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Three 38 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 contains 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 38 ± 6 million years old. Based on the transit shapes and high resolution imaging, they are all most likely planets (false positive probabilities of 6×10^{-9}, 5×10^{-3}, and 1×10^{-4} for Kepler-1643, KOI-7368, and KOI-7913 respectively). Kepler-1643 and KOI-7913 are therefore the first empirical demonstration that mini-Neptunes with sizes of ≈2 Earth radii exist at ages of roughly 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, *e.g.*,) 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, *e.g.*,).

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). Broadly speaking these analyses cluster on the stellar positions and on-sky velocities measured by Gaia, with varying degrees of filtering and super-

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vision. One important result is the identification of diffuse streams and tidal tails comparable in stellar mass to the previously known cores of many open clusters (Meingast et al. 2019; Meingast et al. 2021; Gagné et al. 2021). These spatially diffuse groups typically have velocity dispersions of $\sim$1 km s^{-1}, and can be verified to be "co-eval" 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 (*e.g. 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 reliably 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 $\approx$300 parsecs from the Sun, appears to span Cepheus to Hercules (galactic longitudes, l, between 40° and 100°), with galactic latitudes spanning roughly 0 and 20 degrees. We therefore refer to it as the Cep-Her complex. It exhibits significant sub-structure over its $\approx$250 parsec length, and a detailed analysis that delves into the memberships, kinematics, and possible origin of the group 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 (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 **??**). We conclude with a discussion of implications for the size-evolution of close-in mini-Neptunes (Section **??**).

2. THE CLUSTER

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). Both of these clusters were known before Gaia, and have reported ages between $\approx$30 and $\approx$60 million years. Early empirical evidence that these two clusters are likely 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 30–60 Myr 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 a few nearby sub-populations in this quadrant of the sky share a common origin has yet to be fully substantiated, and will be the subject of an 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 10–100 Myr 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.

TODO RONAN: PLEASE VET ENTIRE SECTION, AND UPDATE WHERE APPROPRIATE!.

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

The second step is to then perform in an unsupervised HDBScan clustering on the photometrically selected popula-

[1] A useful visualization is available online at http://mkounkel.com/mw3d/mw2d.html (accessed 15 March 2022)

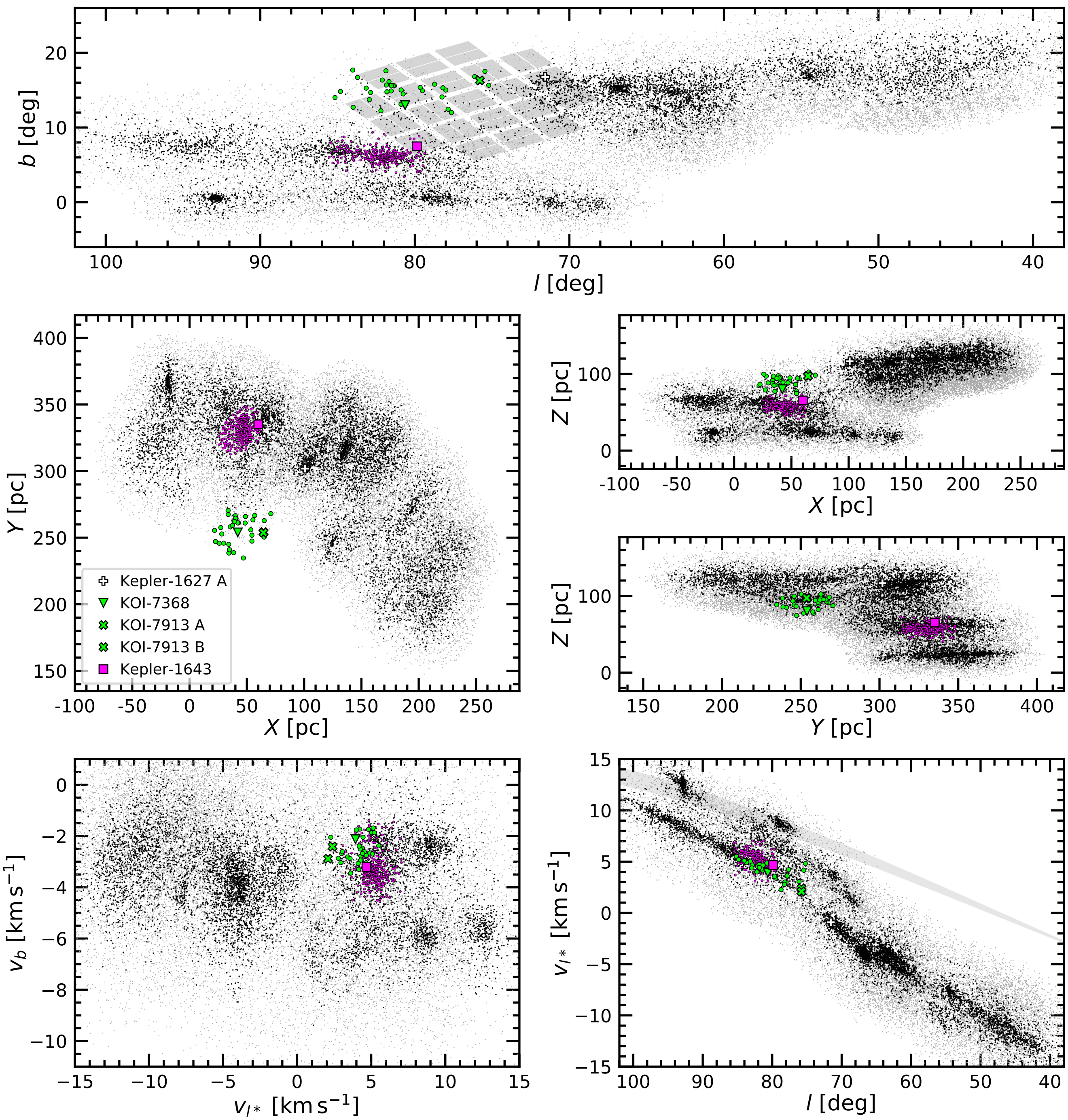

Figure 1. Positions and velocities of candidate members of the Cep-Her complex. *Top row*: On-sky positions in galactic coordinates. Black points are stars for which group membership is more secure than for gray points (see Section 2.2). Kepler-1627 is in the outskirts of the δ Lyr cluster (Bouma et 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. *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", and treat it with additional skepticism The **interactive figure** enables overplotting the candidate cluster members.

tion (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 $c = 6\,\mathrm{pc/km\,s^{-1}}$ 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 that are spatially and kinematically consistent with each of the groups, **WORDING NEEDS WORK FOR CLARITY at least as close to the 10$^{\text{th}}$ nearest HDBSCAN-identified member in space-velocity coordinates as the most peripheral HDBSCAN-identified member**. 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 26,960 objects with weight exceeding 0.02 as gray points, and overplot 7,560 objects with weights exceeding 0.10 as black points. **TODO: FIXME these object numbers impose pretty weak quality cuts and include junk at G>18... use get_clean_gaia_photometric_sources too, since they come in for the CAMDs**.

The previously known δ Lyr cluster ($l, b = 68°, 15°$; $v_{l'}, v_b = -4.5\mathrm{kms}, -4\mathrm{kms}$) is visible, as is RSG-5 ($l, b = 83°, 6°$, $v_{l'}, v_b = +5.5\mathrm{kms}, -3.5\mathrm{kms}$). Most of the other subclusters, including in Cep-Cyg ($l, b = 90°, 7°$) and Cerberus ($l, b = 48°, 18°$) are too small or dispersed to have previously been analyzed in great detail.

The fourth and final step was cross-matching our candidate Cep-Her member list against all known Kepler Objects of Interest, including known false positives (Thompson et al. 2018). This yields 32 matches, of which 5 are "confirmed" planets according to the NASA Exoplanet Archive. A cursory inspection of the Kepler data validation summaries and Robovetter classifications for these objects quickly showed whether they were potentially consistent with being *i)* planets, and *ii)* $\lesssim 10^8$ years old population, 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 these objects along various projections. Kepler-1643 is near the core RSG-5 population both spatially and kinematically. KOI-7368 and KOI-7913 are in a more diffuse region ≈40 parsecs above RSG-5 in Z and ≈100 parsecs closer in Y. In tangential galactic velocity space, there appears to 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, in order to verify whether they are indeed the same age. For candidate RSG-5 members, we require:

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

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

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

and we call this latter set of stars "CH-2".

2.3. *The Cluster's Age*

The evidence for the RSG-5 and CH-2 sub-groups at least roughly sharing the age of the δ Lyra cluster is shown in Figure 2.

2.3.1. *Color-Absolute Magnitude Diagram*

2.3.2. *Stellar Rotation Periods*

3. THE STARS

Many of the relevant stellar parameters can be gleaned by inspecting Figure 2. The known planet-hosting stars in Cep-Her 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 (SpType ≈M0V). The latter system is 3.″501 A Solar-mass star with solar metallicity arrives at the zero-age main sequence at $t \approx 40$ million years

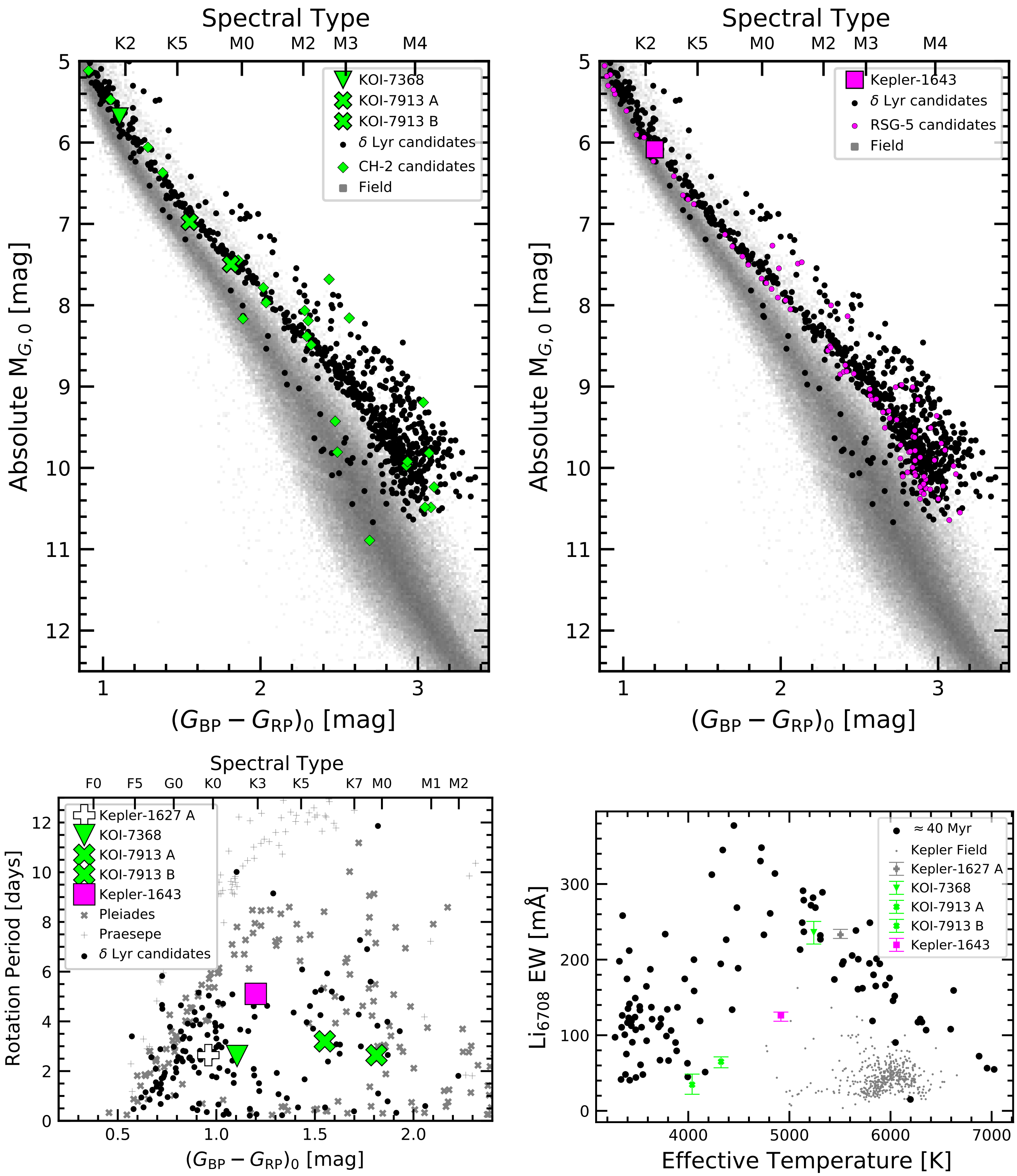

Figure 2. The Cep-Her complex is 38^{+6}_{-5} **Myr old.** The top row shows CAMDs. Left shows CH-2, right shows RSG-5. The bottom left shows gyro (and is a **place-holder since we might want to add CH-2 and RSG5**). The bottom right shows lithium (black points are NGC2547 and IC2602 from Randich+18 and probably are not believable at the red end; for Kepler-1643 I'm less confident, but it might be tied to the "slow" rotation period – this is why we need RSG5 rotation periods). Also, we might want an H-alpha plot?).

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]	X	$\pm X$	A
$T_{\rm eff}$ [K]	X	$\pm X$	B
$\log g_\star$ [cgs]	X	$\pm 0.X$	B
$R_\star$ [$R_\odot$]	X	X	C
$M_\star$ [$M_\odot$]	X	X	C
$\rho_\star$ [g cm^{-3}]	X	X	C
$P_{\rm rot}$ [days]	X	X	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	$\pm 0.X$	D
t_{14} [hours]	X	X	D
		KOI-7368	
Stellar parameters:			
Gaia G [mag]	X	$\pm X$	A
$T_{\rm eff}$ [K]	X	$\pm X$	E
$\log g_\star$ [cgs]	X	$\pm 0.X$	E
$R_\star$ [$R_\odot$]	X	X	C
$M_\star$ [$M_\odot$]	X	X	C
$\rho_\star$ [g cm^{-3}]	X	X	C
$P_{\rm rot}$ [days]	X	X	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	$\pm 0.X$	D
t_{14} [hours]	X	X	D
		KOI-7913 A	
Stellar parameters:			
Gaia G [mag]	X	$\pm X$	A
$T_{\rm eff}$ [K]	X	$\pm X$	B
$\log g_\star$ [cgs]	X	$\pm 0.X$	B
$R_\star$ [$R_\odot$]	X	X	C
$M_\star$ [$M_\odot$]	X	X	C
$\rho_\star$ [g cm^{-3}]	X	X	C
$P_{\rm rot}$ [days]	X	X	D
Li EW [mÅ]	X	X	B
$\Delta G_{\rm AB}$ [mag]	X	X	F
$\Delta r_{\rm AB}$ [au]	X	X	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	$\pm 0.X$	D
t_{14} [hours]	X	X	D

NOTE— (A) CITE Gaia EDR3. (B) HIRES SM-Synth/Emp CITE CITE (C) Isochrones (values: MIST: uncs MIST/PARSEC). (D) Kepler light curve. The full set of transit parameters is given in CITE APPENDIX TABLE. (E) TRES CITE. (F) Magnitude difference and physical distance between primary and secondary; from Gaia EDR3.

(CITE CHOI MESA), and so these stars are in the end stages of their pre-main-sequence contraction. Their Gaia EDR3 parallaxes span X.X to Y.Y, corresponding to distances between X.X and Y.Y parsecs.

To derive the spectroscopic parameters ($T_{\rm eff}, \log g_\star$, [Fe/H]) and the equivalent width of the Li I from the 6708 Å doublet, we acquired spectra. Specifically, we acquired iodine-free HIRES spectra for Kepler-1643 (YYYY/MM/DD) and KOI-7913 (YYYY/MM/DD and YYYY/MM/DD), where for the latter the two different epochs corresponded to observations of the secondary and primary respectively. The acquisition and analysis followed the standard reduction techniques of the California Planet Survey (Howard et al. 2010). For KOI-7368, we acquired TRES spectra on YYYY/MM/DD and YYYY/MM/DD. CITE METHOD PAPER. The results are given in Table 1.

Table 1 summarizes

3.1. *Kepler 1643*

3.2. *KOI-7368*

3.3. *KOI-7913*

Is a binary.

4. THE PLANETS

5. DISCUSSION & CONCLUSIONS

ACKNOWLEDGMENTS

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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),

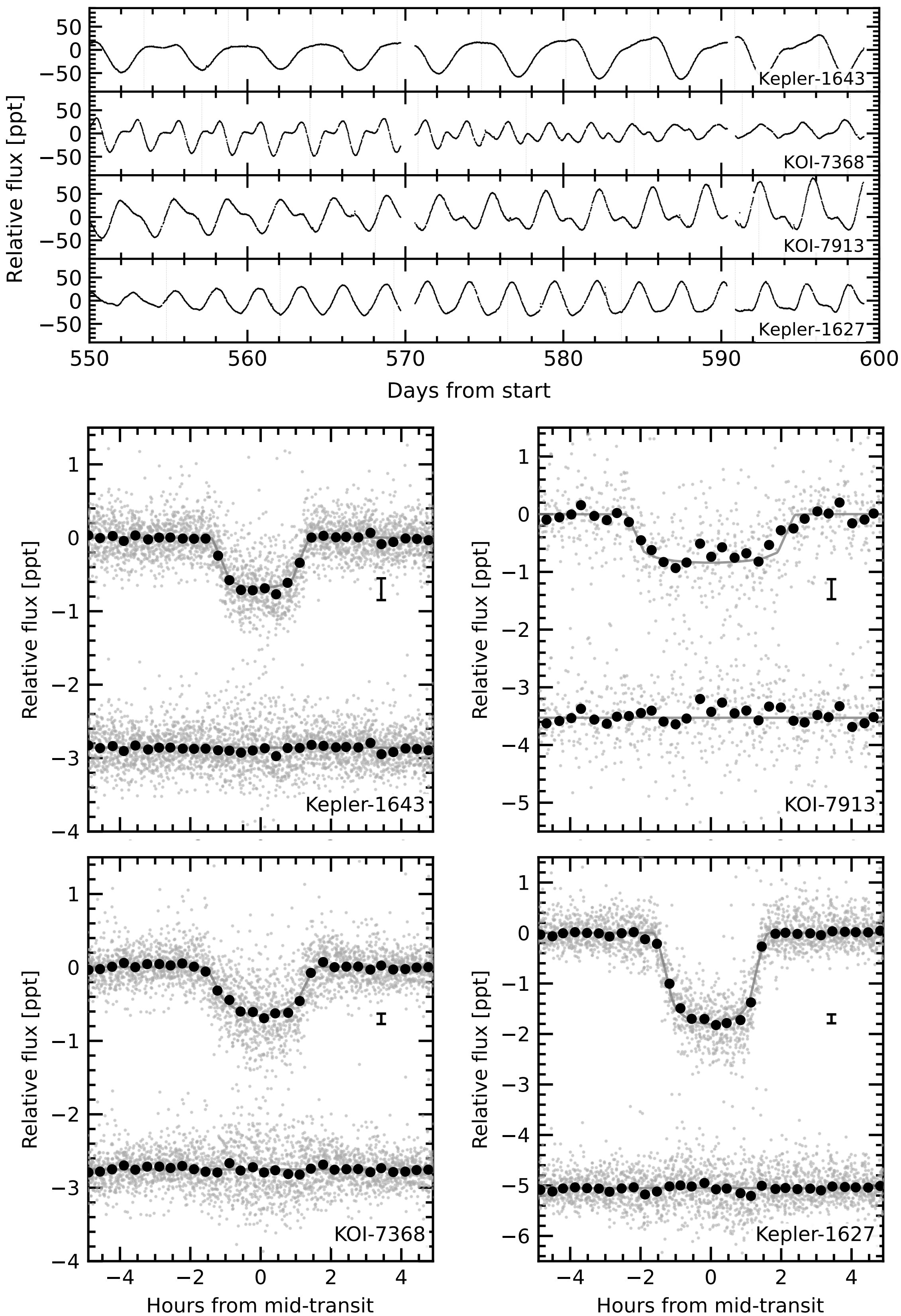

Figure 3. Raw and processed light curves for the objects of interest. Top: raw. Bottom: processed. The increased scatter during transit is likely due to starspot crossing events. KOI-7913 is janky, but P=24 days.

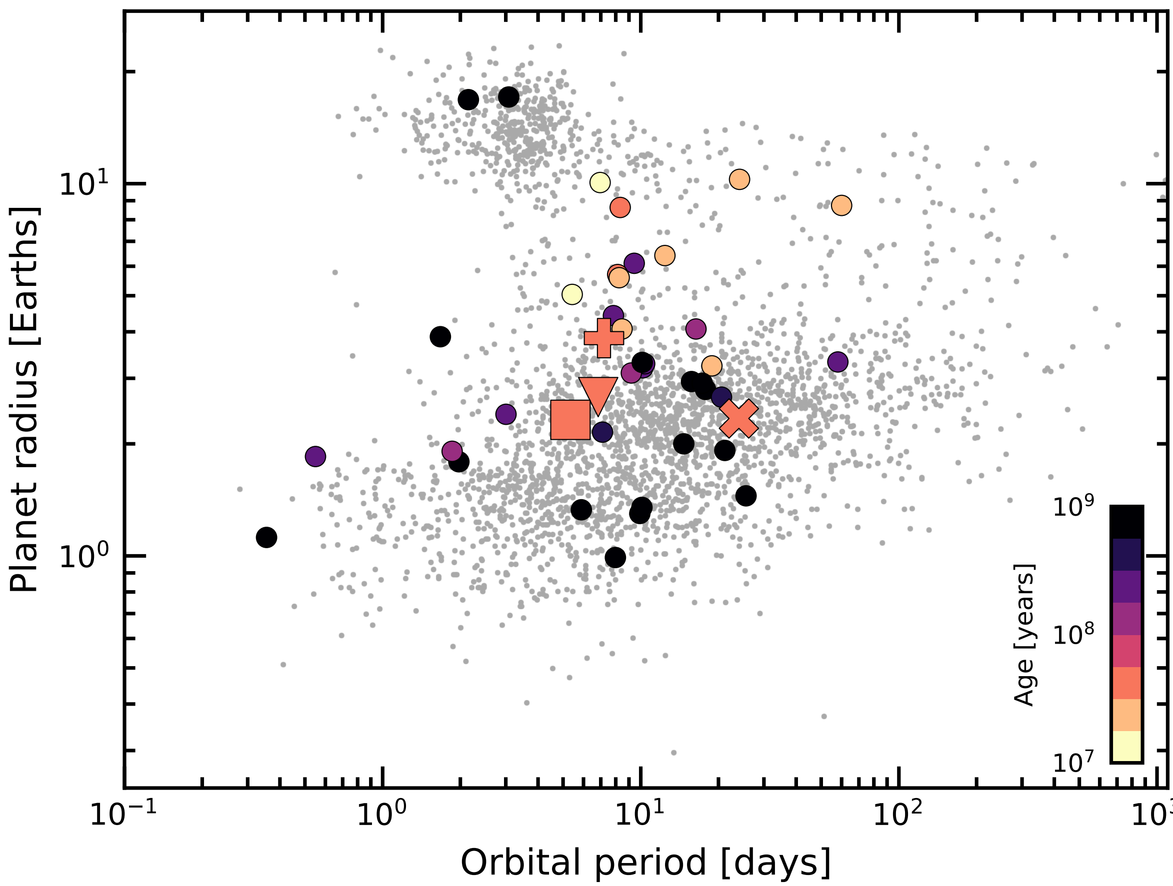

Figure 4. Radii, orbital periods, and ages of transiting exoplanets. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where τ is the age and σ_τ is its uncertainty. Kepler-1627 (+), KOI-7368 (down-triangle), KOI-7913 (X), Kepler-1643 (diamond). The large sizes of the youngest 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).

Facilities: *Astrometry*: Gaia (Gaia Collaboration et al. 2018, 2021). *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).

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