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Age spread and sequential star formation in the young cluster NGC 2264

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Abstract. We investigate the structure and star formation history of the NGC 2264 cluster (3 Myr). We combine spectroscopic $T_{\rm eff}$ with multi-color photometry to derive homogeneous extinction and stellar parameters for 655 cluster members ($M_\star = 0.2 - 1.8\ M_\odot$). We infer an intrinsic age spread of ~4 Myr across the cluster. NGC 2264 members were born in the course of sequential star formation activity, which still continues in the most embedded regions of the cluster. We find evidence for photoevaporation effects driven by OB stars in the region that locally impact the timescales for disk evolution within the cluster.

1. Introduction

Young star clusters often exhibit a complex and hierarchical structure, with multiple subclusterings (e.g., Allen et al. 2007), and spatially and kinematically distinct subpopulations (e.g., Sacco et al. 2017). This suggests a “bottom-up” scenario for star cluster formation, where several subclusters form and evolve separately, and eventually merge.

If this scenario is correct, we would expect some age spread among cluster members. Individual stellar ages can be estimated via isochrone-fitting on a HR diagram; however, unrelated factors like accretion, surface spots, binarity, reddening, or model systematics, can yield uncertainties of several Myr on the age estimates for pre-main sequence (PMS) stars (e.g., Soderblom 2010).

2. The NGC 2264 cluster: Data

In this work, we explore the star formation history of NGC 2264 (distance ~ 760 pc, age ~ 3 Myr, $\langle A_V \rangle \sim 0.4$ mag). The cluster population comprises >1000 known members, with a disk fraction of ~50%. Between 2011 and 2013, NGC 2264 was targeted in two extensive observing programs: the *Gaia*-ESO Survey (GES; Randich et al. 2013) and the Coordinated Synoptic Investigation of NGC 2264 (CSI 2264; Cody et al. 2014.

GES This spectroscopic suvey, performed with VLT/FLAMES, covered 1892 objects in the NGC 2264 field. Data products include: effective temperatures $T_{\rm eff}$; Li equivalent widths EW(Li); EW(Hα) and W10%(Hα); spectral γ-index (Damiani et al. 2014), sensitive to stellar gravity.

CSI 2264 The backbone of the survey consisted in simultaneous photometric monitoring from X-rays to the mid-IR domain. Data products include accretion diagnostics (UV excess from CFHT/MegaCam photometry; Venuti et al. 2014 and disk signatures (IR excess from

Spitzer/IRAC observations). Our study focuses on 655 objects, selected from the combined GES+CSI 2264 dataset and classified as cluster members upon several diagnostics (EW(Li), Hα emission, UV/IR excess, X-ray emission, variability). The sample spans the mass range between 0.2 and 1.8 $M_\odot$; about one third of objects possess a disk.

3. Age spread in NGC 2264

We combined optical g,r,i photometry from CSI 2264 with spectroscopic $T_{\rm eff}$ estimates from GES to determine individual A_V and bolometric luminosities $L_{\rm bol}$ homogeneously across the sample (Venuti et al. 2018). We used the $T_{\rm eff}$ and $L_{\rm bol}$ parameters to construct the HR diagram of the cluster, and adopted PMS evolutionary models from Baraffe et al. (2015) to derive mass and age estimates for individual objects.

The NGC 2264 locus on the HR diagram exhibits a significant spread in $L_{\rm bol}$ at any $T_{\rm eff}$. A comparison with model isochrones suggests an average age of 3.6 Myr and an age spread of ∼10 Myr across the cluster. Although part of this dispersion may be contributed by observational uncertainties, the presence of some genuine age spread is supported by correlations between isochronal ages and independent, directly measurable stellar properties:

- objects with disks appear on average younger than objects without disks;
- younger objects statistically exhibit lower gravities than older objects (as assessed by running a two-sample K-S test).

Thus, objects classified as "younger" based on model isochrones statistically exhibit physical properties that coherently qualify them as "less evolved" with respect to "older" objects.

4. Star formation history of NGC 2264

As reported in previous studies (e.g., Sung et al. 2009), several subclusterings can be identified within NGC 2264. We find that the disk fraction is highest ($\gtrsim$50%) in the southern, innermost regions of the cluster, close to the Cone Nebula tip (Cone(C)), where the Spokes subcluster (Teixeira et al. 2006) is located. The disk fraction decreases to ∼30% toward the northern part of the cluster, around the O-type binary star S Mon, and to ∼20% toward the outer region of the cluster (Halo); these two regions together host >60% of the cluster population.

Disk-bearing objects in the Spokes and Cone(C) subregions are on average younger (∼1.5 Myr) than those in the S Mon and Halo regions of the cluster (∼3-4 Myr). This suggests that star formation activity was ignited in Spokes and Cone(C) later than in the S Mon region. At the same time, we observe a sudden drop in number of disk-bearing objects around S Mon after an age of ∼2.5 Myr. This behavior is qualitatively different from what observed elsewhere in the cluster. An analysis of the spatial distribution of NGC 2264 members as a function of age shows a clear dearth of disk-bearing objects within 1 parsec from the massive binary S Mon after an age of ∼2 Myr. We suggest that external photoevaporation induced by the FUV flux from S Mon, coupled with internal disk viscosity, may trigger rapid disk dissipation (a few Myr) in the vicinity of S Mon.

5. Conclusions

The median ages associated with young stars at different locations within the region indicate an age spread of ∼4 Myr among cluster members. NGC 2264 was assembled in the course of a sequential process, with multiple episodes of star formation taking place over ∼5 Myr. The star formation activity started in the northern regions of the cluster, close to S Mon, then propagated toward the Cone Nebula, where it is still ongoing in the most embedded areas. Massive stars in the region locally impact the timescales of early stellar evolution, via photoevaporation effects that favor rapid disk dissipation.

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