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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 of young transiting planets is a major frontier in current exoplanet research. The reason is that the properties of these planets can help constrain the timescales for processes including hot Jupiter migration (CITE), the cooling and contraction of planets with massive gaseous envelopes (CITE Rizzuto), the early evolution of close-in multiplanet systems (CITE David), and whether and how mass-loss explains the radius valley (e.g., CITE, CITE, Lee+21 on theory; CITE CITE CITE on observations).

Understanding the formation and evolution of stellar clusters is similarly an emerging frontier in analyses of star formation and cluster evolution. In particular, it is understood that most embedded clusters disperse within a few tens of millions of years after forming their first stars (CITE). The discovery of tidal tails (CITE CITE)... streams (CITE Meingast18, Curtis19), etc... Connect to moving groups (CITE Gagne 21). What are the typical densities for star formation? How does gas expulsion and the SFE affect cluster morphology? **FIXME**

Assuming a constant star formation rate in the Galaxy, ≈1% of stars are $\lesssim 10^8$ years old. While ≈5,000 transiting exoplanets are known (CITE), 11 currently meet this age cut. The discrepancy between the ≈50 expected and ≈10 known likely has a contribution from selection effects in planetary detection, which include photometric and spectroscopic starspot modulation, and the rarity of young stars.

While detecting planets around young and active stars is challenging, so is measuring stellar ages (see CITE Soderblom for a review). It should therefore not be surpris-

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ing that advances along either dimension can yield advances in the census of young transiting planets.

The prime Kepler mission (CITE) found most of the currently known transiting exoplanets, and it was conducted before the positions, velocities, and stellar brightnesses measured by Gaia revolutionized our understanding of stellar clusters (CITE, CITE, CITE). This revolution is slated to continue with the upcoming third Gaia data release (DR3 CITE). Nonetheless, it seems sensible to revisit the Kepler field, given our new knowlege of the stellar ages.

In this work, we expand on a previous study of a 38 million year (Myr) old Neptune-sized planet in the Kepler field (Kepler-1627Ab; CITE). The age of this planet was derived based on its host star's membership in the δ Lyr cluster. Our analysis of this cluster focused on the immediate kinematic vicinity of Kepler-1627A in order to reliably confirm the age of the planet. However it also became clear that the δ Lyr cluster is spatially and kinematically close to a much larger group of similarly aged stars. This group, which is at a distance of roughly 300 parsecs, appears to span Cepheus ($l = 100°$) to Hercules ($l = 40°$), at galactic latitudes, b, between roughly 0 and 20 degrees. We therefore refer to it as the Cep-Her complex. Viewed top-down in the plane of the Galaxy, the complex spans roughly 250 parsecs in the direction toward the galactic center, and 150 parsecs in the perpendicular direction of galactic rotation. A detailed kinematic analysis and exploration is currently being prepared by R. Kerr and collaborators.

The subject of this study is the intersection of the Cep-Her complex with the Kepler field, and an analysis of the consequent transiting planets and planet candidates. Cross-matching the full set of candidate Cep-Her members against all known Kepler Objects of Interest (CITE) yielded XX candidate matches. Given the purported XX Myr age of the group, a visual inspection of the light curves quickly enabled a decision about whether the matches could be valid, based on the presence or non-presence of stellar rotation signals of the appropriate periods and amplitudes (CITE REBULL). Four possible matches remained from this exercise: Kepler-1627, Kepler-1643, KOI-7368, and KOI-7913. Given our previous analysis of Kepler-1627, we will focus for the most part on the latter three.

2. THE CLUSTER

2.1. *Selecting Cluster Members*

2.2. *General Context*

Our focus is on a region of the Galaxy roughly 200 to 500 parsecs from the Sun, above the galactic plane, and spanning galactic longitudes of roughly 40° to 100° degrees. Querying the Gaia archive and imposing the cuts suggested by Gaia Collaboration et al. (2018a, Appendix B) on the photometric signal to noise ratio, the number of visibility periods used, the astrometric χ^2 of the single-source solution, the $G_{\rm BP} - G_{\rm RP}$ color excess factor and the parallax precision ($\varpi/\sigma_\varpi > 5$) yields $\approx 5.0 \times 10^6$ sources.

Imposing a thin slice in color-absolute magnitude space around the pre-main-sequence of the δ Lyr cluster's previously established ≈40 Myr locus, and imposing kinematics cut for $-8 < v_b/{\rm km\,s^{-1}} < 0$ and $-15 < v_{l'}/{\rm km\,s^{-1}} < 15$, where $l' = l \cos b$, yields $\approx 5.2 \times 10^3$ sources. These objects are all in the range BP-RP 1.5 to 3.2, so roughly K5V to M4.5V, or ≈0.2 to 0.7 solar masses. Much more manageable, but according to IMF arguments, missing at least a factor of two in mass of any clusters.

In XYZ, and in tangential velocity space, these five thousand sources are visually clustered in between a few to a dozen groups, depending on the characteristic size and velocity scales of interest. The first suggestion that these objects could all be part of a monolithic structure, to our knowledge, came from the manual grouping that was performed between them by Kounkel & Covey (2019) when defining the structure they dubbed "Theia 73". Different subsets of these stars have however previously been noticed and studied. They include the δ Lyr cluster, also known as Stephenson-1 (Stephenson 1959), which comprises a major grouping around $(l, b) = (68°, 15°)$, with typical velocities $(v_{l'}, v_b) = (-4.5{\rm kms}, -4{\rm kms})$. Another individual component that has previously been recognized is RSG-5 (Röser et al. 2016). This group is at roughly $(l, b) = (83°, 6°)$, with velocities $(v_{l'}, v_b) = (+5.5{\rm kms}, -3.5{\rm kms})$. Most of the other subclusters, including CH-2, and those in Cep-Cyg and Cerberus are too small or dispersed to have previously been analyzed in great detail.

2.3. *Actual Membership Selection*

To identify stars in this region of space that could be members of the Cep-Her complex, we follow the methods of Kerr et al. (2021). The analysis therefore broadly consists of two steps. The first step is to select stars that photometrically appear young based on the Gaia EDR3 magnitudes $\{G, G_{\rm RP}, G_{\rm BP}\}$, in combination with the parallaxes and reddening estimates. This method works best for low-mass stars due to their long pre-main-sequence contraction timescale, and for massive stars because of their fast evolutionary timescale. The second step in the analysis is to use the photometrically-identified young stars as the "seed" for a candidate population in a spatial and kinematic clustering analysis in $\{X, Y, Z, cv_b, cv_{l*}\}$. The latter step helps identify F, G, and K-type stars that cannot be identified as young based solely on their positions in color versus absolute magnitude.

2.4. *The Cluster's Age*

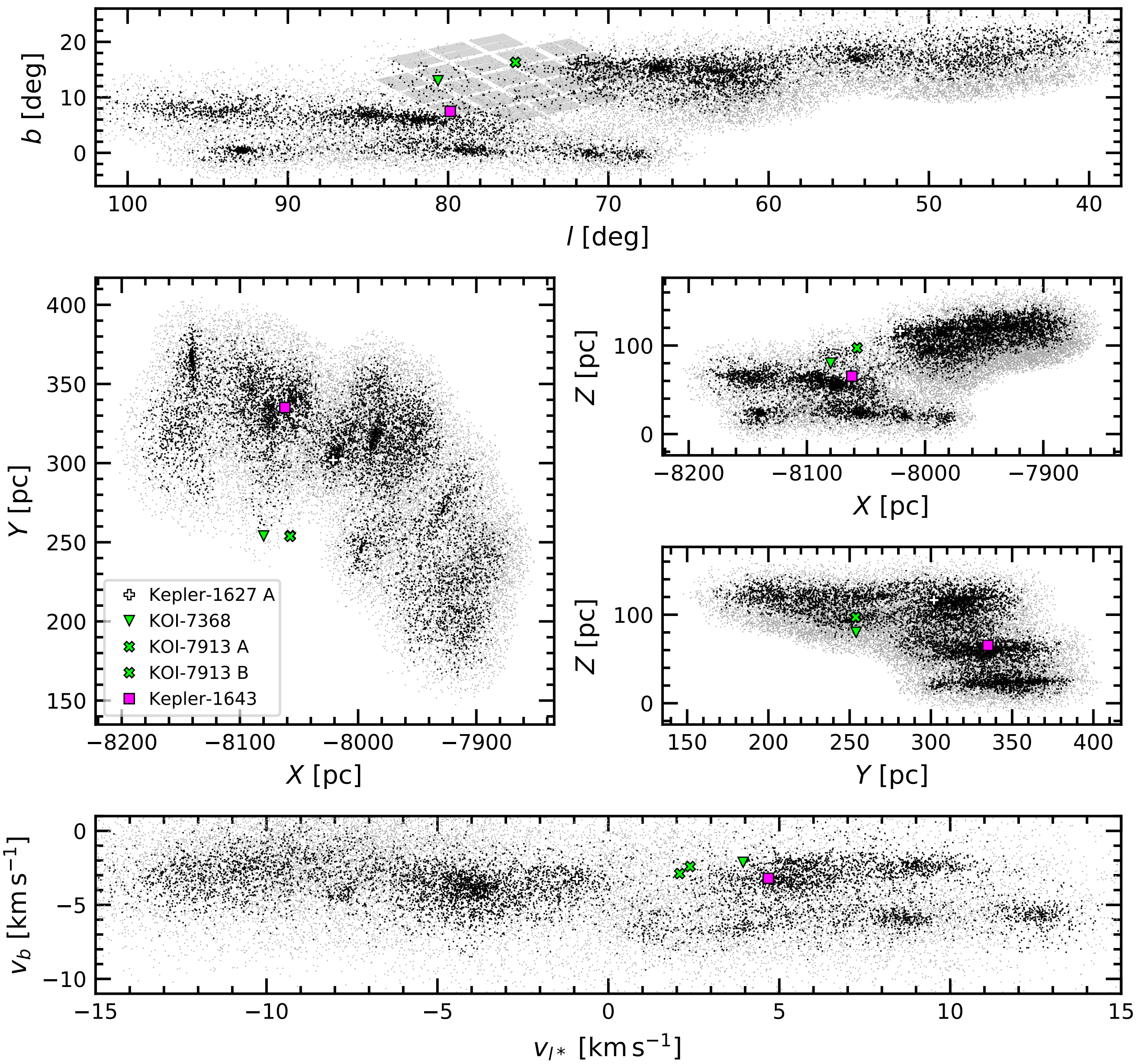

Figure 1. Galactic positions and tangential velocities of candidate members of the Cep-Her complex. *Top row*: On-sky positions in galactic coordinates. Black points are stars for which membership is more likely than for gray points ("weight" cuts above 0.10 and 0.02 respectively; see text). The δ Lyr cluster, at $\{l,b\} \approx \{66^\circ, 12^\circ\}$, contains Kepler-1627 (Bouma et al. 2022). *Middle row*: Galactic positions. The Sun is at $\{X,Y,Z\} = \{-8122, 0, 20.8\}$ pc. *Bottom row*: Galactic tangential velocities. The spatial and kinematic overlap between RSG-5 ($\{l,b\} \approx \{82^\circ, 6^\circ\}$; $\{X,Y,Z\} \approx \{-8070, 330, 50\}$ pc) and Kepler-1643 is fairly obvious. KOI-7368 and KOI-7913 however are candidate members of a more diffuse region, that we dub "CH-2". Although CH-2 appears close to RSG-5 in (X,Y) and (v_b, v_{l*}) projections, it is spatially distinct in (Z,Y).

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.

2.4.1. *Color-Absolute Magnitude Diagram*

2.4.2. *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 $\approx$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 (CITE CHOI MESA), and so these stars are in the end stages

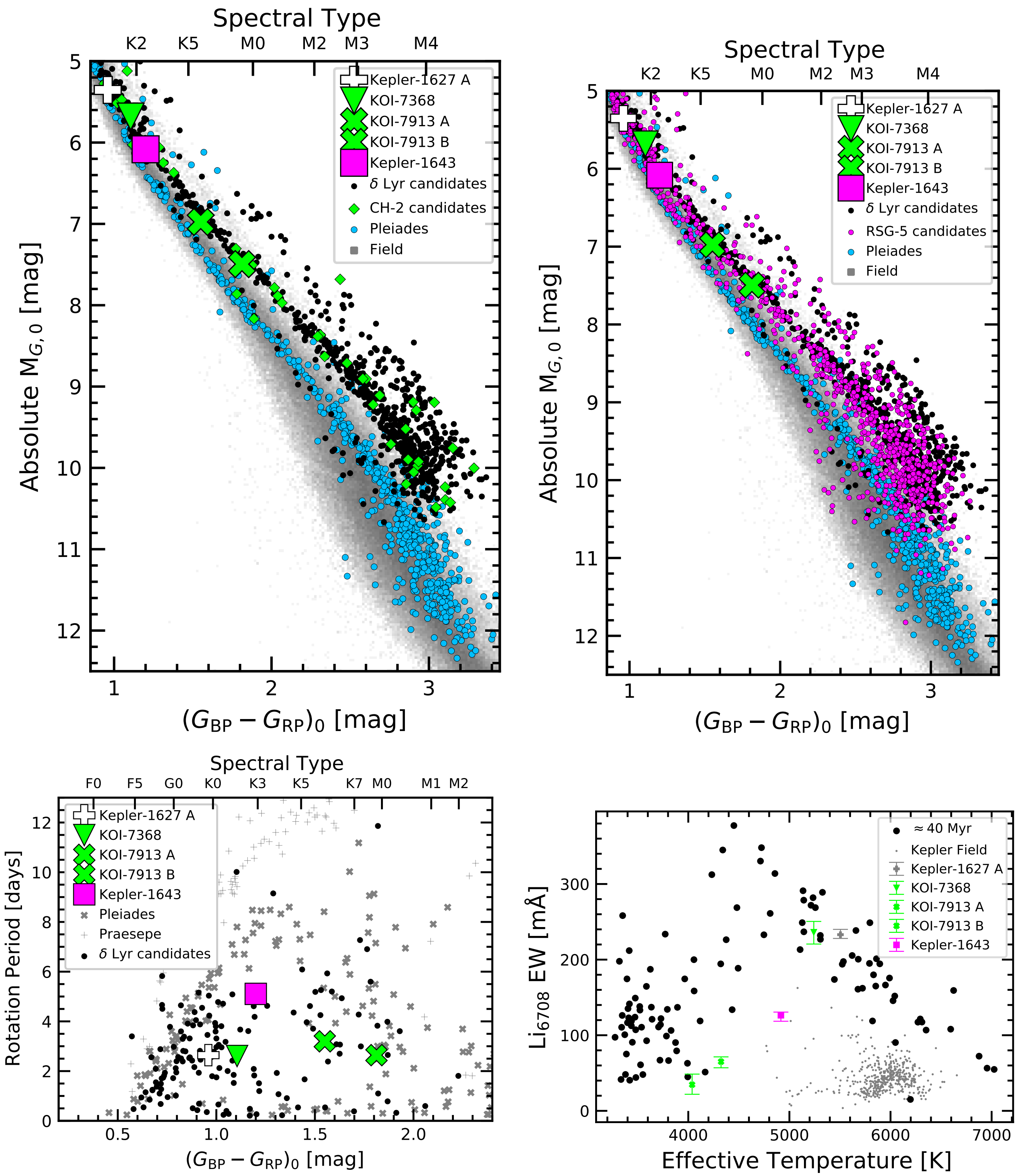

Figure 2. The Cep-Her complex is 38^{+6}_{-5} Myr old. The top row shows CAMDs. Left shows CH-2, right shows RSG-5. The bottom left shows gyro (and is a **place-holder since we might want to add CH-2 and RSG5**). The bottom right shows lithium (black points are NGC2547 and IC2602 from Randich+18 and 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.

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

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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),

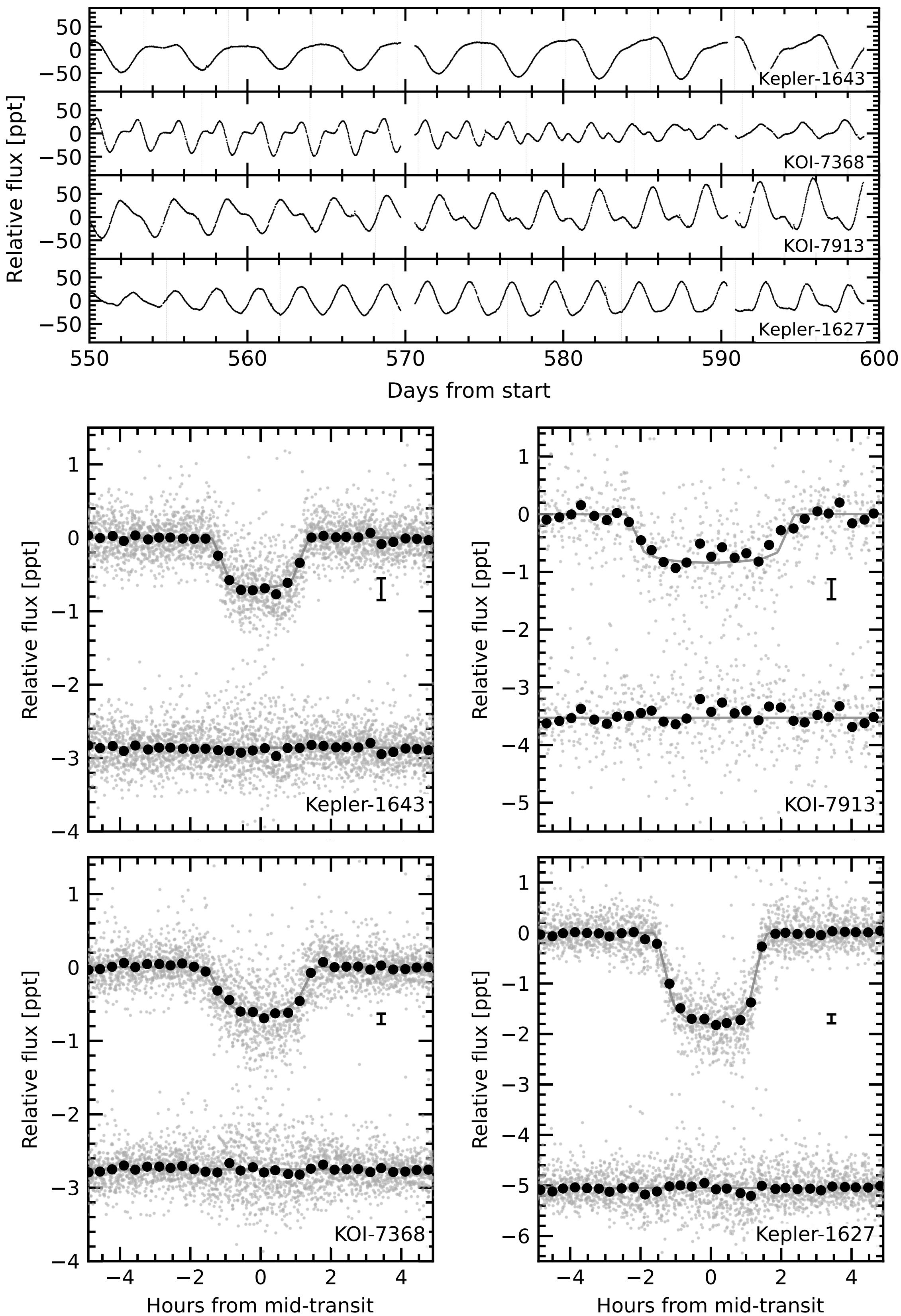

Figure 3. Raw and processed light curves for the objects of interest. Top: raw. Bottom: processed. The increased scatter during transit is likely due to starspot crossing events. KOI-7913 is janky, but P=24 days.

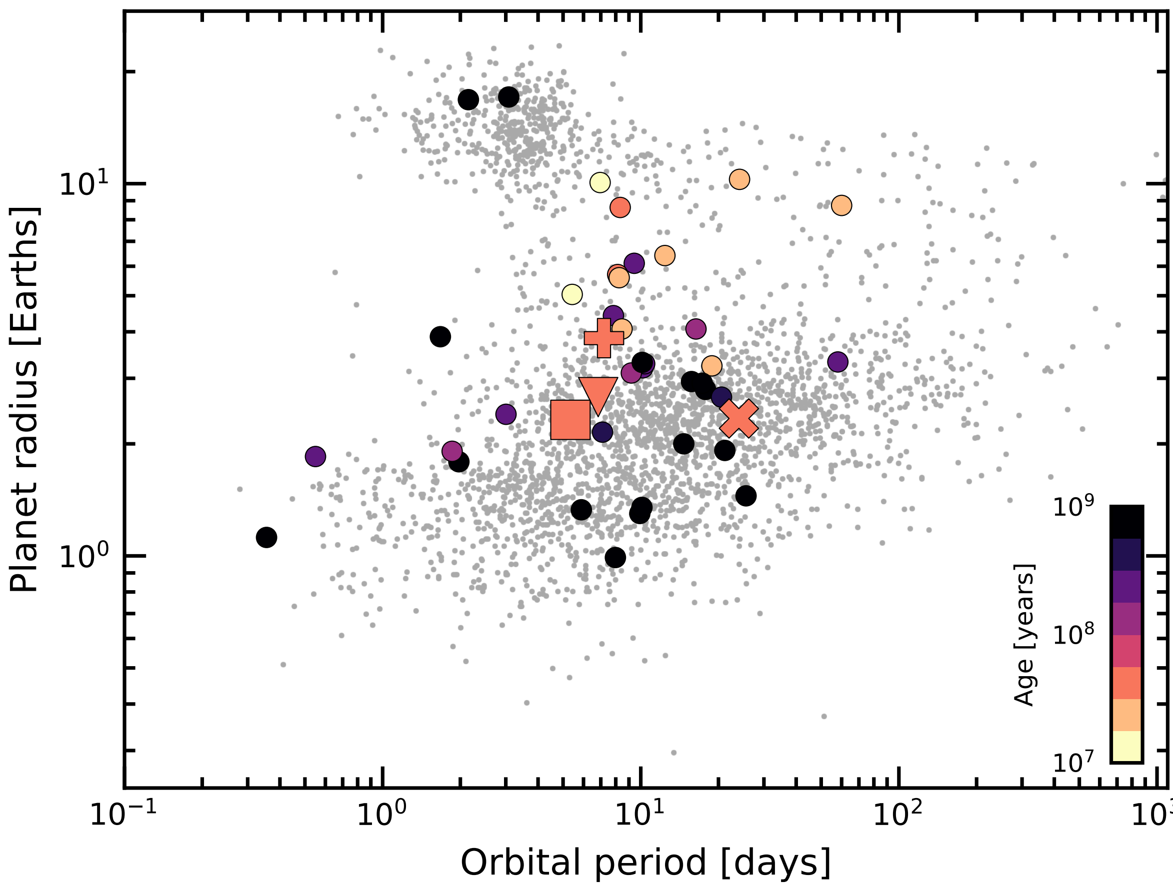

Figure 4. Radii, orbital periods, and ages of transiting exoplanets. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where τ is the age and σ_τ is its uncertainty. Kepler-1627 (+), KOI-7368 (down-triangle), KOI-7913 (X), Kepler-1643 (diamond). The large sizes of the youngest 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. 2018b, 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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