. & Goodwin, S. P. 2006, *MNRAS*, 369, L9
- Baumgardt, H. & Kroupa, P. 2007, *MNRAS*, 380, 1589
- Baumgardt, H. & Makino, J. 2003, *MNRAS*, 340, 227
- Bender, C. F. & Simon, M. 2008, *ApJ*, 689, 416

- Bergbusch, P. A. & Blake, R. M. 1996, in *Astronomical Society of the Pacific Conference Series*, Vol. 90, *The Origins, Evolution, and Destinies of Binary Stars in Clusters*, ed. E. F. Milone & J.-C. Mermilliod, 489
- Bildsten, L., Brown, E. F., Matzner, C. D., & Ushomirsky, G. 1997, *ApJ*, 482, 442
- Binney, J. & Tremaine, S. 2008, *Galactic Dynamics: Second Edition* (Princeton University Press)
- Blitz, L. 1993, in *Protostars and Planets III*, ed. E. H. Levy & J. I. Lunine, 125–161
- Boily, C. M. & Kroupa, P. 2003a, *MNRAS*, 338, 665
- Boily, C. M. & Kroupa, P. 2003b, *MNRAS*, 338, 673
- Bok, B. J. 1934, *Harvard College Observatory Circular*, 384, 1
- Bonatto, C., Kerber, L. O., Bica, E., & Santiago, B. X. 2006, *A&A*, 446, 121
- Bonnell, I. A., Bate, M. R., & Vine, S. G. 2003, *MNRAS*, 343, 413
- Bouvier, J., Barrado, D., Moraux, E., et al. 2018, *A&A*, 613, A63
- Bouvier, J., Kendall, T., Meeus, G., et al. 2008, *A&A*, 481, 661
- Bragaglia, A. & Tosi, M. 2006, *AJ*, 131, 1544
- Bravi, L., Zari, E., Sacco, G. G., et al. 2018, *A&A*, 615, A37
- Bressan, A., Marigo, P., Girardi, L., et al. 2012, *MNRAS*, 427, 127
- Bressert, E., Bastian, N., Gutermuth, R., et al. 2010, *MNRAS*, 409, L54
- Burgasser, A. J., Reid, I. N., Siegler, N., et al. 2007, *Protostars and Planets V*, 427
- Carraro, G., Costa, E., & Ahumada, J. A. 2010, *AJ*, 140, 954
- Cartwright, A. 2009, *MNRAS*, 400, 1427
- Cartwright, A. & Whitworth, A. P. 2004, *MNRAS*, 348, 589
- Chabrier, G. 2005, in *Astrophysics and Space Science Library*, Vol. 327, *The Initial Mass Function 50 Years Later*, ed. E. Corbelli, F. Palla, & H. Zinnecker, 41
- Chabrier, G., Baraffe, I., & Plez, B. 1996, *ApJL*, 459, L91
- Cignoni, M., Beccari, G., Bragaglia, A., & Tosi, M. 2011, *MNRAS*, 416, 1077
- Cirasuolo, M., Afonso, J., Bender, R., et al. 2011, *The Messenger*, 145, 11

- Clarkson, W. I., Ghez, A. M., Morris, M. R., et al. 2012, *ApJ*, 751, 132
- Cottaar, M., Meyer, M. R., Andersen, M., & Espinoza, P. 2012a, *A&A*, 539, A5
- Cottaar, M., Meyer, M. R., & Parker, R. J. 2012b, *A&A*, 547, A35
- Cummings, J. D., Deliyannis, C. P., Maderak, R. M., & Steinhauer, A. 2017, *AJ*, 153, 128
- Dalton, G., Trager, S. C., Abrams, D. C., et al. 2012, in *Proceedings of the SPIE*, Vol. 8446, *Ground-based and Airborne Instrumentation for Astronomy IV*, 84460P
- Damiani, F., Prisinzano, L., Micela, G., et al. 2014, *A&A*, 566, A50
- de Bruijne, J. H. J. 2012, *Astrophysics & Space Science*, 341, 31
- de Jong, R. 2011, *The Messenger*, 145, 14
- de Marchi, G. & Paresce, F. 2001, in *Astronomische Gesellschaft Meeting Abstracts*, Vol. 18, *Astronomische Gesellschaft Meeting Abstracts*, ed. E. R. Schielicke
- Dias, W. S., Alessi, B. S., Moitinho, A., & Lépine, J. R. D. 2002, *A&A*, 389, 871
- Donati, P., Cantat Gaudin, T., Bragaglia, A., et al. 2014, *A&A*, 561, A94
- Duchêne, G. & Kraus, A. 2013, *ARA&A*, 51, 269
- Elmegreen, B. G. 1993, in *Protostars and Planets III*, ed. E. H. Levy & J. I. Lunine, 97–124
- Elmegreen, B. G. 2007, *ApJ*, 668, 1064
- Elmegreen, B. G., Efremov, Y., Pudritz, R. E., & Zinnecker, H. 2000, *Protostars and Planets IV*, 179
- Elmegreen, B. G., Elmegreen, D. M., Chandar, R., Whitmore, B., & Regan, M. 2006, *ApJ*, 644, 879
- Elmegreen, B. G. & Hunter, D. A. 2010, *ApJ*, 712, 604
- Elson, R. A. W., Fall, S. M., & Freeman, K. C. 1987, *ApJ*, 323, 54
- Fleck, J.-J., Boily, C., Lançon, A., Heggie, D., & Deiters, S. 2005, in *SF2A-2005: Semaine de l’Astrophysique Française*, ed. F. Casoli, T. Contini, J. M. Hameury, & L. Pagani, 605
- Fleck, J.-J., Boily, C. M., Lançon, A., & Deiters, S. 2006, *MNRAS*, 369, 1392

- Friel, E. D. 1995, *ARA&A*, 33, 381
- Friel, E. D. 2013, *Open Clusters and Their Role in the Galaxy*, ed. T. D. Oswalt & G. Gilmore, 347
- Gaia Collaboration, Babusiaux, C., van Leeuwen, F., et al. 2018a, *A&A*, 616, A10
- Gaia Collaboration, Babusiaux, C., van Leeuwen, F., et al. 2018b, *A&A*, 616, A10
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018c, *ArXiv e-prints* [[arXiv]1804.09365]
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018d, *A&A*, 616, A1
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016a, *A&A*, 595, A2
- Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016b, *A&A*, 595, A1
- Gaia Collaboration, van Leeuwen, F., Vallenari, A., et al. 2017, *A&A*, 601, A19
- Geller, A. M., Mathieu, R. D., Braden, E. K., et al. 2010, *AJ*, 139, 1383
- Geller, A. M., Mathieu, R. D., Harris, H. C., & McClure, R. D. 2008, *AJ*, 135, 2264
- Giersz, M. & Heggie, D. C. 1997, *MNRAS*, 286, 709
- Gilmore, G., Randich, S., Asplund, M., et al. 2012, *The Messenger*, 147, 25
- Goodwin, S. P. 1997, *MNRAS*, 284, 785
- Goodwin, S. P. 2009, *Astrophysics & Space Science*, 324, 259
- Goodwin, S. P. & Bastian, N. 2006, *MNRAS*, 373, 752
- Hénault-Brunet, V., Evans, C. J., Sana, H., et al. 2012, *A&A*, 546, A73
- Hills, J. G. 1980, *ApJ*, 235, 986
- Hurley, J. R. & Shara, M. M. 2012, *MNRAS*, 425, 2872
- Jackson, R. J., Jeffries, R. D., Lewis, J., et al. 2015, *A&A*, 580, A75
- Jacobson, H. R., Friel, E. D., Jílková, L., et al. 2016, *A&A*, 591, A37
- Jeans, J. H. 1902, *Philosophical Transactions of the Royal Society of London Series A*, 199, 1
- Jeffries, R. D. 2006, *Pre-Main-Sequence Lithium Depletion*, ed. S. Randich & L. Pasquini, 163

- Jeffries, R. D., Jackson, R. J., Cottaar, M., et al. 2014, *A&A*, 563, A94
- Jeffries, R. D., Jackson, R. J., James, D. J., & Cargile, P. A. 2009a, *MNRAS*, 400, 317
- Jeffries, R. D., Naylor, T., Devey, C. R., & Totten, E. J. 2004, *MNRAS*, 351, 1401
- Jeffries, R. D., Naylor, T., Walter, F. M., Pozzo, M. P., & Devey, C. R. 2009b, *MNRAS*, 393, 538
- Jeffries, R. D. & Oliveira, J. M. 2005, *MNRAS*, 358, 13
- Jeffries, R. D., Oliveira, J. M., Barrado y Navascués, D., & Stauffer, J. R. 2003, *MNRAS*, 343, 1271
- Jeffries, R. D. & Tolley, A. J. 1998, *MNRAS*, 300, 331
- Jeffries, R. D., Totten, E. J., & James, D. J. 2000, *MNRAS*, 316, 950
- Kenyon, S. J. & Hartmann, L. 1995, *ApJS*, 101, 117
- Kharchenko, N. V., Piskunov, A. E., Schilbach, E., Röser, S., & Scholz, R.-D. 2016, *A&A*, 585, A101
- Kobulnicky, H. A. & Fryer, C. L. 2007, *ApJ*, 670, 747
- Kouwenhoven, M. B. N., Brown, A. G. A., Goodwin, S. P., Portegies Zwart, S. F., & Kaper, L. 2009, *A&A*, 493, 979
- Kouwenhoven, M. B. N., Brown, A. G. A., & Kaper, L. 2007a, *A&A*, 464, 581
- Kouwenhoven, M. B. N., Brown, A. G. A., Portegies Zwart, S. F., & Kaper, L. 2007b, *A&A*, 474, 77
- Kouwenhoven, M. B. N., Brown, A. G. A., Zinnecker, H., Kaper, L., & Portegies Zwart, S. F. 2005, *A&A*, 430, 137
- Kouwenhoven, M. B. N. & de Grijs, R. 2008, *A&A*, 480, 103
- Kroupa, P. 1995, *MNRAS*, 277 [astro-ph/9508117]
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Kroupa, P., Aarseth, S., & Hurley, J. 2001, *MNRAS*, 321, 699
- Kroupa, P. & Boily, C. M. 2002, *MNRAS*, 336, 1188
- Kruijssen, J. M. D., Maschberger, T., Moeckel, N., et al. 2012, *MNRAS*, 419, 841

- Kruijssen, J. M. D., Pelupessy, F. I., Lamers, H. J. G. L. M., Portegies Zwart, S. F., & Icke, V. 2011, *MNRAS*, 414, 1339
- Krumholz, M. R. 2014, *Physics Reports*, 539, 49
- Krumholz, M. R., Klein, R. I., McKee, C. F., Offner, S. S. R., & Cunningham, A. J. 2009, *Science*, 323, 754
- Krumholz, M. R., McKee, C. F., & Klein, R. I. 2005, *ApJL*, 618, L33
- Lada, C. J. & Lada, E. A. 2003, *ARA&A*, 41, 57
- Lada, C. J., Margulis, M., & Dearborn, D. 1984, *ApJ*, 285, 141
- Lada, E. A. 1999, in *NATO Advanced Science Institutes (ASI) Series C*, Vol. 540, *NATO Advanced Science Institutes (ASI) Series C*, ed. C. J. Lada & N. D. Kylafis, 441
- Lamers, H. J. G. L. M., Baumgardt, H., & Gieles, M. 2010, *MNRAS*, 409, 305
- Lamers, H. J. G. L. M. & Gieles, M. 2006, *A&A*, 455, L17
- Lamers, H. J. G. L. M., Gieles, M., Bastian, N., et al. 2005, *A&A*, 441, 117
- Lee, H. M. & Goodman, J. 1995, *ApJ*, 443, 109
- Lindegren, L., Hernández, J., Bombrun, A., et al. 2018, *A&A*, 616, A2
- Lindegren, L., Madsen, S., & Dravins, D. 2000, *A&A*, 356, 1119
- Magrini, L., Spina, L., Randich, S., et al. 2018, *ArXiv e-prints* [[arXiv]1806.03068]
- Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2017, *AJ*, 154, 94
- Makino, J. 1996, *ApJ*, 471, 796
- Manzi, S., Randich, S., de Wit, W. J., & Palla, F. 2008, *A&A*, 479, 141
- Mapelli, M., Vallenari, A., Jeffries, R. D., et al. 2015, *A&A*, 578, A35
- Marks, M., Kroupa, P., & Oh, S. 2011, *MNRAS*, 417, 1684
- Marsden, S. C., Carter, B. D., & Donati, J.-F. 2009, *MNRAS*, 399, 888
- Martin, E. L. & Montes, D. 1997, *A&A*, 318, 805
- Mason, B. D., Hartkopf, W. I., Gies, D. R., Henry, T. J., & Helsel, J. W. 2009, *AJ*, 137, 3358
- McKee, C. F. & Ostriker, E. C. 2007, *ARA&A*, 45, 565

- McKee, C. F. & Tan, J. C. 2003, *ApJ*, 585, 850
- Mengel, S. & Tacconi-Garman, L. E. 2007, *A&A*, 466, 151
- Mermilliod, J.-C. & Mayor, M. 1999, *A&A*, 352, 479
- Metchev, S. A., Kirkpatrick, J. D., Berriman, G. B., & Looper, D. 2008, *ApJ*, 676, 1281
- Miller, G. E. & Scalo, J. M. 1978, *PASP*, 90, 506
- Miller, G. E. & Scalo, J. M. 1979, *ApJS*, 41, 513
- Moraux, E. 2016, in *EAS Publications Series*, Vol. 80, *EAS Publications Series*, ed. E. Moraux, Y. Lebreton, & C. Charbonnel, 73–114
- Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C. 2003, *A&A*, 400, 891
- Naylor, T., Totten, E. J., Jeffries, R. D., et al. 2002, *MNRAS*, 335, 291
- Offner, S. S. R., Clark, P. C., Hennebelle, P., et al. 2014, *Protostars and Planets VI*, 53
- Offner, S. S. R., Klein, R. I., & McKee, C. F. 2008, *ApJ*, 686, 1174
- O’Leary, R. M., Stahler, S. W., & Ma, C.-P. 2014, *MNRAS*, 444, 80
- Parker, R. J. & Dale, J. E. 2013, *MNRAS*, 432, 986
- Parker, R. J. & Dale, J. E. 2015, *MNRAS*, 451, 3664
- Parker, R. J. & Goodwin, S. P. 2009, *MNRAS*, 397, 1041
- Parker, R. J., Goodwin, S. P., Wright, N. J., Meyer, M. R., & Quanz, S. P. 2016, *MNRAS*, 459, L119
- Parker, R. J., Maschberger, T., & Alves de Oliveira, C. 2012, *MNRAS*, 426, 3079
- Parker, R. J. & Meyer, M. R. 2012, *MNRAS*, 427, 637
- Parker, R. J. & Wright, N. J. 2016, *MNRAS*, 457, 3430
- Parker, R. J., Wright, N. J., Goodwin, S. P., & Meyer, M. R. 2014, *MNRAS*, 438, 620
- Pasquini, L., Avila, G., Blecha, A., et al. 2002, *The Messenger*, 110, 1
- Patience, J., Ghez, A. M., Reid, I. N., & Matthews, K. 2002, *AJ*, 123, 1570
- Patten, B. M. & Simon, T. 1996, *ApJS*, 106, 489

- Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, *A&A*, 369, 339
- Piskunov, A. E., Kharchenko, N. V., Röser, S., Schilbach, E., & Scholz, R.-D. 2006, *A&A*, 445, 545
- Platais, I., Melo, C., Mermilliod, J.-C., et al. 2007, *A&A*, 461, 509
- Plummer, H. C. 1911, *MNRAS*, 71, 460
- Portegies Zwart, S. F., Hut, P., Makino, J., & McMillan, S. L. W. 1998, *A&A*, 337, 363
- Portegies Zwart, S. F., McMillan, S. L. W., & Gieles, M. 2010, *ARA&A*, 48, 431
- Prosser, C. F. 1993, *AJ*, 105, 1441
- Prosser, C. F., Randich, S., & Stauffer, J. R. 1996, *AJ*, 112, 649
- Proszkow, E.-M. & Adams, F. C. 2009, *ApJS*, 185, 486
- Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, *ApJS*, 190, 1
- Randich, S., Aharpour, N., Pallavicini, R., Prosser, C. F., & Stauffer, J. R. 1997, *A&A*, 323, 86
- Randich, S., Gilmore, G., & Gaia-ESO Consortium. 2013, *The Messenger*, 154, 47
- Randich, S., Pallavicini, R., Meola, G., Stauffer, J. R., & Balachandran, S. C. 2001, *A&A*, 372, 862
- Randich, S., Schmitt, J. H. M. M., Prosser, C. F., & Stauffer, J. R. 1995, *A&A*, 300, 134
- Randich, S., Tognelli, E., Jackson, R., et al. 2018, *A&A*, 612, A99
- Reggiani, M. & Meyer, M. R. 2013, *A&A*, 553, A124
- Rigliaco, E., Wilking, B., Meyer, M. R., et al. 2016, *A&A*, 588, A123
- Rochau, B., Brandner, W., Stolte, A., et al. 2010, *ApJL*, 716, L90
- Sacco, G. G., Jeffries, R. D., Randich, S., et al. 2015, *A&A*, 574, L7
- Sacco, G. G., Morbidelli, L., Franciosini, E., et al. 2014, *A&A*, 565, A113
- Sacco, G. G., Spina, L., Randich, S., et al. 2017, *A&A*, 601, A97
- Salaris, M., Weiss, A., & Percival, S. M. 2004, *A&A*, 414, 163
- Salpeter, E. E. 1955, *ApJ*, 121, 161

- Savage, B. D. & Mathis, J. S. 1979, *ARA&A*, 17, 73
- Seleznev, A. F., Carraro, G., Capuzzo-Dolcetta, R., Monaco, L., & Baume, G. 2017, *MNRAS*, 467, 2517
- Sharma, S., Pandey, A. K., Ogura, K., et al. 2006, *AJ*, 132, 1669
- Siess, L., Dufour, E., & Forestini, M. 2000, *A&A*, 358, 593
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
- Smith, R. J., Longmore, S., & Bonnell, I. 2009, *MNRAS*, 400, 1775
- Soderblom, D. R. 2010, *ARA&A*, 48, 581
- Spera, M., Mapelli, M., & Jeffries, R. D. 2016, *MNRAS*, 460, 317
- Spina, L., Randich, S., Magrini, L., et al. 2017, *A&A*, 601, A70
- Spina, L., Randich, S., Palla, F., et al. 2014a, *A&A*, 568, A2
- Spina, L., Randich, S., Palla, F., et al. 2014b, *A&A*, 567, A55
- Spitzer, L. 1987, *Dynamical evolution of globular clusters*
- Spitzer, Jr., L. 1958, *ApJ*, 127, 17
- Spurzem, R. & Aarseth, S. J. 1996, *MNRAS*, 282 [astro-ph/9605003]
- Stahler, S. W. & Palla, F. 2005, *The Formation of Stars*, 865
- Stauffer, J. R., Hartmann, L. W., Prosser, C. F., et al. 1997, *ApJ*, 479, 776
- Takahashi, K. 1995, *PASJ*, 47, 561
- Takahashi, K. 1996, *PASJ*, 48, 691
- Takahashi, K. & Lee, H. M. 2000, *MNRAS*, 316, 671
- Thies, I. & Kroupa, P. 2007, *ApJ*, 671, 767
- Tiongco, M. A., Vesperini, E., & Varri, A. L. 2016, *MNRAS*, 455, 3693
- Tognelli, E., Prada Moroni, P. G., & Degl’Innocenti, S. 2011, *A&A*, 533, A109
- Tutukov, A. V. 1978, *A&A*, 70, 57
- Vallée, J. P. 2005, *AJ*, 130, 569
- Vesperini, E., Varri, A. L., McMillan, S. L. W., & Zepf, S. E. 2014, *MNRAS*, 443, L79

Wright, N. J., Bouy, H., Drew, J. E., et al. 2016, MNRAS, 460, 2593

Wright, N. J., Parker, R. J., Goodwin, S. P., & Drake, J. J. 2014, MNRAS, 438, 639