

Ruprecht-Karls-Universität

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

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Dissertation

submitted to the  
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of Heidelberg University, Germany  
for the degree of

Doctor of Natural Sciences

Put forward by

Emily Lauren Hunt  
born in: Coventry, United Kingdom

Oral examination: July 12th, 2023



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

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

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# 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



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# Introduction

” *TODO*

— **TODO**  
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## 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. Liu and Pang, 2019; Castro-Ginard et al., 2019; Castro-Ginard et al., 2020; Castro-Ginard et al., 2022), and a number of works deriving dramatically improved parameters and members for OCs in the Milky Way (e.g. Cantat-Gaudin et al., 2018; 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



Fig. 1.1.: TODO

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 first present a definition of OCs I will adopt throughout the rest of this work, contrasting them from related types of star clusters such as globular clusters (GCs) and hopefully minimising confusion that could arise in the rest of this thesis.

## 1.2 The definition of an open cluster

## 1.3 The history and techniques of open cluster observations

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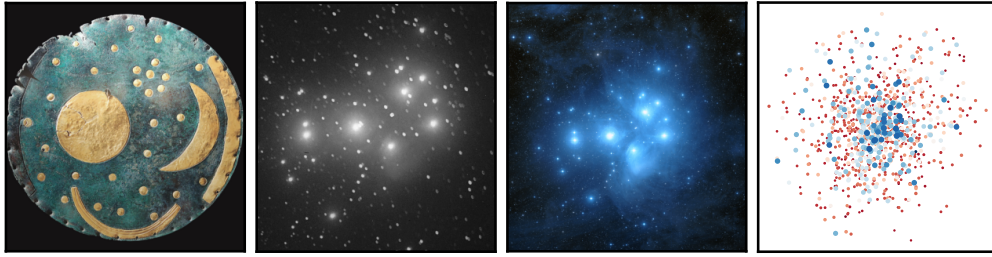


Fig. 1.2.: TODO

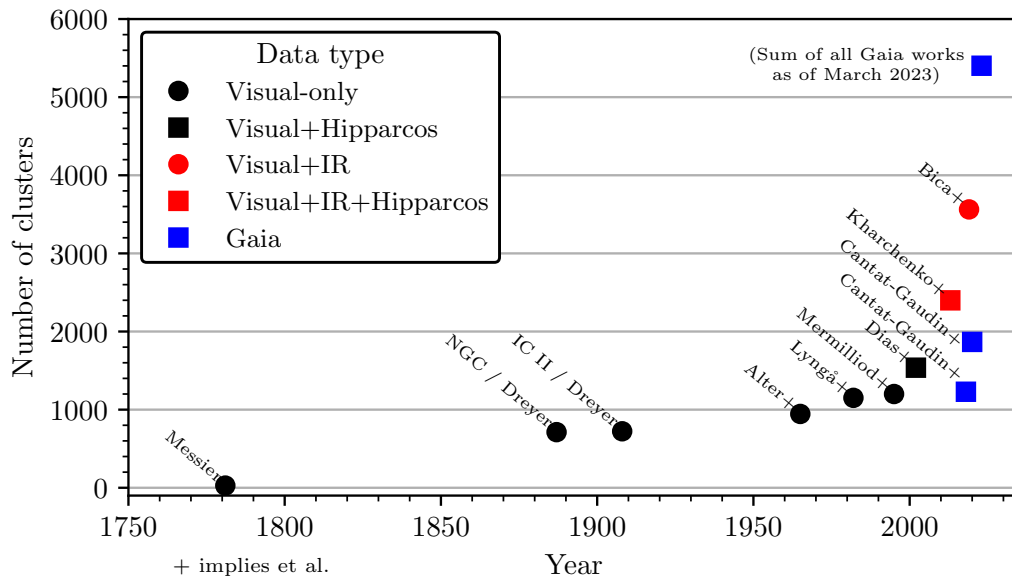


Fig. 1.3.: TODO

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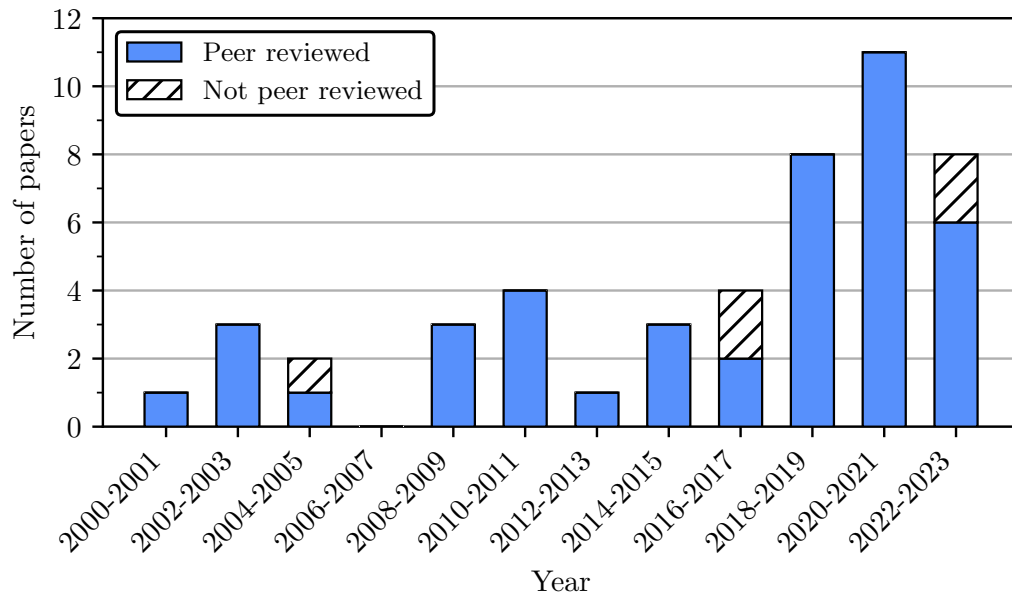


Fig. 1.4.: TODO

## 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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### Chapter 1

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# 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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## 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

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

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## 2.2 System Section 2

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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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## 2.3 System Section 3

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## 2.4 Conclusion

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## 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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## 3.2 System Section 2

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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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# The dynamics of Milky Way star clusters

” *Innovation distinguishes between a leader and a follower.*

— **Steve Jobs**  
(CEO Apple Inc.)

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## 4.1 System Section 1

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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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## 4.4 Conclusion

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## 5.3 Future Work

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## List of Listings





# Example Appendix

A

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

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.

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.

Alpha	Beta	Gamma
0	1	2
3	4	5

**Tab. A.2.:** This is a caption text.

After this fourth paragraph, we start a new paragraph sequence. 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.

## Colophon

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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*

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Emily Lauren Hunt

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