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Cluster Difference Imaging Photometric Survey. III. The Coeval Halo and Core of NGC 2516

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ABSTRACT

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1. INTRODUCTION

In the traditional picture of star formation molecular clouds go gravitationally unstable, and collapse into little knots. The knots produce many stars close to each other. The resulting “open star clusters” are, as with any first-order guess, spherical.

How does the cluster evolve? The answer depends on the total stellar mass. The smallest 90% of star clusters disperse during the “embedded phase” (CITE). This is driven mostly by *process A* (CITE). The more massive clusters make it to maybe 100 Myr. Maybe a bit longer. Their evaporation is thought to be driven by collisions with molecular clouds (CITE, Spitzer 1958), and the galactic tide (CITE), and *process A*, and *process B*. Of course, the expected evaporation time should depend on factors including the mass of the cluster itself, how many high-mass (O and B) stars form, since their winds [and maybe supernovae] clear out most of the cloud, and the initial density of the gas cloud to begin with.

Assuming that the cluster achieves virial equilibrium, stellar fly-bys then conspire to segregate the stellar mass distribution within the cluster, evaporating the lowest mass stars soonest (2T+U=0, U=-GM/r, assuming equipartition of the specific “thermal energy” per star, then kT = $0.5mv^2$ at lower masses requires higher velocities).

Identification of the stars that disperse into the galactic field is an important task for understanding the conditions under which stars and star clusters form, and for understanding how they subsequently evolve. For instance, how does the process of radial migration across the galactic disk affect cluster dispersal? Did the Sun form in an open cluster? If so, how massive was its cluster, and is there any hope at identifying the stars that formed near the Sun? Qualitatively, the dispersal of open clusters also provides perhaps the best “test case” for the concept of “chemical tagging”, also referred to as “galactic archaeology” (CITE).

Outside of the issue of star formation, identifying the remnant halos of open clusters is important for a separate project: that of discovering young transiting planets. Young transiting planets are hard to find because young stars are rare (CITE), and often reside in crowded regions of the sky (CITE). If the halos of nearby star clusters can be reliably identified, this could expand the census of nearby sub-Gyr stars by a factor of 2 or even 3 (CITE Meingast). A fortuitous benefit of searching for planets in cluster environments is that issues with stellar crowding are also alleviated.

Recent clustering studies using Gaia have begun to report the identification of structures that could correspond to low-density halos of stars that may have evaporated from open clusters (e.g., Kounkel+19, Kounkel+20, Meingast+21). However, different clustering methods on the Gaia data tend to give different results (CITE: Hunt & Reffert 2020). Employing say Gaussian Mixture Modelling, or any analogous method that requires “clusters” to be ellipses in spatial/velocity phase-space unsurpsingly yields open clusters that are roughly elliptical (CITE: Cantat-Gaudin+18). Unsupervised clustering methods such as HDBScan (e.g., Kounkel+19) have been found to yield additional structures, particularly in lower density regions such as the Psc-Eri stream (CITE: Meingast+18, Curtis+19, Newton+21), but also more generally around many open clusters (Kounkel+19). Unsupervised approaches that incorporate physical constraints (e.g., imposing a maximum velocity dispersion on putative members) yield similar results, potentially with higher purity (Meingast+21).

We’ve recently been making TESS light curves of age-dated stars across the sky, as part of a Cluster Difference Imaging Photometry Survey (CDIPS, CITE Bouma+19). Our analysis of Cycle 1 (Sectors 1-13) yielded light curves of 483,407 candidate cluster members in the Southern Ecliptic hemisphere, available on MAST [1,2]. Based on rotation periods, $\approx$25% appear to be bonafide cluster members.

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As part of a broader project of identifying a large and clean sample of young stars for a transit search, we take the opportunity of this paper to answer a rather modest question: in just a single rich southern open cluster, is the cluster halo coeval with the core? The cluster we chose for this analysis was NGC 2516, since it was young ($\sim$110 Myr) and close ($d = 400$ pc) enough to facilitate rotation measurements using TESS, and some degree of spectroscopic analysis. We want to know: is the halo real? To what extent can we use Gaia alone to reliably identify age-dated needles in the haystack of boring field stars? And more generally, what are the implications for the evolution of open clusters if they do have halos?

Section 2 presents the astrometric and photometric data from Gaia, and clarifies our usage of the terms "core" and "halo". Section 3 age-dates the halo of NGC 2516, using TESS gyrochronology (Section **??**), and lithium depletion (Section **??**). In Section 4 we discuss the implications of this analysis for NGC 2516 specifically and stellar spin-down and open cluster evolution generally. Section 5 presents our conclusions.

2. A 250 PC HALO AROUND A CORE?

2.1. *Gaia Astrometry*

Figure 1 shows the problem we would like to address. In this figure, the "core" comprises NGC 2516members that Cantat-Gaudin et al. (2018) reported to have "membership probability" exceeding 10%, based on the Gaia DR2 astrometric data. The exact meaning of this probability, and details concerning their clustering algorithm, are discussed in Appendix A. The "halo" comprises NGC 2516members that Kounkel & Covey (2019) reported as members, also based on the Gaia DR2 data. That study did not report continuous membership probabilities, instead opting for the binary "member" or "not". These two different clustering methods yielded wildly different results. What is the true structure of NGC 2516? Are the core and halo truly coeval?

3. AGE-DATING THE HALO OF NGC 2516

3.1. *HR Diagram from Gaia*

The first check on whether this membership assignment is plausible was already performed by Kounkel & Covey (2019) and more recently by Meingast et al. (2021). That check is to see whether the HR diagrams of these cluster components that were selected based on positions and velocities photometrically support the claim that they are coeval.

Figure 2 presents similar results to what these investigators have already found. The core members of the cluster show a clean sequence consistent with stars with a fixed age and metallicity, and varying mass. The halo members are roughly consistent with this, but they do show greater scatter. One possible explanation for this scatter is that the halo is more contaminated by field stars.

Comparing these HR diagrams to the PARSEC isochrone models, we find that X, Y, and Z. In particular, "the faintest M dwarfs in the core and halo are brighter than in the field star comparison sample, consistent with these stars having not yet reached the ZAMS." This is consistent with the main-sequence turn-off being at $Bp-Rp \approx 0.05$, which implies an age of XXX. The resulting photometric age we adopt for the core is XXX. For the halo, the claimed age from photometry is YYY. Applying the same procedure to the field star comparison sample, we get an age of ZZZ.

3.2. *Rotation from TESS*

TESS: S7 + S9

3.3. *Lithium from Gaia-ESO and GALAH*

4. DISCUSSION

4.1. *How did it form?*

4.2. *Mass differences between center and outer reaches?*

4.3. *Fast rotators: are we going faster than other clusters?*

5. CONCLUSION

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Software: `astrobase` (Bhatti et al. 2018), `astropy` (Astropy Collaboration et al. 2018), `astroquery` (Ginsburg et al. 2018), `cdips-pipeline` (Bhatti et al. 2019), `corner` (Foreman-Mackey 2016), `IPython` (Pérez & Granger 2007), `matplotlib` (Hunter 2007), `numpy` (Walt et al. 2011), `pandas` (McKinney 2010), `scipy` (Jones et al. 2001), `wotan` (Hippke et al. 2019).

Facilities: *Astrometry*: Gaia (Gaia Collaboration et al. 2016, 2018). *Imaging*: Second Generation Digitized Sky Survey, SOAR (HRCam; Tokovinin 2018). *Spectroscopy*: CTIO1.5 m (CHIRON; Tokovinin et al. 2013), *Photometry*: TESS (Ricker et al. 2015).

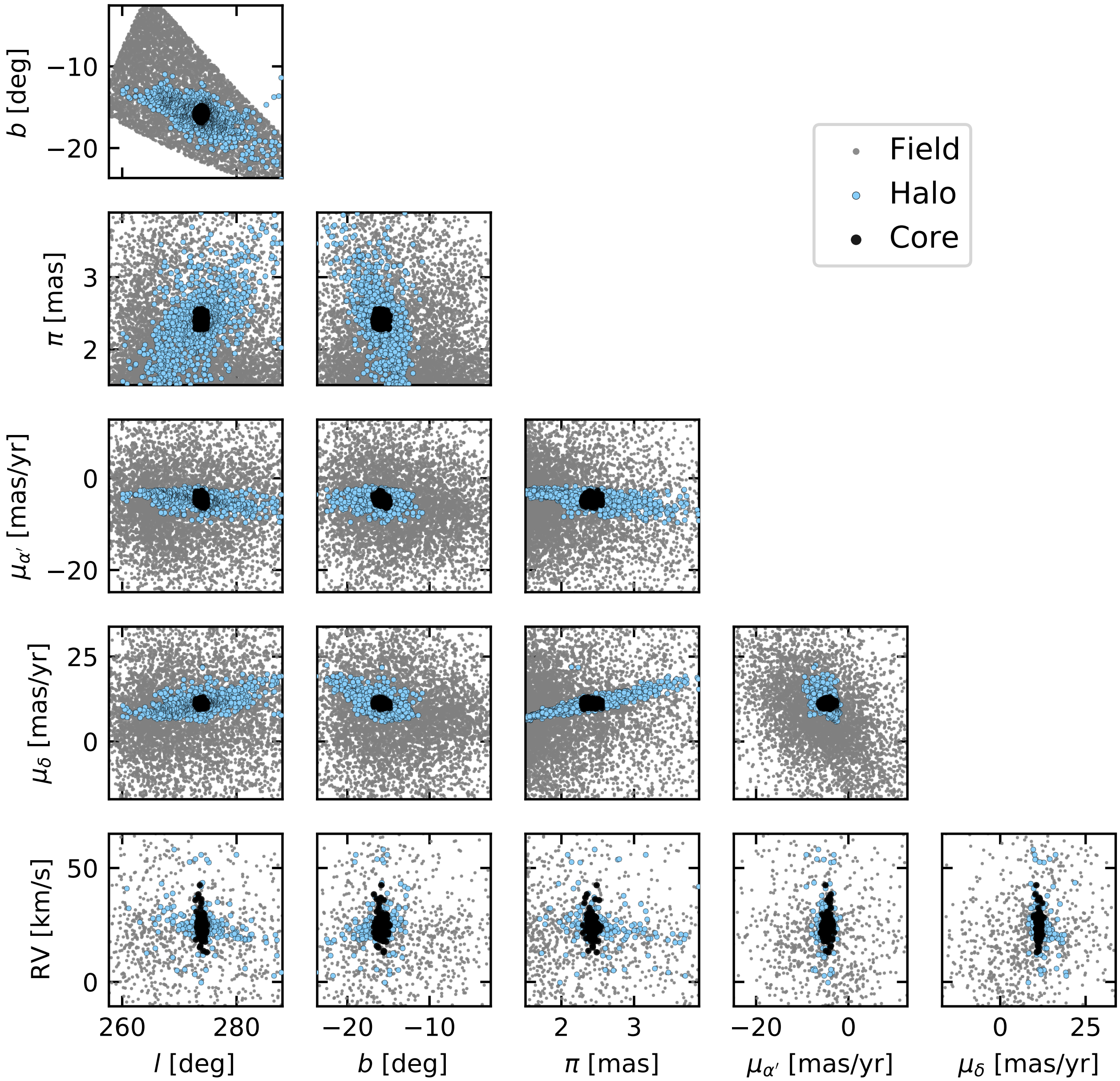

Figure 1. Reported components of NGC 2516 in position and velocity space. The "core", identified by Cantat-Gaudin et al. (2018) using Gaia DR2, is visually coincident with where you would think the cluster is if you looked at it through a pair of binoculars. The "halo" was identified by Kounkel & Covey (2019) using a less restrictive membership assignment algorithm (discussed in the appendices). The "field" is a set of randomly drawn and non-overlapping stars within a (α, δ, π) cone centered on the cluster.

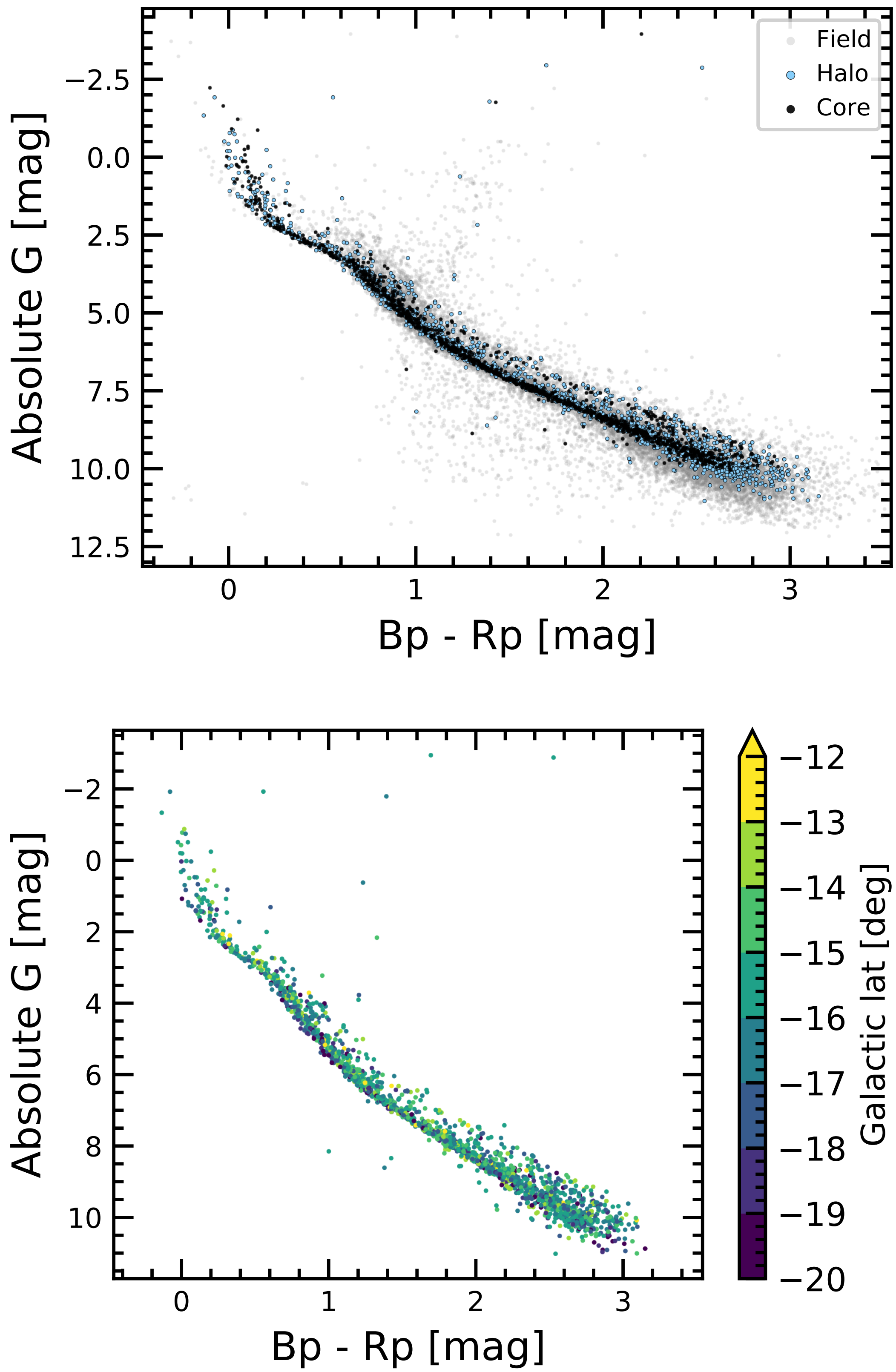

Figure 2. HR diagrams of NGC 2516, using Gaia EDR3 photometry. *Top:* The core (black) shows a clean sequence consistent with stars with a fixed age and metallicity, and varying mass. The halo (blue) is similar, but somewhat noisier. The faintest M dwarfs in the core and halo are brighter than in the field star comparison sample (gray), consistent with these stars having not yet reached the ZAMS. *Bottom:* Reported members of the halo, as a function of galactic latitude. Can the additional scatter in the halo be understood through differential reddening? **Maybe**.

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APPENDIX

A. CLUSTERING METHOD DETAILS

Cantat-Gaudin et al. (2018) applied a procedure that ultimately yielded what we call "the core". Their procedure was to first query a Gaia DR2 cone around the previously reported RA and dec of the cluster, and within ± 0.5 mas of its previously reported distance. The outer radius of their cone was either r2 from MWSC (CITE Kharchenko 2013), or twice the "cluster radius" listed by Dias. No proper motion cut was applied. They then applied an unsupervised classification scheme called UPMASK to $G < 18$ mag stars within this cone (CITE). The steps of UPMASK are first to perform a k-means clustering in the "astrometric space" $(\mu_{\alpha'}, \mu_\delta, \pi)$. Then, a "veto" step is applied to assess whether the groups of stars output from the k-means clustering are or are not more concentrated than a random distribution. This is implemented by "comparing the total branch length of the minimum spanning tree connecting the stars with the expected branch length for a random uniform distribution covering the investigated field of view". "To turn this yes/no flag to a membership probability, Cantat-Gaudin et al. (2018) then redraw new values of $(\mu_{\alpha'}, \mu_\delta, \pi)$ for each source based on the listed value, uncertainty, and covariance. After a certain number of redrawings, the final probability is the frequency with which a given star passes the veto". In the case of NGC 2516, this yielded a reported "`r50`" within which half of the cluster members were found to be within 0.496°.

Kounkel & Covey (2019) applied a different unsupervised clustering method to the 5-dimensional Gaia DR2 data (omitting radial velocities, due to their sparsity). Their selection function (see their Section 2) yielded $\approx 2 \times 10^7$ stars, mostly within ≈ 1 kpc and typically with $G < 18$ mag. Their clustering algorithm was the "hierarchical density-based spatial clustering of applications with noise" (HDBSCAN, CITE McInnes17). The classical DBSCAN algorithm "identifies clusters as overdensities in a multi-dimensional space in which the number of sources exceeds the required minimum number of points within a neighborhood of a particular linking length ϵ. HDBSCAN does not depend on ϵ; instead it condenses the minimum spanning tree by pruning off the nodes that do not meet the minimum number of sources in a cluster and reanalyzing the nodes that do. Depending on the chosen algorithm, it would then either find the most persistent structure (through the excess of mass method), or return clusters as the leaves of the tree (which results in somewhat more homogeneous clusters). In both cases it is more effective at finding structures of varying densities in a given data set than DBSCAN." " The two main parameters that control HDBSCAN are the number of sources in a cluster and the number of samples. The former is the parameter that rejects groupings that are too small; the latter sets the threshold of how conservative the algorithm is in its considerations of the background noise (even if the resulting noisy groupings do meet the minimum cluster size). By default, the sample size is set to the same value as the cluster size, but it is possible to adjust them separately."