Ruprecht-Karls-Universität

# Detection and characterisation of open clusters in the Milky Way with *Gaia*

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Referees: PD Dr. Sabine Reffert
Prof. Dr. Hans-Walter Rix

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Supervisor: PD Dr. Sabine Reffert

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69117 Heidelberg

# Abstract

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# Abstract (different language)

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# Acknowledgement

Even after eight years at university, it still feels *surprising* to see myself writing this PhD thesis and reaching this stage in my life. As a child, I looked up at the planets and the stars and I saw a universe of wonder. But as a teenager, I looked around me (here on the Earth) and I felt different, outcast, and fundamentally undeserving of the future I have managed to have. This thesis is for every LGBTQ+ child who grew up thinking the world is not for them.

I will forever be eternally indebted and grateful to the many, many people without whom I would never be here.

Dr. Michelle Cuthbert, your phenomenal commitment and passion for teaching had an impact on me that I will carry with me for the rest of my life. I still remember my first lesson of Year 12 physics, where you asked those of us intending to study physics at university to raise our hands. I think one or two hands were raised, of which I was not one. You proudly remarked that you would change our minds in just eight months. By the end of Year 13, a majority of our class went on to study physics, in no small part thanks to your teaching. This thesis would never have happened had I never been exposed to your infectiously passionate physics teaching.

I next thank those I know from the University of Bath where I did my undergraduate degree. Dr. Vicky Scowcroft, the summer project I did with you and your

# Contents

# 1 Introduction

> Δέδυκε μὲν ἀ σελάννα
> *The moon and the Pleiades*
>
> καὶ Πληΐαδες, μέσαι δέ
> *have set, it is*
>
> νύκτες, πάρα δ' ἔρχετ' ὤρα,
> *midnight, time is passing,*
>
> ἔγω δὲ μόνα κατεύδω.
> *but I sleep alone.*
>
> — **Sappho, 'The Midnight Poem'**
> (c. 600 BC)

## 1.1 From seven sisters to a powerhouse of astronomy

In all of astronomy, few objects have retained relevance throughout the centuries as much as open clusters (OCs). Easily visible to the naked eye, the Pleiades has been observed since at least the dawn of civilisation CITEME, along with a handful of other OCs visible without a telescope. In the present day, the now thousands of known OCs are a key tool in modern astronomy for understanding stellar and galactic evolution.

Star clusters are formed when clouds of cold molecular gas collapse due to gravity, forming stars. Sometimes, when star formation occurs densely enough, these stars fall further into gravitationally bound clusters that can survive in the galactic disk for as long as $\sim 10^9$ years (Lada and Lada 2003; Portegies Zwart et al. 2010). It is this property of the formation of OCs that makes them so useful: all stars in an OC will have the same age and initial composition, allowing parameters of the overall group of stars to be measured significantly more precisely than when studying stars in isolation.

For instance, when a parameter such as the distance of member stars can simply be averaged over all member stars, then the precision of the mean distance of an

OC (and hence the distance to all of its member stars) will be a factor $\sqrt{n}$ more precise than the distance to any individual star. Alternatively, when a property such as chemical composition is highly time consuming to derive, it can be derived for a fraction of stars in an OC and be applied to all stars in a cluster.

The ease of studying stellar astrophysics with OCs results in OCs having an extremely wide range of scientific use cases. For instance, OCs are used as testing grounds for stellar evolution models CITEME, as tracers of galactic structure (Cantat-Gaudin et al. 2020; Castro-Ginard et al. 2021), or even as calibrators of cepheid variable stars (Medina et al. 2021), which are an essential first rung on the cosmic distance ladder and are vital in the derivation of the cosmological parameters of the universe. It is somewhat of a cliché to describe OCs as 'the laboratories of stellar evolution', but it really is true: OCs are a fantastic way to observe stars of a given age and composition across a broad range of masses, and to do so with orders of magnitude more precision than when studying isolated field stars.

The best part of the modern story of the OC's contribution to astrophysics comes with the *Gaia* satellite, however. In just five years since its first full data release (Brown et al. 2018), *Gaia* has revolutionised the study of our galaxy, including the study of OCs; with dozens of papers reporting thousands of new objects (e.g. Castro-Ginard et al. 2019, 2022, 2020; Liu and Pang 2019), and a number of works deriving dramatically improved parameters and members for OCs in the Milky Way (e.g. Cantat-Gaudin et al. 2018a; Tarricq et al. 2020). Arguably, there has never been a better time to do science with OCs, owing to the incredible quantity and quality of data that *Gaia* has provided.

There is, however, a catch. Even though the Milky Way is estimated to contain as many as $10^5$ OCs (Dias et al. 2002), there are still only a few thousand currently known in the literature – representing a small fraction of the total number of OCs in our galaxy. It has been shown that the census of OCs is incomplete within even 1 kpc from the Sun (e.g. Castro-Ginard et al. 2018), and the extent of the remaining incompleteness is unknown. Worse still, it has been shown that many of the OCs catalogued previously in the literature may not exist (Cantat-Gaudin and Anders 2020; Piatti 2023), with it being largely unknown which OCs are or are not real. The many fantastic uses of OCs in other areas of astronomy are contingent on a reliable, accurate, and complete census of OCs; and the many current caveats with the census of OCs limit the science potential of these fantastic objects in a time when we have more available data with which to study them than ever before.

In this thesis, I will present solutions to a number of the current issues with the OC census in the era of *Gaia*, using a range of data analysis and parameter inference techniques. I will then use these techniques to create the largest census of OCs to date and derive a range of parameters for these OCs. With this thesis, I also hope to present methods that could continue to be used to maximise the quality of the OC census for the coming decade of *Gaia* data releases – as well as for whatever instruments supercede *Gaia* in the future.

Before launching into the chapters detailing my work over the past three and a half years, it is worth first conducting an overview of the science behind OCs in the introduction to this thesis. In Sect. 1.3, I will discuss the history of OC observations up to before the release of *Gaia* DR2 in 2018, as well as briefly discussing the techniques and results from pre-*Gaia* observations. Section 1.4 will then discuss the stunning data of *Gaia* and how it has already thoroughly revolutionised our understanding of OCs in just a handful of years. Finally, Sect. 1.5 will briefly discuss some key pieces of theory surrounding the structure, dynamics, and lifetime of OCs, providing a good background on our theoretical knowledge of OCs that will assist with the reading of this thesis.

The nomenclature and definition of star clusters varies throughout the literature. Hence, in the next section, I will quickly discuss a definition of OCs that I will adopt throughout the rest of this work.

## 1.2 The definition of an open cluster

There are many different types of star cluster in the universe. This thesis will exclusively discuss clusters observed in the Milky Way, and will primarily discuss open clusters (OCs), although I will also touch on globular clusters (GCs) and moving groups (MGs). Avoiding confusion when talking about star clusters is important; hence, I differentiate between these three types of cluster approximately as follows, matching the definition in Portegies Zwart et al. 2010.

OCs are gravitationally bound clusters with a typical age of around 100 Myr, although some are older than 1 Gyr and some are as young as 0.1 Myr. OCs have masses of typically no greater than $10^4$ $M_\odot$and may be made up of a few dozen to a few thousand stars, with a typical minimum being ten stars. OCs are remants of recent star formation and are hence predominantly located in the galactic disk where the star formation rate is highest. Most OCs have a size of around 3 to 10 pc. Other than some exceptions, OCs contain a single population of stars.

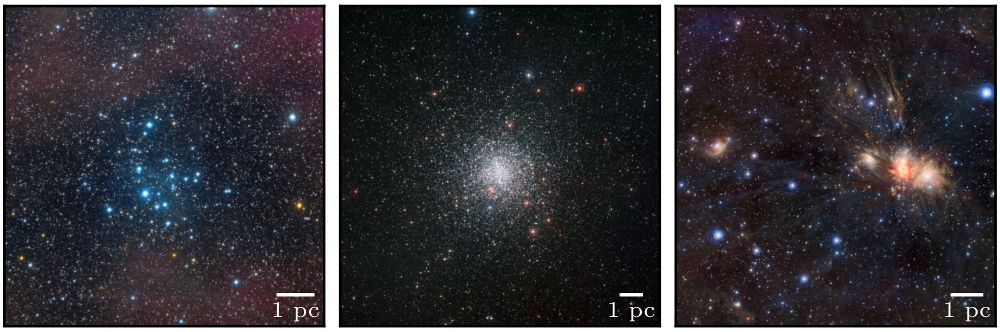



Fig. 1.1.: A visual comparison between the three main types of star cluster found in the Milky Way. *Left:* the open cluster NGC 2547. *Middle:* the globular cluster M 4. *Right:* the moving group/OB association Monoceros R2. All images contain a scale in the bottom right showing a length of 1 pc at the distance of each cluster. NGC 2547 is a sparser OC that has a clear core of young blue stars at its center, about $\sim 1$ pc across. On the other hand, despite being only slightly larger, M 4 clearly contains significantly more stars. The stars in M 4 are older, with the cluster having a whiter or redder appearance. On the other hand, Monoceros R2 is simply a group of young blue stars, with no discernible core. *Credit, left to right:* ESO / J. Pérez; ESO; ESO / J. Emerson / VISTA.

GCs are much older and more massive gravitationally bound clusters, with ages typically greater than 10 Gyr and masses typically greater than $10^5$ $M_\odot$. The largest GCs can contain a million stars or more. GCs have a typical size around 10 to 20 pc. GCs tend to reside in the galactic bulge or in the galactic halo. Many GCs contain multiple populations of stars. Almost all OCs have masses significantly lower than the typical present day mass of GCs, although observations of a handful of young massive clusters in the Milky Way such as Westerlund 1 (sometimes also referred to as 'super star clusters') as well as observations of galaxies with more active star formation suggest that the highest mass star clusters will be long-lived and will evolve into GCs. However, this is not the case for almost all OCs that I will study in this thesis, as the only young massive clusters in the Milky Way are generally distant, heavily reddened, and outside of the reach of the visual-band observations of the *Gaia* telescope.

On the other hand, MGs are of a similar mass and number count to OCs, except they are not gravitationally bound. Due to this, they disperse much more quickly, and hence often have much younger ages. MGs have the widest definition, and encompass any group of stars that are comoving and coeval, but are specifically *not* gravitationally bound. Some MGs are also referred to as 'OB associations' in the literature, due to them often containing a number of young, high mass O and B stars.

| Type | Bound? | Age | Mass | Location |
|---|---|---|---|---|
| Open cluster (OC) | Weakly | $\lesssim 1$ Gyr | $\lesssim 10^4$ M$_\odot$ | Disk |
| Globular cluster (GC) | Strongly | $\gtrsim 10$ Gyr | $\gtrsim 10^5$ M$_\odot$ | Halo/Bulge |
| Moving group (MG) | No | $\lesssim 50$ Myr | $\lesssim 10^3$ M$_\odot$ | Disk |

Tab. 1.1.: Approximate definitions for the three types of star cluster that will be discussed in this thesis.

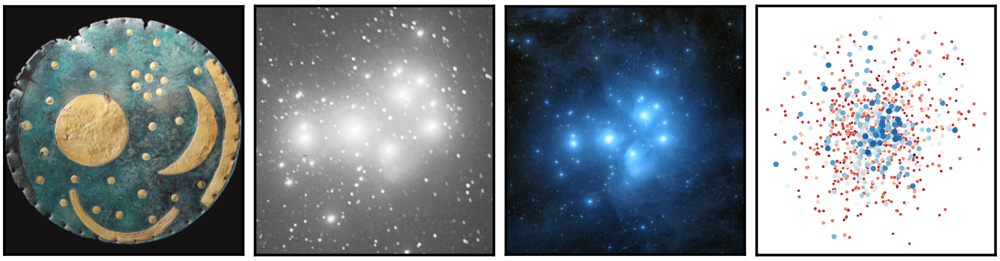


Fig. 1.2.: The Pleiades, as depicted throughout history and showing the clear improvements in astronomical data gathering over time. *Left:* the Nebra Sky Disc, depicting the Pleiades with its seven naked-eye visible stars in the upper center. The disc was discovered in 1999 in northern Germany and is dated to between 1800-1600 BC. *Middle left:* the Pleiades, as imaged in 1909 with Wolf's Doppelastrograph at the Landessternwarte Heidelberg-Königstuhl. *Middle right:* the Pleiades, as imaged by Hubble. *Right:* the $\sim$1000 member stars for the Pleiades extracted from *Gaia* DR2 data and isolated from field stars by Cantat-Gaudin et al. 2018b. Each star is represented by a point scaled by its magnitude and coloured according to its $BP - RP$ colour. *Image credits:* Frank Vincentz; Heidelberg Digitized Astronomical Plates; Davide De Martin / NASA/ESA Hubble.

These definitions are summarised in Table 1.1 and compared visually in Fig. 1.1.

## 1.3 Open clusters in the pre-*Gaia* era: history and techniques

### 1.3.1 The history of open cluster observations

To truly understand just how groundbreaking the current data of the *Gaia* satellite is, it is worth first briefly reviewing the history of OC observations.

Our ability to observe OCs has progressed incredibly far throughout the history of astronomy (Fig. 1.2). The invention of the refracting telescope allowed for early astronomers such as Galileo to observe that OCs and GCs are in fact clusters of

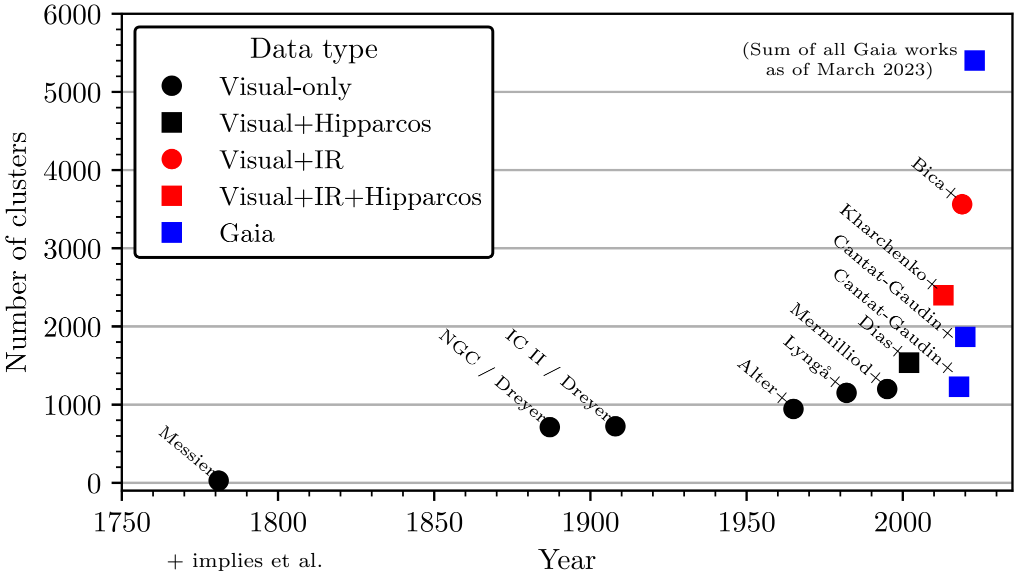



**Fig. 1.3.:** The size of OC catalogues over time. After the initial rise in the size of catalogues due to the advent of reflecting telescopes in the 18th and 19th centuries, it was not until the past 25 years and the advent of large-scale astrometric and IR datasets that the OC census significantly increased in size.
N.B.: this is not an exhaustive plot of all catalogues, and a number of old catalogues such as Herschel 1786 and Herschel 1864 without digitised versions are not included.

many stars, as opposed to being dispered single sources as previously believed from unaided observations. It was, however, the invention and widespread adoptation of the reflecting telescope in the 17th and 18th centuries that led to catalogues of clusters like we use today.

The power of reflecting telescopes allowed astronomers to scan the sky to signficantly greater depth, searching for clusters of stars and discovering many new objects in the process (e.g. Herschel 1786), with the number of known OCs jumping from a few dozen to around 700 in a little over a century. Figure 1.3 shows the evolution in size of OC catalogues over time, showing the peak of around 700 clusters by the turn of the 20th century. Many of the OCs known and catalogued by astronomers at this point were some of the largest and most scientifically useful, with many of these OCs (especially those in the NGC catalogue) being some of the most frequently studied objects even today.

The 20th century saw improvements to data gathering and techniques, with early photometric and spectroscopic methods allowing authors such as Rosenberg 1910 and Hertzsprung 1911 to plot the brightness of the stars in the Pleiades and the Hyades against their spectral features, noticing for the first time that the brightness

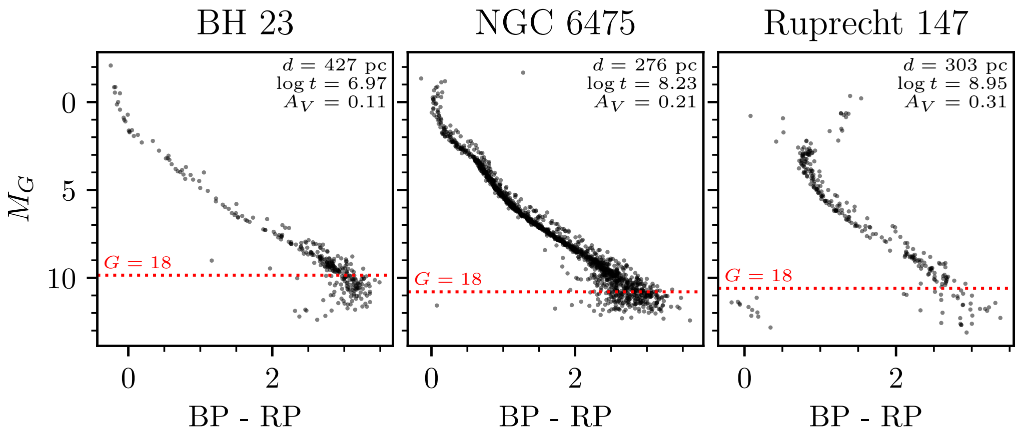



Fig. 1.4.: A comparison of the CMDs of a number of nearby OCs, using membership lists from later in this thesis in Sect. 3 and plotted with their absolute magnitude $M_G$ against colour $BP - RP$. The OCs are plotted from left to right in order of increasing age, with their distance $d$, logarithmic age $\log t$ and extinction $A_V$ shown in the top right. The dashed red line indicates the approximate 100% completeness limit of these OC membership lists, with sources fainter than an apparent magnitude of $G = 18$ frequently being missed and often having underestimated $BP - RP$ colours. BH 23 is less than 10 Myr old and has almost no main sequence turn off; NGC 6475 is over 100 Myr old and has a clear turn off; Ruprecht 147 is around 1 Gyr old and even has a clear population of white dwarf stars.

of stars is related to their colour and spectral features. Russell 1914 derived the absolute magnitude of stars in the Hyades and ploted this against an early spectral analogue of the temperature of its member stars, plotting the luminosity of stars against their temperature for the first time and inventing 'Hertzsprung-Russell' or 'colour-magnitude' diagrams (CMDs), a type of plot used extensively in the present day as an essential tool to understand stellar evolution. Later, the differences in CMDs between different clusters were noticed and was interpreted as being a difference in age between the clusters, allowing for the ages of stars within star clusters to be estimated and beginning the foundation of our knowledge of stellar evolution.

While the 20$^{\text{th}}$ century saw huge strides in our understanding of stars and star clusters, the size of OC catalogues went relatively unchanged (Fig. 1.3). It was not until the 1990s and the arrival of new methodologies that the OC census itself has begun its largest upheaval since the widespread adoptation of reflecting telescopes more than 200 years prior.

The launch of the *Hipparcos* satellite and subsequent data releases (Perryman et al. 1997) produced a catalogue of around $10^5$ sources with five-parameter milliarcsecond-precision astrometry. OCs stand out as overdensities in *Hipparcos* data, in particular in proper motions, as OCs are comoving groups of stars that often have different velocities to background field sources. This new data allowed works such as Platais et al. 1998 to discover a number of new OCs, with many being small objects near to the Sun that evaded detection with only two-dimensional visual observations.

This resulted in the catalogue of Dias et al. 2002 including over 300 more objects than the roughly ten years prior catalogue of Mermilliod 1995 (Fig. 1.3), representing the largest major jump in the size of the OC census in over a century, in addition to the much more accurate mean cluster proper motions and parallaxes provided by *Hipparcos*. However, this was just the beginning, and more new science was to come.

The release of the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006) in the 2000s provided the next major jump in data availability for furthering OC science. The infrared (IR) data of 2MASS and its associated catalogue of 471 million point sources allowed works such as Froebrich et al. 2007 to uncover over a thousand new OC candidates in the galactic disk, using IR data to peer through insterstellar dust and unveil many previously-obscured objects for the first time. In addition, works around this time began to make increasing use of advances in computing power, with works such as Froebrich et al. 2007 using automated retrieval to extract cluster candidates. CITEME MORE REFERENCES HERE

Work predominantly with IR data culminated in the catalogue of Kharchenko et al. 2013, who derived homoegeneous membership lists, ages, extinctions, distances, proper motions, radii, and many other parameters for a total of 3006 clusters, 2399 of which are OCs or probable OCs. Until *Gaia* DR2, the catalogue of Kharchenko et al. 2013 remained the largest catalogue of OCs.

In around 20 years, the OC census had more than doubled in size between the work of Mermilliod 1995 to the work of Kharchenko et al. 2013. Yet catalogue size is just one tracer of the major improvements in knowledge of OCs that happened during this time. Before going any further, and talking about how *Gaia* is powering a new charge to revolutionise the OC census for the second time in a quarter century, it is worth providing some background on the landscape of methods and knowledge from the pre-*Gaia* era, discussing the many basic observational parameters of OCs (and how they are determined), as well as the flaws of various approaches.

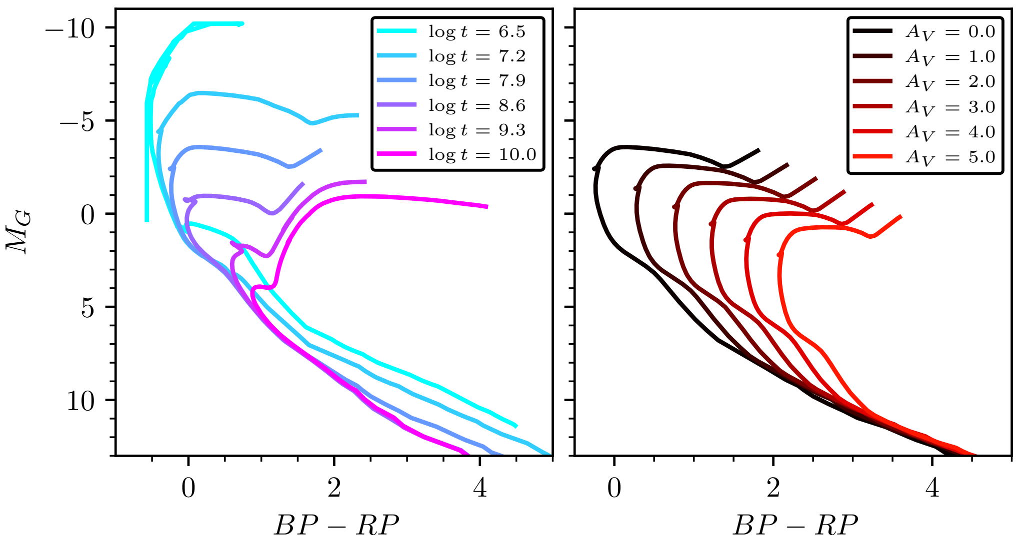



**Fig. 1.5.:** A comparison between stellar isochrones of various different parameters, derived from PARSEC stellar evolution models (Bressan et al. 2012) and shown in *Gaia* photometric bands. *Left:* isochrones of solar metallicity and zero extinction shown for six different ages. Most noticeably, as cluster age increases, the magnitude of the turn-off point decreases, with ever-more stars evolving into red giants and eventually reaching the end of their lives. The rest of the stars in the cluster also move down slightly, relaxing onto the main sequence as they age. *Right:* the $\log t = 7.9$ isochrone from the left plotted at a range of different extinction values. Extinction reddens cluster stars as well as reducing their overall brightness. Extinction in *Gaia* photometry has a strong affect on the location of the turn-off point.

### 1.3.2 Common techniques in open cluster observations

#### Membership determination

TODO. I honestly don't know enough here already lol

#### Blind searches for OCs

TODO. Should lead in from the previous section.

#### Isochrone fitting

As discussed previously, CMDs are essential tools to derive many key parameters of a star cluster (Fig. 1.4). The most common method to determine the age, extinction, and to a lesser extent the distance of a cluster is by fitting isochrones to cluster CMDs.

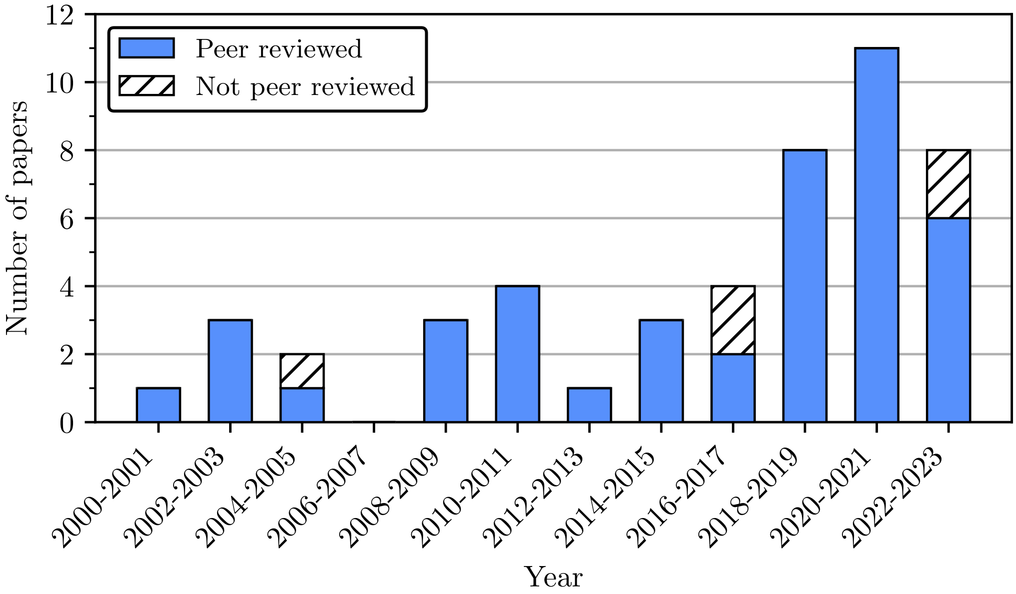
An isochrone gives the predicted colour and luminosity of a population of stars with a range of masses given that the stars have the same age, extinction, composition and distance. Stellar isochrones are derived from stellar evolution models such as PARSEC (Bressan et al. 2012) and are widely used in many areas of observational astronomy.

In practice, isochrones are difficult to fit, with age, extinction, distance and metallicity all being somewhat degenerate with one another. Figure 1.5 shows the effect of varying age and extinction on stellar isochrones, with both age and extinction moving the location of the cluster turn-off point. Cluster distance merely shifts the isochrone up or down based on the cluster's distance modulus, although this is still slightly degenerate with age and extinction. Finally, the chemical composition of a cluster (most often parameterised with its metallicity [Fe/H]) has the smallest impact on cluster isochrones and is not shown, but will nevertheless slightly impact age and extinction determination.

Isochrone fitting is further complicated by the presence of other cluster features, such as the presence of a binary sequence due to unresolved binaries (see binary sequences in Fig 1.4, showing a clear second line of stars sat slightly above the main cluster population).

Probably unsurprisingly, there are hence many methods used in the literature to fit isochrones to data. Particularly as computational power is a major hindrance to performing three or four-parameter fits with stellar isochrones, it was common to simply fit isochrones by hand (CITEME SOME EXAMPLES), which includes no robust uncertainty estimate and can open the door to human biases. The isochrones in Kharchenko et al. 2013 were fit using a hybrid method, with the authors fitting distances manually but then using $\chi^2$ minimisation to fit cluster age and reddening values. Yen et al. 2018 developed this methodology further to perform $\chi^2$ fitting of all cluster parameters. Finally, Hippel et al. 2006 created a full Bayesian methodology to fit isochrones to cluster CMDs, which is still used by works today in the *Gaia* era such as Bossini et al. 2019.

By far the main flaw of cluster isochrone fitting is speed. Three or four-parameter fits using complicated stellar isochrones are simply not



Peer reviewed
Not peer reviewed
Number of papers
0
2
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2014-2015
2016-2017
2018-2019
2020-2021
2022-2023
Year


**Fig. 1.6.:** TODO

#### Radial profile fitting

#### Mass determination

### 1.3.3 Other important observations

#### Binary stars in OCs

#### Blue stragglers: some stars stay young for longer

#### Extended main-sequence turn-offs (eMSTOs): not all OCs are perfect single populations

## 1.4 The *Gaia* revolution in open cluster science

## 1.5 Some theoretical background into star clusters

## 1.6 Thesis structure

**Chapter 1**

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# 2 Comparison of clustering algorithms applied to *Gaia* DR2 data

> *Innovation distinguishes between a leader and a follower.*
>
> — **Steve Jobs**
> (CEO Apple Inc.)

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This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

## 2.1 System Section 1

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.


**Fig. 2.1.:** Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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**Fig. 2.2.:** Another Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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## 2.4 Conclusion

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# 3 A census of star clusters with *Gaia* DR3

> *These circumstances, but more especially the last-mentioned, render it extremely desirable to have presented in one work, without the necessity of turning over many volumes, a general catalogue of all the nebulae and clusters of stars actually known.*
>
> — **John Herschel** (1864)

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## 3.1 System Section 1

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**Fig. 3.1.:** Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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**Fig. 3.2.:** Another Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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## 3.4 Conclusion

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# 4 The dynamics of Milky Way star clusters

> *TODO.*
>
> — **TODO**
> (TODO)

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Fig. 4.1.: Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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Fig. 4.2.: Another Figure example: *(a)* example part one, *(c)* example part two; *(c)* example part three

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## 4.3 System Section 3

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## 4.4 Conclusion

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# 5 Conclusion

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## 5.1 System Section 1

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## 5.2 System Section 2

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## 5.3 Future Work

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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# List of Figures

# List of Tables

# List of Listings

# A Example Appendix

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

## A.1 Appendix Section 1

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| Alpha | Beta | Gamma |
|---|---|---|
| 0 | 1 | 2 |
| 3 | 4 | 5 |

Tab. A.1.: This is a caption text.

## A.2 Appendix Section 2

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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# Colophon

This thesis was typeset with $\LaTeX\,2_\varepsilon$. It uses the *Clean Thesis* style developed by Ricardo Langner. The design of the *Clean Thesis* style is inspired by user guide documents from Apple Inc.

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# Declaration

I hereby declare that this thesis is my own work and that I have used no other than the stated sources and aids.

Ich versichere, dass ich diese Arbeit selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

*Heidelberg, May 2nd, 2023*

Emily Lauren Hunt