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A 30 Million Year Old Mini-Neptune in the Kepler Field

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ABSTRACT

The Gaia satellite is revitalizing our understanding of nearby open clusters and moving groups. Here, we focus on the underappreciated δ Lyr cluster. Based on rotation periods from TESS and lithium measurements from ground-based spectrographs, we find the age of the cluster to be $30 \pm XX$ Myr. Kepler 1627 is a binary system in the cluster, serendipitously observed by the Kepler satellite because the primary is nearby and Sun-like. Kepler 1627A was previously found to host a $3.7 \pm X.X\,R_\oplus$ mini-Neptune on a 7.2 day orbit. We re-validate the existence of Kepler 1627Ab, and cement it as the youngest planet with a well-measured age observed by the main Kepler mission. Newly derived ages from Gaia offer the opportunity to significantly expand the census of age-dated planets – we offer a literature compilation of young stars to enable this expansion. The properties of Kepler 1627Ab are may also help clarify how the orbits and atmospheres of the mini-Neptune planets evolve.

Keywords: planetary evolution (XXXX), stellar associations (1582), open star clusters (1160), stellar ages (1581),

1. INTRODUCTION

At the time of the main Kepler mission (2009–2013), only four open clusters were known in the Kepler field: NGC 6866, NGC 6811, NGC 6819, and NGC 6791, with ages spanning 0.7 Gyr to 9 Gyr (Meibom et al. 2011).

Section 2. Section 3. In Section 4, we discuss. Section 5 gives our conclusions.

2. FIRST

3. SECOND

4. DISCUSSION

5. CONCLUSION

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Software: `astrobase` (Bhatti et al. 2018), `astropy` (Astropy Collaboration et al. 2018), `astroquery` (Ginsburg et al. 2018), `corner` (Foreman-Mackey 2016), `exoplanet` (Foreman-Mackey et al. 2020), and its dependencies (Agol et al. 2020; Kipping 2013; Luger et al. 2019; Theano Development Team 2016), `IPython` (Pérez & Granger 2007), `matplotlib` (Hunter 2007), `numpy` (Walt et al. 2011), `pandas` (McKinney 2010), `PyMC3` (Salvatier et al. 2016), `scipy` (Jones et al. 2001), `TESS-point` (Burke et al. 2020), `wotan` (Hippke et al. 2019).

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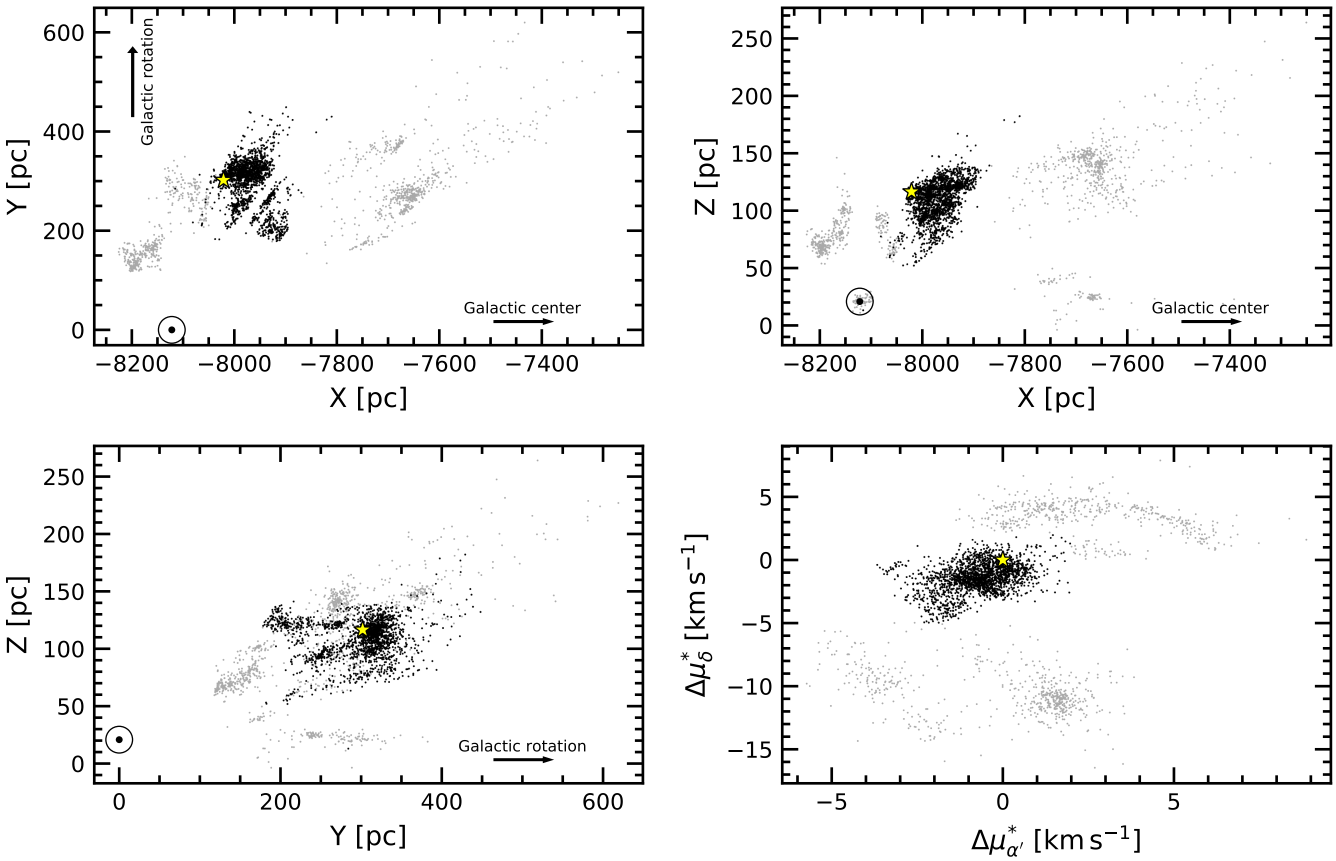

Figure 1. Galactic position and tangential velocities of the δ Lyr cluster (also known as Theia 73 and Stephenson 1). Points are candidate cluster members with $\varpi/\sigma_\varpi > 20$, reported to be in the group by Kounkel & Covey (2019). We focus on stars in a small region (black points) in the kinematic vicinity of Kepler 1627 (yellow star). The other candidate cluster members (gray points) may or may not share the ages of the selected kinematic group. The location of the Sun is ($\odot$) is shown.

Facilities: *Astrometry*: Gaia (Gaia Collaboration et al. 2018b, 2020). *Imaging*: Second Generation Digitized Sky Survey. *Spectroscopy*: CTIO1.5 m (CHIRON; Tokovinin et al. 2013), AAT (HERMES; Lewis et al. 2002; Sheinis et al. 2015), VLT:Kueyen (FLAMES; Pasquini et al. 2002). *Photometry*: TESS (Ricker et al. 2015).

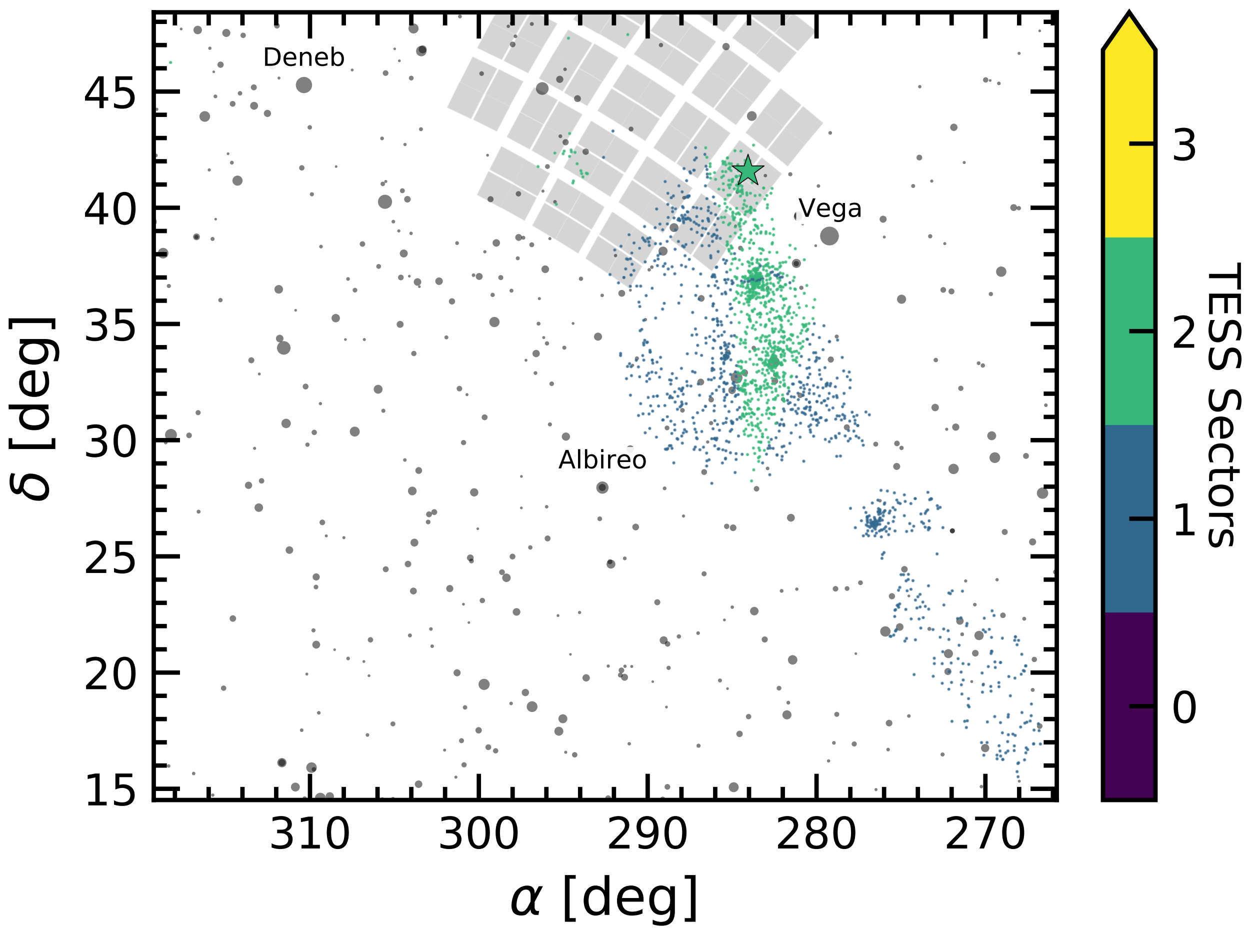

Figure 2. Kepler and TESS views of the δ Lyr cluster. Colored points are kinematically selected members of the δ Lyr cluster (black points in Figure 1). Both Kepler (gray panels) and TESS (colored points) observed members of the cluster. Gray points are naked-eye stars ($m_V < 6.5$), three of which are annotated. Kepler 1627 (green star) was observed for two TESS sectors, and during the entirety of the Kepler mission.

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Table 1. Provenances of Young and Age-Dateable Stars.

Reference	$N_{\rm Gaia}$	$N_{\rm Age}$	$N_{G_{\rm RP}<16}$
Kounkel et al. (2020)	987376	987376	775363
Cantat-Gaudin & Anders (2020)	433669	412671	269566
Cantat-Gaudin et al. (2018)	399654	381837	246067
Kounkel & Covey (2019)	288370	288370	229506
Cantat-Gaudin et al. (2020)	233369	227370	183974
Zari et al. (2018) UMS	86102	0	86102
Wenger et al. (2000) `Y*?`	61432	0	45076
Zari et al. (2018) PMS	43719	0	38435
Gaia Collaboration et al. (2018a) $d > 250$ pc	35506	31182	18830
Castro-Ginard et al. (2020)	33635	24834	31662
Wenger et al. (2000) `Y*O`	28406	0	16205
Villa Vélez et al. (2018)	14459	14459	13866
Cantat-Gaudin et al. (2019)	11843	11843	9246
Damiani et al. (2019) PMS	10839	10839	9901
Oh et al. (2017)	10379	0	10370
Meingast et al. (2021)	7925	7925	5878
Wenger et al. (2000) `pMS*`	5901	0	3006
Gaia Collaboration et al. (2018a) $d > 250$ pc	5378	817	3968
Kounkel et al. (2018)	5207	3740	5207
Ratzenböck et al. (2020)	4269	4269	2662
Wenger et al. (2000) `TT*`	4022	0	3344
Damiani et al. (2019) UMS	3598	3598	3598
Rizzuto et al. (2017)	3294	3294	2757
Akeson et al. (2013)	3107	868	3098
Tian (2020)	1989	1989	1394
Goldman et al. (2018)	1844	1844	1783
Cotten & Song (2016)	1695	0	1693
Gagné et al. (2018b)	1429	0	1389
Röser & Schilbach (2020) Psc-Eri	1387	1387	1107
Röser & Schilbach (2020) Pleiades	1245	1245	1019
Wenger et al. (2000) `TT?`	1198	0	853
Gagné & Faherty (2018)	914	0	913
Pavlidou et al. (2021)	913	913	504
Gagné et al. (2018a)	692	0	692
Ujjwal et al. (2020)	563	0	563
Gagné et al. (2020)	566	566	351
Esplin & Luhman (2019)	377	443	296
Roccatagliata et al. (2020)	283	283	232
Meingast & Alves (2019)	238	238	238
Fürnkranz et al. (2019) Coma-Ber	214	214	213
Fürnkranz et al. (2019) Neighbor Group	177	177	167
Kraus et al. (2014)	145	145	145

NOTE— Table 1 describes the provenances for the young and age-dateable stars in Table **??**. $N_{\rm Gaia}$: number of Gaia stars we parsed from the literature source. $N_{\rm Age}$: number of stars in the literature source with ages reported. $N_{G_{\rm RP}<16}$: number of Gaia stars we parsed from the literature source with either $G_{\rm RP} < 16$, or a parallax S/N exceeding 5 and a distance closer than 100 pc. The latter criterion included a few hundred white dwarfs that would have otherwise been neglected. Some studies appear multiple times when multiple tables from the analysis were included in the concatenation.

APPENDIX

A. YOUNG, AGE-DATED, AND AGE-DATEABLE STAR COMPILATION

The `v0.5` CDIPS target catalog includes some important updates from previous versions. As in Bouma et al. (2019), we collected membership information for young, age-dated, or age-dateable stars from across the literature. Table 1 gives a list of the sources included, and some brief summary statistics.

The first major important change is that the extent of analyses performed on the Gaia data at the time of our compilation was wide and deep enough that we opted to neglect pre-Gaia analyses, except in cases for which spectroscopically confirmed samples of stars had been collected. The membership lists for instance of Kharchenko et al. (2013) and Dias et al. (2014) (MWSC and DAML) were no longer required, especially given their relatively high field-star contamination rates compared to Gaia-derived membership catalogs.

For any of the catalogs for which Gaia DR2 identifiers were not immediately available, we either followed the spatial (plus proper-motion) crossmatching procedures described in Bouma et al. (2019), or else we pulled the Gaia DR2 source identifiers associated with the catalog from SIMBAD. We consequently opted to drop the `ext_catalog_name` and `dist` columns maintained in Bouma et al. (2019), as these were only populated for a small number of stars.

The most crucial parameters of a given star for our purposes are the Gaia DR2 source identifier (`source_id`), the cluster name (`cluster`), and the (`age`). Given the hierarchical nature of many stellar associations, we do not attempt to resolve the cluster names to a single unique string. The Orion complex for instance, can be divided into almost one hundred kinematic subgroups (Kounkel et al. 2018). Similar complexity applies to the problem of determining homogeneous ages, which we do not attempt to resolve. Instead, we simply merged the cluster names and ages reported by various authors together.

This means that our "age" column can be null, for cases in which the original authors did not report an age, and a reference literature age was not readily available. Nonetheless, since we do generally prefer stars with known ages, we made a few additional efforts to populate this column. When available, the age provenance is from the original analysis of the cluster. However, in a few cases we adopted other ages when the string-based crossmatches on the "cluster" name was straightforward. In particular, we used the ages determined by Cantat-Gaudin et al. (2020) to assign ages to the catalogs from Gaia Collaboration et al. (2018a), Cantat-Gaudin et al. (2018), Castro-Ginard et al. (2020), and Cantat-Gaudin & Anders (2020).

The catalogs we included for which ages were not immediately available were those of Cotten & Song (2016), Oh et al. (2017), Zari et al. (2018), Gagné et al. (2018b), Gagné et al. (2018a),Gagné & Faherty (2018), and Ujjwal et al. (2020). While in principle the moving group members discussed by Gagné et al. (2018b,a); Gagné & Faherty (2018) and Ujjwal et al. (2020) have easily associated ages, our SIMBAD cross-matching lost the moving group association from those studies, which should therefore be recovered tools such as BANYAN Σ.[1]. We also included the SIMBAD object identifiers `TT⋆`, `Y⋆O`,`Y⋆?`, `TT?`, and `pMS⋆`. Finally, we also included every star in the NASA Exoplanet Archive `ps` table that had a Gaia identifier available (Akeson et al. 2013). If the age had finite uncertainties, we also included it, since stellar ages determined through the combination of isochrone-fitting and transit-derived stellar densities typically have higher precision than from isochrones alone.

The technical manipulations for the merging, cleaning, and joining were performed using `pandas` (McKinney 2010). The eventual crossmatch (using the Gaia DR2 `source_id`) against the Gaia DR2 archive was performed asychronously on the Gaia archive website[2].

[1] http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php

[2] https://gea.esac.esa.int/archive/