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Three 40 Million Year Old Mini-Neptunes from Kepler, TESS, and Gaia

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ABSTRACT

Stellar positions and velocities from Gaia are yielding a new and refined view of how stellar clusters evolve. Here we present an analysis of a group of ≈40 million year old stars spanning Cepheus ($l = 100°$) to Hercules ($l = 40°$), hereafter the Cep-Her complex. The group includes four known Kepler Objects of Interest: Kepler-1627 Ab ($R_p = 3.85 \pm 0.11\,R_\oplus$, $P = 7.2$ days), Kepler-1643 b ($R_p = 2.32 \pm 0.14\,R_\oplus$, $P = 5.3$ days), KOI-7368 b ($R_p = 2.22 \pm 0.12\,R_\oplus$, $P = 6.8$ days), and KOI-7913 Ab ($R_p = 2.34 \pm 0.18\,R_\oplus$, $P = 24.2$ days). Kepler-1627 is a Neptune-sized planet in a sub-component of the complex called the δ Lyr cluster (Bouma et al. 2022). Here we focus on the latter three systems, which are in other sub-components of the complex (RSG-5 and CH-2). Based on kinematic evidence from Gaia, stellar rotation periods from TESS, and spectroscopy, these three systems are also ≈40 million years old. More specifically, we find that Kepler-1643 (in RSG-5) is 46^{+9}_{-7} Myr old, while KOI-7368 and KOI-7913 (in CH-2) are 36^{+10}_{-8} Myr old. Based on the transit shapes and high resolution imaging, they are all most likely planets, with false positive probabilities of 6×10^{-9}, 5×10^{-3}, and 1×10^{-4} for Kepler-1643, KOI-7368, and KOI-7913 respectively. These planets are therefore the first empirical demonstration that mini-Neptunes with sizes of ≈2 Earth radii exist at ages of ≈40 million years.

Keywords: exoplanet evolution (491), open star clusters (1160), stellar ages (1581)

1. INTRODUCTION

The discovery and characterization of transiting planets younger than a billion years is a major frontier in current exoplanet research. The reason is that the properties of young planets provide benchmarks for studies of planetary evolution. For instance, there are the questions of when hot Jupiters arrive on their close-in orbits (Dawson & Johnson 2018), how the sizes of planets with massive gaseous envelopes evolve (Rizzuto et al. 2020), when and if close-in multiplanet systems fall out of resonance (Arevalo et al. 2022; Goldberg & Batygin 2022), and whether and how mass-loss explains the radius valley (Lopez et al. 2012; Owen & Wu 2013; Fulton et al. 2017; Ginzburg et al. 2018; Lee & Connors 2021).

The discovery of a young planet requires two claims to be fulfilled: the planet must exist, and its age must be secured. Spaced-based photometry from K2 and TESS has yielded a number of young planets for which the planetary evidence comes from transits, and the age evidence is based on either cluster membership (Mann et al. 2017; David et al. 2019; Newton et al. 2019; Bouma et al. 2020; Nardiello et al. 2020) or else on correlates of youth such as stellar rotation, photospheric lithium abundances, x-ray activity, or emission line strength (Zhou et al. 2021; Hedges et al. 2021).

In this work, we leverage recent analyses of the Gaia data, which have greatly expanded our knowledge of stellar group memberships (*e.g.*, Cantat-Gaudin et al. 2018; Kounkel & Covey 2019; Kerr et al. 2021). To date these analyses have

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mostly clustered on the stellar positions and on-sky velocities measured by Gaia, with varying degrees of filtering and supervision. One important result is the identification of diffuse streams and tidal tails comparable in stellar mass to the previously known cores of nearby open clusters (Meingast et al. 2019; Meingast et al. 2021; Gagné et al. 2021). These spatially diffuse groups typically have velocity dispersions of $\approx 1\,\mathrm{km\,s^{-1}}$, though they can be much higher due to both projection effects and internal dynamics. As an extreme example, in the Hyades the velocities of stars in the tidal tails are thought to span up to $\pm 40\,\mathrm{km\,s^{-1}}$ relative to the cluster center (Jerabkova et al. 2021). The stars in such diffuse regions can be verified to be the same age as the core members (*i.e.*, coeval) through analyses of color-absolute magnitude diagrams, stellar rotation periods (Curtis et al. 2019; Bouma et al. 2021), and chemical abundances (Hawkins et al. 2020). While there are many implications for our understanding of star formation and cluster evolution (Dinnbier & Kroupa 2020), a more immediate consequence is that we now know the ages of many more stars, including previously known planet hosts.

The prime Kepler mission (Borucki et al. 2010) found most of the currently known transiting exoplanets, and it was conducted before Gaia. It therefore seems sensible to revisit the Kepler field, given our new knowlege of the stellar ages.

In this work, we expand on our previous study of a 38^{+7}_{-6} million year old Neptune-sized planet in the Kepler field (Kepler-1627 Ab; Bouma et al. 2022). The age of this planet was derived based on its host star's membership in the δ Lyr cluster. Our analysis of the cluster focused on the immediate spatial and kinematic vicinity of Kepler-1627 A in order to confirm the age of the planet. However it became clear that the δ Lyr cluster seems to also be part of a much larger group of similarly aged stars. This group, which is at a distance of $\sim$330 parsecs from the Sun, appears to span Cepheus to Hercules (galactic longitudes, l, between 40° and 100°), at galactic latitudes roughly between 0° and 20°. We therefore refer to it as the Cep-Her complex. It exhibits significant substructure over its $\approx$250 parsec length, and a detailed analysis of its memberships, kinematics, and possible origin is currently being prepared by R. Kerr and collaborators.

Here, our focus is on the intersection of the Cep-Her complex with the Kepler field. Cross-matching the full set of candidate Cep-Her members against known Kepler Objects of Interest (KOIs) (Thompson et al. 2018) yielded four candidate cluster members: Kepler-1627, Kepler-1643, KOI-7368, and KOI-7913. Given our previous analysis of Kepler-1627, we will mostly focus on the latter three. After analyzing the relevant properties of Cep-Her (Section 2), we discuss the stellar properties (Section 3) and validate the planetary nature of each system using a combination of the Kepler photometry and high-resolution imaging (Section 4). We conclude with a discussion of implications for the size-evolution of close-in mini-Neptunes (Section 5).

2. THE CEP-HER COMPLEX

2.1. *Previous Related Work*

Our focus is on a region of the Galaxy approximately 200 to 500 parsecs from the Sun, above the galactic plane, and spanning galactic longitudes of roughly 40° to 100° degrees. Two rich clusters in this region are the δ Lyra cluster (Stephenson 1959) and RSG-5 (Röser et al. 2016). Each of these clusters was known before Gaia. They have reported ages between $\approx$30 and $\approx$60 million years. Early empirical evidence that these two clusters could be part of a large and more diffuse population was apparent in the Gaia-based photometric analysis of pre-main-sequence stars by Zari et al. (2018, see their Figures 11 and 13). Further kinematic connections and complexity were highlighted by Kounkel & Covey (2019), who included these previously known groups in the larger structures dubbed "Theia 73" and "Theia 96"[1]. The connection made by Kounkel & Covey (2019) between the previously known open clusters and the other groups in the region was made as part of an unsupervised clustering analysis of the Gaia DR2 positions and tangential velocities with a subsequent manual "stitching" step, and generally supports the idea that there is an overdensity of $\approx$30 and $\approx$60 million year old stars in this region of the Galaxy. Kerr et al. (2021), in a volume-limited analysis of the Gaia DR2 point-source catalog out to one third of a kiloparsec, identified three of the nearest sub-populations, dubbed "Cepheus-Cygnus", "Lyra", and "Cerberus". Kerr et al. (2021) reported ages for each of these subgroups between 30 and 35 million years.

2.2. *Member Selection*

The possibility that the δ Lyr cluster, RSG-5, and the sub-populations identified by Kerr et al. (2021) share a common origin has yet to be fully substantiated, and will be the subject of the upcoming study by R. Kerr and collaborators. Our primary interest in the region stems from the fact that a portion of it was observed by Kepler (Figure 1, top panel). To further explore the population of stars that were observed, we select candidate Cep-Her members through four steps, the first three being identical to those described in Section 3 of Kerr et al. (2021). We briefly summarize them here.

The first step is to select stars that are photometrically distinct from the field star population based on Gaia EDR3 magnitudes $\{G, G_{\rm RP}, G_{\rm BP}\}$, parallaxes and auxiliary reddening estimates (Lallement et al. 2019). This step yielded 1097 stars with high-quality photometric and astrometry, which are either pre-main-sequence K and M dwarfs due to their

[1] See their visualization online at http://mkounkel.com/mw3d/mw2d.html (accessed 15 March 2022)

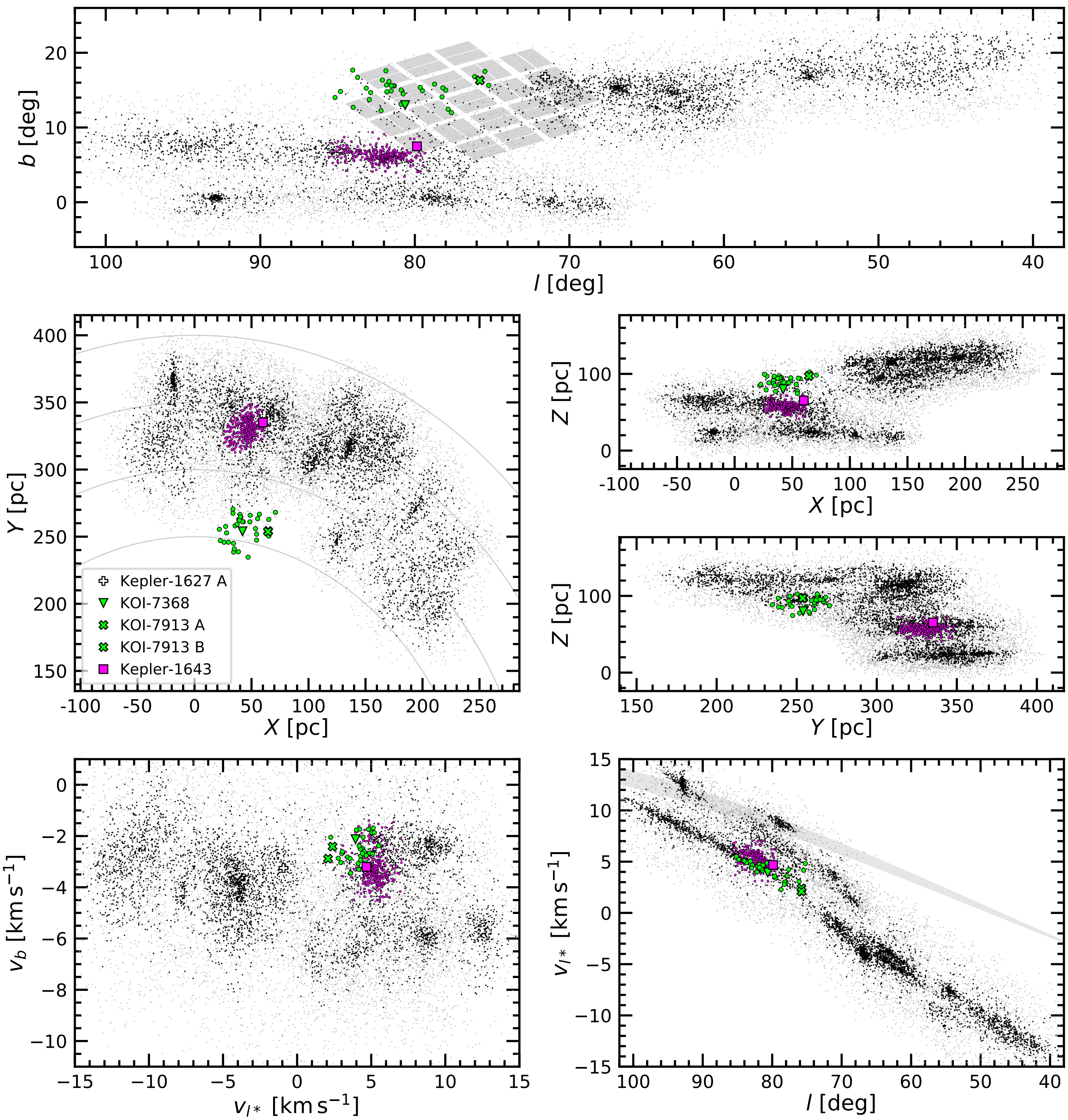

Figure 1. Positions and velocities of candidate members of the Cep-Her complex. *Top row*: On-sky positions in galactic coordinates. Black points are stars for which group membership is more secure than for gray points (see Section 2.2). Kepler-1627 is in the outskirts of the δ Lyr cluster (Bouma et al. 2022), which is centered at $\{l, b\} \approx \{66°, 12°\}$. *Middle row*: Galactic positions. The Sun is at $\{X, Y, Z\} = \{0, 0, 20.8\}$ pc; lines of constant heliocentric distance are shown between 250 and 400 pc, spaced by 50 pc. *Bottom row*: Galactic tangential velocities (left) and longitudinal tangential velocity versus galactic latitude (right). The gray band in the lower-right shows the ± 1-σ projection of the Solar velocity with respect to the local standard of rest. There is a strong spatial and kinematic overlap between Kepler-1643 and RSG-5 ($\{l, b\} \approx \{82°, 6°\}$; $\{X, Y, Z\} \approx \{60, 330, 50\}$ pc). The local population of candidate young stars around KOI-7368 and KOI-7913 is more diffuse – we call this region "CH-2". The **interactive figure** enables a few different cuts to be shown.

long contraction timescales, or massive stars near the zero-age main sequence due to their rapid evolutionary timescales.

The second step is to perform in an unsupervised HDB-Scan clustering on the photometrically selected population (Campello et al. 2015; McInnes et al. 2017). The parameters we use in this clustering analysis are $\{X,Y,Z,cv_b,cv_{l^*}\}$, where c is the size-velocity corrective factor, which is taken as $c = 6\,\mathrm{pc}/\mathrm{km\,s^{-1}}$ to ensure that the spatial and velocity scales have identical standard deviations. Positions are computed assuming the `astropy v4.0` coordinate standard (Astropy Collaboration et al. 2018), which places the Sun 8122 pc from the galactic center, and assumes the solar velocity with respect to the local standard of rest from Schönrich et al. (2010). As input parameters to HDBScan, we set the minimum ϵ threshold past which clusters cannot be fragmented as 25 parsecs in physical space, and c $\mathrm{km\,s^{-1}}$ in velocity. The minimum cluster size N is set to 10, as is k, the parameter used to define the "core distance" density metric.

This unsupervised clustering in our case yielded 8 distinct groups. These groups are then used as the "seed" populations for the third step, which is to search for objects at least as close to the 10th nearest HDBSCAN-identified member in space-velocity coordinates. This third step yields stars that are spatially and kinematically close to the photometrically-young stars, but which cannot be identified as young based on their positions in color versus absolute magnitude.

The outcome of the analysis up to the point of the third step is shown in Figure 1. To enable a selection cut that filters out field-star contaminants, we also compute a weight metric, defined such that the group member with the smallest core distance has a weight of 1, the group member with the greatest core distance has a weight of 0, and weights for the other group members are log-normally distributed between these two extremes. In Figure 1, we show 12,436 objects with weight exceeding 0.02 as gray points, and overplot 4,763 objects with weights exceeding 0.10 as black points.[2] The previously known δ Lyr cluster ($l,b = 68^\circ, 15^\circ$; $v_{l'}, v_b = -4.5\,\mathrm{km\,s^{-1}}, -4\,\mathrm{km\,s^{-1}}$) is visible, as is RSG-5 ($l,b = 83^\circ, 6^\circ$; $v_{l'}, v_b = 5.5\,\mathrm{km\,s^{-1}}, -3.5\,\mathrm{km\,s^{-1}}$). Most of the other subclusters, including in Cep-Cyg ($l,b = 90^\circ, 7^\circ$) and Cerberus ($l,b = 48^\circ, 18^\circ$) are too small or dispersed to have previously been analyzed in great detail.

The fourth and final step was to cross-match our candidate Cep-Her member list against all known Kepler Objects of Interest. We used the Cumulative KOI table from the NASA Exoplanet Archive from 27 March 2022, and also compared against the `q1_q17_dr25` table (Thompson et al. 2018). From the candidate members with weights exceeding 0.02, this yielded yielded 25 matches, of which 11 were known false positives, 6 were designated "confirmed", and 8 were designated "candidates". Inspection of the Kepler data validation summaries and Robovetter classifications for these objects then showed whether they were potentially consistent with being *i)* planets, and *ii)* $\lesssim 10^8$ years old, based on the presence of rotational modulation at the expected period and amplitude (*e.g.*, Rebull et al. 2020, Figure 9). Four objects remained after this inspection: Kepler-1627, Kepler-1643, KOI-7368, and KOI-7913.

Figure 1 shows the positions of the KOIs along various projections. Kepler-1643 is near the core RSG-5 population both spatially and kinematically. KOI-7368 and KOI-7913 are in a diffuse region $\approx$40 parsecs above RSG-5 in Z and $\approx$100 parsecs closer to the Sun in Y. In tangential galactic velocity space, there may be some kinematic overlap between the region the latter two KOIs are in, and the main RSG-5 group.

We define two sets of stars in the local vicinity of our objects of interest. For candidate RSG-5 members, we require:

$$\begin{aligned}
X/\mathrm{pc} &\in [45, 75] \\
Y/\mathrm{pc} &\in [320, 350] \\
Z/\mathrm{pc} &\in [40, 70] \\
v_b/\mathrm{km\,s^{-1}} &\in [-4, -3] \\
v_{l^*}/\mathrm{km\,s^{-1}} &\in [4, 6]
\end{aligned}$$

For the diffuse stars near KOI-7368 and KOI-7913, we require

$$\begin{aligned}
X/\mathrm{pc} &\in [20, 70] \\
Y/\mathrm{pc} &\in [230, 270] \\
Z/\mathrm{pc} &\in [75, 105] \\
v_b/\mathrm{km\,s^{-1}} &\in [-3.5, -1.5] \\
v_{l^*}/\mathrm{km\,s^{-1}} &\in [2, 6]
\end{aligned}$$

and we call this latter set of stars "CH-2". These cuts yield 141 candidate RSG-5 members, and 37 candidate CH-2 members. An important consideration, especially for CH-2, is the contamination rate by field stars. We assess this in the following section.

2.3. *The Cluster's Age*

2.3.1. *Color-Absolute Magnitude Diagram*

Color-absolute magnitude diagrams (CAMDs) of the candidate RSG-5 and CH-2 members are shown in the upper row of Figure 2. The stars from the δ Lyr cluster are from Bouma et al. (2022), and the field stars are from the Gaia EDR3 Catalog of Nearby Stars (Gaia Collaboration et al. 2021b). To make these diagrams, we imposed the data filtering criteria from Gaia Collaboration et al. (2018a, Appendix B), which are designed to include binaries while omitting instrumental

[2] These counts only include objects with reliable astrometry and photometry: $\varpi/\sigma_\varpi > 5$; $G/\sigma_G > 50$; $G_{\rm RP}/\sigma_{G_{RP}} > 20$; $G_{\rm BP}/\sigma_{G_{BP}} > 20$.

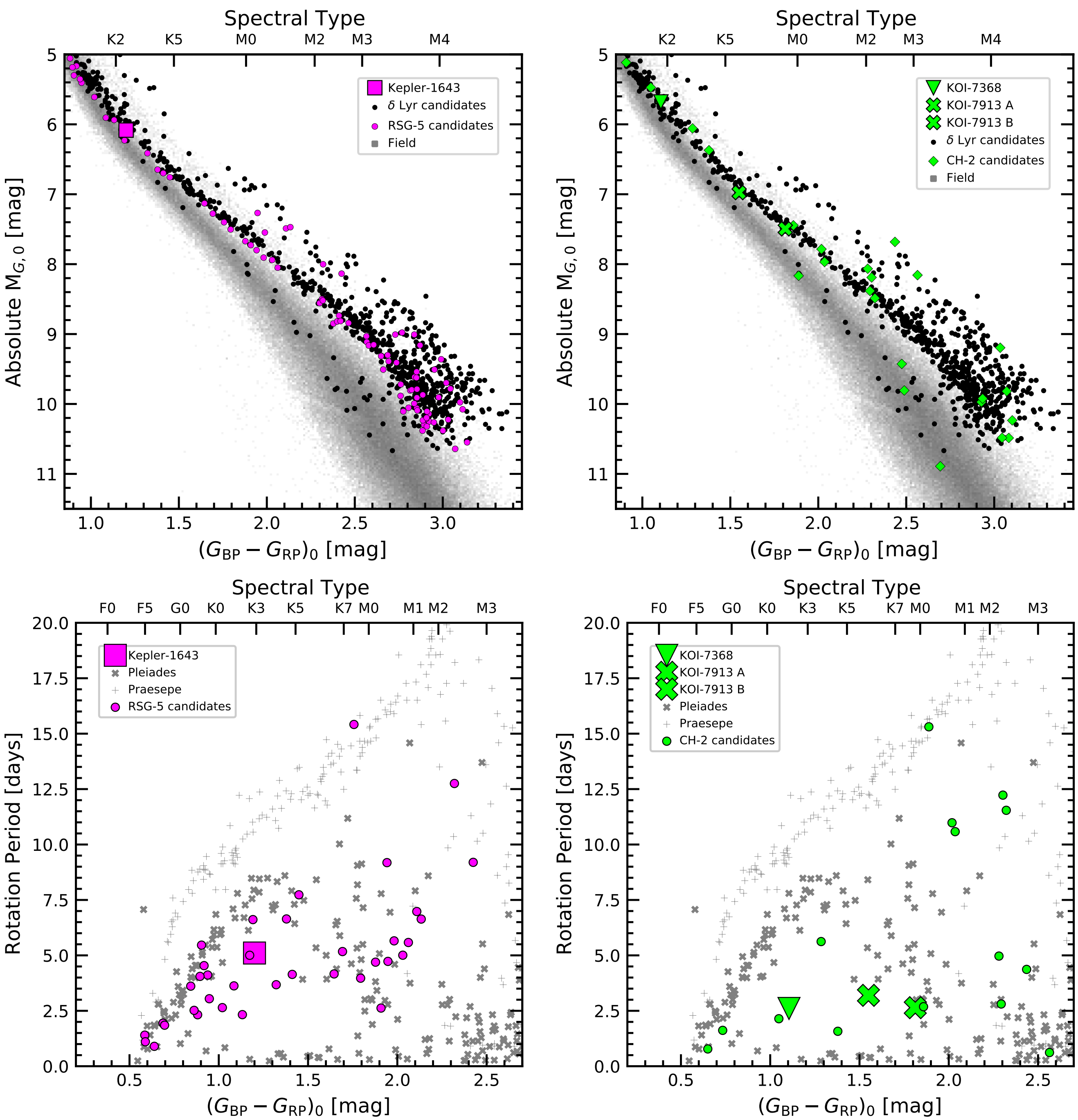

Figure 2. The stellar groups near KOI-7368, KOI-7913, and Kepler-1643 are ≈40 million years old. *Top row*: Color-absolute magnitude diagram of candidate Cep-Her members, in addition to candidate members of the δ Lyr cluster (≈ 38 Myr; Bouma et al. 2022) and and the Gaia EDR3 Catalog of Nearby Stars (gray background). The left and right columns shows stars in RSG-5 and CH-2, respectively. The range of colors is truncated to emphasize the pre-main-sequence. *Bottom row*: TESS and ZTF-derived stellar rotation periods, with the Pleiades (≈ 112 Myr) and Praesepe (≈ 650 Myr) shown for reference (Rebull et al. 2016; Douglas et al. 2017). The detection efficiency for reliable rotation periods falls off beyond $(G_{BP}-G_{RP})_0 \gtrsim 2.6$.

artifacts from for instance low photometric signal to noise, or a small number of visibility periods. We then corrected for extinction using the Lallement et al. (2018)[3] dust maps and the extinction coefficients $k_X \equiv A_X/A_0$ from Gaia Collaboration et al. (2018a), assuming that $A_0 = 3.1E(B-V)$. This yielded a mean and standard deviation for the reddening of $E(B-V) = 0.036 \pm 0.002$ for RSG-5, and $E(B-V) = 0.017 \pm 0.001$ for CH-2. By way of comparison, in Bouma et al. (2022) the same query for the δ Lyr cluster yielded $E(B-V) = 0.032 \pm 0.006$. Finally, for the plots we set the $(G_{\rm BP}-G_{\rm RP})_0$ color range to best visualize the region of maximal age information content: the pre-main-sequence.

The CAMDs show that for RSG-5, our membership selection gives stars that photometrically seem to almost all be on a tight pre-main-sequence locus. This implies a false positive rate of a few percent, at most. By comparison, our control sample (the δ Lyr candidates) has a false positive rate of $\approx$12%, based on the number of stars that photometrically appear to be more consistent with the field population than the bulk cluster population. For CH-2, our membership selection gives 27 objects in the color range displayed, and 23 of them appear to be consistent with being on the pre-main-sequence. This implies a false positive rate of $\approx$15%.

In addition, Figure 2 shows that the candidate RSG-5 and CH-2 members overlap with the δ Lyr cluster, and are therefore roughly the same age. To quantify this, we use the empirical method introduced by Gagné et al. (2020, see their Section 6.3). This idea of the method is to fit the pre-main-sequence loci of a set of reference clusters, and to then model the locus of the target cluster as a linear combination of these reference cluster loci. For our reference clusters, we used UCL, IC 2602, and the Pleiades, from the memberships reported by Damiani et al. (2019) and Cantat-Gaudin et al. (2018) respectively. We adopted ages of 16 Myr for UCL (Pecaut & Mamajek 2016), 38 Myr for IC 2602[4], and 112 Myr for the Pleiades (Dahm 2015). These assumptions and the consequent processing steps taken to exclude field stars as well as photometric and astrometric binaries were identical to those described in Bouma et al. (2022). The mean and standard deviation of the resulting age posterior are 46^{+9}_{-7} Myr for RSG-5, and 36^{+10}_{-8} Myr for CH-2. For comparison, the this procedure yields an age for the δ Lyr cluster of 38^{+6}_{-5} Myr. The slightly older isochronal age of RSG-5 is expected given that its locus is slightly bluer and less luminous in the upper left panel of Figure 2 relative to the δ Lyr cluster.

[3] https://stilism.obspm.fr/

[4] Ages for IC 2602 vary from 40 to 46 Myr based on lithium-depletion-boundary (LDB) measurements (Dobbie et al. 2010; Randich et al. 2018), and from 30 to 46 Myr based on isochronal analyses (Stauffer et al. 1997; David & Hillenbrand 2015; Bossini et al. 2019).

2.3.2. *Stellar Rotation Periods*

An independent way to assess the age of the candidate cluster members is to measure their stellar rotation periods. This approach can be achieved using surveys such as TESS (Ricker et al. 2015) and ZTF (Bellm et al. 2019), and it leverages a storied tradition of rotation period measurement for benchmark open clusters (see *e.g.*, Skumanich 1972; Curtis et al. 2020). The TESS data in our case are especially useful, since they provide 3 to 5 lunar months of photometry for all of our candidate CH-2 and RSG-5 members.

We selected stars suitable for gyrochronology by requiring $(G_{\rm BP}-G_{\rm RP})_0 \geq 0.5$ and $G < 16$. The latter cut corresponds to $(G_{\rm BP}-G_{\rm RP})_0 \lesssim 2.6$, at the relevant distances. These cuts gave 19 stars in CH-2 and 42 stars in RSG-5. We extracted light curves from the TESS images for these stars using the `unpopular` package (Hattori et al. 2021), and regressed them against systematics with its causal pixel model. **For the ZTF light curves, we used the default photometry? Ran aperture photometry on the image cutouts?**. We then measured candidate rotation periods using a Lomb-Scargle periodogram, and visually inspected them following the methods discussed in Curtis et al. (2020).

The lower panels of Figure 2 show the results. In RSG-5, 36/42 stars have rotation periods faster than the Pleiades (86%). This numerator omits the two stars with periods > 12 days visible in the lower-left panel of Figure 2. The age interpretation for these latter stars, particularly the $\approx$M2.5 dwarf, is not obvious. Rebull et al. (2018) for instance have found numerous M-dwarfs with 10-12 day rotation periods at ages of USco ($\sim$ 8 Myr), and some may still exist at ages of LCC ($\sim$ 16 Myr; L. Rebull in preparation). Regardless, given that nearly no field star outliers seem to be present on the RSG-5 CAMD, the fact that we do not detect rotation periods for $\approx$14% of stars should perhaps be taken as an indication for the fraction of stars for rotation periods might not be detectable, due to *e.g.*, pole-on stars having lower amplitude starspot modulation.

For CH-2, 13/19 stars have rotation periods that are obviously faster than their counterparts in the Pleiades (68%). 4 stars, not included in the preceding numerator, are M-dwarfs with rotation periods between 10 and 12.5 days. The age interpretation for these M-dwarfs is, as just discussed, not obvious. Regardless, the $\approx$15% false positive rate determined from the CAMD seems consistent with our fraction of detected rotation periods, given that RSG-5 was also missing rotation period detections for $\approx$15% of its candidate members, which all seemed photometrically consistent with being part of a single pre-main-sequence locus.

It is challenging to convert these stellar rotation periods to a precise age estimate, since on the pre-main-sequence the stars are spinning up due to thermal contraction rather than down due to magnetized braking. Regardless, the rotation period distributions of both CH-2 and RSG-5 seem consistent with other 30 Myr to 50 Myr clusters (*e.g.*, IC 2602 and IC 2391; Douglas et al. 2021). They also seem consistent with the false positive rate estimates determined from the color-absolute magnitude diagrams.

3. THE STARS

Some salient stellar parameters of the KOIs in Cep-Her can be gleaned by inspecting Figure 2. They span spectral types of G8V (Kepler-1627) to K8V (KOI-7913 A). The secondary in the KOI-7913 system is only marginally cooler than the primary. And since a Solar-mass star with solar metallicity arrives at the zero-age main sequence at $t \approx 40$ million years (Choi et al. 2016), these stars are all in the late stages of their pre-main-sequence contraction. Their heliocentric distances are ≈260 pc (KOI-7913 and KOI-7368, in CH-2) and ≈340 pc (Kepler-1643, in RSG-5).

The adopted stellar parameters are listed in Table 1. The stellar surface gravity, radius, mass, and density are found by interpolating against the MIST isochrones (Choi et al. 2016). The statistical uncertainties from this technique mostly originate from the parallax uncertaintes; the systematic uncertainties are taken to be the absolute difference between the PARSEC (Bressan et al. 2012) and MIST isochrones. Reported uncertainties are a quadrature sum of the statistical and systematic components.

To verify these parameters and to also analyze spectroscopic youth proxies such as the Li I 6708 Å doublet and Hα, we acquired spectra. We also acquired high resolution imaging for each system, to constrain the existence of visual companions, including possible bound binaries. The system-by-system details follow, and the the relevant results are also summarized in Table 1.

3.1. *Kepler 1643*

Spectra—For Kepler-1643, we acquired two iodine-free spectra from Keck/HIRES on the nights of 2020 August 16 and 2021 October 25. The acquisition and analysis followed the standard reduction techniques of the California Planet Survey (Howard et al. 2010). We derived the stellar parameters ($T_{\rm eff}, \log g, R_\star$) using `SpecMatch-Emp` (Yee et al. 2017), which yielded values in < 1-σ agreement with those from the cluster-isochrone approach. This approach also yielded [Fe/H] = 0.13 ± 0.09. Using the broadened synthetic templates from `SpecMatch-Synth` (Petigura et al. 2017), we found $v \sin i = 9.3 \pm 1.0$ km s^{-1}. The systemic radial velocity at the two sequence epochs was -9.1 ± 1.9 km s^{-1} and -7.8 ± 1.2 km s^{-1} respectively. To infer the equivalent width of the Li I 6708 Å doublet, we followed the procedure described by Bouma et al. (2021). This yielded a strong detection: EW$_{\rm Li}$ = 126^{+8}_{-4} mÅ, with values consistent at < 1-σ between the two epochs. The quoted value does not correct for the Fe I blend at 6707.44Å.

Table 1. Selected system parameters of Kepler-1643, KOI-7368, and KOI-7913.

Parameter	Value	68% Confidence Interval	Comment
Kepler-1643			
Stellar parameters:			
Gaia G [mag]	13.836	±0.003	A
$T_{\rm eff}$ [K]	4916	±110	B
$\log g_\star$ [cgs]	4.502	±0.035	C
$R_\star$ [R$_\odot$]	0.855	±0.044	C
$M_\star$ [M$_\odot$]	0.845	±0.025	C
$\rho_\star$ [g cm^{-3}]	1.910	±0.271	C
$P_{\rm rot}$ [days]	5.106	±0.044	D
Li EW [mÅ]	126	+8, −4	E
Transit parameters:			
P [days]	X	X	D
$R_{\rm p}/R_\star$	0.X	+0.X, −0.X	D
b	X	X	D
$R_{\rm p}$ [R$_\oplus$]	X	±0.X	D
t_{14} [hours]	X	X	D
KOI-7368			
Stellar parameters:			
Gaia G [mag]	12.831	±0.004	A
$T_{\rm eff}$ [K]	5241	±50	F
$\log g_\star$ [cgs]	4.499	±0.030	C
$R_\star$ [R$_\odot$]	0.876	±0.035	C
$M_\star$ [M$_\odot$]	0.879	±0.018	C
$\rho_\star$ [g cm^{-3}]	1.840	0.225	C
$P_{\rm rot}$ [days]	2.606	0.038	D
Li EW [mÅ]	X	X	B
Transit parameters:			
P [days]	X	X	D
$R_{\rm p}/R_\star$	0.X	+0.X, −0.X	D
b	X	X	D
$R_{\rm p}$ [R$_\oplus$]	X	±0.X	D
t_{14} [hours]	X	X	D
KOI-7913 A			
Stellar parameters:			
Gaia G [mag]	14.200	±0.003	A
$T_{\rm eff}$ [K]	4324	±70	B
$\log g_\star$ [cgs]	4.523	±0.043	C
$R_\star$ [R$_\odot$]	0.790	±0.049	C
$M_\star$ [M$_\odot$]	0.760	±0.025	C
$\rho_\star$ [g cm^{-3}]	2.172	±0.379	C
$P_{\rm rot}$ [days]	3.387	0.016	D
Li EW [mÅ]	X	X	B
$\Delta G_{\rm AB}$ [mag]	0.51	0.01	F
Apparent sep. [au]	959.4	1.9	F
Transit parameters:			
P [days]	X	X	D
$R_{\rm p}/R_\star$	0.X	+0.X, −0.X	D
b	X	X	D
$R_{\rm p}$ [R$_\oplus$]	X	±0.X	D
t_{14} [hours]	X	X	D

NOTE— (A) Gaia Collaboration et al. (2021a). (B) HIRES SpecMatch-Emp (Yee et al. 2017). (C) Cluster isochrone (Choi et al. 2016; Bressan et al. 2012). (D) Kepler light curve. The full set of transit parameters is given in CITE APPENDIX TABLE. (E) HIRES; this work. (F) TRES SPC (Buchhave et al. 2010; Bieryla et al. 2021). (G) Magnitude difference and physical distance between primary and secondary; from Gaia EDR3. (H) HIRES SpecMatch-Synth (Petigura et al. 2017).

High-Resolution Imaging—We acquired adaptive optics imaging of Kepler-1643 on the night of 2019 June 28 using the NIRC2 imager on Keck-II (PI: E. Petigura). Using the narrow camera (FOV = 10.2″), we obtained 4 images in the K' filter ($\lambda = 2.12\,\mu$m) with a total exposure time of 320 s. We analyzed these data following Kraus et al. (2016), and determined the detection limits to visual companions by analyzing the residuals after subtracting an empirical PSF template. This procedure yielded contrast limits of $\Delta K' = 4.1$ mag at $\rho = 150$ mas, $\Delta K' = 5.8$ mag at $\rho = 300$ mas, and $\Delta K' = 8.3$ mag at $\rho > 1000$ mas.

3.2. *KOI-7368*

Spectra—For KOI-7368, we acquired a spectrum on 2015 June 1 using the echelle spectrograph (TRES; Fűrész et al. 2008) mounted at the Tillinghast 1.5m at the Fred Lawrence Whipple Observatory on Mt. Hopkins, AZ. The stellar parameter classification pipeline for the TRES spectra has been described by Bieryla et al. (2021). It is based on the synthetic template library originally constructed by Buchhave et al. (2010). The resulting stellar parameters ($T_{\rm eff}, \log g, R_\star$) agreed with those from the cluster-isochrone method within 1-σ, though the effective temperature is more precise by a factor of three. Auxiliary spectroscopic parameters included the metallicity [Fe/H] = –0.02 ± 0.08, the equatorial velocity $v \sin i = 20.21 \pm 0.50\,{\rm km\,s^{-1}}$, and the systemic velocity ${\rm RV_{sys}} = -10.9 \pm 0.2\,{\rm km\,s^{-1}}$. The Li 6708Å EW measurement procedure yielded ${\rm EW_{Li}} = 236^{+16}_{-14}$ mÅ.

High-Resolution Imaging—We acquired adaptive optics imaging of KOI-7368 on the night of 2019 June 12 using the NIRC2 imager on Keck-II (PI: D. Huber). The observational configuration and reduction was identical as for Kepler-1643. No companions were detected, and the analysis of the image residuals yielded contrast limits of $\Delta K' = 5.2$ mag at $\rho = 150$ mas, $\Delta K' = 6.7$ mag at $\rho = 300$ mas, and $\Delta K' = 8.7$ mag at $\rho > 1000$ mas.

3.3. *KOI-7913*

Binarity—KOI-7913 appears to be a binary.[5] The north-west primary is ≈0.5 magnitudes brighter than the south-east secondary in optical passbands. The two stars are separated in Gaia EDR3 by 3.″54 on-sky, and have parallaxes consistent within 1-σ (with an average $\varpi = 3.66 \pm 0.01$ mas). This corresponds to an apparent on-sky separation of 959 ± 2 au. Gaia EDR3 quotes $(\mu_{\alpha'}, \mu_\delta) = (2.439 \pm 0.015, 1.009 \pm 0.016)\,{\rm mas\,yr^{-1}}$ for the primary, and $(\mu_{\alpha'}, \mu_\delta) = (2.696 \pm 0.020, 0.650 \pm 0.021)\,{\rm mas\,yr^{-1}}$ for the secondary. Since two stars were resolved in the Kepler Input Catalog and are roughly one Kepler pixel apart, an accurate crowding metric has already been applied in the NASA Ames data products to correct the mean flux level (Morris et al. 2017). This is important for deriving accurate transit depths.

[5] Relevant identifiers for the primary are KIC 8873450 = Gaia DR2/EDR3 2106235301785454208. For the secondary, they are KIC 8873448 = Gaia DR2/EDR3 2106235301785453824.

Spectra—We acquired Keck/HIRES spectra for KOI-7913 A on the night of 2021 Nov 13, and KOI-7913 B on the night of 2021 Oct 26. The usual `SpecMatch-Emp` (Yee et al. 2017) machinery yielded $T_{\rm eff,A} = 4324 \pm 70$ K, $T_{\rm eff,B} = 4038 \pm 70$ K. The remaining parameters were in agreement with those from the cluster isochrone. For the primary, we also found [Fe/H] = –0.06 ± 0.09, $v \sin i = 13.3 \pm 1.0\,{\rm km\,s^{-1}}$, and ${\rm RV_{sys}} = -17.8 \pm 1.1\,{\rm km\,s^{-1}}$. These same parameters for the secondary were [Fe/H] = –0.01 ± 0.09, $v \sin i = 10.7 \pm 1.0\,{\rm km\,s^{-1}}$, and ${\rm RV_{sys}} = -18.8 \pm 1.1\,{\rm km\,s^{-1}}$.

Regarding indicators of youth, the primary has a spectral type ≈K6V, while the secondary is ≈M0V. At ≈40 Myr, lithium 6708 Å absorption is not expected for the secondary, but might be present for the primary (*e.g.*, Soderblom et al. 2014, Figure 8). Conversely, Hα is expected to be in emission for for all M-dwarfs younger than ≈ 150 Myr (Kiman et al. 2021).

Turning to the actual data, we find **X for lithium**. For Hα, **we see Y**.

High-Resolution Imaging—We acquired adaptive optics imaging of KOI-7913 on the night of 2020 Aug 27 using the NIRC2 imager on Keck-II (PI: D. Huber). The observational configuration and reduction was identical as before. The images showed KOI-7913 A, KOI-7913 B, and an additional faint star ≈ 0.″99 due East of KOI-7913 B. Applying the PSF-fitting routines from Kraus et al. (2016), the tertiary star has a separation $\rho = 4397 \pm 3$ mas from the primary, at a position angle $231.17^\circ \pm 0.02^\circ$, with a $\Delta K' = 6.97 \pm 0.04$. While it is too faint to affect the interpretation of the KOI itself, it would be amusing if the faint neighbor were also comoving and young – at the age of the system, it would have a mass roughly between 10 and 15 $M_{\rm Jup}$. Additional imaging epochs will be required to tell.

4. THE PLANETS

4.1. *Kepler Data*

The Kepler space telescope observed Kepler-1643, KOI-7913, and KOI-7368 at a 30-minute cadence between May 2009 and April 2013. For all three systems quarters 1 through 17 were observed without any data gaps other than the usual quarterly roll. The top panel of Figure 3 shows a 50-day slice of the `PDCSAP` light curves for the three new Cep-Her candidates, along with Kepler-1627. In `PDCSAP`, nonastrophysical variability is removed through a cotrending approach that uses a set of basis vectors derived using singular value decomposition of a set of systematics-dominated stellar light curves (Smith et al. 2017). In our analysis, we used

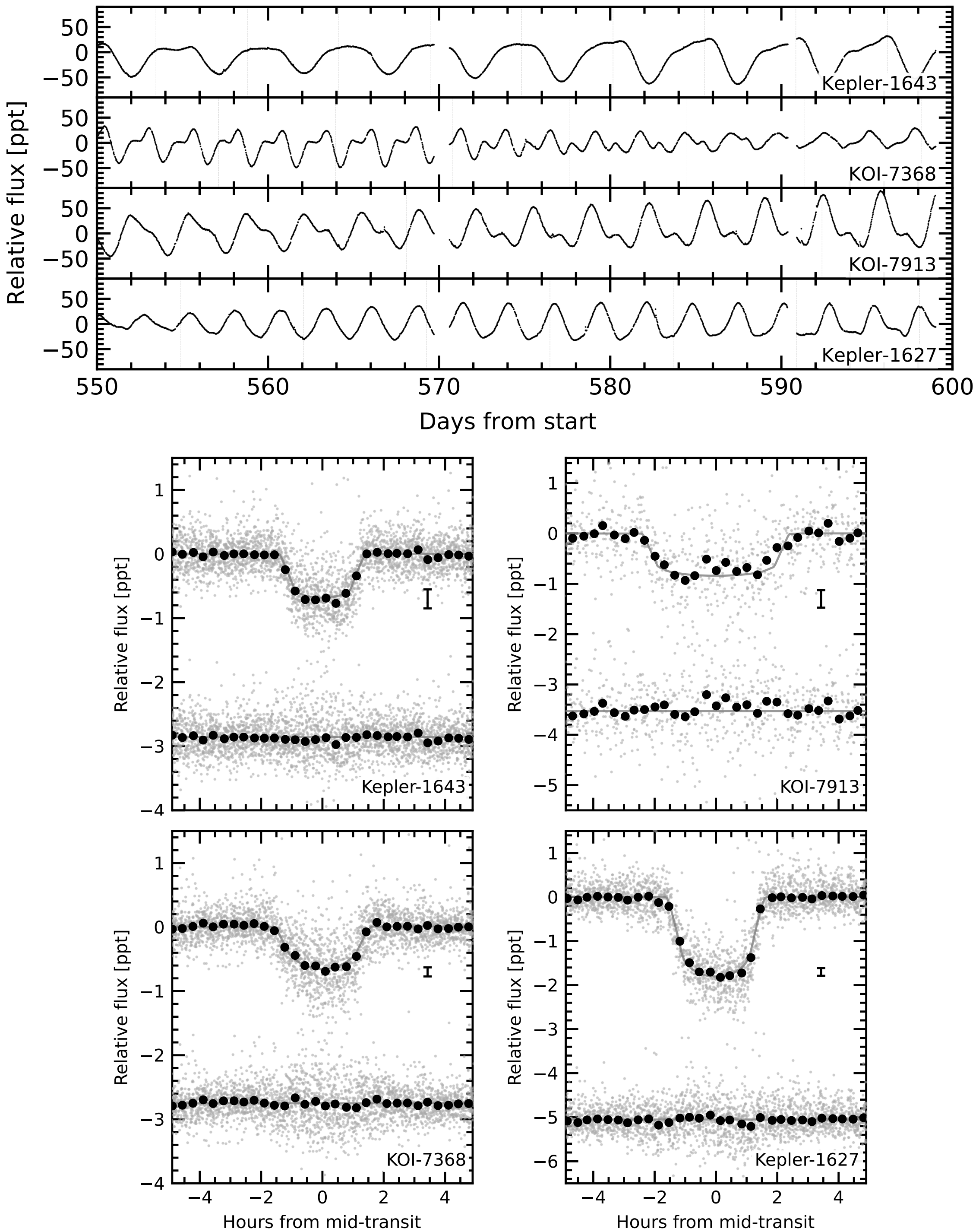

Figure 3. Raw and processed light curves for the Kepler Objects of Interest in Cep-Her. *Top*: 50 day light curve segment from the 3.9 years of Kepler data. The ordinate shows the `PDCSAP` median-subtracted flux in units of parts-per-thousand ($\times 10^{-3}$). The dominant signal is induced by starspots. *Bottom*: Phase-folded transits of Kepler-1643, KOI-7913, KOI-7368, and Kepler-1627 with stellar variability removed. The maximum *a posteriori* transit model is shown with the gray line, and the residual after subtracting the transit model is vertially displaced. Windows over 10 hours are shown. Gray points are individual flux measurements; black points are binned to 20 minute intervals, and have a representative 1-σ error bar in the center-right of each panel.

the `PDCSAP` light curves with the default optimal aperture (Smith et al. 2016). Cadences with non-zero quality flags were omitted. In all cases, the stars are dominated by spot-induced modulation with peak-to-peak variability between 2% and 10%. These signals are much larger than the transits, which have depth ≈0.1%. To quantify the stellar rotation periods, we calculated the Lomb-Scargle periodogram for each Kepler quarter independently. The resulting means and standard deviations are quoted in Table 1.

4.2. *Transit and Stellar Variability Model*

Our goals in fitting the Kepler light curves are twofold. First, we want to derive accurate planetary sizes and orbital properties. Second, we want to remove the stellar variability signal to enable a statistical assessment of the probability that the transit signals are planetary.

Our adopted approach was as follows. Given an initial guess for the transit ephemeris from the `q1_q17_dr25` analysis (Thompson et al. 2018), the light curve was first trimmed to a local window around each transit of duration $\pm 3 \times t_{14}$. The local out-of-transit points were then fitted with a fourth-order polynomial, which was then divided out from the light curve. The resulting flattened transits were then fitted with a planetary transit under the assumption of quadratic limb darkening. Our model therefore included 8 free parameters for the transit ($\{P, t_0, \log R_{\rm p}/R_\star, b, u_1, u_2, R_\star, \log g\}$), 2 free parameters for the light curve normalization and a white noise jitter ($\{\langle f \rangle, \sigma_f\}$), and an additional 5 implicit parameters per transit through the polynomial.

We fitted the models using `exoplanet` (Foreman-Mackey et al. 2020). We assumed a Gaussian likelihood, and sampled using `PyMC3`'s No-U-Turn Sampler (**?**), after having initialized using the maximum *a posteriori* (MAP) model. We used the **?** statistic ($\hat{R}$) as our convergence diagnostic. Abbreviated results are in Table **??**, the full results are in Appendix B.

One weakness of our fitting approach is that we have fixed 5 implicit parameters per individual transit to their MAP values to remove the stellar variability signal. An alternative could be to fit the planetary transits simultaneously with the starspot-induced variability using, say, a quasiperiodic Gaussian process (GP). We explored this approach, but found that it required careful fine-tuning of the hyperparameter priors, otherwise the GP would tend to incorporate anything that was not part of the transit, even if it was short-term variability attributable to for instance flares, or simply instrumental noise. This failure mode is particularly pernicious, in that it yields an inflated and ill-founded sense of confidence in the transit model results. While our model is simpler, it has the benefit that its white noise jitter never trades off with any parameter equivalent to a damping timescale for the coherence of the GP. It is also computationally efficient, while capturing the planetary parameters that we actually care about.

4.3. *Planet Validation*

5. DISCUSSION & CONCLUSIONS

5.1. *Is CH-2 really a star cluster?*

RSG-5, and Kepler-1643's membership inside it, clearly meet the typical expectations of a star claimed to be in an open cluster. RSG-5 shows an obvious overdensity relative to the local field population (*e.g.*, Figure 1), and our membership selection easily produces a clean pre-main-sequence locus in color-absolute magnitude space (Figure 2). CH-2, and KOI-7913 and KOI-7368's membership inside it, do not meet those expectations in as obvious a manner. This is because this association of stars is diffuse.

To quantify the density discrepancy, we can compare the spatial and velocity volumes searched to select candidate members of each cluster. For RSG-5, we drew 141 candidate members from a $30\,\mathrm{pc} \times 30\,\mathrm{pc} \times 30\,\mathrm{pc}$ spatial cube, given a $1\,\mathrm{km\,s^{-1}} \times 2\,\mathrm{km\,s^{-1}}$ rectangle in apparent galactic velocity. For CH-2, our 37 candidate members came from a spatial cube of dimension $50\,\mathrm{pc} \times 40\,\mathrm{pc} \times 30\,\mathrm{pc}$, and the velocity rectangle of $2\,\mathrm{km\,s^{-1}} \times 4\,\mathrm{km\,s^{-1}}$. If we define the "searched volume" in units of $\mathrm{pc}^3(\mathrm{km\,s^{-1}})^2$, then the volume ratio of CH-2:RSG-5 is ≈9:1. The density (number of stars per unit searched volume) within RSG-5 relative to CH-2 similarly comes out to 34 to 1.

So what makes a star cluster? Historic answers to this question have recently by reviewed by Krumholz et al. (2019): some definitions that have been offered include criteria such as being gravitationally bound, and having a mass density that significantly exceeds the mean in a cluster's galactic neighborhood. We prefer a modified version of the definition adopted by Krumholz et al. (2019): for our purposes a star cluster is a group of at least 12 stars that was physically associated at its time of formation. The somewhat arbitrary "12" is set to distinguish clusters from high-order multiple star systems. We therefore explicitly include dissolved clusters and their tidal tails in our concept of clusters. We also explicitly exclude the idea that a particular number of stars per unit spatial volume is required to define a cluster. The latter point acknowledges the fact that an important factor in cluster identification is now also the number per unit velocity volume, whether in 2-dimensional tangential velocity, or when including the third radial component. Perhaps once stellar rotation periods and chemical abundances reach the same level of ubiquity as stellar proper motions, they might enable further refinement of our ability in cluster discovery.

From a data-driven perspective, how do we demonstrate that a star is in a cluster, *i.e.*, that it is part of a group of stars that was physically associated at its time of formation? Backintegrating the orbits is one convincing approach, but it does not always work **(CITE)**. The relatively minimal approach suggested by Tofflemire et al. (2021) is intriguing: search for coeval, phase-space neighbors, measure their ages, and determine if they share a common age. This approach is more accurately be described as a method for determining whether a star is currently associated with a set of coeval stars, which is much easier to determine than what the association looked like in the past. From this standard, our analysis thus far of CH-2 has already demonstrated the existence of such an assocation.

A crucial logical step in this method however is to ensure that the (automated) search process for coeval phase-space neighbors in fact produces neighbors at a rate different from what it would for field stars.

And so we ask: what is the density of field stars in the CH-2 region? If we had applied Ronan's pre-main-sequence selection, + HDBScan, + local neighbors... what would we have gotten? Similarly... if you just applied Adam Kraus' Comove What is the likelihood we are fooling ourselves?

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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), `PyMC3` (Salvatier et al. 2016), `scipy` (Jones et al. 2001),

Facilities: *Astrometry*: Gaia (Gaia Collaboration et al. 2018b, 2021a). *Imaging*: Second Generation Digitized Sky Survey. Keck:II (NIRC2; www2.keck.hawaii.edu/inst/nirc2). *Spectroscopy*: Tillinghast:1.5m (TRES; Fűrész et al. 2008). Keck:I (HIRES; Vogt et al. 1994). *Photometry*: Kepler (Borucki et al. 2010), TESS (Ricker et al. 2015).

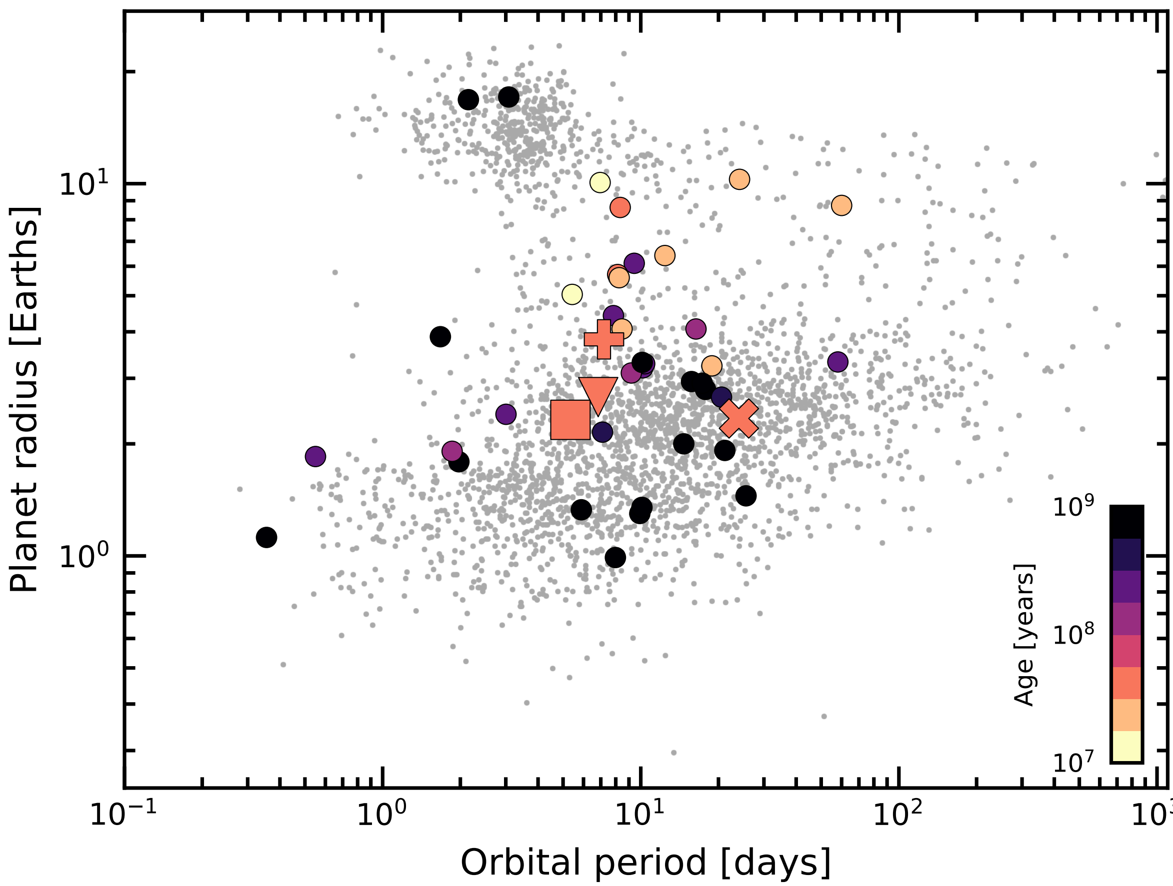

Figure 4. Radii, orbital periods, and ages of transiting exoplanets. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where τ is the age and σ_τ is its uncertainty. Kepler-1627 (+), KOI-7368 (down-triangle), KOI-7913 (X), Kepler-1643 (diamond). The large sizes of the youngest transiting planets could be explained by their primordial atmospheres not yet having evaporated; direct measurements of the atmospheric outflows or planetary masses would help to confirm this expectation. Selection effects may also be important. Parameters are from the NASA Exoplanet Archive (2022 Feb 27).

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APPENDIX

A. TABLE OF CANDIDATE RSG-5 AND CH-2 MEMBERS

Gaia source lists and abbreviated info. Include rotation periods.

B. TABLE OF TRANSIT FIT PARAMETERS

Table goes here