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A super-Earth and sub-Neptune transiting the late-type M dwarf LP 791-18

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ABSTRACT

Planets occur most frequently around cool dwarfs, but only a handful of specific examples are known to orbit the latest-type M stars. Using *TESS* photometry, we report the discovery of two planets transiting the low-mass star called LP 791-18 (identified by *TESS* as TOI 736). This star has spectral type M6V, effective temperature 2960 K, and radius $0.17R_{\odot}$, making it the third-coolest star known to host planets. The two planets straddle the radius gap seen for smaller exoplanets; they include a $1.1R_{\oplus}$ planet on a 0.95 day orbit and a $2.3R_{\oplus}$ planet on a 5 day orbit. Because the host star is small the decrease in light during these planets' transits is fairly large (0.4% and 1.7%). This has allowed us to detect both planets' transits from ground-based photometry, refining their radii and orbital ephemerides. In the future, radial velocity observations and transmission spectroscopy can both probe these planets' bulk interior and atmospheric compositions, and additional photometric monitoring would be sensitive to even smaller transiting planets.

1. INTRODUCTION

Cool, low-mass stars — M dwarfs — are more numerous and host more short-period planets per star than the more massive stars that host most of the known planets (Bonfils et al. 2013; Dressing & Charbonneau 2015; Mulders et al. 2015). Whether they are seen to transit, inferred from radial velocity spectroscopy, or detected via gravitational microlensing, exoplanets tend to be easier to characterize when they orbit M dwarfs instead of larger, hotter, more massive stars. These red dwarfs are therefore popular targets for exoplanet surveys of all types.

The *Kepler* mission surveyed several thousand M dwarfs for transiting exoplanets and revealed that planet occurrence rates increase with decreasing stellar mass and T_{eff} for $P < 1$ yr (Howard et al. 2012). However, most of *Kepler*'s M dwarfs were early-type: fewer than 600 had $T_{\text{eff}} < 3300$ K (Dressing & Charbonneau 2013; Morton & Swift 2014; Hardegree-Ullman et al. 2019) and would therefore be in the regime of stars with fully convective interiors. Just seven stars cooler than $T_{\text{eff}} < 3100$ K are known to host planets¹. Coolest of these is TRAPPIST-1 ($T_{\text{eff}} \approx 2600$ K, $0.08M_{\odot}$; Gillon et al. 2017), whose seven transiting planets hint that the number of planets per star may be high for the very lowest-mass stars and which has sparked a flurry of theoretical and observational follow-up studies.

It remains an outstanding question as to whether planet occurrence continues to increase toward the lowest stellar masses (or beyond: do brown dwarfs host planets?), and how these planets compare to those orbiting hotter stars. Although not a statistical mission, the *TESS* nearly-all-sky transit survey (Ricker et al. 2014) can help to answer this question. *TESS* will survey 70% of the sky over its two year prime mission, and is therefore well positioned to aid the search for planets around nearby M dwarfs. Compared to *Kepler*, a much larger percentage of the *TESS* project's high-priority target list consists of M dwarfs, including some of the latest-type M dwarfs. One of the first planets discovered by *TESS*, LHS 3844b (Vanderspek et al. 2019), orbits an M5V star and is consequently proving an excellent target for detailed characterization.

We report here the statistical validation of two exoplanets orbiting LP 791-18 (2MASS J11024596-1624222, TIC 181804752), which was recently observed by *TESS*. At $T_{\text{eff}} = 2960$ K this is the third-coolest star known to host exoplanets. Thus like TRAPPIST-1 (Gillon et al. 2017), GJ 1214 (Charbonneau et al. 2009), Proxima Centauri (Anglada-Escudé et al. 2016), and other similar systems, it represents another rare laboratory to study exoplanets around the very smallest stars.

2. OBSERVATIONS

Our target was first identified as a star of more than average interest by Luyten (1979), who noted its high proper motion and red color as part of the Luyten Palomar survey. Therefore we henceforth refer to the star as LP 791-18. The star's properties were more recently estimated in the *TESS* Cool Dwarf Catalog (Muirhead et al. 2018). It was found to be an attractive target for *TESS* transit photometry, and was scheduled for observations at a two-minute cadence

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¹ According to the NASA Exoplanet Archive, June 2019

during Sector 9 of the *TESS* prime mission on account of its inclusion on the high-priority *TESS* Candidate Target List (Stassun et al. 2018b) and as part of *TESS* Guest Investigator program GO 11180 (PI Dressing). We note that all data products used in the succeeding sections have been made available to the community on the ExoFOP-TESS website². A summary of all relevant stellar and planet properties are given in Tables 1 and 2, respectively.

2.1. *TESS* Transit Photometry

TESS observed LP 791-18 nearly continuously from March 1–25, 2019 at a two-minute (“short”) cadence. Initial data processing was similar to that of π Men (Huang et al. 2018), LHS 3844b (Vanderspek et al. 2019), and other recent *TESS* discoveries. Analysis by the *TESS* Science Processing Operations Center (Jenkins 2002; Jenkins et al. 2016) identified two possible planetary signals, and human vetting of the data reports (N. Guerrero et al., in prep., Twicken et al. 2018; Li et al. 2019) resulted in the announcement of planet candidates TOI-736.01 and .02. The *TESS* PDC.SAP light curve (Smith et al. 2012; Stumpe et al. 2014) is shown in Fig. 1. Individual transits of the larger, longer-period TOI-736.01 are visible by eye, while the shallower, shorter-period TOI-736.02 can only be seen in the phase-folded photometry. We also used the *TESS* Quick-Look Pipeline (Huang et al., in prep.) to confirm that the transit-like events are visible in the *TESS* long-cadence data, but the short transit durations make those data unsuitable for a detailed light-curve analysis.

We used the short-cadence light curve to conduct a transit analysis of both signals, using the same software as described by Crossfield et al. (2016, 2017). The only difference from those analyses of long-cadence K2 photometry is that we now numerically integrate each model light curve over just the two-minute (not 30-minute) duration of each point. As in those analyses, we impose priors on the quadratic limb-darkening coefficients. Based on the stellar parameters derived below and the distribution of coefficients from Claret (2018), we adopted Gaussian priors of $u_1 = 0.26 \pm 0.06$ and $u_2 = 0.55 \pm 0.07$. Our best-fit transit models for both signals are shown in Fig. 1, and the model parameters are listed in Table 2. The best-fit mid-transit times (in BJD_{TDB}) from the *TESS* photometry are $T_0 = 2458546.50885 \pm 0.00096$ and 2458543.5584 ± 0.0017 for TOI-736.01 and .02, respectively.

We performed an independent check on our light curve analysis, using an approach similar to that described by Chontos et al. (2019). This parameterization fits for P , T_0 , quadratic limb-darkening coefficients (u_1, u_2), $\rho_{*,\text{circ}}$, b , R_P/R_* , and a photometric normalization. Again, we assume a linear ephemeris, circular orbit, and quadratic limb darkening law with Gaussian priors imposed. Additional priors were used to constrain u_1 to the interval $[0,2]$, u_2 to $[-1,1]$, and to ensure $\rho_{*,\text{circ}} > 0$. We explored the parameter space using the `emcee` Markov chain Monte Carlo algorithm (Foreman-Mackey et al. 2012), initializing 100 walkers and having each take 20000 steps. A burn-in phase of 5000 steps was removed before compiling the final posterior distribution for each parameter. Our two transit analyses are consistent, agreeing to within 1σ for all of the derived quantities.

Following the methodology of Berardo et al. (2019), we also conducted a search for transit timing variations (TTVs) by fitting each transit of TOI-736.01 individually, allowing only the transit midpoints to vary. By comparing these individual times to a linear ephemeris, we conclude that there are no significant TTVs for either of the signals.

2.2. *Stellar Properties From Archival Photometry*

We estimate the spectral type of LP 791-18 by comparing the Gaia DR2 photometry and parallax (Gaia Collaboration et al. 2018) to color-type and absolute magnitude-type relations (Kiman et al. 2019). The six possible relations indicate an M dwarf with subclass mean and standard deviation of 6.1 ± 0.7 , which we adopt as the spectral type of our target. LP 791-18 is not elevated above the main sequence when plotted on an optical-infrared color-magnitude diagram, indicating that the star is not an unresolved near-equal mass binary — unless it has a markedly sub-solar metallicity, which we rule out below.

We estimate the stellar mass using the K_S -band mass-luminosity relation of Mann et al. (2019). The statistical and systematic uncertainties on the derived mass are both $0.0033 M_\odot$, so we report $M_* = 0.139 \pm 0.005$. This mass is consistent with that derived from earlier V - and K -band mass-luminosity relations (Benedict et al. 2016).

We estimate the stellar radius using the absolute-magnitude vs. radius relations of Mann et al. (2015). Those authors indicate that the JHK_S relations are their most precise. Taking the weighted mean of the three derived radii, we find $R_* = 0.171 \pm 0.018$. This radius and the mass are consistent with the mass-radius relation for low-mass stars (Mann et al. 2015).

² <https://exofop.ipac.caltech.edu/tess/target.php?id=181804752>

We estimate the stellar effective temperature using calibrated photometric color relations. Mann et al. (2015) demonstrate a tight correlation between T_{eff} and $(V - J)$, $(r - z)$, and $(r - J)$. These relations all have intrinsic scatters of about 55 K, so we take the mean of the three derived temperatures to find $T_{\text{eff}} = 2960 \pm 55$ K. This value is consistent with temperatures estimated from tabulated photometric relations and from our derived spectral type (Kraus & Hillenbrand 2007; Pecaut & Mamajek 2013).

We estimate the stellar metallicity using photometric relations. The approach of Schlafman & Laughlin (2010) gives the best agreement with near-infrared spectroscopic metallicities (Rojas-Ayala et al. 2012). Using their methodology, we find $\Delta(V - K_S) = 0.2$, which implies $[\text{Fe}/\text{H}] = -0.02 \pm 0.21$ (accounting for the relation’s intrinsic scatter and our uncertainty on V). Comparison to the $(G_R - J)$, M_K color-magnitude diagram of Kesseli et al. (2019) indicates a consistent metallicity of -0.5 ± 0.5 . We report the weighted mean of these two independent estimates, $[\text{Fe}/\text{H}] = -0.09 \pm 0.19$.

As previously noted, LP 791-18’s properties were also estimated by Muirhead et al. (2018) using broadband photometry but without the benefit of Gaia DR2. All of their stellar parameters are within 1σ of ours (Table 1).

2.3. High-Resolution Spectroscopy

To further characterize the system and check for any evidence of spectroscopic binaries that could indicate a non-planetary origin for the transit signals, we obtained high-resolution spectra from Keck/HIRES and Subaru/IRD.

2.3.1. Keck/HIRES

We acquired an optical spectrum using Keck/HIRES (Vogt et al. 1994) on 2019/06/12. The observation took place in $1.0''$ effective seeing and using the C2 decker without the iodine gas cell, giving an effective resolution of $\lambda/\Delta\lambda \approx 55,000$. We exposed for 1386 s and obtained S/N of roughly 30 per pixel. Data reduction followed the standard approach of the California Planet Search consortium (Howard et al. 2010).

Using the approach of Kolbl et al. (2015), we examined our spectrum for secondary components that would indicate the presence of another star. We found no evidence of additional lines down to the method’s standard sensitivity limit of $\Delta V = 5$ mag for $\Delta v > 10$ km s $^{-1}$, consistent with LP 791-18 being a single, isolated star. Finally, we measured LP 791-18’s absolute radial velocity following Chubak et al. (2012), finding 14.1 ± 0.1 km s $^{-1}$.

We compare our HIRES spectrum with several archival spectra of other cool M dwarfs (Fig. 2). LP 791-18’s spectrum is very similar to an archival HIRES spectrum of the M5V GJ 1214 (suggesting generally similar metallicity and temperature), but with slightly broader K I line (consistent with higher surface gravity). Aside from this pressure-broadened line, the widths of weaker lines in these two stars are indistinguishable, consistent with a low projected rotational velocity for both stars ($v \sin i < 2$ km s $^{-1}$ for GJ 1214; Charbonneau et al. 2009). In comparison, LP 791-18’s lines are noticeably narrower than those seen in archival HIRES spectra of the M6V Wolf 359, which has $v \sin i < 3$ km s $^{-1}$ (Jenkins et al. 2009). However, we note that if LP 791-18 is typical of old, low-mass M dwarfs and has a rotation period of roughly 100 days (Newton et al. 2017), then $v \sin i \sim 0.1$ km s $^{-1}$. The lack of H α emission (see Fig. 2) in a star of this mass also indicates that the star likely has a rotation period > 100 days (Newton et al. 2017). Thus the value reported in Table 1 of $v \sin i < 2$ km s $^{-1}$ should be taken as a conservative upper limit.

Several additional lines of evidence are consistent with this interpretation of LP 791-18 as a relatively old star. First, we do not detect the Li line, indicating that LP 791-18 is older than 0.5 Gyr (Reiners & Basri 2009). Second, H α is not seen in emission (see Fig. 2); though there is no true continuum against which to compare the line, H α appears to be slightly in absorption (with a similar depth and profile to GJ 1214), suggesting a long rotation period (as noted above) and therefore an age of several Gyr (Newton et al. 2016). Furthermore, comparison of our inferred M_* , R_* , and L_* to evolutionary models of ultracool dwarfs (Fernandes et al. 2019) also indicates an age $\gtrsim 0.4$ Gyr. In addition, the Galactic space velocity of LP 791-18 is not consistent with any of the known young moving groups or associations (Gagné et al. 2018), with a 95.7% likelihood of it being a field star (according to BANYAN-SIGMA; Gagné et al. 2018); its dynamics are consistent with the thin disk rather than with the thick disk or halo. All these points, combined with the lack of large-amplitude variations in TESS or MEarth photometry (Newton et al. 2018) suggest that LP 791-18 has an age $\gtrsim 0.5$ Gyr, and likely at least several Gyr.

2.3.2. Subaru/IRD

We observed LP 791-18 with the InfraRed Doppler instrument (IRD; Kotani et al. 2018) behind an adaptive optics system (AO188; Hayano et al. 2010) on the Subaru 8.2 m telescope on 2019/06/17. We took 3 spectra with exposure times of 600 s each, with airmass of 1.8–2.0, covering the wavelength range from 0.95–1.76 μm at spectral resolution

$\approx 70,000$. We processed the spectra using standard tools. An absolute wavelength solution was assigned using Th-Ar calibration spectra (Kerber et al. 2008) and laser frequency comb spectra, both of which were previously taken during daytime observations.

We combined our three exposures into one template spectrum for visual inspection of possible contamination of additional faint star. Achieved signal-to-noise ratio around the peaks of blaze function in the combined spectrum is roughly 30 in Y , 50 in J , and 80 in H . As with our HIRES analysis, we do not see any evidence of contaminating lines in the spectrum.

2.4. High-resolution Imaging

TESS has large pixels ($21''$ across), which are large enough to contain many additional stars that could potentially be the source of the detected transits. To identify any additional stars around LP 791-18, we obtained several sets of high-resolution imaging data, as described below.

2.4.1. Gemini/‘Alopeke Optical Speckle Imaging

We observed LP 791-18 with the ‘Alopeke speckle imaging instrument (Howell et al. 2011; Scott & Howell 2018) on the Gemini-North 8.1 m telescope on 2019/06/08. The observations consisted of 18 simultaneous image sets of one thousand 60 ms frames in narrow band filters centered at 562 and 832 nm in good observing conditions, with the native seeing measured to be $0.4''$. Because our target is quite red, the data at 832 nm are superior to those at 562 nm. The speckle images were reduced alongside the point source calibrator star HR 4284 standard reduction procedures (Howell et al. 2011; Matson et al. 2018). Data products include the power spectrum of the speckle patterns of LP 791-18 divided by those of HR 4284, and a reconstructed image of the $2.5 \times 2.5''$ field centered on the target (shown in Fig. 4).

These data products were inspected for neighboring sources and none were found. Contrast curves were produced from the reconstructed images by normalizing the peak flux of the star and determining the standard deviation in magnitudes among local minima and maxima in the background noise as a function of angular separation from the star. A flux level 5σ brighter than the mean of the local extrema is used to define the limiting contrast relative to the LP 791-18. At 832 nm we achieve a contrast of 4.8 mag at $0.1''$, increasing steadily to 7.0 mag at $1.2''$, as shown in Fig. 4.

2.4.2. Keck/NIRC2 AO Imaging and Aperture Masking

On 2019/06/12 we obtained laser guide star adaptive optics (LGS-AO) imaging (Wizinowich et al. 2000) and non-redundant aperture masking interferometry (NRM; Tuthill et al. 2006) of LP 791-18 in two visits separated by 15 minutes with Keck/NIRC2. The observations were taken in vertical angle mode without dithering and using the K’ filter, and the NRM used the 9-hole mask. We also observed two nearby calibrator stars. In all cases we used the smallest pixel scale of $9.952 \text{ mas pix}^{-1}$. For imaging we took 12 exposures, each with 20 coadds of 1 s duration and four Fowler samples. For NRM we took 16 interferograms, each with one coadd lasting 20 s and comprising 64 Fowler samples. For the first calibrator we obtained eight images and eight interferograms in similar setups. For the second calibrator we obtained eight images and four interferograms.

On 2019/06/13 we obtained additional LGS-AO imaging of LP 791-18 and the first calibrator star, again in K’ at the same pixel scale. The observations were taken in position angle mode, rotated to align the +y axis of NIRC2 with North. We observed in a 3-point dither pattern that avoided the NIRC2 bad quadrant while stepping the target in offsets of $1.0''$, $1.5''$, and $2.0''$; we did not dither on the calibrator. We took 20 exposures of LP 791-18 using the same settings as in the preceding night, and took eight exposures of the first calibrator.

We reduced each frame and searched the resulting data for companions following Kraus et al. (2016). We used two different strategies for PSF subtraction, applied individually to each image. To search for faint, wide companions at $>500 \text{ mas}$, we subtracted a model constructed from the azimuthally-averaged flux profile of LP 791-18. This added no additional noise at wide separations, but left the speckles in place, making it non-ideal for detecting close-in companions. To probe smaller inner working angles we then also subtracted a scaled version of the best-fitting empirical PSF taken from the set of all imaging observations of the calibrator stars. We measured the flux as a function of position within each residual image using 40 mas (radius) apertures centered on every image pixel, and stacked the Strehl-weighted significance maps of each frame in order to compute the final significance map for potential detections around LP 791-18. We measured our detection limits from the distribution of confidence levels among all apertures in a series of 5-pixel annuli around the primary. No apertures contain a statistically significant excess of flux within the NIRC2

field of view, and hence there are no detected astrophysical sources. We pursued similar analysis for both calibrators and found that they also have no astrophysical sources within the observed FOV.

The non-redundant masking observations use a pupil plane mask to resample the telescope into a sparse interferometric array. This allows the use of the complex triple product, or closure-phase observable, to remove non-common path errors produced by atmospheric conditions or variable optical aberrations. To remove systematics in the closure-phase observable, the observation of LP 791-18 was paired with observations of the two calibrator stars, both of which have similar color and brightness and are located within 1° of LP 791-18. Our analysis followed the methods described in the appendix of Kraus et al. (2008). Binary-source models were fit to the calibrated closure phases to search for significant evidence of binarity, and the detection limits were calibrated by repeatedly scrambling the phase errors and determining the distribution of binary fits. Again, no sources were detected in the masking data for LP 791-18.

Fig. 3 shows the effective contrast achieved by our NIRC2 observations. The combination of aperture masking and imaging data excludes many companions to LP 791-18, reaching contrast ratios of $\Delta K' = 3.56$ mag at $\rho = 20$ mas, $\Delta K' = 4.67$ mag at $\rho = 40$ mas, $\Delta K' = 5.5$ mag at $\rho = 150$ mas, $\Delta K' = 6.6$ mag at $\rho = 200$ mas, and an ultimate limiting magnitude of $\Delta K' = 9.3$ mag at $\rho > 1''$. Comparison to the MIST isochrones (Dotter 2016; Morton 2015) for all stars at the same distance and with $t > 100$ Myr shows that our suite of high-resolution imaging data rule out all companions down to the H-burning limit from the NRM inner limit of 20 mas (0.8 AU) out to the edge of the NIRC2 FOV in the dithered data set ($9''$, 230 AU). We rule out all companions with spectral types $>L5$ beyond 1.1 AU, $>T4$ beyond 5.4 AU, and $>T8$ beyond 22 AU (Dupuy & Liu 2012, 2017).

3. GROUND-BASED TRANSIT PHOTOMETRY

3.1. *Las Cumbres Observatory*

We also observed both transit signals using 1.0 m telescopes of the Las Cumbres Observatory (LCO; Brown et al. 2013). We used the TESS Transit Finder, a customized version of the Tapir software package (Jensen 2013), to schedule the photometric follow-up observations. All observations used a 4096^2 LCO SINISTRO camera with an image scale of $0''.389$ pixel $^{-1}$ resulting in a $26' \times 26'$ field of view.

We acquired one transit light curve of TOI-736.01 on 2019/06/16 at the South Africa Astronomical Observatory, and two light curves of TOI-736.02 on 2019/06/11 from two telescopes at Siding Spring. The transit of TOI-736.01 comprised 114 images in Bessel-I band using 60 s exposures, for a total duration of 169 minutes. The two transits of TOI-736.02 included 99 min in I_C band with 60 s exposures, and 192 min in Sloan i' with 100 s exposures. The target star had an average FWHM of $2.2''$, $2.4''$, and $1.4''$, respectively. The nearest known Gaia DR2 star is $15''$ from LP 791-18: it has $\Delta G_{RP} = 4.3$ and so is too faint to significantly dilute the TESS transit photometry, (and our high-resolution imaging detected no additional companions), so the LCO follow-up apertures are negligibly contaminated by neighboring stars.

All data were calibrated by LCO's standard BANZAI pipeline and the photometric data were extracted using AstroImageJ (Collins et al. 2017). In all cases, the target star light curve shows a clear transit detection, while a search for eclipsing binaries within $2.5'$ that could have caused the transit signal reveals nothing. The transit signal can be reliably detected with apertures having radii as small as $1''.95$, but systematic effects start to dominate for smaller apertures. Fig. 5 shows our LCO photometry, in which transits are clearly visible.

We model all three LCO light curves with BATMAN (Kreidberg 2015) keeping all parameters — except for R_p/R_* and the mid-transit time — fixed to the values derived from the TESS light curve (Table 2). We also include a linear airmass correction model to account for the out-of-transit baseline, and limb darkening was calculated using LDTK (Parviainen & Aigrain 2015) based on the parameters in Table 1. For TOI-761.01 we measure $R_p/R_* = 0.1233 \pm 0.0024$ and $T_0 = 2458651.29807 \pm 0.00041$, while for TOI-761.02 we measure $R_p/R_* = 0.0624 \pm 0.0044$ and $T_0 = 2458645.94429 \pm 0.00078$ (times in BJD_{TDB}). The LCO transit depths are all consistent with those measured by TESS.

3.2. *MEarth-South*

LP 791-18 is also a target of the MEarth transit survey (Nutzman & Charbonneau 2008; Irwin et al. 2015). The MEarth data set consists of 4534 photometric observations obtained with the MEarth-South telescope array between May 2015 and June 2019. These photometric data do not reveal any coherent periodic variations that would indicate a stellar rotation period.

A Box-Least Squares (BLS) search of the MEarth photometry independently reveals a signal with a period of 0.948002 days (shown in Fig. 5), consistent with the TESS ephemeris of TOI-736.02. Due to the near-integer orbital

period of TOI-736.01, its transits cannot be recovered in the MEarth photometry (though some combinations of P and T_0 are ruled out).

We used `BATMAN` and `emcee` to model the transits of TOI-736.02 using the combined TESS and MEarth photometry. The values of a/R_* and i were kept fixed at the values obtained from the TESS analysis (Table 2) while T_0 , P , and R_p/R_* were allowed to vary. From this analysis we measure $T_0 = 2458645.9434 \pm 0.0013$, $P = 0.9480048 \pm 0.0000058$ days, and $R_p/R_* = 0.059^{+0.0033}_{-0.0042}$.

3.3. Refined transit parameters

We use the LCO and MEarth-South data sets to improve the ephemerides and transit depths of both transit signals by taking the weighted mean of R_p/R_* and combining the T_0 values using weighted least-squares and assuming a linear ephemeris. For TOI-736.01 (undetected by MEarth) we use the results of the TESS and LCO transit analyses, while for TOI-736.02 we use the results of the LCO transit and the combined TESS+MEarth analysis.

We find that for each signal, R_p/R_* is consistent across all our analyses and T_0 is consistent with a linear ephemeris. Including the ground-based data decreases the uncertainty on P by an order of magnitude (for TOI-736.01) and two orders of magnitude (for TOI-736.02). We report the final values of R_p/R_* , R_p , T_0 , and P for both TOIs in Table 2.

4. STATISTICAL VALIDATION OF THE CANDIDATES

Although transits are clearly seen by TESS (Fig. 1) and from the ground (Fig. 5), many TESS candidates have been identified as false positives³ and so we must verify that the observed signals are planetary in origin. Since the precise Doppler spectroscopy needed to confirm these signals as planets will likely need to wait until LP 791-18 rises again for the next season, we demonstrate below that the signals are far more likely to be planetary than of any other origin. Below, we consider whether LP 791-18 could be blended with a background eclipsing binary, and then whether LP 791-18 itself could be a multiple star system. We find that both scenarios are unlikely, indicating that our planet candidates are likely to be true transiting planets.

4.1. Independent Signal Validation

We used the Discovery and Validation of Exoplanets tool⁴ (`dave`; Kostov et al. 2019a,b), along with the short-cadence pixel files and photometry, to independently estimate the quality of the candidate planet signals. We find no significant secondary eclipses or odd-even differences (which would otherwise indicate an eclipsing binary instead of a transiting planet) for either TOI. We find no significant photocenter shift (which would indicate a blend of multiple stars, and possible source confusion) for TOI-736.01. For TOI-736.02 the individual difference images per transit are too noisy for DAVE to provide an accurate photocenter analysis. Nonetheless, neither candidate shows indications of being a false positive.

The `dave` results are consistent with the TESS project’s data validation tests (Twicken et al. 2018; Li et al. 2019), which both TOIs passed. These tests include the odd-even transit depth test, the weak secondary test, the ghost diagnostic test, the difference image centroid offset test (0.35 and 0.5 sigma for the TIC offset for candidates 1 and 2, respectively, representing less than 1'' offsets from the TIC position), and the statistical bootstrap test (which gave 7×10^{-73} and 3×10^{-15} for TOIs 736.01 and .02, respectively).

4.2. Unassociated background scenarios:

Our ground-based photometry demonstrates that transits occur close to LP 791-18, but a background system could lie near the star and mimic planetary transits. Given its high proper motion, LP 791-18 has moved considerably since its detection by the Palomar Optical Sky Survey in the 1950s. No source is visible in the digital POSS-I images at the star’s location during the TESS epoch. By comparing these images to SDSS DR9 photometry, we confidently exclude any background object down to a limit of approximately $r = 19.5$, $i = 18.6$ (AB mags), corresponding to $R \approx 19.2$, $I_C \approx 18.3$ (Vega mags⁵). Since the broad TESS bandpass is quite red (Ricker et al. 2014) we assume that the limiting TESS magnitude is $T \approx I_C \approx 18.3$, 4.8 mag fainter than LP 791-18. We therefore exclude all background sources as the source of TOI-736.01’s transits.

From POSS-I and TESS alone we cannot rule out all such background scenarios for the shallower TOI-736.02 (since its transit depth is $< 10^{-0.4 \times 4.8}$), but our LCO transit observations demonstrate that these events occur within a

³ <https://exofop.ipac.caltech.edu/tess/>

⁴ <https://github.com/barentsen/dave>

⁵ <http://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php>

few arcsec of LP 791-18. Since our high-resolution imaging shows no additional sources, this all but eliminates the chance that this shallower candidate is a background system. A 4.8 mag-fainter source could reproduce the 736.02 transits (with depth roughly 0.4%) if it had a 40% (intrinsic) transit depth – or if it had $T \approx 19.4$ mag and were completely eclipsed. The only allowable brightness of a background source is T in the range 18.3–19.4 mag. We used the TRILEGAL Galactic stellar population simulator⁶ (Girardi et al. 2005) to find a 0.2% chance that our LCO photometric aperture would contain a star with this brightness. If these simulated stars were actually equal-mass binaries with $P = 0.95$ day, the average transit probability of the ensemble (assuming $e = 0$) is 17%. The median star in this distribution is a $0.4M_{\odot}$ M dwarf, and the tight binary fraction of such stars is about 3% (Blake et al. 2010; Clark et al. 2012). The product of these factors is the likelihood that TOI-736.02 is a background false positive: this is 10^{-5} , so we conclude that both transit signals are unlikely to arise from blends with a background eclipsing binary.

4.3. Bound, Multi-star scenario:

We now consider the scenario that LP 791-18 is itself a multiple system with transits occurring around just one component — this, too, turns out to be unlikely. M dwarfs in the Solar neighborhood with $0.075\text{--}0.3M_{\odot}$ have a multiplicity fraction of about 20% (Winters et al. 2019). Following the parameters given in that work, we simulated a distribution of binary companions to LP 791-18 with a log-normal distribution in a that peaks at 10 AU, with $\sigma_{\log_{10}(a/\text{AU})} = 1$, and with a linearly-increasing mass fraction distribution from 0.1 to unity.

We then compare this population of plausible companions to our observations: we see no companions in our high-resolution imaging; the system is not overluminous relative to the M dwarf H-R diagram; the host star’s density is constrained by the transit light curve analysis ($\rho_{*,\text{circ}}$ in Table 2; Seager & Mallén-Ornelas 2003); companions of later type than roughly L5 ($M \lesssim 0.03M_{\odot}$) would be too faint to be the source of the transit signals (Dahn et al. 2002); and we see no evidence for secondary lines in our high-resolution optical spectrum. Fig. 6 shows that our observations cover all relevant regions of false positive parameters space.

After accounting for the possibility that, by chance, some wide companions could have a very low projected separation from LP 791-18 and some short-period companions could have had zero velocity offset from LP 791-18, we still find just a 0.7% chance that an additional companion is the source of the transit signals and went unnoticed by our observations. The remaining possible configurations involve a $0.03\text{--}0.04M_{\odot}$ brown dwarf orbiting LP 791-18 with $a \approx 0.7$ AU and nearly or fully eclipsed by a giant planet or brown dwarf.

Taking the distribution of mass fractions and semimajor axes of low-mass stellar binaries (Winters et al. 2019), and accounting for random orbital alignments, we calculate that a star like LP 791-18 has a 0.04% chance of being in an eclipsing binary with $P \leq 10$ days and companion mass $0.03\text{--}0.04M_{\odot}$. This is far less than its 66% chance of having a planet with $R_P < 3R_{\oplus}$ on a similar period (Dressing & Charbonneau 2015). It is therefore far more likely that LP 791-18 is a single planet-hosting star than that it is a false positive with a eclipsing brown-dwarf binary. Thus we conclude that the signals detected by *TESS* represent exoplanets transiting the M6V star LP 791-18. Henceforth we denote TOI-736.02 (the smaller, inner planet) as LP 791-18b and TOI-736.01 as LP 791-18c.

5. DISCUSSION

5.1. On Multiplicity and Additional Planets

There is evidence that the multiplicity of short-period planets is high for stars at the latest spectral types, even though few planet host stars are known at these coolest temperatures (cf. Fig. 7). Aside from LP 791-18, just seven planetary systems are known with $T_{\text{eff}} < 3100$ K. Four of these are multiple systems: TRAPPIST-1 (seven planets; Gillon et al. 2016, 2017), YZ Ceti (three planets; Astudillo-Defru et al. 2017; Robertson 2018), Kepler-42 (three planets; Muirhead et al. 2012), and Teegarden’s Star (two planets; Zechmeister et al. 2019). Three have just a single known planet: GJ 1214 (Charbonneau et al. 2009), LHS 3844 (Vanderspek et al. 2019), and Proxima Centauri (Anglada-Escudé et al. 2016).

To verify that additional planets could exist on stable orbits around LP 791-18 with P between the two transiting planets, we performed a series of N-body dynamical simulations using the Mercury Integrator Package (Chambers 1999) and following the methodology of Kane (2015). We assessed the stability of circular orbits between the two known planets by placing a hypothetical Earth-mass planet at a in the range 0.01–0.03 AU in steps of 0.0005 AU. Each simulation was run for 10^5 yr, a sufficient time span given the very short orbital periods involved. Our simulations

⁶ <http://stev.oapd.inaf.it/cgi-bin/trilegal>

show that stable orbits are possible in the range 0.011–0.0255 AU (although large planets close to low-order resonance with LP 791-18 c are unlikely due to the absence of observed TTVs).

To look for additional planets, we ran a BLS analysis of the *TESS* photometry but found no significant signals. We also injected a series of planet transit signals into the *TESS* photometry and ran a BLS analysis on the simulated data. For an intermediate period (e.g., 2.5 days), transiting planets with $R_P \gtrsim 1.2R_\oplus$ should have been seen in the *TESS* data. For planets on longer periods (e.g., $P = 7 - 10$ days), $R_P \gtrsim 1.4R_\oplus$ would have been detected. Thus planets the size of those orbiting TRAPPIST-1 would be unlikely to have been detected by *TESS* around LP 791-18. There could easily be Earth-sized planets orbiting LP 791-18 that went undetected by *TESS*. In particular, the cloud-free habitable zone for a star like LP 791-18 extends from approximately $P = 10 - 30$ days (Kopparapu et al. 2013, 2014), a range only poorly sampled by the existing *TESS* photometry.

Additional planets could be identified by long-duration time-series photometry (as were sought around GJ 1214; Fraine et al. 2013; Gillon et al. 2014, and seen around TRAPPIST-1; Gillon et al.; Luger et al.). However, just a few degrees of mutual misalignment between the planets’ orbits would result in any extra planets failing to transit. Assuming circular orbits, Earth-size planets with $P = 2.5$ days and 7 days would need to be misaligned by 2.7° and 1.3° , respectively, in order not to transit. For reference, the mutual misalignments of the TRAPPIST-1 planets are $< 0.4^\circ$ (Gillon et al. 2017), while many other ultra-short period planets have much higher mutual inclinations of 6.7° (Dai et al. 2018).

5.2. LP 791-18 b and c

These two small planets have sizes of $1.1R_\oplus$ and $2.3R_\oplus$, and so straddle the radius gap at about $1.8R_\oplus$ that separates smaller, higher-density super-Earths from larger, more rarified sub-Neptunes (Fulton et al. 2017; Fulton & Petigura 2018). It remains an open question as to whether this radius gap (measured from FGK systems) extends to planets orbiting M dwarfs, or to planets with this combination of small size and low irradiation.

It seems entirely likely that the masses of these new planets can be measured in the near future, which would help to better determine their overall composition. By comparison to theoretical mass-radius relations (Valencia 2011) we expect the two planets to have masses of $0.5-4M_\oplus$ (for bulk compositions ranging from Moon-like to Mercury-like) and $5-20M_\oplus$ (for bulk compositions ranging from a 50-50 water-rock mix to a 0.01% H_2/He veneer on a rocky core) for planets b and c, respectively. These compositions correspond to RV semiamplitudes of $1-9 \text{ m s}^{-1}$ and $7-26 \text{ m s}^{-1}$. A mass and radius could distinguish between different refractory compositions of LP 791-18b, but the degeneracies inherent in modeling larger planets means that RV observations can constrain, but not uniquely determine, the bulk makeup of LP 791-18c. The star’s red color and relatively low apparent brightness means that RV follow-up is likely to be most productive when pursued by facilities on large ($\geq 8 \text{ m}$) telescopes and/or with extended coverage into the red-optical or near-infrared.

Because of the poor constraints on the impact parameters in the light curve, we cannot deduce much about the mutual inclination of these two planets; measurement of the Rossiter-McLaughlin effect or Doppler tomography observations would provide an orthogonal constraint on the dynamical architecture. However, these measurements are probably only feasible if LP 791-18 has $v \sin i \gtrsim 2 \text{ km s}^{-1}$, substantially larger than expected for a quiescent star of this type (though barely consistent with our Keck/HIRES and Subaru/IRD spectra). Even then, the short transit durations would make it difficult to obtain the necessary S/N in exposures that are short enough to provide good temporal sampling of the transit.

Atmospheric characterization of these planets is also feasible. We simulated model transmission spectra for these planets using ExoTransmit (Kempton et al. 2017) and assuming planet masses of $2M_\oplus$ and $7M_\oplus$, and atmospheric compositions of 100% H_2O and $100\times$ Solar metallicity, for LP 791-18b and c, respectively. Our model atmospheres assumed no clouds and chemical equilibrium, and set the 1 bar radius equal to the transit radius observed by *TESS*. These models predict peak-to-valley transmission signals for planets b and c of roughly 150 ppm and 500 ppm, with the difference set largely by the two models’ differing mean molecular weights. If the planets have lower masses or lower-metallicity atmospheres than assumed above, the desired atmospheric signals would be even stronger.

We then used PandExo⁷ (Greene et al. 2016; Batalha et al. 2017) to simulate JWST observations of a single transit of each planet using the NIRSpec prism ($0.6 - 5\mu\text{m}$) and MIRI LRS ($5-12\mu\text{m}$) instruments modes, with a baseline of equal time to the transit time and zero noise floor. Assuming an effective resolution of 35 we find that the median

⁷ <https://github.com/natashabatalha/PandExo>

per-channel uncertainty on the transit depth would be 220 ppm and 150 ppm, respectively, with the difference set by the planets' transit durations. For the larger, cooler LP 791-18c JWST should be able to identify atmospheric features in the spectrum between $1 - 5\mu\text{m}$ with just a single transit, indicating that it could be a compelling target for atmospheric follow up. For the smaller, warmer LP 791-18b multiple transits would likely be needed to probe the composition of the planet's atmosphere (if any).

5.3. Concluding Thoughts

Fig. 7 shows that LP 791-18 is the third-coolest star known to host planets. The discovery of the TRAPPIST-1 system spurred many new studies into star-planet interactions (Dong et al. 2018), multiplanet dynamics (Luger et al. 2017), atmospheric escape (Wang & Dai 2018), planet formation (Haworth et al. 2018), and atmospheric measurements (Barstow & Irwin 2016) of small planets around low-mass stars. Along with the new planets orbiting Teegarden's Star (Zechmeister et al. 2019), LP 791-18 now adds another multiplanet system against which to test these theories via the system properties presented here, through further detailed characterization of the planets and their host star, and by searching for additional planets orbiting this cool dwarf.

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Data and materials availability: All associated data products are available for download from ExoFOP-TESS website, <https://exofop.ipac.caltech.edu/tess/target.php?id=181804752>.

Facilities:

Facility: TESS, Gaia, Gemini ('Alopeke), Keck I (HIRES), Keck II (NIRC2), Subaru (IRD), LCO

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Table 1. Stellar Parameters of LP 791-18

Parameter	Value	Source
<i>Identifying information</i>		
TIC ID	181804752	TIC v8 (Stassun et al. 2018a)
α R.A. (hh:mm:ss)	11:02:45.96	
δ Dec. (dd:mm:ss)	-16:24:22.29	
μ_α (mas yr ⁻¹)	-221.08 \pm 0.22	Gaia DR2
μ_δ (mas yr ⁻¹)	-59.00 \pm 0.14	Gaia DR2
Distance (pc)	26.493 \pm 0.064	Gaia DR2 (Bailer-Jones et al. 2018)
<i>Photometric Properties</i>		
V (mag)	16.9 \pm 0.2	TIC v8
G (mag)	15.0715 \pm 0.0013	Gaia DR2 (Gaia Collaboration et al. 2018)
G_{BP} (mag)	17.23831 \pm 0.0072	Gaia DR2
G_{RP} (mag)	13.69512 \pm 0.0029	Gaia DR2
u (mag).....	21.28 \pm 0.14	SDSS (Albareti et al. 2017)
g (mag).....	17.8827 \pm 0.0057	SDSS
r (mag)	16.2672 \pm 0.0039	SDSS
i (mag).....	14.3142 \pm 0.0035	SDSS
z (mag).....	13.2565 \pm 0.0035	SDSS
J (mag).....	11.559 \pm 0.024	2MASS (Skrutskie et al. 2006)
H (mag)	10.993 \pm 0.022	2MASS
Ks (mag)	10.644 \pm 0.023	2MASS
W1 (mag)	10.426 \pm 0.023	AllWISE (Cutri et al. 2012)
W2 (mag)	10.233 \pm 0.021	AllWISE
W3 (mag)	10.024 \pm 0.062	AllWISE
<i>Spectroscopic and Derived Properties</i>		
Spectral Type	M(6.1 \pm 0.7)V	This work
Barycentric rv (km s ⁻¹)	+14.1 \pm 0.3	This work
Age (Gyr)	> 0.5	This work
[Fe/H]	-0.09 \pm 0.19	This work
T_{eff} (K)	2960 \pm 55	This work
$\log_{10} g$ (cgs)	5.115 \pm 0.094	This work
$v \sin i$ (km s ⁻¹)	<2	This work
M_* (M_\odot)	0.139 \pm 0.005	This work
R_* (R_\odot)	0.171 \pm 0.018	This work
L_* (L_\odot)	0.00201 \pm 0.00045	This work

Table 2. Planet Parameters

Parameter	Units	LP 791-18b	LP 791-18c
		(TOI-736.02)	(TOI-736.01)
T_0	$BJD_{\text{TDB}} - 2457000$	1645.94405 ± 0.00066	1651.29807 ± 0.00041
P	d	0.9480050 ± 0.0000058	4.989963 ± 0.000050
i	deg	$87.3^{+2.0}_{-4.9}$	$89.55^{+0.32}_{-0.50}$
R_P/R_*	–	0.0604 ± 0.0028	0.1238 ± 0.0022
R_*/a	–	$0.090^{+0.058}_{-0.016}$	$0.0290^{+0.0035}_{-0.0016}$
T_{14}	hr	$0.612^{+0.068}_{-0.079}$	$1.208^{+0.056}_{-0.046}$
T_{23}	hr	$0.466^{+0.076}_{-0.259}$	$0.899^{+0.041}_{-0.048}$
b	–	$0.54^{+0.36}_{-0.37}$	$0.28^{+0.24}_{-0.19}$
$\rho_{*,\text{circ}}$	g cm^{-3}	28 ± 22	$31.1^{+5.6}_{-9.1}$
a	AU	$0.00969^{+0.00032}_{-0.00035}$	$0.029392^{+0.00098}_{-0.00105}$
R_P	R_E	1.12 ± 0.13	2.31 ± 0.25
S_{inc}	S_E	$21.5^{+5.4}_{-4.6}$	$2.35^{+0.59}_{-0.51}$
T_{eq}^a	K	650 ± 120	370 ± 30

^a Assuming a uniform random distribution of Bond albedos (0–0.4) and heat redistribution factors (0.25–0.5).

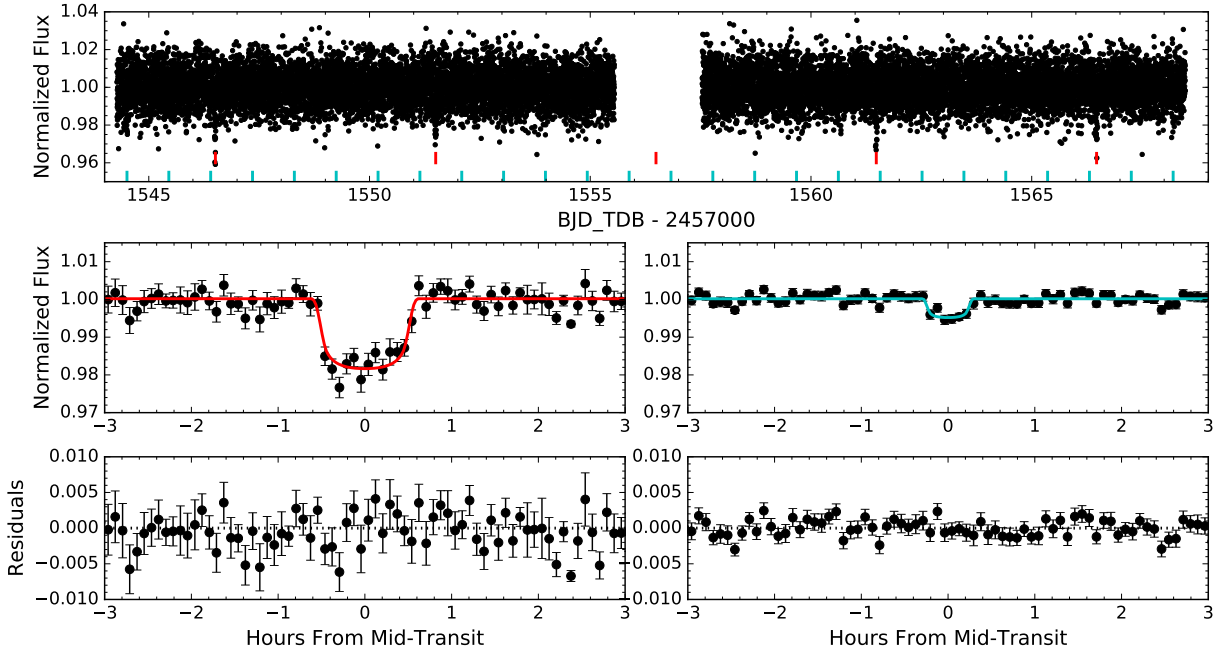


Figure 1. *Top:* TESS short-cadence photometry of LP 791-18. Vertical ticks indicate the locations of each planets' transits. *Middle:* Phase-folded photometry (binned to five-minute intervals, with error bars indicating the standard error on the mean in each bin) and best-fit light curves for each planet. *Bottom:* Residuals to the transit fits.

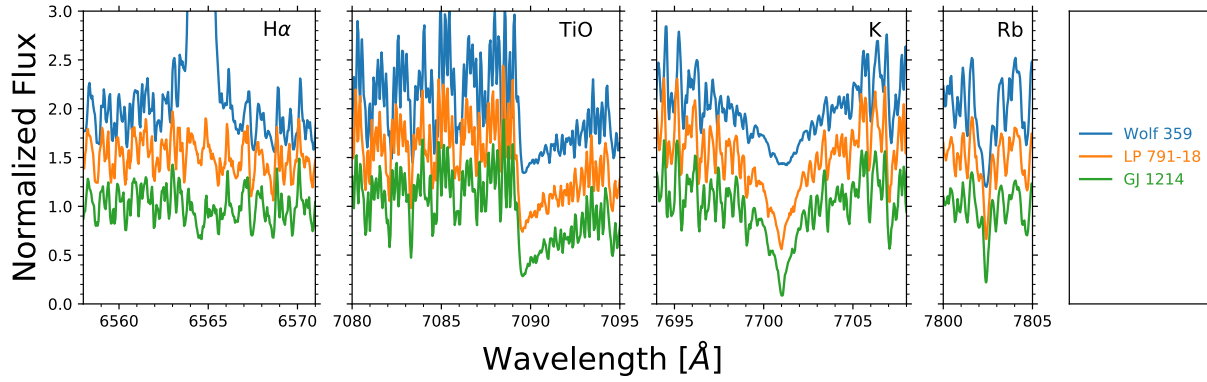


Figure 2. Comparison of Keck/HIRES spectra of LP 791-18 (orange) with GJ 1214 (green) and Wolf 359 (blue) in the vicinity of the expected locations of H α , TiO bands, K I (7701.0 \AA), and Rb I (7802.4 \AA). No secondary spectral lines are detected.

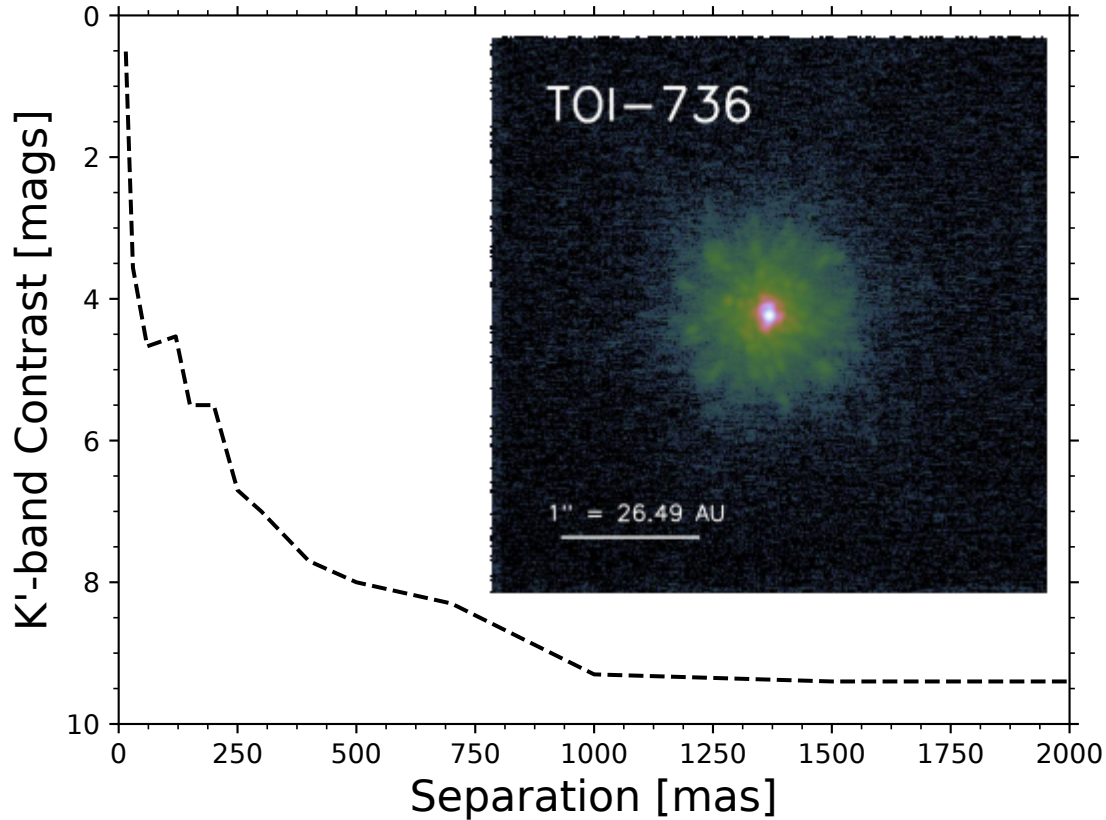


Figure 3. K'-band contrast limits set by our Keck/NIRC2 adaptive optics imaging and aperture masking data, with the imaging data shown at inset. No secondary sources are detected.

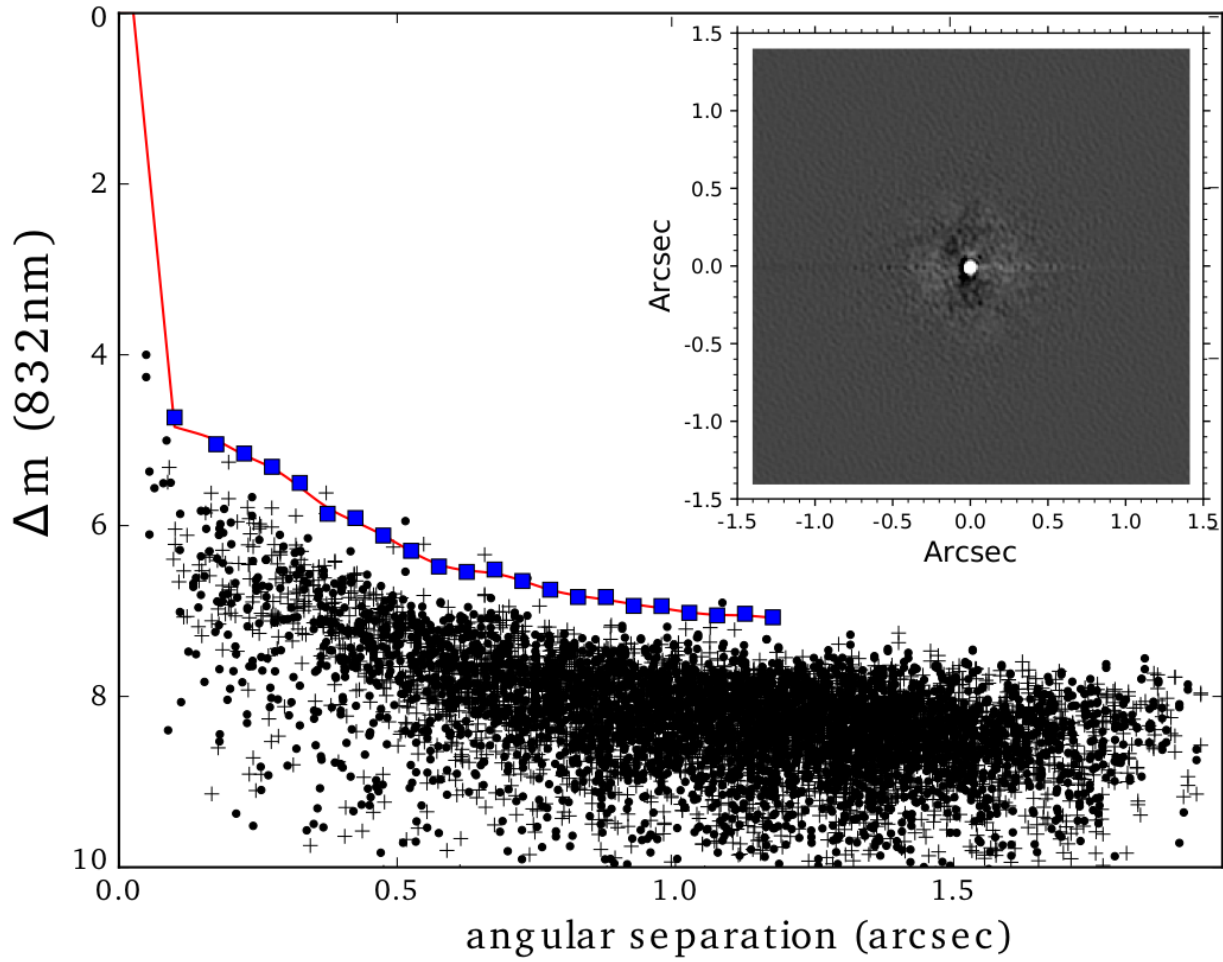


Figure 4. Red-optical contrast limits set by our Gemini/Alopeke speckle imaging data, with the reconstructed image shown at inset. No secondary sources are detected.

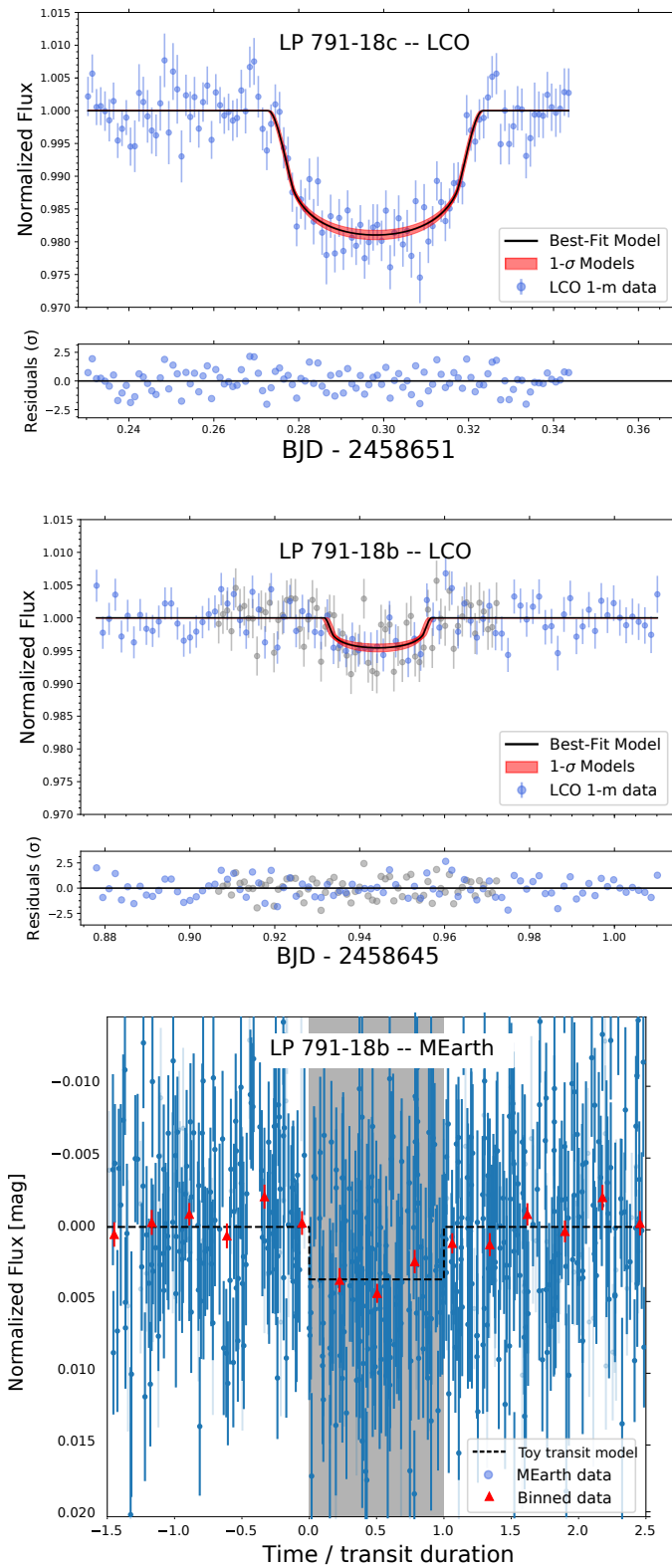


Figure 5. Ground-based photometry of LP 791-18. *Top:* one LCO 1 m transit of LP 791-18c. *Middle:* two LCO 1 m transits of LP 791-18b. *Bottom:* Phase-folded MEarth-South photometry of LP 791-18b during transit.

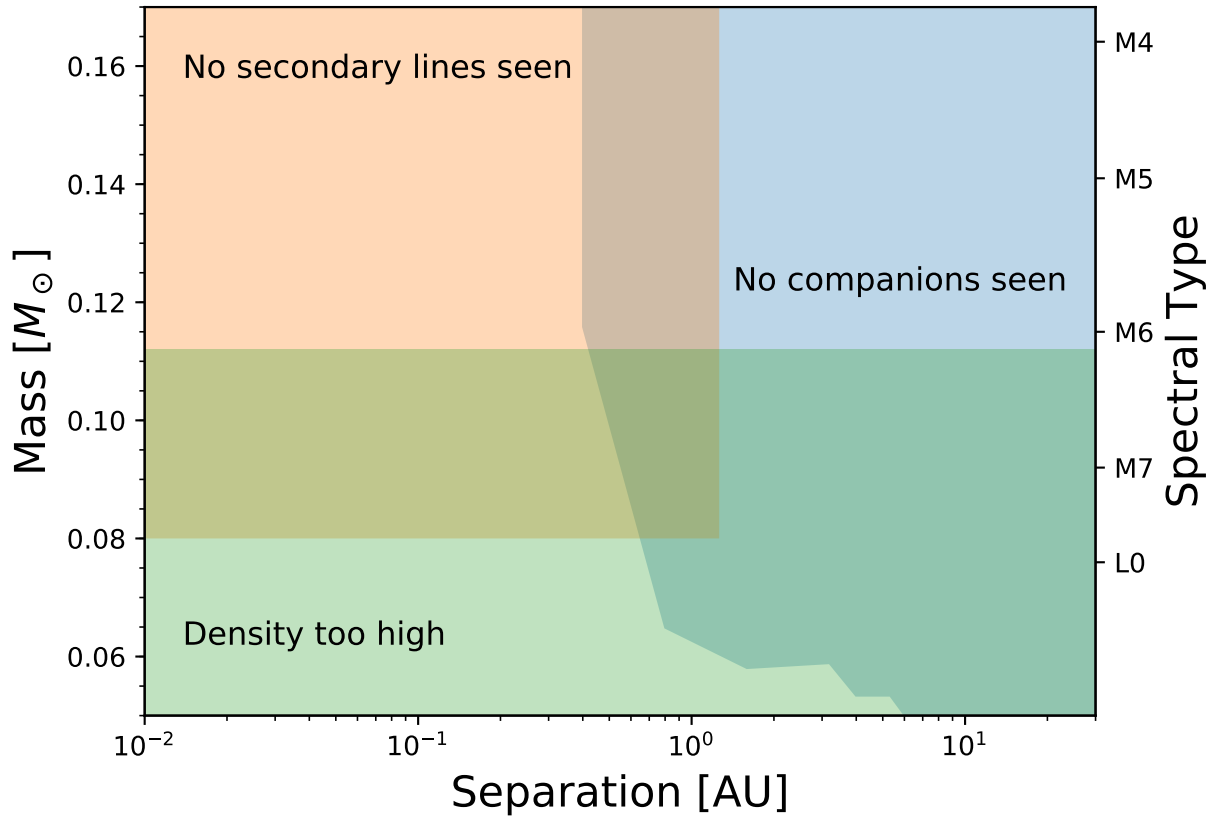


Figure 6. Our analysis rules out bound companions of all types as the hosts of the detected transits. Clockwise from upper left: we see no secondary lines in our high-resolution spectra, ruling out bright, short-period companions; we see no companions in our high-resolution imaging data, ruling out long-period companions; and our transit analysis indicates a density that excludes objects with $< 0.11 M_{\odot}$. See Sec. 4.3 for details.

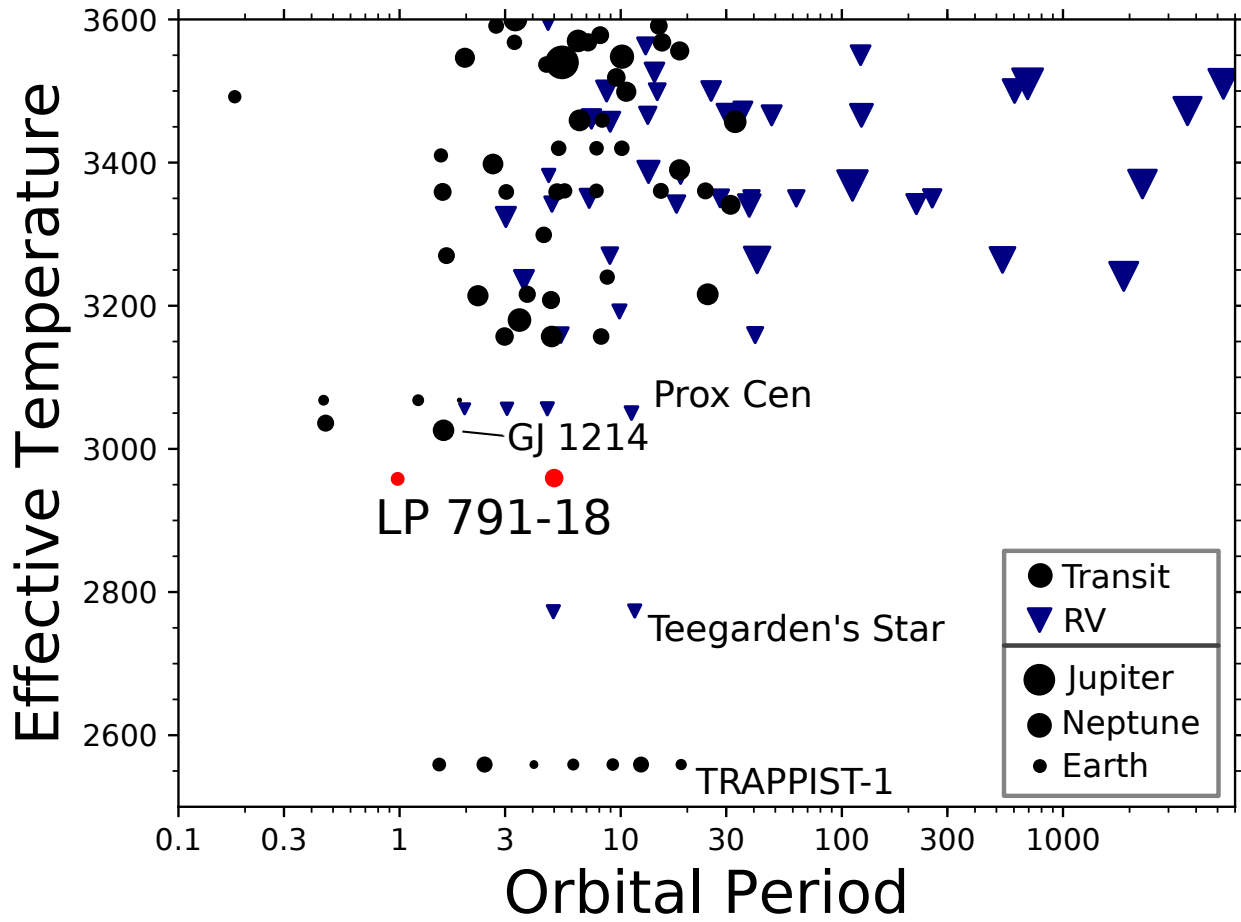


Figure 7. Planets orbiting cool dwarfs. The point size increases as the logarithm of planet mass (inferred from radius when the mass are unknown). Transiting planets are shown with circles and planets not known to transit with triangles; our two new planets are indicated by red stars.