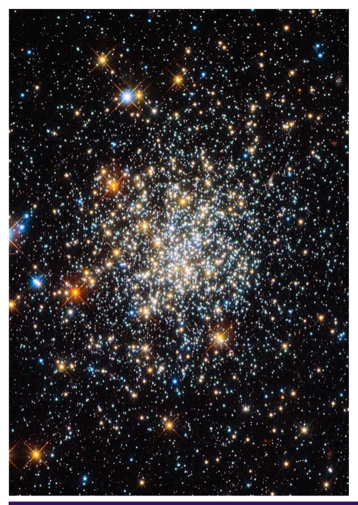

# It Takes Two to Tango:

## Finding the Binary Companions of Known Stars

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**BINOCS**

**Binary INformation from Open Clusters using SEDS**

**Abstract:** When stars form from collapsing gas clouds, about half of them form in pairs (binary systems). However, identifying which stars in the Milky Way and other nearby galaxies are binaries is difficult; even nearby two-star systems look like a single point of light. Due to the distances of even the most nearby galaxies, a method to reliably identify these binary systems is needed. We will apply the Binary Information from Open Clusters Using SEDs (BINOCS) code to aid in separating the light emitted from each star. Open clusters have known ages, distances, and metallicities, so we can apply these parameters to the stars in the clusters to determine their masses and fit to their spectral energy distributions (SEDs). The BINOCS method has successfully been applied to some open clusters; we want to identify which globular clusters and nearby dwarf galaxies the method can be applied to. In order to reach these more distant objects, we need to use deep space-based data. The data we explore in this work is from stars in ~200 cluster or galaxy targets observed by the Hubble Space Telescope (HST), James Webb Space Telescope (JWST), and Spitzer Space Telescope. The fraction of binaries is a key factor in measuring the amount of dark matter in dwarf galaxies. One example system we plan to analyze is NGC 104, a globular cluster ~15 thousand light years away from Earth, with an age of ~13 billion years.

## BINOCS Calibration Sample:

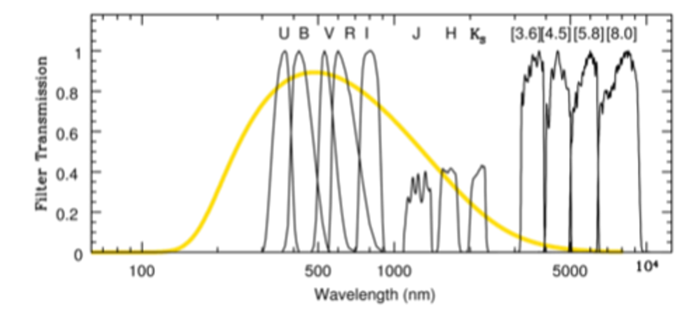
The used sample was designed to cover open clusters spanning a wide range of ages and metallicities, as well as to expand the BINOCS method (Thompson et al. 2021) to larger stellar samples for verification. The method depends on having high-quality photometry over a wide range of wavelengths. We want to test if the method works on larger, more distant groups of stars in globular clusters and dwarf galaxies.

The following photometry sources were used:

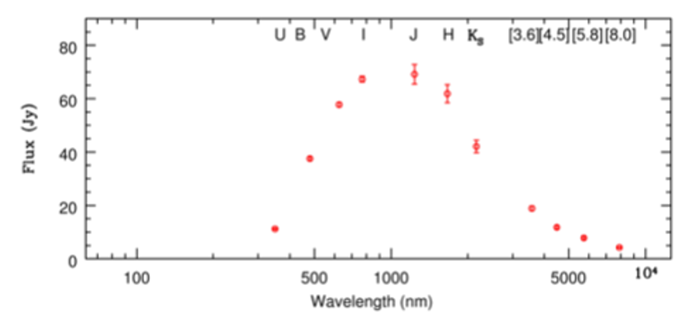
**Optical [300 - 900 nm]**
SDSS or MOSAIC (WIYN 0.9m)

**Near-IR [1000 - 2500 nm]**
2MASS and NEWFIRM (KPNO 4m)

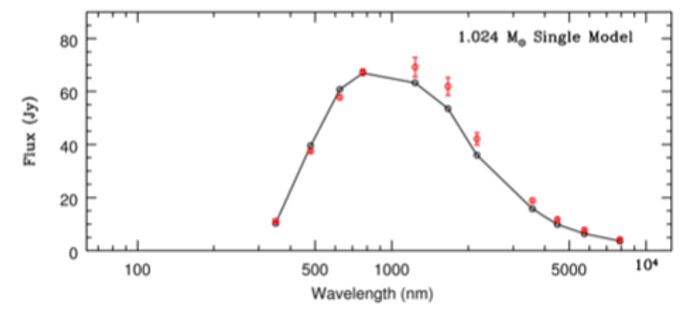
**Mid-IR [3000 - 8000 nm]**
*WISE* and *Spitzer* (IRAC)



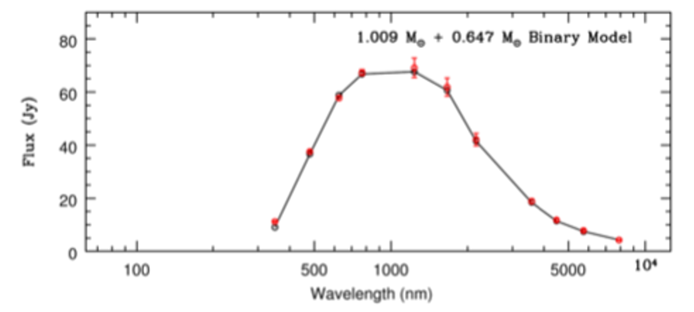

(1) Example filters used in the BINOCS work over plotted with a 6000 K blackbody curve.




(2) Measured flux for a BINOCS cluster star with data spanning 11 filters from U-[8.0].




(3) Using the star above in (2), the single star model is fit to the data, which shows a poor fit in the NIR (1000-2000 nm).



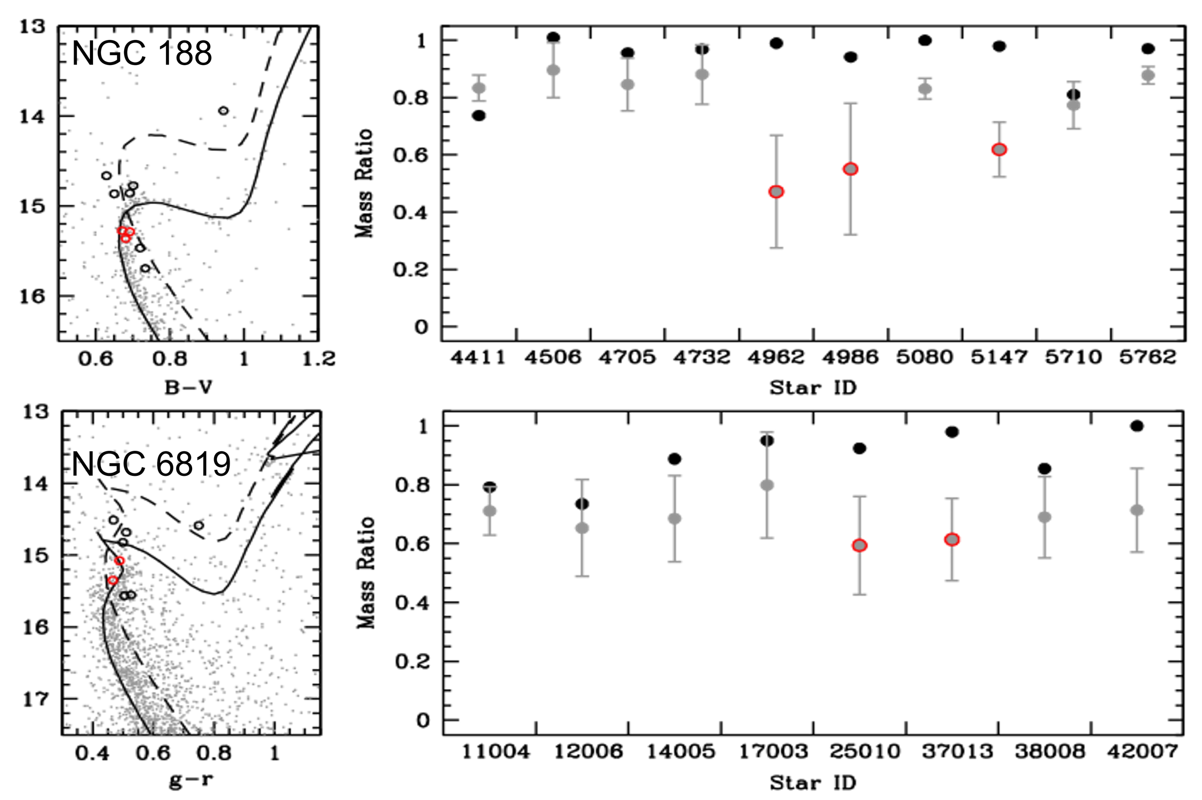

(4) Best fit binary model for the star in (2) that provides a much better fit and results in masses for the two components.

## BINOCS Method:

In practice, stars are not blackbodies, but the main premise stays the same. Stellar structure models exist which predict the spectral energy distribution (SED) of a star given its parameters: age, metallicity, and mass. The star is a member of a cluster with known parameters, so age and metallicity are given. By matching stars to models of a library of synthetic single-star SEDs, mass can be determined. If a star does not fit any of the single-star SEDs, it is determined to be a binary system, and is compared to combinations of SEDs. Isochrones often come in coarse mass grids. To overcome this issue, stellar parameters and magnitude are cubically interpolated with respect to mass onto a new mass grid. For open clusters used by Thompson et al. (2021), a grid spacing of 0.01 $M_{\odot}$ is used. An example of this method is shown in Figures 1-4.

## BINOCS Verification:

Thompson et al. (2021) conducted a detailed comparison to the decades long RV-based studies of the WIYN Open Cluster Study (WOCS). The WOCS studies are limited to bright stars, typically with a faint limit at least 5+ magnitudes brighter than the BINOCS faint limit, but the RV-based binary studies provide good mass ratios for comparison. There is good agreement between mass ratios, with most differences being due to model uncertainties and systematics. However, near the Main Sequence Turn-Off (MSTO), the BINOCS method suffers due to degeneracy where the binary and single evolutionary sequences cross, as seen by the red points in Figures 5 & 6. This minor flaw is acceptable, as the strength in BINOCS is for lower mass stars unreachable by RV-based studies.




(5 & 6: Left) Comparison of mass ratios for stars common in open clusters NGC 1888 and NGC 6819 between BINOCS and the WOCS RV-based (NGC 188: Geller at al. 2009; NGC 6819: Milliman et al. 2014). These ratios show good agreement except near the cluster turnoff (the end of the main sequence).

**BINOCS CODE:** **(https://github.com/J4ninja/BINOCS_GAIA_Calibration)**

## The NEW BINOCS Survey:

The BINOCS method was successful when used on eight open clusters (Thompson et al. 2021). We plan to expand the method into a new BINOCS survey using a larger nearby open cluster, *plus* a sample of ***over 200 targets*** in the form of more distant globular clusters and dwarf galaxies to see if it remains accurate at greater distances.

***Due to the greater distances of globular clusters and dwarf galaxies, we need to rely more on deep space-based data that we focus on here (see Figure 7).***

| Object Type | Total Number of Stars | Distance to Object |
|---|---|---|
| Open Cluster | 20-10,000 | 100 pc-20 kpc |
| Globular Cluster | 10,000-10 million | 2 kpc-200 kpc |
| Dwarf Galaxy | 1,000-10 billion | 26 kpc-200 kpc |

(7: ABOVE) Left to right: The *Spitzer Space Telescope (SST)*, *Hubble Space Telescope (HST)*, and *James Webb Space Telescope (JWST)*.

### BINOCS Advantages:

1. Less sensitive to uncertainties than two-band photometric methods
2. Insensitive to inclination as compared with RV-based methods
3. Much faster than RV methods (do not need long-time baselines)
4. Mass ratios to within 10% of more thorough RV studies
5. Can explore large mass range, including low masses
6. Can provide mass estimates over a wide range of masses
7. Updated to work with GAIA BP-RP spectra

## The NEW BINOCS Survey Photometry

We again need coverage over a wide wavelength region, so will use data from the following photometry sources for the distant data:

**Optical [300 - 900 nm]**
*Hubble Space Telescope* (*HST*)

**Near-IR [1000 - 2500 nm]**
*Hubble Space Telescope* (*HST*)
*James Webb Space Telescope* (*JWST*)

**Mid-IR [3000 - 8000 nm]**
*James Webb Space Telescope* (*JWST*)
*Wide-field Infrared Survey Explorer* (*WISE*)
*Spitzer Space Telescope*

## Advantages for Distant Targets

Globular clusters contain between ten thousand and ten million stars, and dwarf galaxies can contain up to ten billion stars. In comparison to open clusters, these structures contain a lot more stars, enabling us to detect a high number of previously unknown binary systems if the BINOCS method holds (see table above).

## Disadvantages for Distant Targets

While globular clusters and dwarf galaxies contain many more stars, they are also significantly further away than open clusters. With each star appearing smaller, there may be challenges with using the BINOCS method to discover binary systems at such distances. Additionally, these larger objects have stellar populations of varying ages and metallicities, therefore making assumptions about such properties can lead to inaccurate results.

## CURRENT BINOCS SURVEY SAMPLE:

| Data Available | Globular Clusters | Dwarf Galaxies |
|---|---|---|
| 3 telescopes | 17 | 5 |
| 2 telescopes | 80 | 33 |
| 1 telescope | 50 | 22 |
| Insufficient data | 10 | 1 |