# Exploring Binary Populations in Open Clusters

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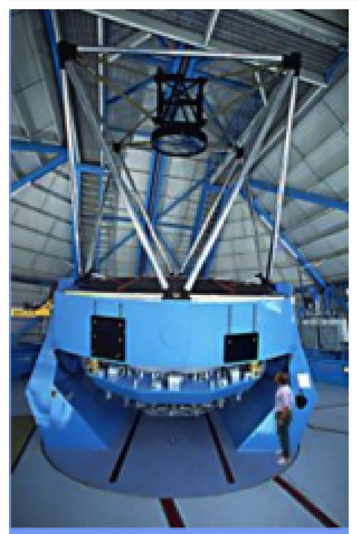


WOCS

WIYN Open Cluster Study

## [1] Introduction

A large portion of Milky Way stars are formed in open clusters, which dissolve over time so that member stars become part of the galactic disc and halo populations. We understand much of cluster dynamical evolution and stellar ejection via detailed N-body simulations. An important input parameter into these simulations is the number and mass distribution of cluster binary systems. Currently, open cluster binary populations are explored using two techniques:

**Two-Band Detection:** Binary stars are separated from singles on a cluster color-magnitude diagram (CMD). While time-efficient, this method is plagued by degeneracies and sensitivity to photometric uncertainties. While some binaries can be identified, little can be determined about masses and mass ratios.

**Radial Velocity Surveys:** Radial velocity (RV) surveys are the ideal solution, as they cannot only determine mass, but orbital period and eccentricity as well. Unfortunately, RV surveys are limited in depth (V < 16) due to the high spectral resolution needed and require large amounts of telescope time due to the number of stars and revisits required to characterize binary orbits.

We introduce a new method of identifying binary systems by sampling stellar spectral energy distributions (SEDs) over a wide wavelength range (0.3 - 8.0 μm). Using this method, component masses of binary systems within open clusters can be determined for all stars using minimal time.

## [2] SED Fitting Method

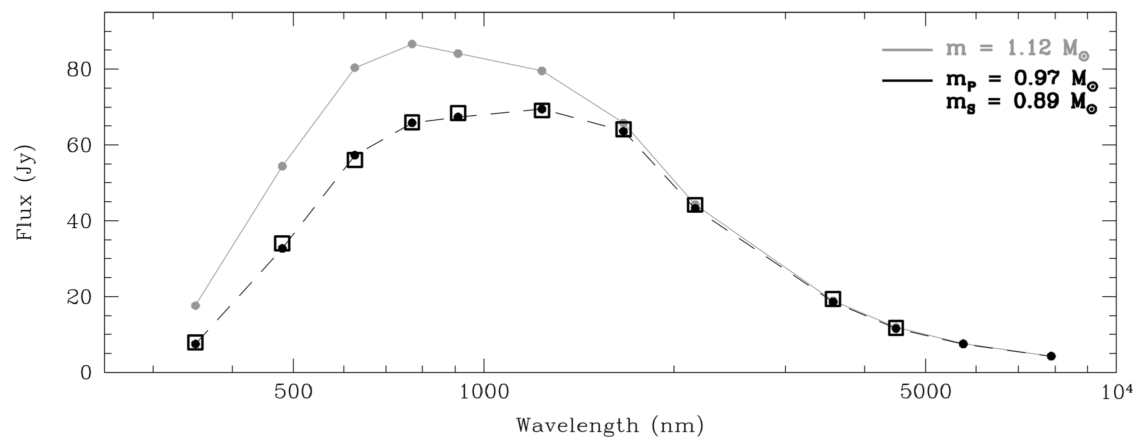
A table of synthetic binary stars are created using an isochrone. Every possible binary system is created by combining fluxes of individual isochrone stars. To ensure there are no degeneracies, a binary model that has 3 or more magnitudes less than 0.001 different than another is removed from the table. Each star in the dataset is then compared to every model in the grid, using:

$$\text{fit} = \sum_{\text{filters}} 1 / (m_{data} - m_{model} + 0.01)$$

If any element of the sum is less than 10 (the difference between magnitudes is greater than 0.1), it is removed. A star must have 3 closely-matching magnitudes in the visual (*UBVRI* or *ugriz*), 3 in the near-IR (*JHK$_S$*) and 2 in the mid-IR ([3.6][4.5][5.8][8.0]). If a star does not meet these qualifications, it is designated as a non-member. For member stars, primary and secondary masses for the model wth the highest fit value are recorded.

This fitting procedure is iterated multiple times. At the beginning of each iteration, every magnitude is resampled from a gaussian distribution using the associated uncertainties. For the results here, each fitting was run 90 times. At the end of all iterations, the median primary and secondary best-fit masses are recorded.

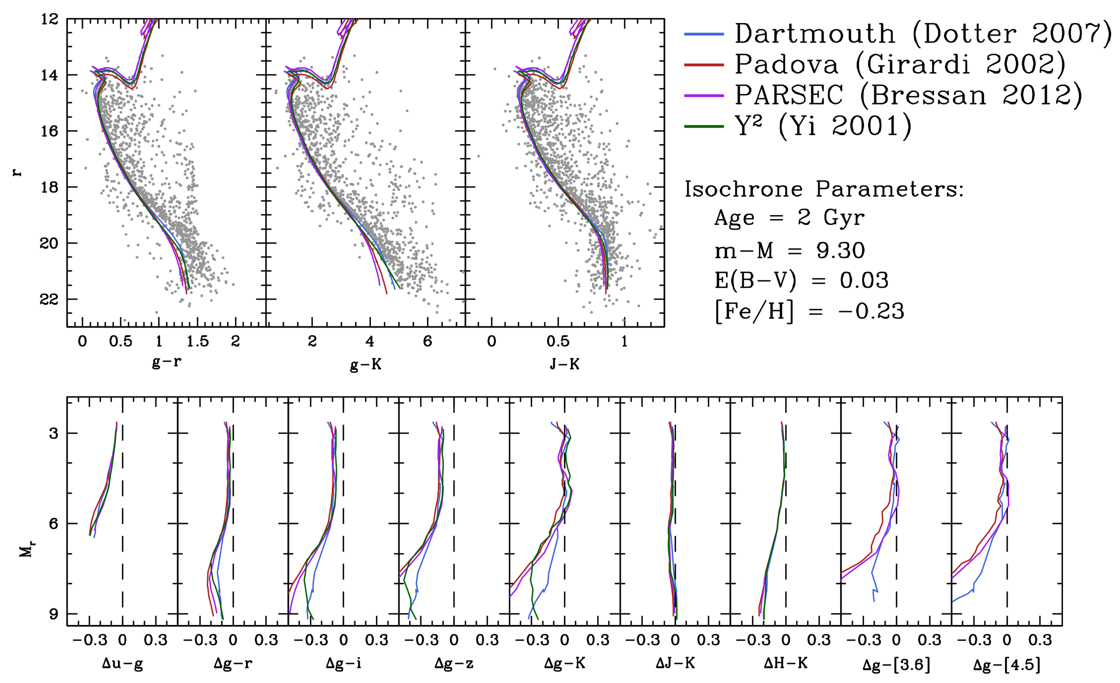
The figure to the right shows an example fitting of a star in M67 using 10 filters: ugrizJHK$_S$[3.6][4.5] (denoted by boxes). Best-fit single and binary models are overplotted. The binary model accurately fits all 10 filters, while the single model can only match the mid-IR portion of the SED. The example star here was classified as a single in previous RV work (Mathieu et al. 1967)




## [3] Isochrone Models

In order to ensure accurate results, the isochrone models used for each cluster must match closely to observation. If isochrone colors are different than those observed, true cluster stars will be rejected by the SED fitting program. To test isochrone accuracy, by-hand empirical ridgelines for various colors were determined using the observed data, and then compared to isochrone predictions. Several popular isochrone systems were tested: Padova (Girardi 2002), PARSEC (Bressan 2012), Dartmouth (Dotter 2007) and Y² (Yi 2001).

Residuals between the empirical ridgeline and isochrone models for the cluster NGC 2420 are shown to the right.




Due to the sensitivity of mass measurement to differences in colors, none of the isochrone systems were suitable matches. Instead, the by-hand ridgelines were used to create an empirical color-temperature relation for the isochrones. For the results here, PARSEC isochrones, with the derived empirical color relations, were used.

## [4] Sensitivity

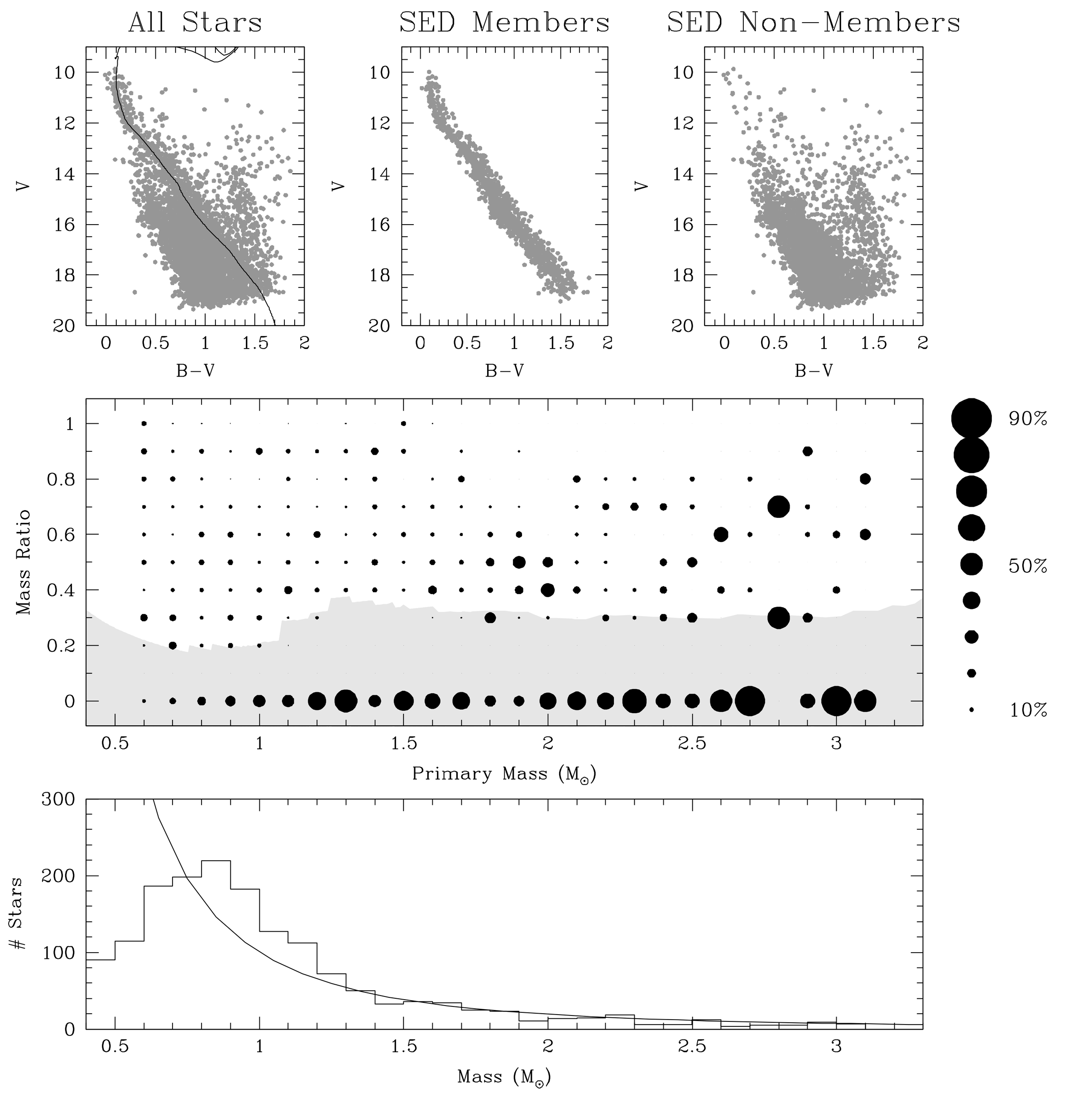
Low mass-ratio binaries are often indistinguishable from single stars. The minimum mass ratio threshold is shown in grey on mass ratio distribution plots to the right. On average, the minimum acceptable mass ratio is approximately 0.3.

## [5] Results

### NGC 2168 (M35)

| Parameters | |
|---|---|
| Age | 251 Myr |
| m-M | 9.6 |
| E(B-V) | 0.20 |
| [Fe/H] | -0.21 |

| Data | |
|---|---|
| *UBVRI* | MOSAIC (Thompson et al., in prep) |
| *JHK$_S$* | NEWFIRM (Thompson et al., in prep) |
| [3.6]-[8.0] | IRAC |




The young cluster M35 provides an excellent starting point for numerical simulations. Mass information is obtained from stars with primary masses greater than 0.65 solar masses, where the visual photometry ends.

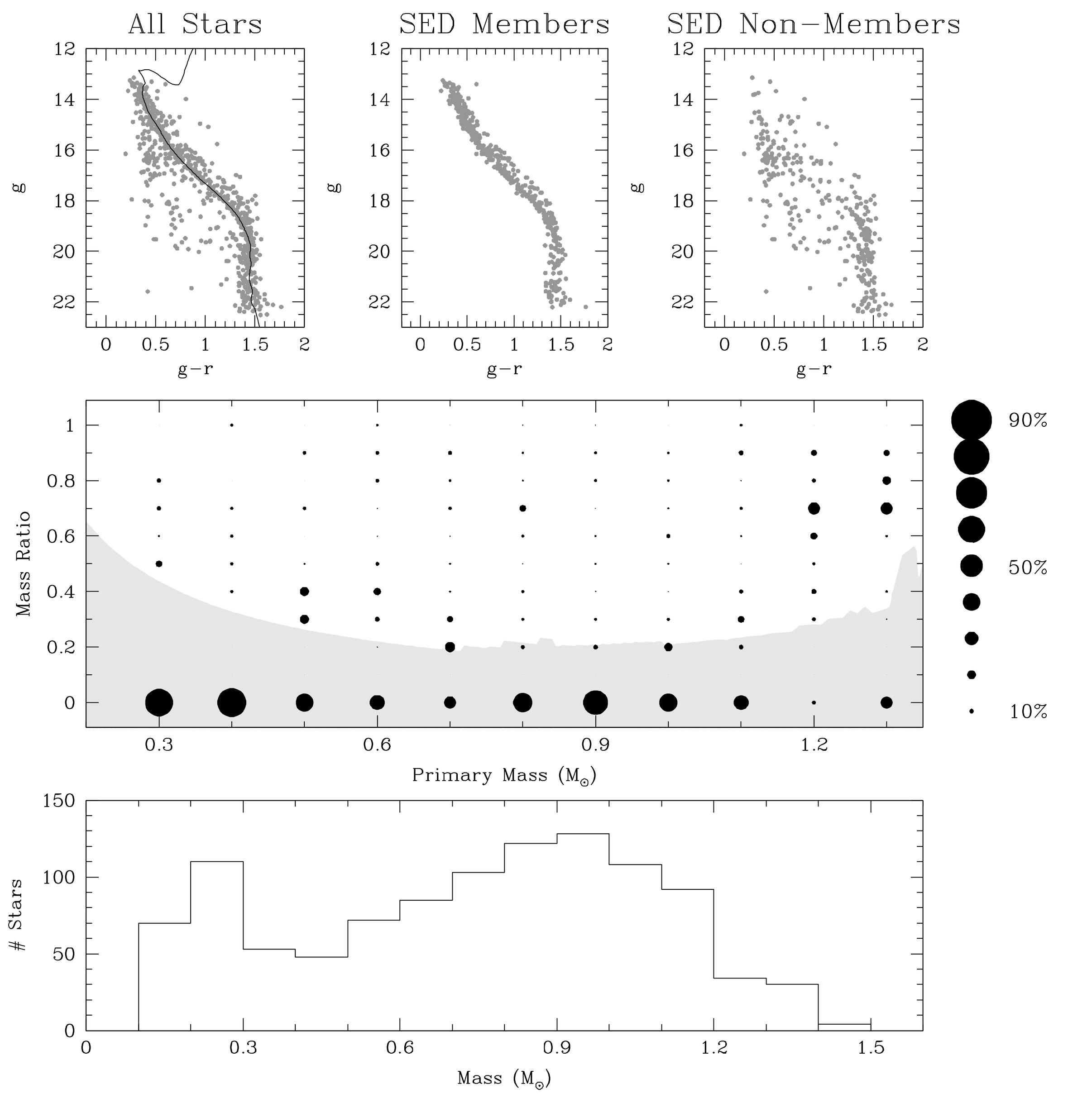
Current SED fitting results place the cluster binary percentage at 71%. This high result may be complicated by differential reddening within the cluster, which will have to be corrected in future work. For stars with primary masses less than 1.7 solar masses, mass ratios are distributed almost uniformly. Above that, the mass ratio distribution becomes more erratic due to low number statistics.

The bottom panel of the figure shows the distrubtion of star masses within the cluster, with an overlayed Salpeter IMF for a cluster mass of 1650 solar masses. Previous studies have placed the mass of M35 near this value (Sung & Bessel 1999). There appears to be some member contamination around a solar mass from background stars.

### NGC 2682 (M67)

| Parameters | |
|---|---|
| Age | 3.5 Gyr |
| m-M | 9.66 |
| E(B-V) | 0.04 |
| [Fe/H] | +0.01 |

| Data | |
|---|---|
| *ugriz* | An et al. (2009) |
| *JHK$_S$* | NEWFIRM |
| [3.6]-[8.0] | IRAC |



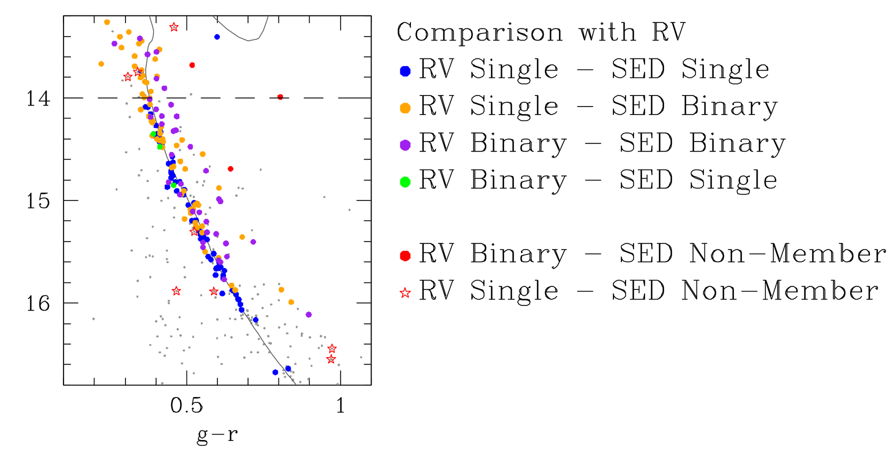

The cluster M67 is a model for old open clusters. *ugriz* photometry is from An et al., which used PSF photometry on SDSS images. Stars at or above the turnoff are saturated due to the depth of SDSS images. Mass information is determined for cluster stars from 0.3 to 1.3 solar masses. While the photometry extends to masses of 0.27 solar masses, it appears that many of the lowest mass stars are classified as non-members in the analysis.

The overall cluster binary percentage is 60%. Far enough below the turn-off, the binary distribution appears to be fairly uniform. Near the turn-off, stars begin to cluster around a mass ratio of 0.7. This may be due to degeneracies in the models, as opposed to reality.

The bottom panel shows the distribution of masses within the cluster. M67 has been disrupted over its 4 Gyr lifetime, leaving an altered mass distribution. No IMF fits this evolved cluster.

**Comparison to RV Results**

The SED binary results are compared to a WOCS RV study of M67 detailed in Mathieu et al. (1967) in the figure and tables to the right.




Comparisons between the RV and SED results are only valid for stars with $g > 14$. The SED method has degeneracies near the turnoff and is therefore inaccurate. Ignoring this region, the SED and RV methods show similar results:

- A majority of RV binaries are detected via SED fitting. The 13% which are not may have small secondaries which fall below the minimum mass-ratio threshold.
- Almost half of RV singles are confirmed as SED singles. The SED method can also detect systems whose orbital periods or inclinations produce velocities that are outside the range detectable using RVs.
- The RV study determined that the *hard* binary percentage is 25%, while the SED method, which can detect hard and soft binaries, indicates that the true cluster binary frequency is 55%. This binary percentage is different than the one above, as we are neglecting the results for binaries near the turn-off.

| | SED Single | SED Binary | SED Non-Member |
|---|---|---|---|
| **RV Single** | 46% | 34% | 19% |
| **RV Binary** | 13% | 63% | 24% |