Establishing Membership Probabilities For Suspected Cluster Stars Using Observational And Simulated Data

Sean McAdam[1], Kevin Covey[1] & The MWBest RAISE Team
Western Washington University[1]

Why Study Clusters?

Star clusters form conatally, with a variety of different stellar types being born at nearly the same time in a galaxy's history. Tracing the evolution of those clusters can provide enormous insight into the evolution of the Milky Way galaxy itself.

- **Motivation for studying star clusters in the galactic bulge**
  - Determining fraction of the original stars formed in clusters near the center of the Milky Way
  - Measuring and explaining mechanism(s) of stellar mass loss
  - Bulge clusters being analyzed: Patchick 99, NGC 6569, NGC 6441, ESO 456-09, BH 261, FSR 1775
- **Motivation for studying Segue 3, a halo cluster**
  - More confidence in halo history allows better insight into cluster evolution
  - Makes for a useful laboratory for studying early disruptions to a cluster as it is small, young and possibly on its first pass through the Milky Way[1]

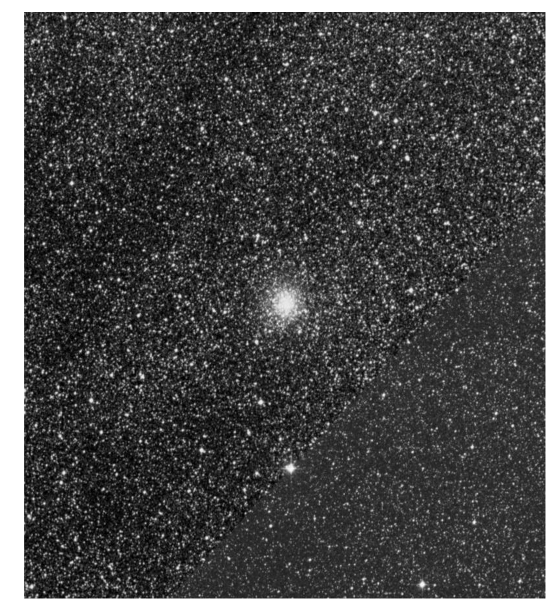

Fig. 1: An image of NGC 6569, seen as an overdensity of stars in the center of frame. *DSS2*

Analytical Framework

Establishing a measure of probability for a star being associated with a given cluster begins with identifying a cluster of interest, simulating both the cluster stars and field stars in view, analyzing and then using the unique properties of the cluster to identify members

- **Uniqueness of Star Clusters**
  - Conatal stars, or stars born at the same time, typically share characteristics such as metallicity, age and kinematics
  - These produce distinct groupings that can be easily distinguished from field stars that have comparatively random distributions
- **Simulation**
  - *Core and tail stars:* Gala[2] and Corespray techniques
  - *Field stars:* The Besancon Galaxy Model[6] uses well-known properties of the Milky Way to determine stellar counts and characteristics
- **Analysis**
  - *Color-Magnitude Diagrams:* In the SDSS 'ugriz' colors, r vs g-r and i vs i-z are the primary focus
  - *Kinematics:* Radial velocity individually and compared to proper motions, and proper motion in right ascension compared to proper motion in declination
- **Calculating membership probabilities**
  - A star's membership probability can be calculated from the ratio of cluster stars to total stars in its region of the CMD and/or proper motion space

$$membership\,probability = \frac{\#\,of\,cluster\,stars}{\#\,of\,field\,stars}$$

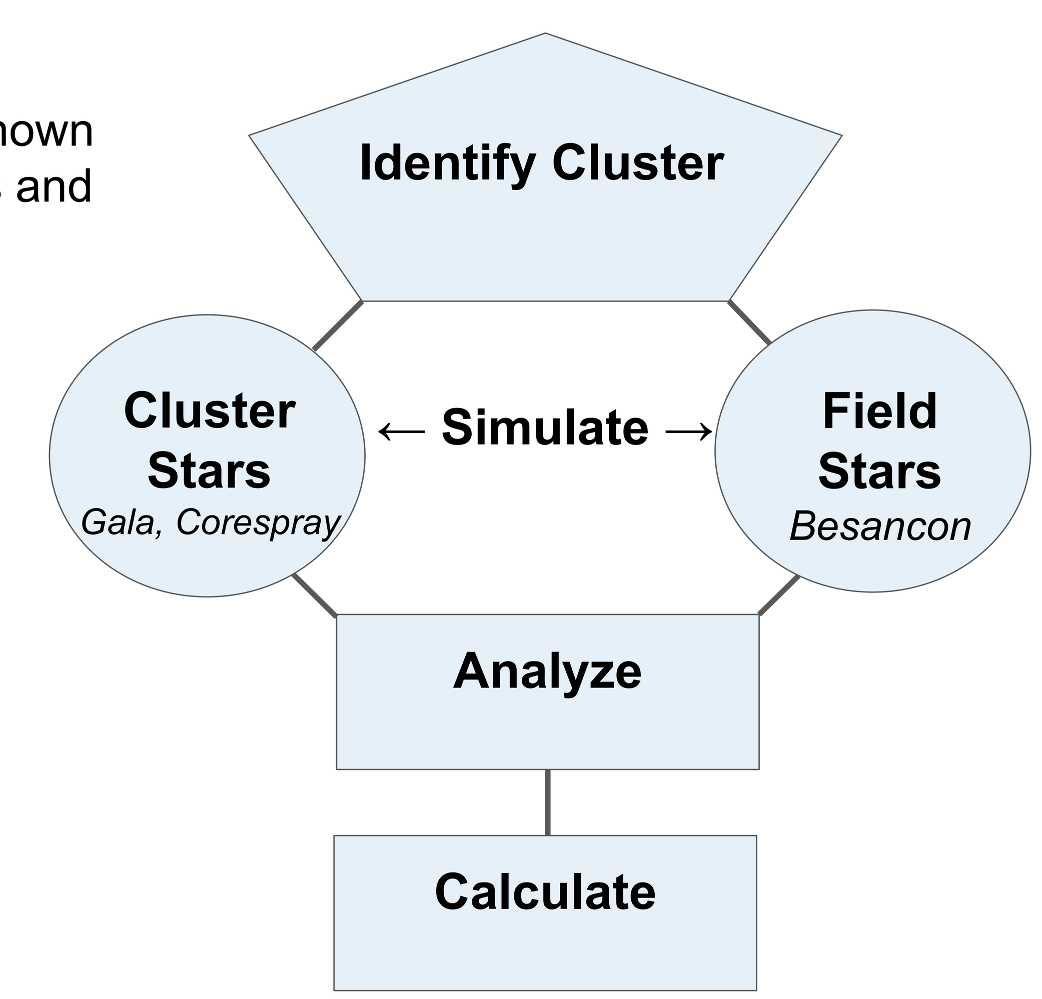

Fig. 5: The analytical process begins with the identification of the cluster and results in a percentage value of membership probability

Membership Results and Insights

- **Color-Magnitude Diagrams**
  - Isochrones produce a distinct and narrow zone of significant membership probabilities
  - Along the isochrone membership probability decreases in areas of prominent field star contamination
  - Extinction effects are currently underestimated, we plan to use a 3D dust model to produce more realistic probabilities
- **Radial Velocity and Proper Motions**
  - All-sky proper motions from Gaia allow identification of high probability members at the clusters' mean velocity
  - Radial velocities require follow-up observations but allow for filtering of field star contaminants which happen to have same proper motions and CMD location as cluster stars

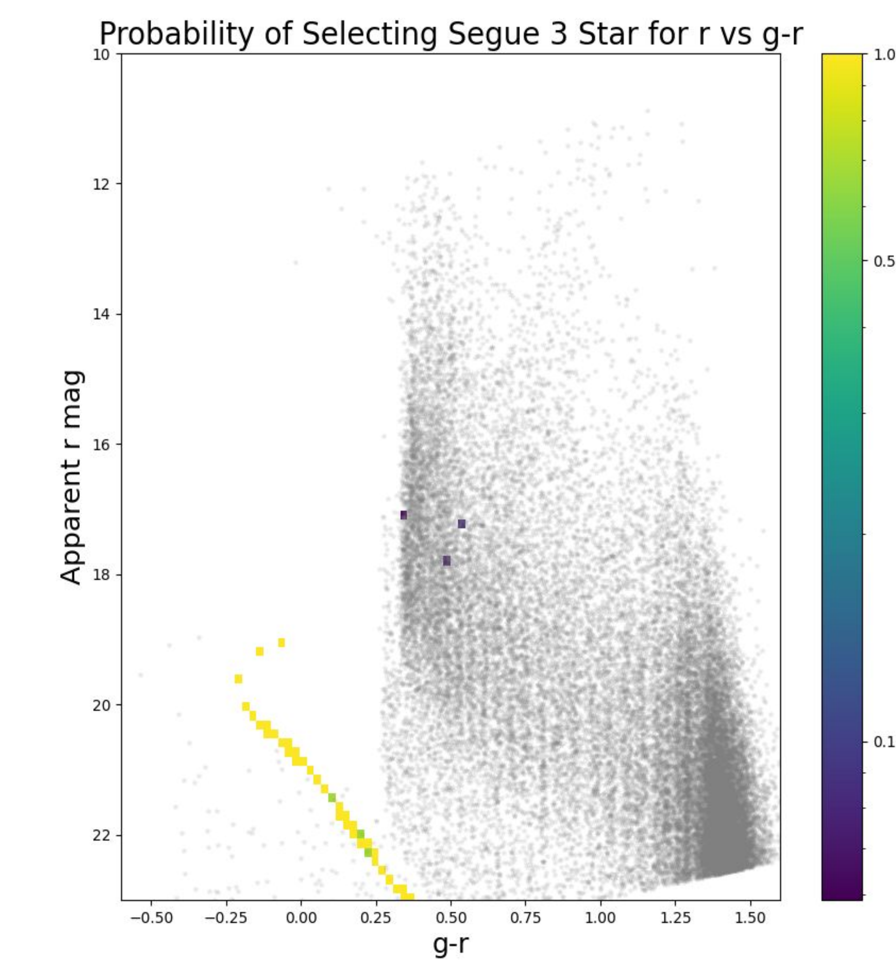

Fig. 6: Color magnitude diagram (CMD) depicting the Segue 3 isochrone (in color) with decreasing probabilities as it intersects the field star population (grey)

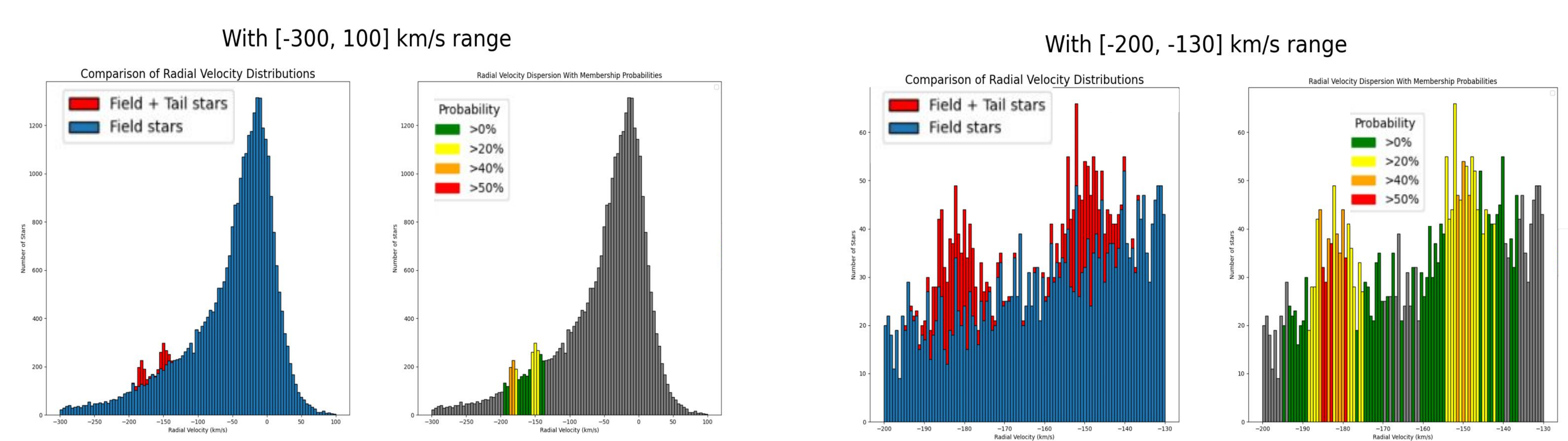

Fig. 7: Narrowing the range of radial velocity values, though challenging due to the need for spectroscopic analysis, provides more distinct probabilities.

Next Steps and Iterations

We are continuing to work on this method of confirming members of star clusters with the goal of maximizing the calculated probabilities for previously confirmed members. Our intention is to refine the process and increase the accuracy, reliability and robustness of the results, with our first priorities being:

- **Besancon input**
  - Fine-tuning simulation range and parameters to accurately reproduce the relative number and types of field stars, relative to the cluster population.
- **Accounting for local and differential extinction**
  - Adjusting the method to account for dust to match up the Segue 3 probabilities with previously identified members

Acknowledgements and References

This work has been made possible by the generous contributions of the RAISE foundation that is aimed at boosting the productivity of research being pursued at private undergraduate colleges and universities in the Pacific Northwest.

1. Hughes, Joanne et al., 2017, AJ, 154:57, 18 **2.** Price-Whelan 2017, JOSS, 2, 388 **3.** Bovy et al 2015, ApJ, 800, 12 **4.** Plummer 1911, MNRAS, 71, 460 **5.** Grondin et al 2023, MNRAS, 518, 4249 **6.** Robin et al 2003, A&A, 409, 523