Using Colour-Magnitude-Diagrams to Study the Evolution of Young Stellar Populations

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Timescales for stellar evolution and star and planet formation are critical to provide constraints on theories. The accuracy of these timescales, and therefore our ability to confidently reject a given model, rely on the accuracy of the derived ages for star-forming-regions (SFRs). In this study I have developed the new techniques and adopted or updated the existing techniques necessary to derive precise age orders for a range of SFRs.

Deriving precise ages for SFRs requires precise distances and extinctions. I have applied a new technique, τ^2 fitting (Naylor & Jeffries, 2006), to derive a set of self-consistent and statistically robust distances (and mean extinctions), with associated uncertainties for 12 SFRs. I have also revised and formalised a widely used method of deriving individual extinctions, the Q-method (Johnson & Morgan, 1953). These new data show that the largest remaining uncertainty in deriving distances to SFRs is composition.

Deriving ages or age orders for pre-main-sequence (pre-MS) populations using pre-MS theoretical isochrones has been shown to be unreliable at present (Naylor et al., 2002; Bonatto et al., 2004; Pinsonneault et al., 2004), largely due to model dependencies and spreads within a colour-magnitude diagram (CMD). Therefore, I have developed a technique to model the pre-MS, generating **empirical isochrones**, which effectively removes spreads in pre-MS populations in a CMD.

The derived distances and extinctions have been applied to the empirical isochrones, enabling the creation of an age ordered ladder in intrinsic colour and absolute magnitude. This has been calibrated using ages for fiducial sequences and nominal ages assigned to the separable groups, which are as follows:

- 1 Myr, NGC2244 and IC5146.
- 2 Myrs, NGC6530 and the ONC.
- 3 Myrs, λ Ori, Cep OB3b, NGC2264 and σ Ori.
- 4 – 5 Myrs, NGC2362 and IC348.
- 10 Myrs, NGC7160.
- 13 Myrs, h and χ Per.
- 20 Myrs, NGC1960.
- 40 Myrs, NGC2547.

Once assigned the nominal ages and age orders were combined with ancillary data to investigate rotation rate and disc evolution. The general trends of rotation rate distribution evolution and disc fraction changes with age confirmed existing estimates for the disc survival, and therefore star-disc interaction through disc-locking, with a timescale of ≈ 5 Myrs. However, this study also revealed some of the first evidence of local environment effects. IC348 appears 'out of sequence' in both the rotation rate distribution and disc fraction. Specifically, IC348 has a larger disc fraction than expected at its nominal age and exhibits a rotation rate distribution expected from a much younger SFR (i.e. the ONC). This could be a consequence of the lower number density of O stars (none exist in IC348) and therefore a lower density of *UV* flux, which acts to hasten disc dissipation.

Finally, a potentially important feature of stellar populations in a CMD, the R-C gap was identified. This separation in a CMD of the fully convective pre-MS and main-sequence (MS) stars with radiative cores was found to vary as a function of age. As the R-C gap is also measurable in colour it provides a distance independent age indicator. I have explained the underlying physics of the R-C gap and discussed possible applications of this phase change of the stellar interior. In addition, an overlap between the pre-MS and MS sections of the R-C gap was apparent in all SFRs where the R-C gap could be unambiguously identified. This R-C gap overlap shows that the studied SFRs must contain a **spread** in **isochronal** ages. However, the interpretation of this spread is dependent on the underlying assumptions. If one assumes stars form by a robust slow-star-formation (SSF) mechanism and isochronal ages represent the true age of a star, then these spreads can be construed as true age spreads. Alternatively, if one adopts a rapid-star-formation model (RSF), this spread can be explained as a variation in accretion histories of the constituent stars. As found by Siess et al. (1999) and Tout et al. (1999) accretion can act to accelerate pre-MS star evolution, meaning the isochronal age does not represent the true age of the star. This increases the advantages of empirical isochrones and age ordering over the derivation of individual ages for SFRs. Indeed, this R-C gap overlap could be used to 'normalise out' any spread in age or accretion history and therefore increase the power of derived age orders.

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Declaration

This thesis contains work published or pending publication as papers. The results of Chapter 4 have been accepted for publication in the Monthly Notices of the Royal Astronomical Society (MNRAS). The results and techniques of Chapter 5 have been published in MNRAS, Volume 375, Issue 4, pp. 1220-1240. The results of Chapter 6 are contained in both of the papers so far mentioned. The preliminary results of Chapter 7 are nearing completion and pending submission for publication (March-April 2008).

Acknowledgments

The data used in Chapter 5 were obtained using the Isaac Newton Telescope (INT), by Stuart Littlefair and Eric Saunders. The INT is operated by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Various literature data have been used in this thesis. In particular, the astrometry in Chapter 5 utilised the Two Micron All Sky Survey, a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

The τ^2 fitting technique used in Chapter 4 was developed by Tim Naylor and Rob Jeffries. Much of the work in this thesis has been improved or was instigated by the perspicacious and well thought out comments of Rob Jeffries. I am particularly thankful to Rob for his hard work and support throughout my PhD. Stuart Littlefair has also proved an invaluable resource and has provided much insight, especially with regards to the periodic variability of stars. The often irritating but always precise insight of my supervisor Tim Naylor, who is particularly adept at uncovering ignorance, obviously provided the most significant source of scientific motivation for the work in this thesis. However, I also owe a debt to Rob King for his cynicism and great knowledge of astrophysics. Eric Saunders has also provided an incredibly measured and thoughtful response to all of my scientific questions. Eric, Rob and Tim are also responsible for translating my over-enthusiastic and often inexact use of the English language. The computing skills required for the work involved in this thesis are due to the input of Alasdair Allan, Chris Reeves, John Rowe and Eric Saunders. In particular Eric has provided an exceedingly patient (and free of charge) computing consultancy service, for which I am very grateful. Almost all of my knowledge of astrophysics has been learned from the staff and students at the astrophysics department of Exeter University, in addition to the people already named of particular note are Matthew Bate, Mark McCaughrean, Daniel Price and Tim Harries. Whilst these people are certainly partly responsible for any success I have in the field they are most certainly not liable for any failures.

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