DRAFT VERSION MARCH 1, 2022
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# Three 38 Million Year Old Mini-Neptunes from Kepler, TESS, and Gaia

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(Received 2021 Oct 12; Revised —; Accepted —)

## 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 ($l = 100°$) to Hercules ($l = 40°$), hereafter the Cep-Her complex. This group of stars includes four previously known Kepler Objects of Interest: Kepler-1627 Ab ($R_{\rm p} = 3.85 \pm 0.11\,R_\oplus$, $P = 7.2$ days), Kepler-1643 b ($R_{\rm p} = 2.32 \pm 0.14\,R_\oplus$, $P = 5.3$ days), KOI-7368 b ($R_{\rm p} = 2.22 \pm 0.12\,R_\oplus$, $P = 6.8$ days), and KOI-7913 Ab ($R_{\rm p} = 2.34 \pm 0.18\,R_\oplus$, $P = 24.2$ 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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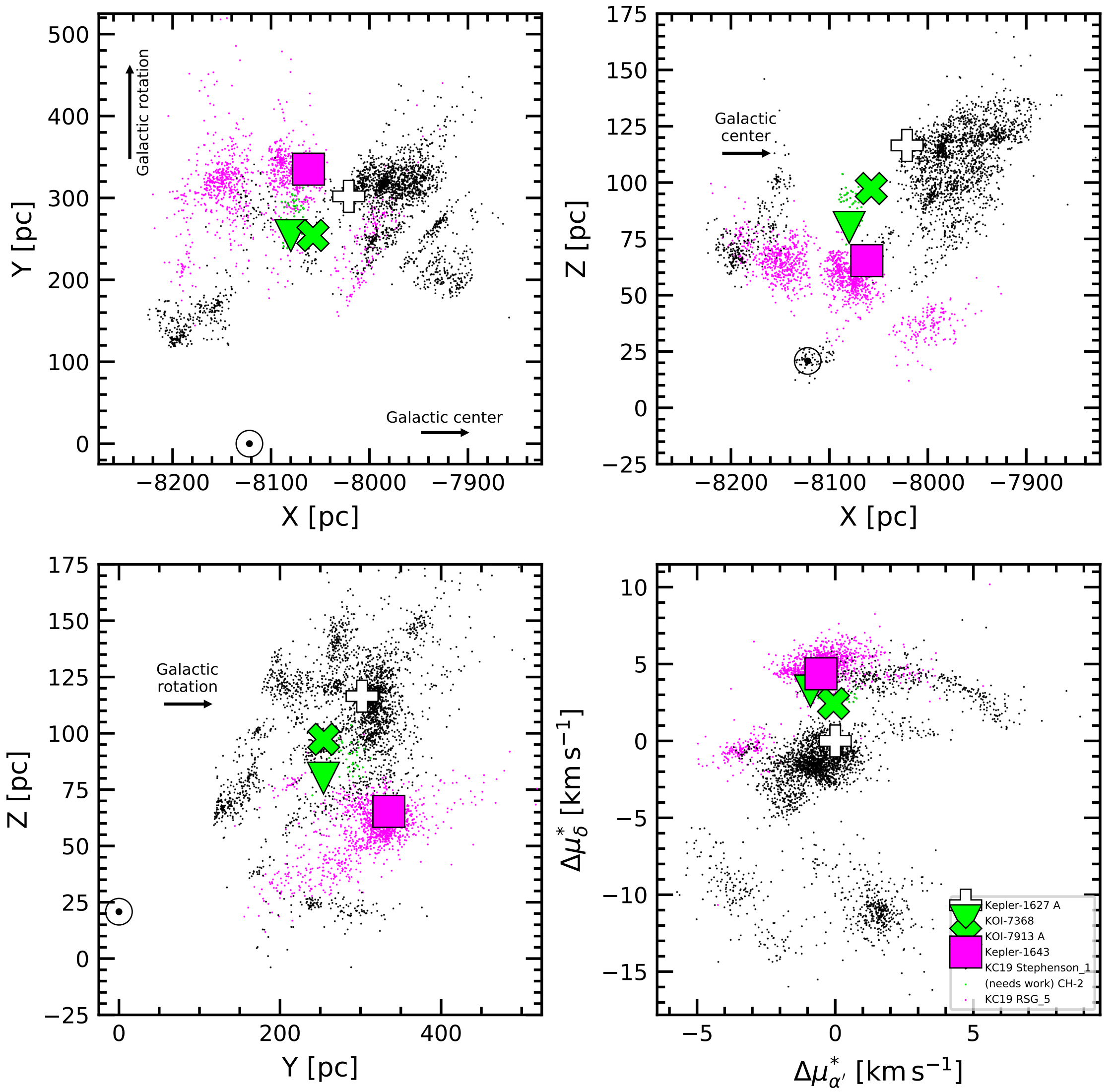


**Figure 1. Galactic positions and tangential velocities of stars in the complex.** Sub-clusters include the $\delta$ Lyr cluster, RSG-5, and the worryingly diffuse "CH-2".

## 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*

### 3.4. *KOI-7913*

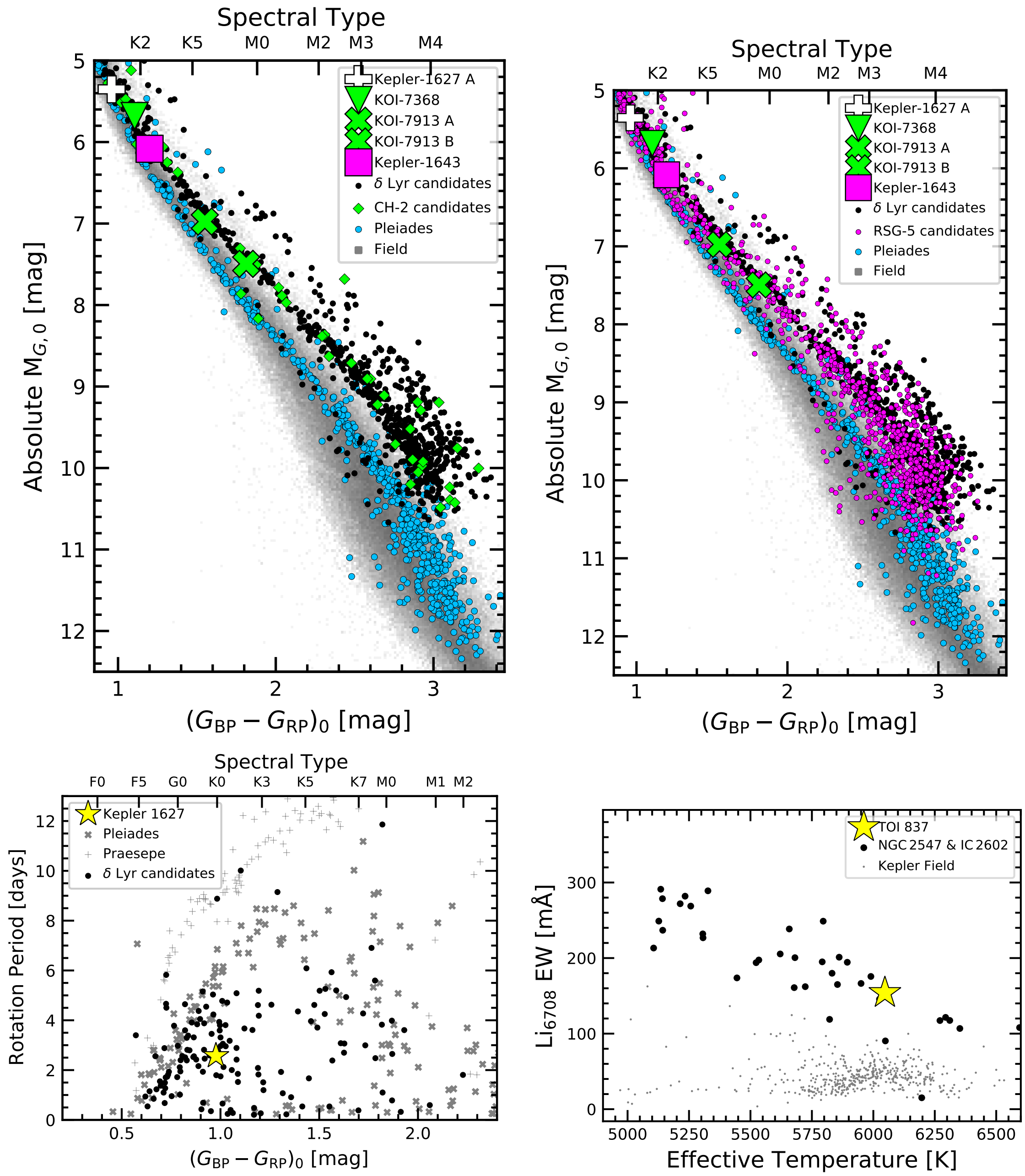


**Figure 2. The Cep-Her complex is $38^{+6}_{-5}$ Myr old.** The top row shows CAMDs. Left shows CH-2, right shows RSG-5. The bottom left shows gyro. The bottom right shows lithium (and is a **place-holder**). (Somewhere we will have H-alpha?).

Is a binary.

## 4. THE PLANETS

## 5. DISCUSSION & CONCLUSIONS

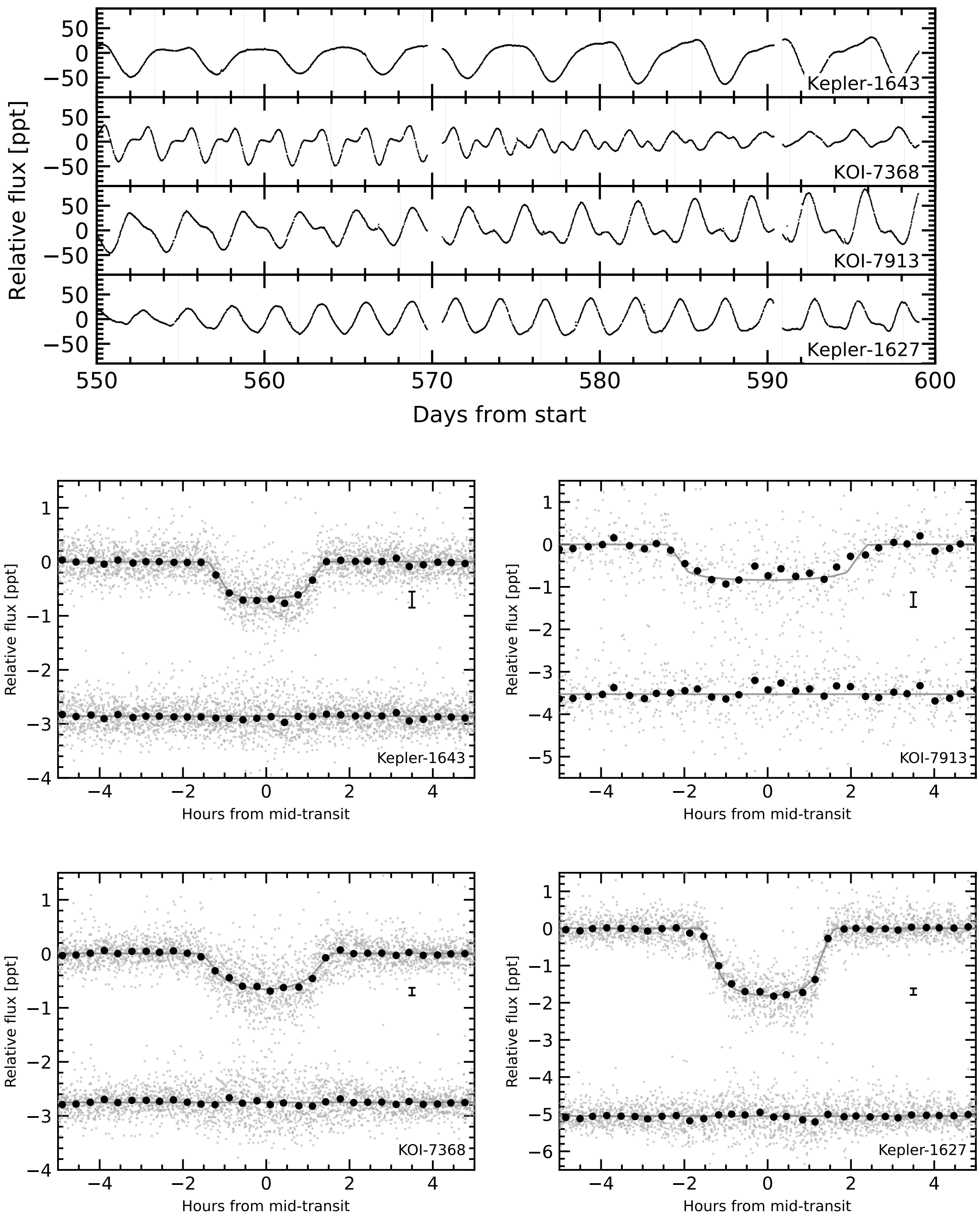


**Figure 3. Raw and processed light curves for the objects of interest.** Top: raw. Bottom: processed. There increases scatter during transit is likely due to starspot crossing events.

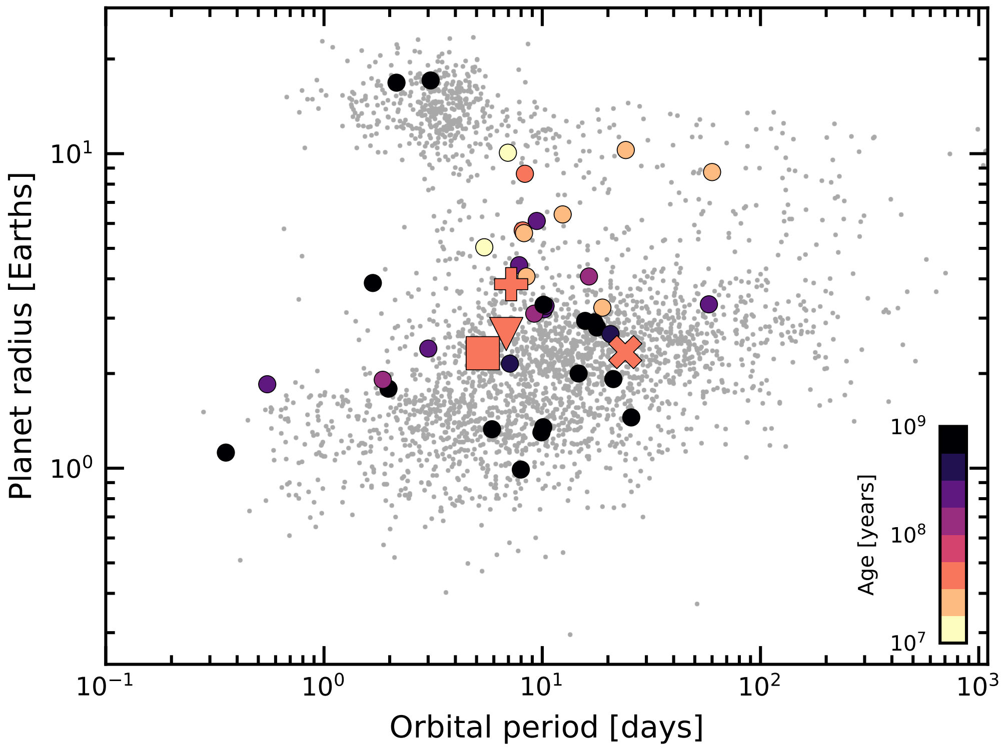


**Figure 4. Radii, orbital periods, and ages of transiting exoplanets**. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where $\tau$ is the age and $\sigma_\tau$ is its uncertainty. Kepler-1627 (+), KOI-7368 (down-triangle), KOI-7913 (X), Kepler-1643 (diamond). The large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

## ACKNOWLEDGMENTS

L.G.B. acknowledges support from the TESS GI Program (NASA grants 80NSSC19K0386 and 80NSSC19K1728) and the Heising-Simons Foundation (51 Pegasi b Fellowship). Keck/NIRC2 imaging was acquired by program 2015A/N301N2L (PI: A. Kraus). This paper also includes data collected by the TESS mission, which are publicly available from the Mikulski Archive for Space Telescopes (MAST). Funding for the TESS mission is provided by NASA's Science Mission directorate. We thank the TESS Architects (G. Ricker, R. Vanderspek, D. Latham, S. Seager, J. Jenkins) and the many TESS team members for their efforts to make the mission a continued success. Finally, we also thank the Keck Observatory staff for their support of HIRES and remote observing. We recognize the importance that the summit of Maunakea has within the indigenous Hawaiian community, and are deeply grateful to have the opportunity to conduct observations from this mountain.

*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). *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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