

## Three 38 Million Year Old Mini-Neptunes from Kepler, TESS, and Gaia

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### ABSTRACT

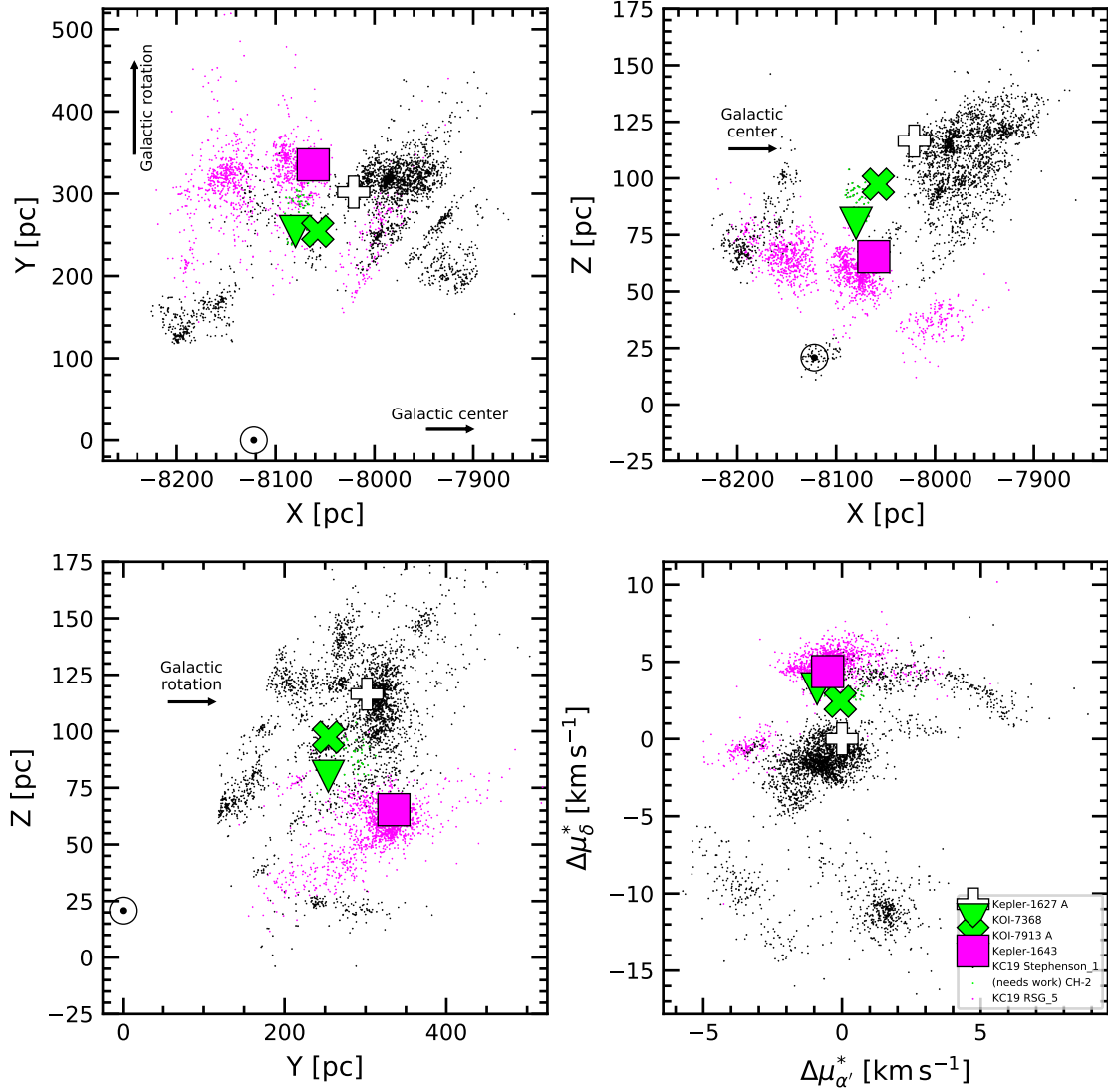
Stellar positions and velocities from Gaia are yielding a refined view of stellar clusters during the first hundred million years of their lives. Here we present an analysis of a group of  $38 \pm 6$  million year old stars spanning Cepheus ( $l = 100^\circ$ ) to Hercules ( $l = 40^\circ$ ), hereafter the Cep-Her complex. This group of stars includes four previously 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 component of the Cep-Her complex called the  $\delta$  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  $38 \pm 6$  million years old. Based on the transit shapes and high resolution imaging, we statistically validate that they are all most likely planets (false positive probabilities of  $6 \times 10^{-9}$ ,  $5 \times 10^{-3}$ , and  $1 \times 10^{-4}$  for Kepler-1643, KOI-7368, and KOI-7913 respectively). Supplemented by Gaia and TESS, the main Kepler mission is now contributing to the census of young close-in planets, and Kepler-1643 and KOI-7913 are the first empirical demonstration that mini-Neptunes with sizes of  $\approx 2$  Earth radii exist at ages of roughly 40 million years.

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

### 1. INTRODUCTION

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**Figure 1. Galactic positions and tangential velocities of stars in the complex. This is a placeholder before we get real kinematics. Sub-clusters include the  $\delta$  Lyr cluster, RSG-5, and the worryingly diffuse “CH-2”.**

## 2. THE CLUSTER

### 2.1. Selecting Cluster Members

### 2.2. The Cluster’s Age

#### 2.2.1. Color-Absolute Magnitude Diagram

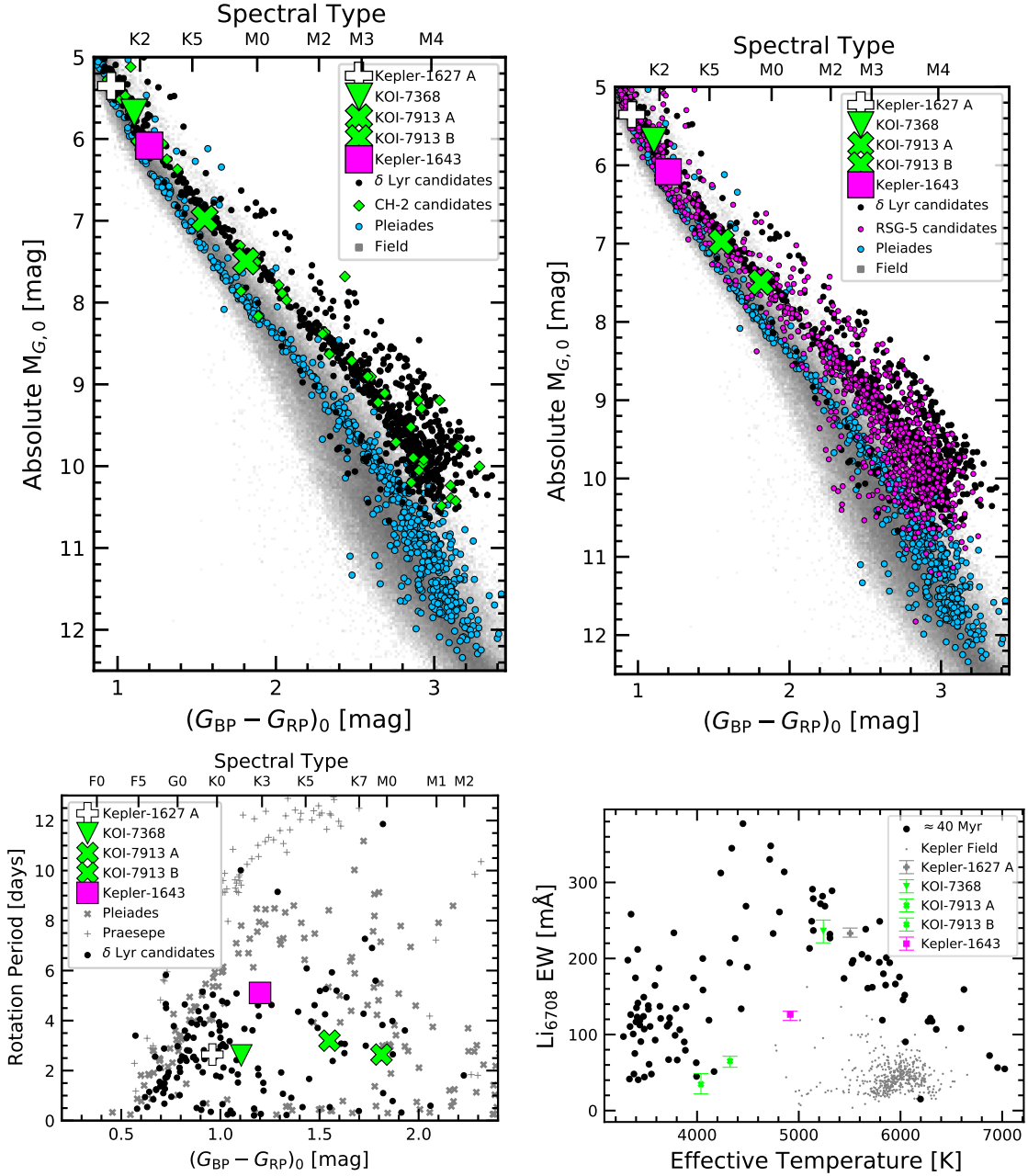
#### 2.2.2. Stellar Rotation Periods

## 3. THE STARS

### 3.1. Kepler 1627A

### 3.2. Kepler 1643

### 3.3. KOI-7368

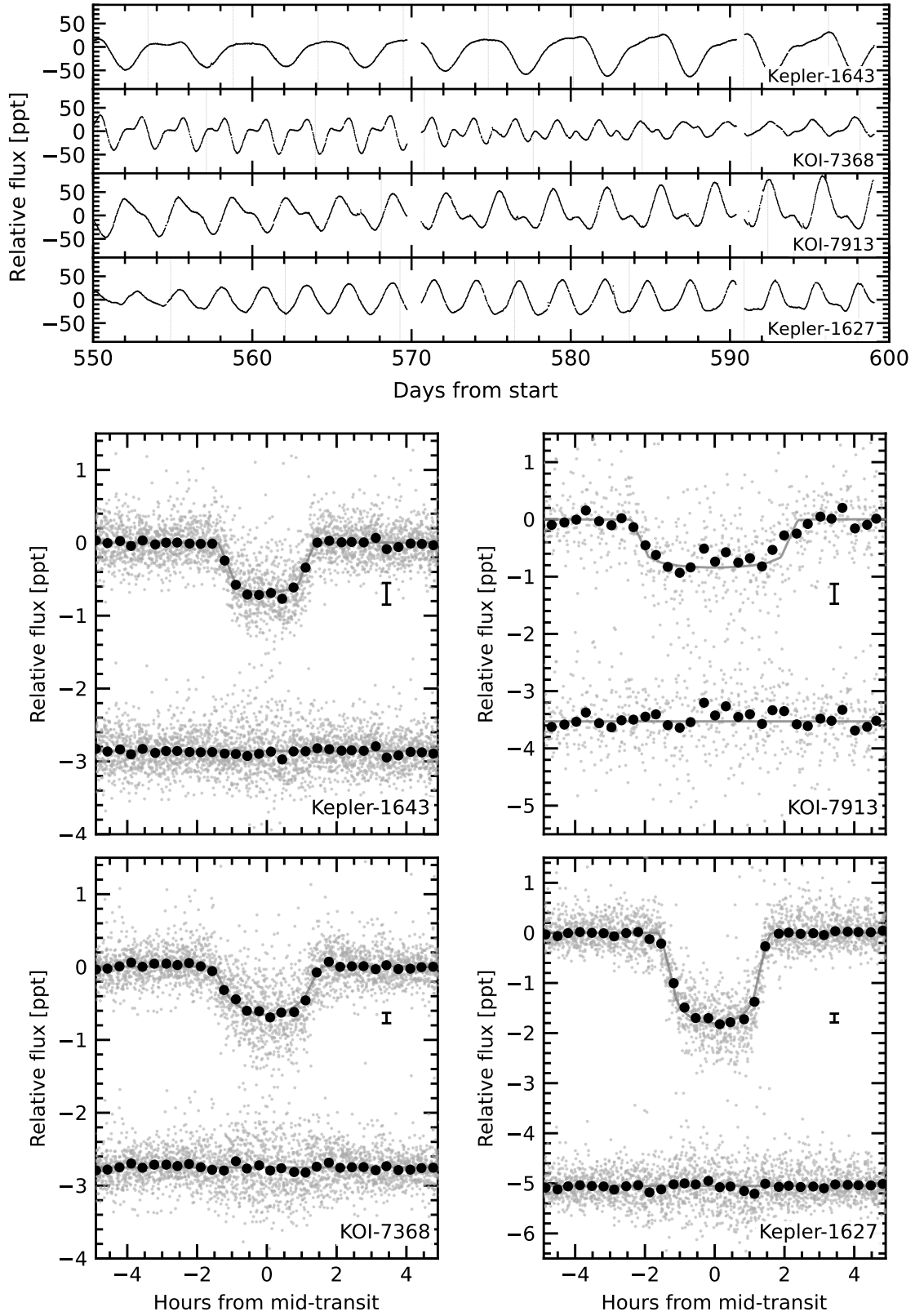


**Figure 2.** The Cep-Her complex is  $38^{+6}_{-5}$  Myr old. The top row shows CAMDs. Left shows CH-2, right shows RSG-5. The bottom left shows gyro (and is a **place-holder** since we might want to add CH-2 and RSG5). The bottom right shows lithium (black points are NGC2547 and IC2602 from Randich+18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

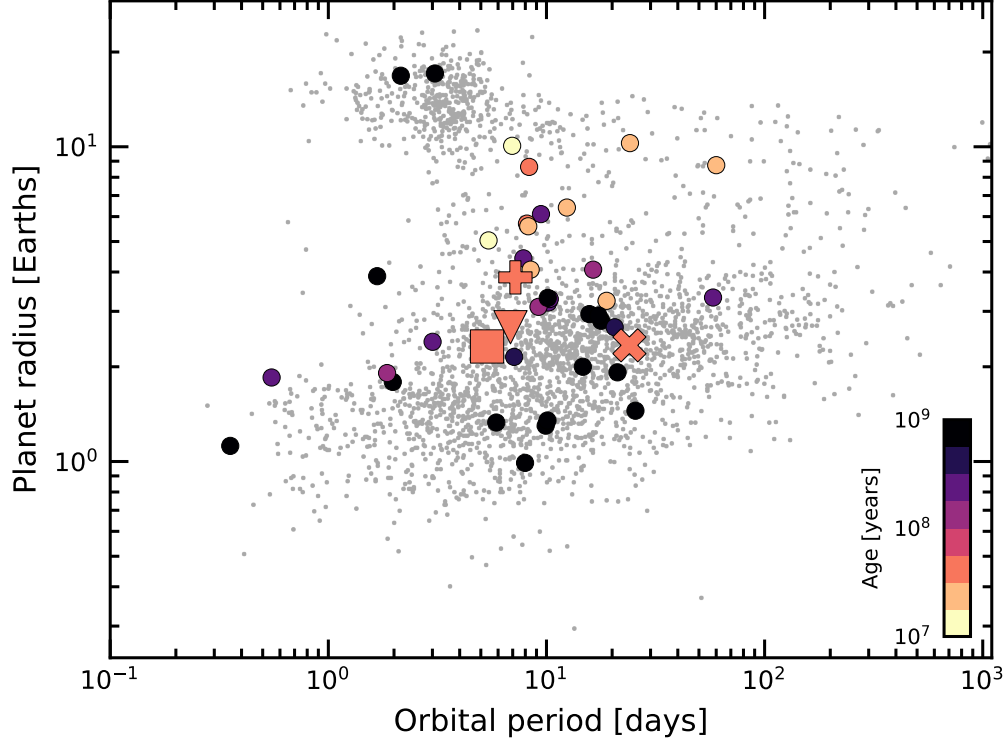
### 3.4. KOI-7913

Is a binary.

## 4. THE PLANETS



**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  $\tau$  is the age and  $\sigma_\tau$  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).

## 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),

*Facilities:* *Astrometry:* Gaia (Gaia Collaboration et al. 2018, 2021). *Imaging:* Second Generation Digitized Sky Survey. Keck:II (NIRC2; [www2.keck.hawaii.edu/inst/nirc2](http://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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