

## Cluster Difference Imaging Photometric Survey (CDIPS) II. TOI837: A Validated Jupiter-Sized Planet in IC 2602

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### ABSTRACT

We report the discovery of TOI 837.01 and its validation as a transiting planet. We characterize the system using data from the NASA *Transiting Exoplanet Survey Satellite* (TESS), the ESA Gaia mission, ground-based photometry, and spectroscopy from CTIO1.5/CHIRON, MPG2.2/FEROS, and AAT/Veloce. We find that TOI837 is a  $T = 9.9$  G-dwarf in IC 2602 (the “Southern Pleiades”). The star and validated planet are therefore  $30 \pm 20$  million years old. The planet is warm ( $P = 8.32$  d) and roughly Jupiter-sized. However, its transits are grazing:  $b > 0.92$  at  $3\sigma$ . From TESS photometry alone, the planetary size lies within  $0.58\text{--}3.87 R_{\text{Jup}}$ , due to the degeneracy between the planetary size and the impact parameter of the transit. From radial velocity monitoring, we limit the mass of planet to less than  $2.XX M_{\text{Jup}}$  ( $3\sigma$ ). Grazing transits are cause for concern: they usually are indicative of astrophysical false positive scenarios. Our follow-up data show that such scenarios are highly unlikely. Multi-color photometry requires eclipsing companions to have nearly identical color as TOI837, ruling out hierarchical eclipsing binary scenarios. Background eclipsing binary scenarios are limited by speckle imaging, but formally remain a 0.2% possibility. TOI 837.01 is therefore a validated adolescent exoplanet. Further observations of its stellar obliquity, atmosphere, and mass should confirm its planetary nature beyond doubt, and could improve our understanding of how the physical and orbital properties of exoplanets change in time.

**Keywords:** Exoplanets (498), Transits (1711), Exoplanet evolution (491), Stellar ages (1581), Young star clusters (1833)

## 1. INTRODUCTION

Over the first one hundred million years of their lives, exoplanet systems are expected to undergo major physical and dynamical changes. For a typical Sun-like star, the protoplanetary disk disperses within  $\sim 3$  million years (CITE IR + sub-mm results). The planet formation process presumably finishes within this time for gas giants (CITE). The rocky planet population will also be mostly evolved within  $\sim 3$  million years (CITE), but may undergo significant changes over the next  $\sim 10$ -100 million years through giant impacts. The Moon, for instance, is thought to have formed when the solar system was XX million years old through such an impact (CITE).

A number of other processes are thought to happen relatively quickly. Physical changes in the sizes of planets are expected as they contract, and as their atmospheres undergo photoevaporation (*e.g.*, Fortney et al. 2007; Owen & Wu 2013; Fulton et al. 2017). The relative importance of these two processes is set by the planetary mass, as well as the radiation environment. Photoevaporation in particular can be directly observed in *e.g.*, the He 10830Å line (CITE, CITE, He-I or He-II?). Dynamical changes are expected in the semi-major axes, eccentricities, and stellar obliquities of young planets. When the gas disk is present, the planetary semi-major axis is thought to change due to viscous coupling (CITE). High-eccentricity migration processes including planet-planet scattering (CITE), secular chaos (CITE), and Kozai-Lidov oscillations (CITE) can also occur. The circularization timescale is thought to be such that for any giant planets that migrated early, their orbits should circularize within 100 million years (CITE).

Finding and studying systems undergoing these evolutionary changes is a major goal in contemporary exoplanet research. To identify stars younger than say 1 Gyr, a number of direct and indirect methods are available (Soderblom 2010). The traditional approach is to isochronally age-date coeval groups of stars, hereafter “clusters” (*e.g.*, Lada & Lada 2003; Zuckerman & Song 2004; Krumholz et al. 2019). Young field stars can also be identified using age indicators such as stellar rotation periods, the abundance of photospheric lithium, and chromospheric diagnostics such as calcium emission and broadband UV emission. Studies by for instance David et al. (2018) and G. Zhou et al. (2020, submitted) have combined these methods for individual field stars. Many of the latter methods were summarized by Mamajek & Hillenbrand (2008), and have since been calibrated by *e.g.*, Barnes et al. (2015); Meibom et al. (2015); Angus et al. (2015) and Curtis et al. (2019b) for stellar rotation, Žerjal et al. (2017) for chromospheric activity, and *e.g.*, Berger et al. (2018) and Žerjal et al. (2019) for lithium abundances.

A few dozen planets in clusters have been detected, and fewer still have been closely characterized. Despite the chal-

lenges of starspot-induced radial velocity (RV) variations, RV surveys found success in the Hyades, NGC 2523, Praesepe, and M 67 (Sato et al. 2007; Lovis & Mayor 2007; Quinn et al. 2012; Malavolta et al. 2016; Brucalassi et al. 2017). RV surveys of highly active pre-main sequence stars in Taurus also led to the youngest hot Jupiters yet reported (Donati et al. 2016; Johns-Krull et al. 2016; Biddle et al. 2018; Flagg et al. 2019).

The transit method was comparatively slow to catch up. Early deep transit searches of open clusters by many groups did not yield definitive planet detections (Mochejska et al. 2005, 2006; Burke et al. 2006; Aigrain et al. 2007; Irwin et al. 2007; Miller et al. 2008; Pepper et al. 2008; Hartman et al. 2009). These searches were typically sensitive to planets larger than Jupiter, on  $\lesssim 3$  day orbital periods. Hot Jupiter occurrence rate limits were derived at the  $\lesssim 5\%$  level (*e.g.*, Burke et al. 2006; Hartman et al. 2009). The modern 0.5-1% occurrence rate suggests that these early transit surveys needed a greater data volume, at higher precision for detection to be possible (Mayor et al. 2011; Wright et al. 2012; Howard et al. 2012; Petigura et al. 2018).

Kepler observed a large enough number of stars with sufficient baseline and precision to detect transiting planets in open clusters: Kepler-66b and 67b, in the gigayear-old NGC 6811 (Borucki et al. 2010; Meibom et al. 2013). Though a broken reaction wheel ended the prime Kepler mission, the repurposed K2 (Howell et al. 2014) switched between fields along the ecliptic every quarter-year, and was able to observe far more clusters and young stars.

The discoveries made by K2 through its surveys of Taurus, the Hyades, Praesepe, and Upper Sco were a major inspiration for the present work (*e.g.*, Mann et al. 2016a; Obermeier et al. 2016; Mann et al. 2017; Vanderburg et al. 2018; Ciardi et al. 2018; Livingston et al. 2018; Mann et al. 2018; Rizzuto et al. 2018; Livingston et al. 2019). Observations with K2 convincingly showed that at least some close-in planets must form within about 10 Myr (Mann et al. 2016b; David et al. 2016). They also led to the first hints that young planets may in fact be qualitatively different from their field counterparts. For instance, based on its observed mass, radius, and UV environment, the 700 Myr K2-100b is probably actively losing its atmosphere, and should become a bare rocky planet over the next few hundred Myr (Mann et al. 2017; Barragán et al. 2019). The four transiting planets in V1298 Tau (23 Myr) are also likely to be actively photoevaporating, and could represent a precursor to Kepler’s compact multiple systems (David et al. 2019a,b).

With the aim of advancing the young planet census, we have been using data from the TESS spacecraft (Ricker et al. 2015) to perform a Cluster Difference Imaging Photometric Survey (CDIPS; Bouma et al. 2019). Our targets in this survey are candidate young stars that have been reported in the literature. At the time writing, of order

$6 \times 10^5$  light curves from the first year of TESS observations have been reduced, and are available at MAST<sup>1</sup> through [DOI.ORG/10.17909/T9-AYD0-K727](https://doi.org/10.17909/T9-AYD0-K727). Searching these light curves yielded the candidate transiting planet, TOI 837.01, that is the subject of this analysis.

Section 2 describes the identification of the candidate, and the follow-up observations collected. Section 3 combines these data to assess the system’s false positive probability, and finds that TOI 837.01 is almost certainly a planet. Section 4 presents our knowledge of the cluster (Section 4.1), the star (Section 4.2) and the planet (Section 4.3). We conclude by discussing avenues for improved characterization in Section 5.

## 2. IDENTIFICATION AND FOLLOW-UP OBSERVATIONS

### 2.1. TESS Photometry

TOI 837 was observed by TESS from 26 March 2019 until 20 May 2019, during the tenth and eleventh sectors of science operations (Ricker et al. 2015). The star was designated TIC 460205581 in the TESS Input Catalog (Stassun et al. 2018, 2019). Pixel data for an  $11 \times 11$  array surrounding the star were averaged and saved at 2-minute cadence. The  $2048 \times 2048$  image from the entire CCD was also averaged into 30-minute stacks, and saved as a “full frame image” (FFI).

The TESS project detected the transits in the 2-minute data and the community was alerted on 17 June 2019. While our CDIPS FFI light curves also show the transits, the 2-minute data have better sampling cadence, and so we opted to use the Presearch Data Conditioning (PDC) light curve with the default aperture for our analysis (Jenkins et al. 2016; ?).

Figure 1 shows the data. The dominant modulation induced by starspots coming into and out of view has a peak-to-peak amplitude of about 2.3%, and a period of about 3 days. The dips suggestive of a grazing transiting planet recur roughly every 8 days, and have a depth of about 0.4%. A few flares are visible. A phase-folded version of the TESS transits with starspot variability removed is shown in Figure 2, and is described in depth in Section 4.3.

### 2.2. Gaia Astrometry and Imaging

Between 25 July 2014 and 23 May 2016, the ESA Gaia satellite measured about 300 billion centroid positions of 1.6 billion stars. The positions, proper motions, and parallaxes of the brightest 1.3 billion were calculated for the second data release (DR2) (Gaia Collaboration et al. 2016; Lindegren et al. 2018; Gaia Collaboration et al. 2018). TOI 837 was assigned the Gaia DR2 identifier 5251470948229949568, and had 276 “good” astrometric observations. Its brightness was measured in the  $G$ ,  $R_p$ , and  $B_p$  bands of the Radial Velocity Spectrometer (Cropper et al. 2018; Evans et al. 2018).

The Gaia imaging, as represented by its point-source catalog, provides the initial context for analyzing the TESS data.

Stars brighter than  $T = 16$ , as queried from the Gaia DR2 source catalog, are shown with orange circles in Figure 3, overlaid on the DSS2 plates and TESS image. Given its galactic latitude of  $b = -6^\circ$ , it is not surprising that the field of TOI 837 is crowded. The stars that were of immediate concern for our false positive analysis were as follows.

- TOI 837  $\equiv$  TIC 460205581 ( $T = 9.9$ ). The target star.
- Star A  $\equiv$  TIC 847769574 ( $T = 14.6$ ),  $2.3''$  west. The proper motions and parallax of this star imply it is co-moving with TOI 837, though with a physical separation of  $6.6 \pm 0.1$  pc, it may not be bound.
- Star B  $\equiv$  TIC 460205587 ( $T = 13.1$ ),  $5.4''$  north. The Gaia parallax implies this is a giant background star.

An additional source, TIC 847769581, is  $4.9''$  from the target, but too faint ( $T=18.8$ ) to be the source of the observed transit signal.

The Gaia DR2 data for Star A seems poorly behaved. While Star A has  $G = 15.1$ , and  $B_p = 14.9$ , no  $R_p$  magnitude is reported. Correspondingly, no RUWE<sup>2</sup> value is available. The astrometric reduced  $\chi^2$  ( $\chi^2/(N-5)$ , for  $N$  the number of good astrometric observations) seems rather poor, at 8.6. We suspect that the photometric failure to produce an  $R_p$  magnitude, as well as the poor astrometric fit, are likely due to blending with TOI 837.

At the  $\approx 1'$  resolution of the TESS data, if either Star A or Star B were eclipsing binaries, they could be the sources of the transit signal. A detailed analysis of ground-based seeing-limited photometry was necessary to assess and rule out this possibility (Section 2.4).

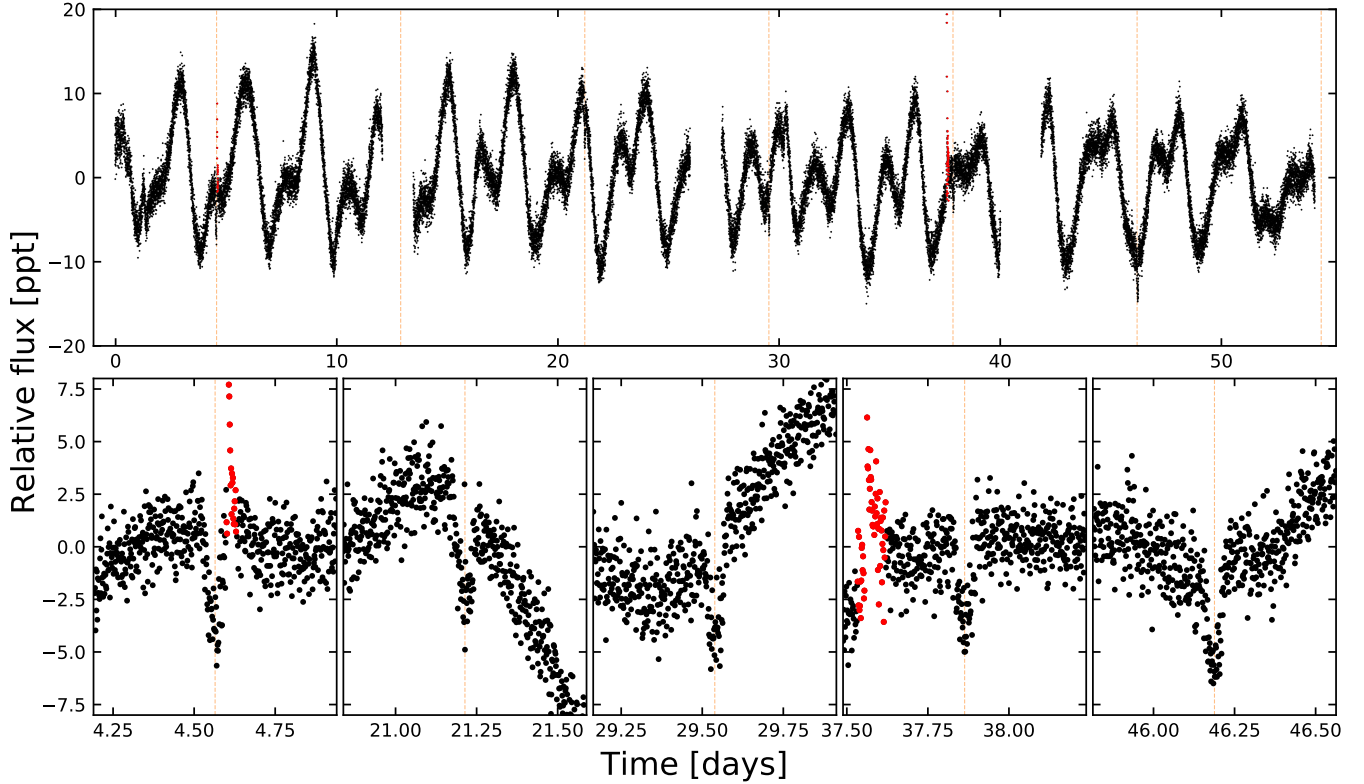
### 2.3. High-Resolution Imaging

To determine if any fainter point sources existed closer to TOI 837 inside of Gaia’s point-source detection limits, we acquired high-resolution speckle images. We then searched the autocorrelation functions of these images for peaks indicative of nearby companions.

**Carl TODO: please describe and correct as appropriate** The observations of TOI 837 were initially acquired by Ziegler et al. (2020) as part of the Southern Astrophysical Research (SOAR) TESS Survey using the High Resolution Camera (HRCam; Tokovinin 2018). The HRCam  $I$ -band filter is described by Tokovinin (2018). The points in Figure 4 show the resulting measured  $5\text{-}\sigma$  detectable contrasts. The lines are linear smoothing fits between the regimes of the diffraction limit, the “knee” at  $\approx 0.2''$ , and the slow decrease until  $\approx 1.5''$ , beyond which the speckle patterns become de-correlated. Star A (TIC 847769574) was detected at the expected location and brightness contrast, and no additional companions were found.

<sup>1</sup> [ARCHIVE.STSCI.EDU/HLSP/CDIPS](https://archive.stsci.edu/hlsp/cdips)

<sup>2</sup> See the Gaia DPAC technical note GAIA-C3-TN-LU-LL-124-01, [http://www.rssd.esa.int/doc\\_fetch.php?id=3757412](http://www.rssd.esa.int/doc_fetch.php?id=3757412), accessed 2020-06-22.



**Figure 1. TESS light curve of TOI 837 from Sectors 10 and 11.** *Top:* PDCSAP median-subtracted relative flux at 2-minute sampling in units of parts-per-thousand ( $\times 10^{-3}$ ). Spot-induced stellar variability is the dominant signal. Dashed lines show the five transits observed by TESS. *Bottom:* Zoomed windows of individual transits. Red points are manually identified stellar flares.

#### 2.4. Ground-based Time-Series Photometric Follow-up

We obtained ground-based seeing-limited time series photometric observations of TOI 837 bracketed around the times of transit. These observations confirmed that the transits occurred on-target to within  $\approx 2''$ , and that they were achromatic. Both features are essential for our ability to eliminate false-positive scenarios.

##### 2.4.1. El Sauce 0.36m

We observed four transits with the 0.36m at Observatorio El Sauce, located in the Río Hurtado Valley in Chile, and operated by co-author P. Evans. The observations were obtained in Cousins-R band on the nights of 1 April 2020 and 26 April 2020, Cousins-I band on the night of 21 May 2020, and Johnson-B band on the night of 14 June 2020. The final 14 June transit began shortly after twilight.

**Phil + Karen TODO: please correct as appropriate** We scheduled the observations using **SOFTWARE** (CITE). The photometric data were calibrated and extracted using the AstroImageJ software package (Collins et al. 2017). Comparison stars of similar brightness were used to produce the final light curves, each of which showed a roughly 4ppt dip near the expected transit time. We produced and examined light curves with at custom positions and with custom aperture sizes, and...

The data were reduced using... (e.g., astroimageJ)

**LGB TODO: Describe custom analysis of apertures**

##### 2.4.2. ASTEP400

**Amaury TODO: please correct as appropriate** We observed N transits with the 0.40m ASTEP 400 telescope at Concordia Station, located at Dome C on the Antarctic Plateau (Daban et al. 2010). ASTEP 400 has a dichroic that sends blue wavelengths to a guiding camera, and red wavelengths to a filter-free science camera with wavelength sensitivity roughly akin to R band. The observations were acquired on the nights of **DATE 1** and **DATE 2**. The outdoor temperature was a balmy **XX** $^{\circ}$ . The data were reduced using **XX** software, and showed the transit roughly at the expected time and depth.

#### 2.5. Spectroscopic Follow-up

##### 2.5.1. CHIRON

9 spectra with CTIO1.5/CHIRON, from January 28 through March 14, 2020. 6 were usable.

##### 2.5.2. FEROS

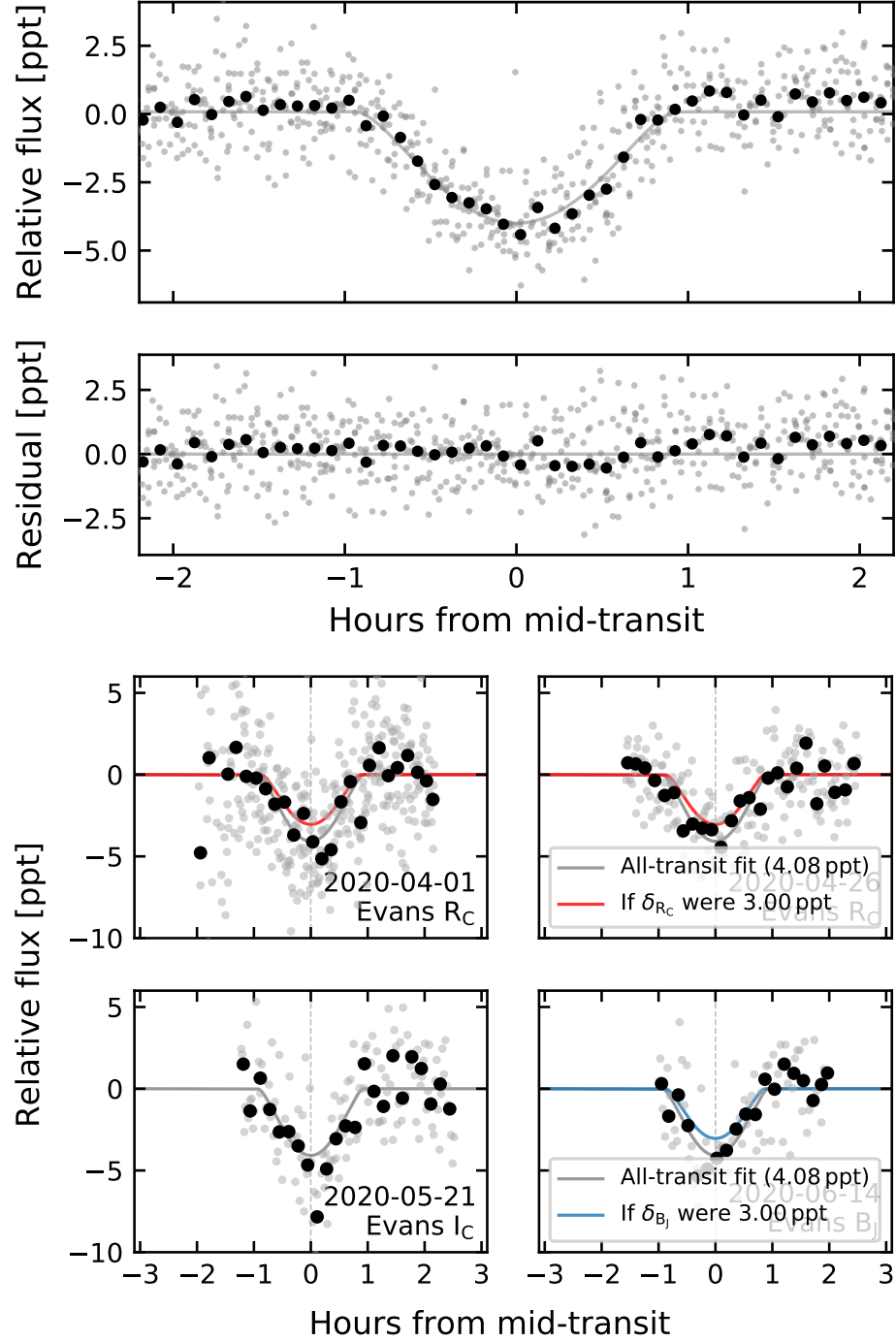
N spectra with XXX/FEROS

##### 2.5.3. Veloce

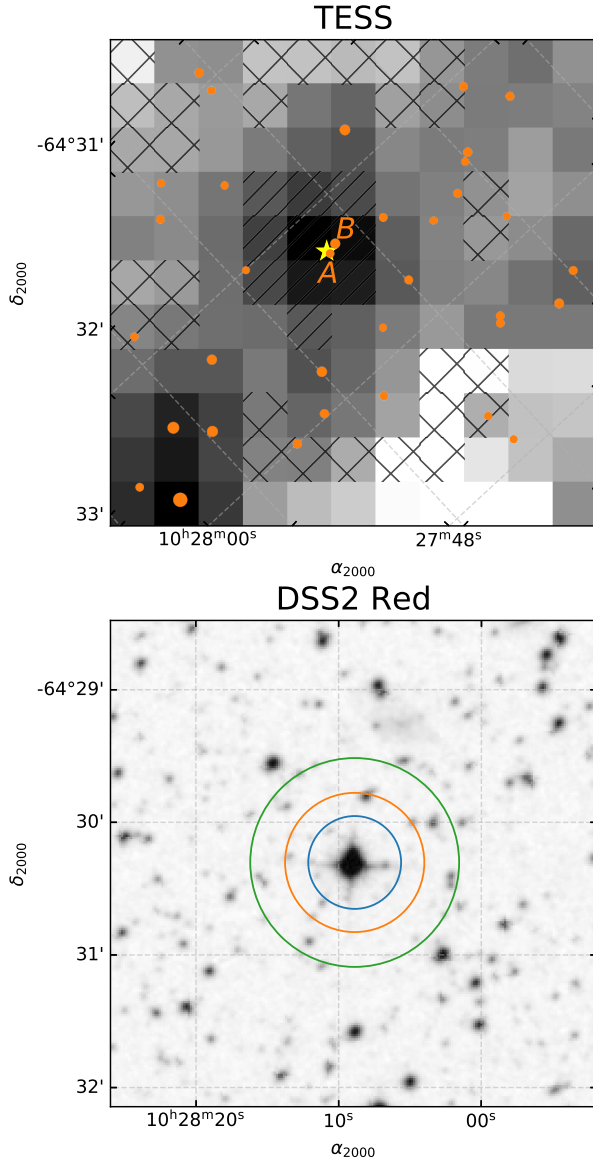
M spectra with AAT/Veloce.

### 3. ELIMINATION OF FALSE POSITIVE SCENARIOS



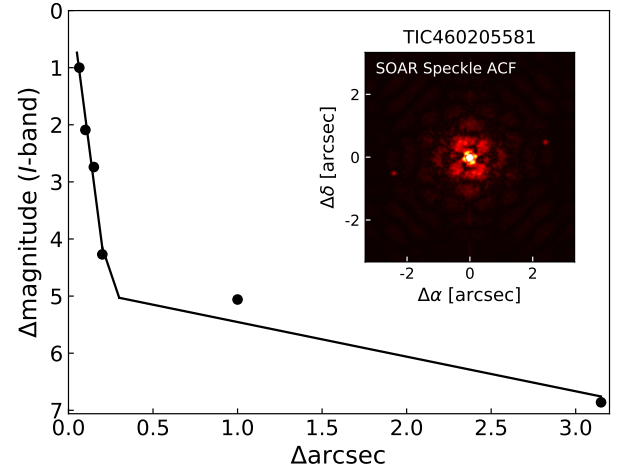


**Figure 2. Joint TESS and multicolor photometry.** *Top:* Phase-folded TESS transit. Gray points are 2-minute PDCSAP flux measurements, detrended with a 0.3-day robust Huber spline (see Section 2.1). Black points are binned to 6 minute intervals. The line shows the transit model corresponding to the median transit parameters (Table 2). *Bottom:* Multicolor photometry from the El Sauce 0.36m. The consistent transit depths between TESS-band and the bluer Cousins-R and Johnson-B bandpasses rules out select false positive scenarios.

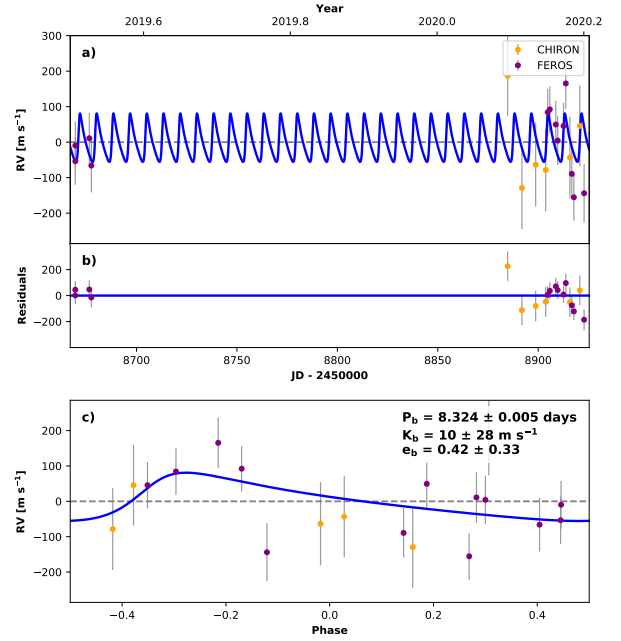


**Figure 3. Scene used for blend analysis.** *Top:* Mean TESS image of TOI 837 over Sector 10, with a logarithmic grayscale. The yellow star is the position of TOI 837. Orange circles are neighboring stars with  $T < 16$ , scaled such that brighter stars are larger. The X and / hatches show the apertures used to measure the background and target star flux, respectively. Dashed lines of constant declination and right ascension are shown. *Bottom:* Digitized Sky Survey  $R$ -band image of the same field, with a linear grayscale. The circles show apertures of radii 1, 1.5, and 2.25 pixels used in our blend analysis (Section ??). Two stars of interest are “Star A” and “Star B”, which were eventually excluded as being possible sources of the transits.

Validation is the process of statistically arguing that a transit-like signal is due to a planet rather than an astrophysical false positive. (CITE blender, Torres+04,05,10; vespa Morton 12, 15; pastis Diaz+14 Santerne+15; triceratops Gialalone & Dressing 20).



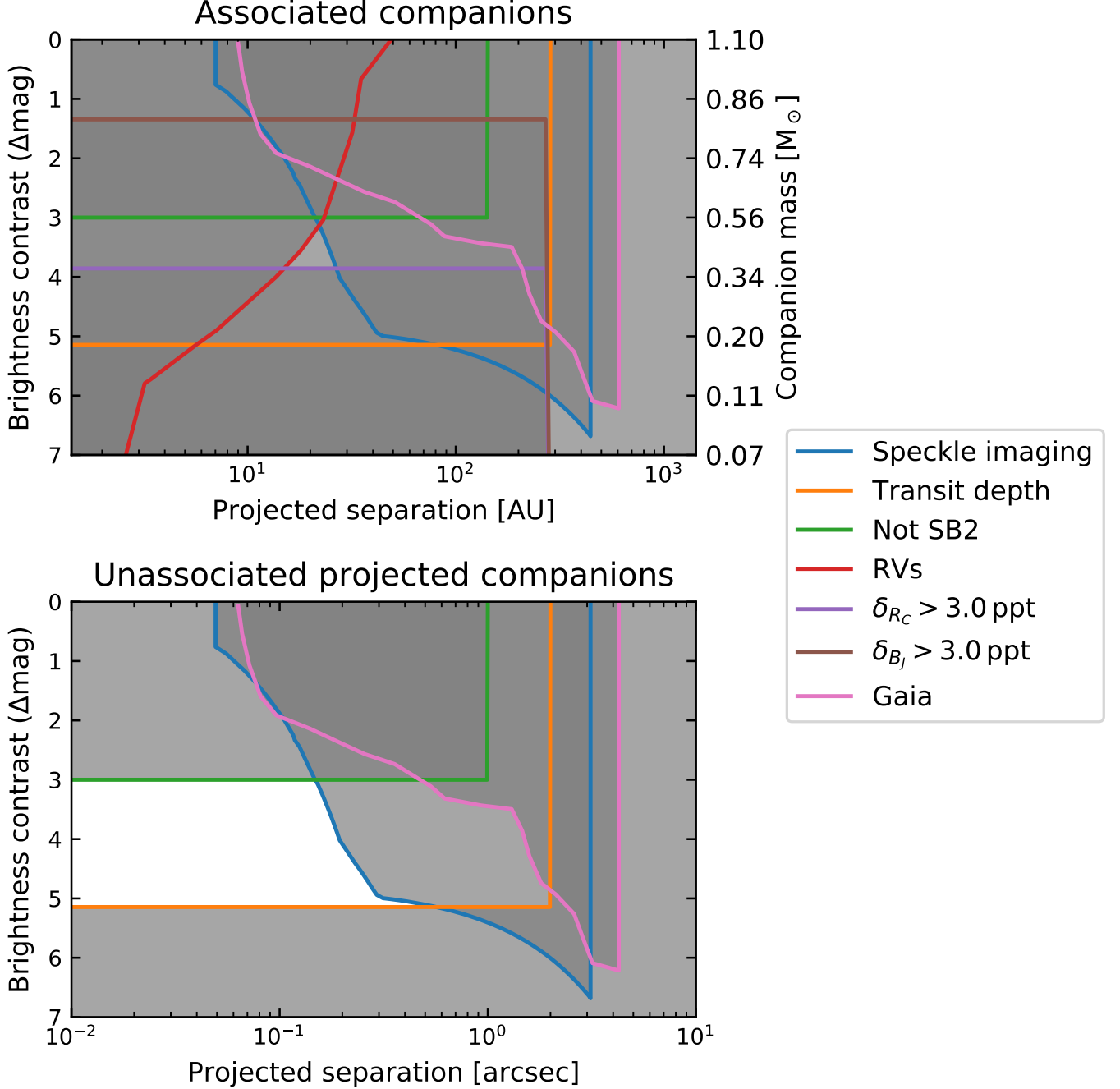
**Figure 4. SOAR HRCam contrast limits derived from point-source injection-recovery experiments.** Star A ( $\Delta T = 4.7$ ,  $\rho = 2.3''$  west) is detected in the autocorrelation function, in addition to being a resolved Gaia source. It is co-moving with TOI 837, and its parallax and on-sky position imply that it is physically separated from TOI 837 by  $6.6 \pm 0.1$  pc.



**Figure 5. Radial velocities.**

Many validation analyses are inherently flawed because they do not deal with the fact that you are conditioned on having observed many stars, and having found an eclipsing system.

Figure 6 provides a visual summary of the possible astrophysical false positive scenarios. If the TOI 837 signal is not planetary, it must come from the near-total eclipse of a background star (a BEB), or else a hierarchical companion of the primary star (an HEB). It must also be verified that to the angular resolution possible, the transit signal originates from



**Figure 6. Astrophysical false positive scenarios.** *Top:* for bound companions, *Bottom:* for unassociated companions along the same line of sight.

TOI 837, and not a neighboring star (an NEB). We proceed by describing each constraint in detail.

### 3.1. Limits on Companions from the Transit Depth

In HEB and BEB scenarios, the flux from TOI 837 and the true eclipsing binary host would blend together, reducing the “true” eclipse depth  $\delta_{\text{true}}$  to produce the observed depth  $\delta_{\text{obs}}$ :

$$\delta_{\text{obs}} = \delta_{\text{true}} \frac{F_{\text{neighbor}}}{F_{\text{total}}}, \quad (1)$$

where the total flux and the flux from the neighbor are labelled as such. The requirement that the eclipse is produced by stars and that  $\delta_{\text{true}} < 0.5$  translates to a bound on the faintest possible blended companion stars:

$$\Delta m < -\frac{5}{2} \log_{10} \left( \frac{0.5}{\delta_{\text{obs}}} \right). \quad (2)$$

For TOI 837 ( $T = 9.93$ ), this implies that any stellar companion invoked to explain the transit depth must be brighter than  $T = 15.07$ .

Typically, the shape of the transits enables this argument to be scaled to even more restrictive depths (e.g., CITE Seager 2003, Vanderburg+2019, Rizzuto+2020, David+2018 1298Tau). However, since the transits of TOI 837 are grazing, these arguments do not apply.

### 3.2. Limits on Companions from Imaging

#### 3.2.1. Gaia Imaging

*empty*

#### 3.2.2. Speckle Imaging

We convert the contrast ratios obtained through the SOAR imaging to constraints on the masses of putative companions following Montet+2014 (CITE and others!). We employed the Baraffe+2003 models for substellar mass objects and the MESA isochrones for stellar mass objects (Choi et al XXXX). We assumed that the system age was 35 Myr, to ensure that companions would be at a plausible state of contraction.

Due to the specific filters of the SOAR HRCam imager, we further assumed that all sources had blackbody spectra. While this is clearly false, we do not readily have access to the planetary and stellar atmosphere models needed for the correct calculation. However, the Baraffe+2003 and MESA models do report effective temperatures and bolometric luminosities. We opt to use these theoretical quantities, combined with the measured transmission functions, to calculate the absolute magnitudes in the HRCam bandpasses (CITE Tokovinin 2018 summary paper with the bandpasses).

#### 3.2.3. Patient Imaging

Archival SERC-J and AAO-SES plates are available for the TOI 837 field<sup>3</sup>. These plates were acquired in 1982 and 1992, respectively. For high proper motion stars archival imagery can be used to detect slowly moving background stars that might be an astrophysical false-positive source (e.g., Huang et al. 2018, CITE VANDERBURG 19). However TOI 837 has only moved  $\approx 0.7''$  between 1982 and present, in comparison to the  $\approx 2.0''$  FWHM of the target on the plates. We therefore cannot resolve it with great confidence from background sources not already resolved through more modern imaging.

### 3.3. Limits on Companions from Radial Velocities

The combined radial velocities from FEROS, CHIRON, and Veloce can be used to place limits on the presence of massive, close-in bounds companion to TOI 837.

We derived the relevant limits using `radvel` (Fulton et al. 2018). We assumed circular orbits for the massive companion. We then fitted the RV data for the semiamplitude, period, time of conjunction, instrument offsets, and jitter parameters. We placed a wide log-uniform prior on the semiamplitude and period to ensure appropriate sampling of the relevant spaces. ( $\log K \sim \mathcal{U}(1, 10^5)$ ,  $\log P \sim \mathcal{U}(0.1, 10^{15})$ ).

We then converting the resulting posterior in period and semiamplitude to minimum mass and semi-major axis assuming Kepler's third law. The resulting  $3\sigma$  limits are shown in Figure 6.

### 3.4. Limits on Companions from Time-Series Photometry

#### 3.4.1. TESS

We examined the CDIPS FFI light curves of the target, which are available on MAST (Bouma et al. 2019). Three light curves are available, based on photometric apertures with a radius of 1, 1.5, or 2.5 pixels. In the raw difference-image light-curves, as well as the PCA-detrended light-curves, dips of depth  $\approx 0.35\%$  are visible, and their properties do not significantly vary with aperture size. Within  $\approx 20''$ , the dips are consistent with originating from the target star.

#### 3.4.2. Custom Apertures on Ground-Based Time-Series Photometry

A total eclipse of Star A would produce a 1.4% dip. A 30% eclipse, more plausible for a NEB scenario, would produce dips of exactly the right depth (0.4%).

To assess this possibility with the ground-based photometry, we produced light curves centered on TOI 837 with circular apertures of radii ranging from  $0.7''$  to  $5.1''$ . We did not detect any statistically significant variation in the depth of the transits.

We also created light curves with a custom set of  $r = 2.1''$  apertures with positions ranging from Star A ( $2.3''$  west of TOI 837) to  $2.3''$  east of TOI 837. We did not detect any variation of the transit depth along this line of light curves, as would be expected if Star A were the eclipse host. The apertures east of TOI 837 are particularly constraining, as they exclude over 90% of the flux from Star A. The eclipse on Star A would therefore need to be excessively deep to produce the observed eclipse depth. We take this to indicate that TOI 837 is the source of the transit signal to within  $\approx 2.0''$ .

<sup>3</sup> [https://archive.stsci.edu/cgi-bin/dss\\_form](https://archive.stsci.edu/cgi-bin/dss_form)



### 3.4.3. Color Photometry

HEB and to a lesser extent BEB scenarios can be limited by color photometry. In the absence of color photometry, the most plausible HEB scenarios for TOI 837 involve pairs of eclipsing M dwarfs (Figure 6). These eclipses are redder than eclipses of the G-dwarf TOI 837. Observations that the transit depth does not decrease going to blue bands therefore limits the plausibility of these scenarios.

*Simple Example*—As a simple example, assume  $M_2 = M_3 = 0.2M_\odot$  in a twin HEB. Assume PMS evolution, and use MIST isochrones for a 35 Myr system to convert between stellar properties. Take transmission functions (filters only; no instrument or atmosphere response) from the SVO filter profile service<sup>4</sup>. Integrate up blackbody functions over each bandpass for each star, and get estimates of the eclipse depths if there were a total eclipse (of either of the secondary or tertiary) with this set of parameters. The apparent eclipse depths in various Bessel and Cousins bandpasses are:

$$\begin{aligned}\delta_{U_B} &= 5.03 \times 10^{-4} \text{ (Bessel U)} \\ \delta_{B_B} &= 1.39 \times 10^{-3} \text{ (Bessel B)} \\ \delta_{V_B} &= 3.31 \times 10^{-3} \text{ (Bessel V)} \\ \delta_{R_C} &= 5.59 \times 10^{-3} \text{ (Cousins R)} \\ \delta_{I_C} &= 9.69 \times 10^{-3} \text{ (Cousins I)} \\ \delta_T &= 9.18 \times 10^{-3} \text{ (TESS)}\end{aligned}\quad (3)$$

Our chief interest is the relative depths, because geometry lets all the depths be scaled to match the observed TESS depth of  $\approx 43$  ppt. (In this case, all depths would be scaled down by a multiplicative factor of 2.1).

The crucial point is that the bluest bands—U and B—are roughly 10 times shallower than TESS-band, because the M dwarf blackbody function turns over at 2 times longer wavelengths than the G dwarf blackbody (Wien’s law).

Therefore if TOI 837 were a hierarchical eclipsing M dwarf pair, Phil’s two R-band observations should have shown eclipses a factor of 1.64x shallower than TESS observed (so, 24ppt, instead of the 40ppt observed). So, the 40 (+/- 10ish) ppt R-band depths seen in Phil’s transits vs TESS-band argue for a planet, but the level of confidence could probably be improved with U or B.

*Limits on Masses of Bound Companions*—With this intuition in place, we derived the limits on masses of bound hierarchical eclipsing companions as follows. We assumed that each system was composed of the primary (TOI 837), plus a tertiary companion eclipsing a secondary companion every 8.3 days.

For secondary masses ranging from 0.07 to  $1.10 M_\odot$ , and mass ratios ( $M_3/M_2$ ) from 0.1 to 1, we then calculated the observed maximal eclipse depth of Star 3 in front of Star 2 in a number of bandpasses. As before, we interpolated between mass, effective temperature, and radius assuming the MIST

isochrones for a 35 Myr old system, and also assumed that each source had a blackbody spectrum.

We excluded systems for which the maximal eclipse depth in TESS-band was less than the observed depth (*i.e.*, systems for which the tertiary was too small). For the systems with maximal eclipse depths in TESS-band greater than the observed TESS-band depth, we then calculated the multiplicative factor required to shrink the depth (from the  $b = 0$  case) to match the observed eclipse depth in the TESS-band. We then scaled the depths in each of the other bandpasses by this fixed geometric factor.

We then asked: given a fixed secondary mass, are there any tertiary companions for which the expected  $\delta_{R_C}$  is larger than the observed  $R_C$ -band depth? In cases for which the answer was yes, we could not rule out such hierarchical eclipsing binary systems. Conversely, we were able to rule out systems for which at fixed secondary mass no tertiary mass would enable eclipses (in  $R_C$ -band) of the necessary depth.

For a lower limit on  $\delta_{R_C}$  of 32 parts per thousand, we found that the transition between systems that would produce eclipses that no matter what were “too red”, and systems that would produce eclipses that could be sufficiently blue happens in TOI 837 (for  $R_C$ -band) at  $0.54M_\odot$ . The corresponding limit is shown in Figure 6.

**If we could obtain a similar limit in B-band, it would solidify this result (because it would drive the HEB system to be even bluer).**

*Limits on Masses of Projected Companions*—Ignoring the effects of interstellar reddening, the constraint that  $M_2 \gtrsim 0.54M_\odot$  based on colors applies to background eclipsing binaries as well. However, the blue eclipses produced by such systems (*e.g.*, a background G2V+K6V binary) can be kept while making the systems fainter by moving them to greater distances. The only way to definitively rule out such scenarios is to prove that the loss of light is from the target star, for instance by detecting the Rossiter-McLaughlin effect during a transit.

Such scenarios are somewhat contrived in that since no secondary eclipse is observed, they require either eccentric orbits to avoid secondary eclipses, or else a background twin binary system at double the orbital period.

<sup>4</sup> <http://svo2.cab.inta-csic.es/theory/fps/>

### 3.4.4. Summary

Possible false-positive scenarios are as follows.

- *Neighboring blends.* Ruled out to within 2 arcseconds by Phil Evans.
- *Hierarchical blends.* Limited by i) FEROS + Veloce RVs, and ii) speckle imaging. Multicolor photometry also limits.

At present our data do not rule out the presence of bound companion stars from  $\approx 10$ – $100$  AU, with masses in the range of  $\approx 0.15$ – $0.25 M_{\odot}$  (Figure 6). Roughly 2–3% of Sun-like stars in the solar neighborhood with binary companions have companions in this region of parameter space (assuming the Raghavan+2010 CITE log-normal binary separation distribution, and a uniform companion mass function.)

Companion statistics for hierarchical triples are somewhat less robust, but they have been studied, for instance by CITE Tokovinin 2014. CITE Tokovinin 2014 found that 7% of Sun-like stars are hierarchical triples with two companions in the compact orbit (the “ $L_{12}$ ” configuration, rather than the “ $L_{11}$ ” configuration of say,  $\alpha$  Centauri). A priori then, given a Sun-like primary, the probability that it is in a hierarchical triple configuration in which the outer orbit satisfies the mass and semi-major axis constraints of Figure 6 is  $\approx 7\% \times 3\% = 0.2\%$ . This is independent of the issue that the inner pair would require finely tuned orbital parameters (i) to eclipse, and (ii) to be so compact.

- *Background blends.* An argument on the a priori probability of background blends follows from counting statistics. Within 360 arcseconds, there are 298 T<16 stars in TIC8 (i.e., Gaia DR2). At 2.0 arcseconds, SOAR archives  $\text{dmag}(I)$  of 6. Inside of 2 arcseconds, we expect  $\pi r^2$  times ( $N_{\text{star}}$  per sq arcsec) =  $9e-3$  T<16 stars. Any with  $T \gtrsim 15$  outside of 0.3 arcseconds would have been detected by SOAR, which brings down the expected number of possible hidden sources by a factor of a few. Within 0.3 arcseconds, where SOAR gets worse than  $\text{dmag}(I)$  of 3, we expect  $2e-4$  T<16 stars. So (order of magnitude), background blends would be a  $\sim 0.1\%$  coincidence.

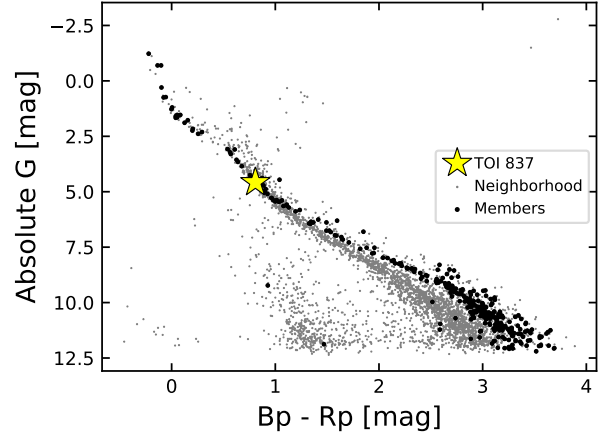
## 4. SYSTEM MODELLING

### 4.1. The Cluster

IC 2602 canonically has an age of  $30 \pm 20$  Myr (CITE: Van Leeuwen 2009). Or logage between 7.533 and 7.563 (Bossini et al. 2019).

Or Li age of 40–50 Myr (David+19, comparison with other Li stars).

Reported mean metallicity values  $[\text{Fe}/\text{H}]$  for the cluster range between slightly super-solar ( $0.04 \pm 0.01$ , Baratella et al. 2020) and slightly sub-solar ( $-0.02 \pm 0.02$ , Netopil et al. 2016).



**Figure 7. Hertzsprung-Russell diagram of TOI 837 and members of IC 2602.** Members (black circles) were identified by Cantat-Gaudin et al. (2018). Gray circles are non-member stars within 5 standard deviations of the mean IC 2602 right ascension, declination, and parallax.  $G$  denotes Gaia broadband magnitudes,  $Bp$  Gaia blue,  $Rp$  Gaia red, and  $\omega_{\text{as}}$  the parallax in arcseconds.

IC 2602 is supervirial, in the sense that the observed stellar velocity dispersion is larger than the value expected if it were in virial equilibrium by about a factor of two (Bravi et al. 2018).

IC 2602 happens to be near the western edge of the Sco OB2 association, and is relatively close to it in proper motion space (Damiani+2019). Damiani+2019 also reported evidence for the ongoing evaporation of IC 2602, in the form of a diffuse halo of young stars around the central density cusps.

While IC 2602 is older than most known Sco OB2 members,

""Although IC 2602 does not belong to Sco OB2, it is spatially and dynamically a close relative, and for this reason we include it in this work, if even marginally"" (Damiani+2019). ""We also find that the open cluster IC 2602 has a similar dynamics to Sco OB2, and its PMS members are currently evaporating and forming a diffuse (size 10deg) halo around its double-peaked core""

### 4.2. The Star

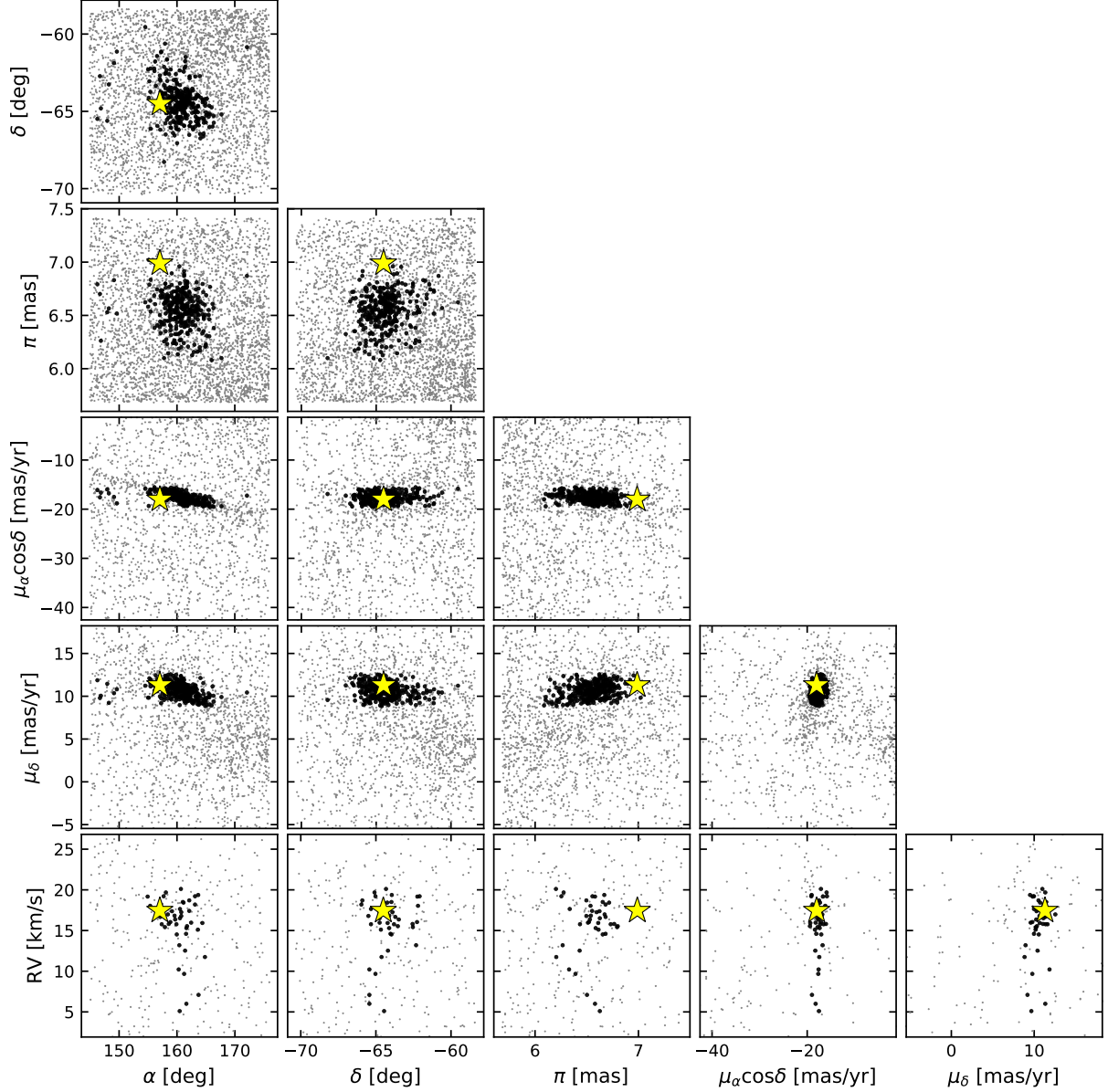
#### 4.2.1. Cluster Membership

TOI 837 has been reported as a member of IC 2602 by multiple independent investigators (Kharchenko et al. 2013; Cantat-Gaudin et al. 2018).

The Gaia kinematics are good; gamma velocity is correct; Li (FEROS + Veloce) is strong; the rotation period and vsini agree with sub-Pleiades age expected for an IC 2602 member.

#### 4.2.2. HR Diagram

Figure 7 shows a Hertzsprung-Russell diagram of TOI 837 in reference to the broader IC 2602 cluster, as well as its neighborhood. Cluster members were identified by Cantat-Gaudin et al. (2018) using Gaia-DR2 positions, proper motions, and parallaxes. We included candidate members



**Figure 8.** Positions and kinematics of TOI 837 (star), IC 2602 members (black circles), and stars in the neighborhood (gray circles). Members were identified by Cantat-Gaudin et al. (2018).  $\alpha$  denotes right ascension,  $\delta$  declination,  $\pi$  parallax,  $\mu_{\delta}$  and  $\mu_{\alpha}$  proper motion in each equatorial direction, and RV radial velocity reported by Gaia-DR2. The RVs are for unblended spectra of bright stars ( $G \lesssim 12$ ). The proper motion projection ( $\mu_{\delta}$  vs.  $\mu_{\alpha} \cos \delta$ ) highlights the membership selection function.

with formal membership probability exceeding 10%. Save for a few low-mass outliers, most members appear to be young and coeval.

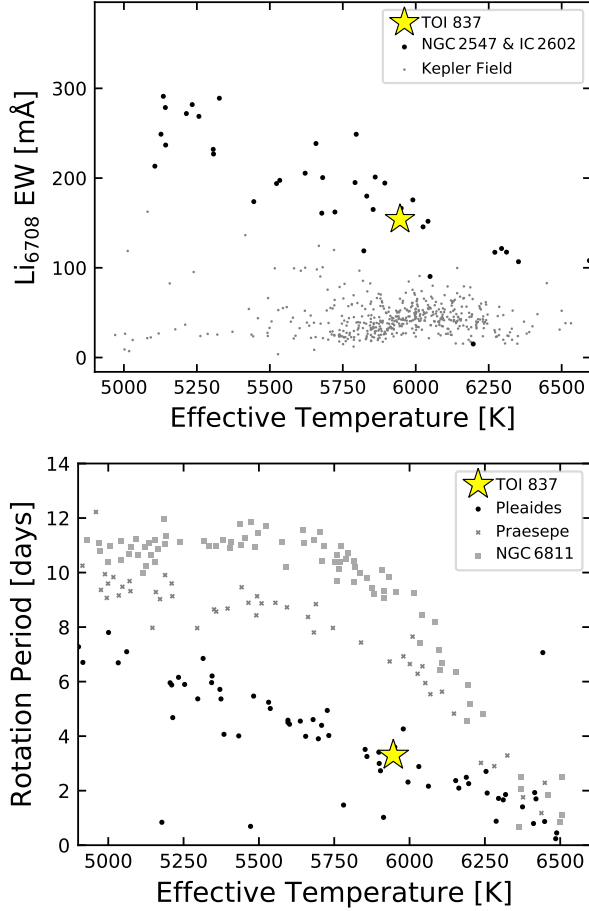
TOI 837 is in its expected position relative to the other members along the cluster isochrone. This photometrically limits the presence of binary companions in the TOI 837 system, to a magnitude difference of perhaps half the brightness of the target star.

Figure 7 also suggests that the membership census of IC 2602 is incomplete. We defined the reference “neighborhood” as the group of at most  $10^4$  randomly selected non-member stars within 5 standard deviations of the mean

IC 2602 right ascension, declination, and parallax. We queried Gaia DR2 for these stars using `astroquery` (Ginsburg et al. 2018). Many low-mass stars appear above the main sequence, even though they were not identified as 5-dimensional kinematic members through the unsupervised ? membership assignment process.

#### 4.2.3. Position and Kinematics

We examine the six-dimensional positions and kinematics in greater depth in Figure 8. The “neighborhood” is defined here identically to as in Figure 7. The axes limits for the right ascension, declination, and parallax dimensions are as in the



**Figure 9. Youth diagnostics.** *Top:* Lithium 6708Å equivalent widths for TOI 837, field stars, and young open clusters. The field star sample is drawn from Kepler planet hosts, and was measured by [Berger et al. \(2018\)](#) using Keck-HIRES. The young open clusters members were surveyed by [Randich et al. \(2018\)](#) using the UVES and GIRAFFE spectrographs at the ESO VLT. [Randich et al. \(2018\)](#) found lithium depletion boundary ages for these clusters of  $37.7^{+5.7}_{-4.8}$  Myr (NGC2547) and  $43.7^{+4.3}_{-3.9}$  Myr (IC 2602). *Bottom:* Rotation periods for TOI 837 and selected open clusters. The Pleiades (120 Myr), Praesepe (670 Myr), and NGC 6811 (1000 Myr) are shown. Their rotation periods were measured by [Rebull et al. \(2016\)](#); [Douglas et al. \(2017, 2019\)](#), and [Curtis et al. \(2019a\)](#), respectively.

Gaia archive query. The axes limits for the proper motion and radial velocity dimensions are set at the 25<sup>th</sup> and 75<sup>th</sup> percentiles, in order to give a sense of the population’s distribution, while excluding outlying points. The radial velocities suffer the greatest incompleteness due to the current  $G \approx 12$  magnitude limit of the Gaia-DR2 data processing.

Figure 8 provides strong evidence (i) for the existence of the IC 2602 open cluster and (ii) for the membership of TOI 837 within IC 2602. The only dimension that could perhaps lead to some worry is the parallax, as TOI 837 is one of the closest IC 2602 members reported by [Cantat-Gaudin](#)

[et al. \(2018\)](#). Fortunately, there are independent means of verifying stellar youth.

#### 4.2.4. Rotation

TESS photometric rotation period = 3.5 days ish.  $v \sin i = 17.48 \pm 0.15$  (CHIRON). The two agree.

For comparison, gyrochrones would “predict” X.XX.

This implies sub-Pleiades age expected for an IC 2602 member.

Figure 9 compares the stellar rotation period of TOI 837 to periods that have been measured in a number of well-studied open clusters. TOI 837 seems to be gyrochronologically coeval with the Pleiades sequence.

We note that this is still in the “sub 500 Myr” range, when classical Skumanich spin-down is not expected to be happening (why is this the number?).

This agrees with recent empirical results from [Rebull et al 2020](#) and perhaps also 2018(?): they observed the Taurus foreground (age 30 Myr) and saw that it was roughly consistent with the Pleiades. Upper Sco had a consistent mean, but a much larger scatter.

#### 4.2.5. Lithium

Rafael’s co-added FEROS spectra gave a Li doublet equivalent width of 154 milliangstrom.

Lithium depletion for a star of TOI-837’s spectral type happens over timescales  $>100$  Myr ([Soderblom+2013](#)). This is because the convective envelopes are very shallow, so they don’t cycle material down to the  $>3e6$  K core until much later.

Nonetheless, comparison of early-G field stars to e.g., 600 Myr old Hyads has shown that the depletion does happen over gigayear timescales ([Berger+2018](#), fig 7).

Figure 9 compares our measured TOI 837 Li EW to stars in the field, and to young open cluster members. The field star measurements were collected by [Berger et al. \(2018\)](#). We have shown the points with lithium detections at  $\text{SNR} > 3$ . TOI-837 is consistent with being younger than almost all CKS planet-hosting field stars.

The young open cluster members were selected for the presence of lithium, as described by [Randich et al. \(2018\)](#). The TOI-837 Li EW measured here (150 milliangstrom) is consistent with what’s seen for stars of similar colors in  $<100$  Myr old moving groups. ([Elliott+2016](#), Fig 11 – attached). This is sensible, because IC 2602 is supposed to be 50 Myr old.

#### 4.2.6. Literature Membership

The membership of TOI 837 in IC 2602 was noted by [Oh et al. \(2017\)](#), in what they dubbed “Group 5”. Analyzing the clusters of [Oh et al. \(2017\)](#), ? fitted the Gaia, 2MASS, and WISE photometry with MIST isochrones, and reported stellar masses, radii, metallicities, ages, distances, and extinction for 9754 stars, including TOI 837.

TOI 837 was also listed as a member of “Theia 92” by [Kounkel & Covey \(2019\)](#). These authors identified 999 candidate cluster members, and reported a cluster isochrone age



$\log t = 7.55$  with uncertainty  $\approx 0.15$  dex. They reported an average extinction of  $A_v = 0.243$  mag.

#### 4.2.7. *Stellar Parameters*

##### 4.2.8. *Physical*

(Lstar, Rstar, Teff, Age and Mstar)

From CHIRON spectra, my current best guess spectroscopic parameters are as follows.  $T_{\text{eff}} = 5946 \pm 39$  logg = 4.48  $\pm$  0.03  $\log g = -0.065 \pm 0.035$  vsini = 17.48  $\pm$  0.15

Figure ???. The SED fit, looking really good with  $\chi^2 = 1.6$ :

The fit parameters are:  $A_v = 0.20 \pm 0.03$   $F_{\text{bol}} = 1.967 \pm 0.046$  e-9 erg/s/cm<sup>2</sup>  $R_{\text{star}} = 1.049 \pm 0.019$   $R_{\text{sun}}$

From the spectroscopic logg and the above Rstar, we get an independent mass estimate of  $M_{\text{star}} = 1.21 \pm 0.10$   $M_{\text{sun}}$ . At face value, the mass seems a bit high for the radius, but I'm guessing that just means the spectroscopic logg is a bit too high.

*Astrometric information*—The RUWE (CITE, CITE) for TOI 837 is 1.02, indicative that there are no obviously present astrometric companions.

##### 4.2.9. *Rotation*

Stellar vsini Stellar rotation

##### 4.2.10. *RVs*

I don't strongly expect the Veloce RVs or the FEROS ones to lead to a mass measurement. The reason is that with vsini=17km/s, and 2% rotation amplitude signal, we expect an RV RMS of 300m/s at the Prot=3.5 day rotation period (vsini\*rotation amplitude). This is probably larger than the expected planet signal (100m/s, 8 days).

#### 4.3. *The Planet*

##### 4.3.1. *Transit Fitting*

Simultaneous dip plus rotation period (GP) fit. Use celerite plus PyMC3/exoplanet. Mention FPP?

##### 4.3.2. *Additional Transits*

None of the extra dips in the PDCSAP light-curve (e.g., "up-down" spikes at BTJD 1572 and 1601) seem likely to be planetary. We checked that i) they were not present in the SAPFLUX light-curves, and ii) that they were not present in the CDIPS light-curves (either raw, or PCA-detrended).

To make this quantitative, we did injection-recovery.

## 5. DISCUSSION

Rossiter measurements will confirm.

After, a mass measurement should be worthwhile.

We'll get more TESS data in January(?).

The authors thank... We also thank the Heising-Simons Foundation for their generous support of this work. The Digitized Sky Survey was produced at the Space Telescope

Science Institute under U.S. Government grant NAG W-2166. Figure 3 is based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain. This research made use of the Exoplanet Follow-up Observation Program website, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. This research has made use of the SVO Filter Profile Service (<http://svo2.cab.inta-csic.es/theory/fps/>) supported from the Spanish MINECO through grant AYA2017-84089 TOI 837 was included on the TESS "short-cadence" target list in part thanks to the Guest Investigator program of G. Sacco (G011265).

*Software:* astrobases (Bhatti et al. 2018), AstroImageJ (Collins et al. 2017), astropy (Astropy Collaboration et al. 2018), astroquery (Ginsburg et al. 2018), cdips-pipeline (Bhatti et al. 2019) corner (Foreman-Mackey 2016), exoplanet (Agol et al. 2019) exoplanet (Foreman-Mackey et al. 2020), and its dependencies (Agol et al. 2019; Kipping 2013; Luger et al. 2019; Theano Development Team 2016). IPython (Pérez & Granger 2007), lightkurve (Lightkurve Collaboration et al. 2018), matplotlib (Hunter 2007), MESA (Paxton et al. 2011, 2013, 2015) numpy (Walt et al. 2011), pandas (McKinney 2010), pyGAM (Servén et al. 2018), PyMC3 (Salvatier et al. 2016), scipy (Jones et al. 2001), tesscut (Brasseur et al. 2019), webplotdigitizer (Rohatgi 2019), wotan (Hippke et al. 2019).

*Facilities:* *Astrometry:* Gaia (Gaia Collaboration et al. 2016, 2018). *Imaging:* Second Generation Digitized Sky Survey, Keck:II (NIRC2; [www2.keck.hawaii.edu/inst/nirc2](http://www2.keck.hawaii.edu/inst/nirc2)). *Spectroscopy:* Keck:I (HIRES; Vogt et al. 1994). **VLT (number)**, **UVES and GIRAFFE** (CITE: Pasquini et al 2002) *Photometry:* TESS (Ricker et al. 2015).



**Table 1.** Model Comparison.

Description	$N_s$	$N_\ell$	$N_{\text{data}}$	$N_{\text{param}}$	$\chi^2$	$\chi^2_{\text{red}}$	BIC	$\Delta\text{BIC}$
Favored	2	2	2585	17	3230.2	1.258	3363.7	0.0
Weakly favored	3	3	2585	21	3203.4	1.249	3368.4	4.7
—	3	2	2585	19	3222.9	1.256	3372.2	8.4
Disfavored	2	3	2585	19	3244.9	1.265	3394.2	30.4
—	2	1	2585	15	3410.6	1.327	3528.5	164.7
—	3	1	2585	17	3396.4	1.323	3530.0	166.3
—	1	2	2585	15	4158.6	1.618	4276.4	912.7
—	1	3	2585	17	4147.4	1.615	4281.0	917.2
—	1	1	2585	13	4313.5	1.677	4415.6	1051.9

NOTE— $N_s$  and  $N_\ell$  are the number of harmonics at the short and long periods, respectively.  $N_{\text{data}}$  is the number of fitted flux measurements.  $N_{\text{param}}$  is the number of free parameters in the model. The Bayesian information criterion (BIC) and the difference from the maximum  $\Delta\text{BIC}$  are also listed.

**Table 2.** Best-fit model priors and posteriors.

Param.	Unit	Prior	Median	Mean	Std. Dev.	3%	97%
$P_s$	d	$\mathcal{N}(8.3247; 0.0050)$	8.3248321	8.3248295	0.0003356	8.3242288	8.3254817
$t_s^{(1)}$	d	$\mathcal{N}(1574.273800; 0.0050)$	1574.2727299	1574.2727323	0.0010770	1574.2707084	1574.2747189
$\log R_p/R_*$	—	$\log \mathcal{U}(0.01; 1.00)$	-2.43072	-2.236	0.55106	-2.74890	-0.99823
$b$	—	$\mathcal{U}(0; 1 + R_p/R_*)$	0.9729	1.0221	0.1533	0.9165	1.2972
$u_1$	—	$\mathcal{U}(0.186; 0.486)^{(2)}$	0.335	0.335	0.088	0.187	0.469
$u_2$	—	$\mathcal{U}(0.075; 0.375)^{(2)}$	0.229	0.227	0.086	0.093	0.374
Mean	—	$\mathcal{U}(0.99; 1.01)$	1.000028	1.000028	0.000006	1.000016	1.000039
$R_*$	$R_\odot$	$\mathcal{T}(1.05; 0.06)$	1.05	1.05	0.06	0.94	1.16
$\log g$	cgs	$\mathcal{N}(4.48; 0.09)$	4.46	4.46	0.08	4.32	4.61
$R_p/R_*$	—	—	0.09	0.13	0.14	0.06	0.37
$\rho_*$	$\text{g cm}^{-3}$	—	1.42	1.44	0.28	0.97	1.97
$R_p$	$R_{\text{Jup}}$	—	0.90	1.38	1.44	0.58	3.87
$a/R_*$	—	—	17.33	17.35	1.11	15.28	19.33
$\cos i$	—	—	0.06	0.06	0.01	0.05	0.08
$T_{14}$	hr	—	1.79	1.79	0.05	1.68	1.87
$T_{13}$	hr	—	0.27	0.28	0.12	0.01	NaN

Note:  $T_{13}$  is ill-defined for a grazing transit.

(1) To convert mean TESS mid-transit time from BTJD to  $\text{BJD}_{\text{TDB}}$ , add 2,457,000.

(2) Assuming an informative quadratic limb-darkening prior with uniform values about those given for the appropriate  $T_{\text{eff}}$  and  $\log g$  from [Claret \(2017\)](#).

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