The LHS 1678 System: Two Small Planets and a Likely Brown Dwarf Orbiting a Nearby M Dwarf in Unconventional Circumstances

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Abstract

We present the LHS 1678 (TOI-696) exoplanet system: two nearly Earth-sized transiting planets detected by TESS and a likely brown dwarf orbiting a bright M2 dwarf at 19.9 pc. The ultra-short-period LHS 1678 b (0.70 Earth radii, 0.9-day orbit) is a captivating target for emission spectroscopy observations with the JWST. LHS 1678 c (0.98 Earth radii, 3.7-day orbit) is in the Venus-zone and may be Venus density: a promising target for greenhouse effect studies. Both planets are favorable targets for EPRV mass measurements and for JWST transmission spectroscopy observations to study their atmospheres. The substellar companion, detected via CTIO/SMARTS 0.9m astrometry, is on a decades-long orbit and may someday eclipse the host star, revealing a rare system architecture in which more and less massive objects orbit in the same plane. There is also a candidate third planet detected in TESS multi-cycle data in near 4:3 resonance with LHS 1678 c. The host star is associated with an observed gap in the HR diagram tied to a change in M dwarf energy transport mechanisms. The effect of the associated stellar astrophysics on exoplanet evolution is currently unknown. In aggregate, LHS 1678 an exciting playground for comparative exoplanet science and understanding the formation and evolution of small, short-period exoplanets orbiting low-mass stars.

System Highlights

- Star
  - **Bright, nearby M dwarf** – good for target follow-up and characterization with JWST and high-precision radial velocity instruments
  - **Older population star** – fast motion, sub-solar metallicity, low magnetic activity, and HR diagram position indicate possible Galactic thick disk membership – useful in studies of **exoplanet system evolution**
  - **Rare Stellar Property – HR Diagram Gap** – host star spent 10^8-10^9 Gyr moving back and forth across the ***Gaia* HR Diagram Gap** (Jao et al. 2018) before settling below it. Unknown how the associated changes in stellar radius affect **exoplanet formation and evolution**
- Brown Dwarf Companion –the planets and the more massive astrometric brown dwarf companion may be **orbiting in the same plane** – among the first of such systems found
- LHS 1678 b - **Ultra-short-period planet (USP)** – extreme environment with intense radiation, good for emission **thermal phase curve** measurements within JWST (to estimate temperature, probe atmosphere, e.g., as in Kreidberg et al. 2019)
- LHS 1678 c - **Venus-zone planet of Venus size** – Not enough stellar flux to strip away the atmosphere, but enough to evaporate oceans. Helpful to understand the runaway greenhouse effect, along with the history of Venus and Venus-like planets that could be habitable.
- TOI-696.03 – This candidate third planet is **near 4:3 mean motion resonance** with LHS 1678 c, suggesting the planets may have formed via convergent disk migration (Goldreich & Schlichting 2014).

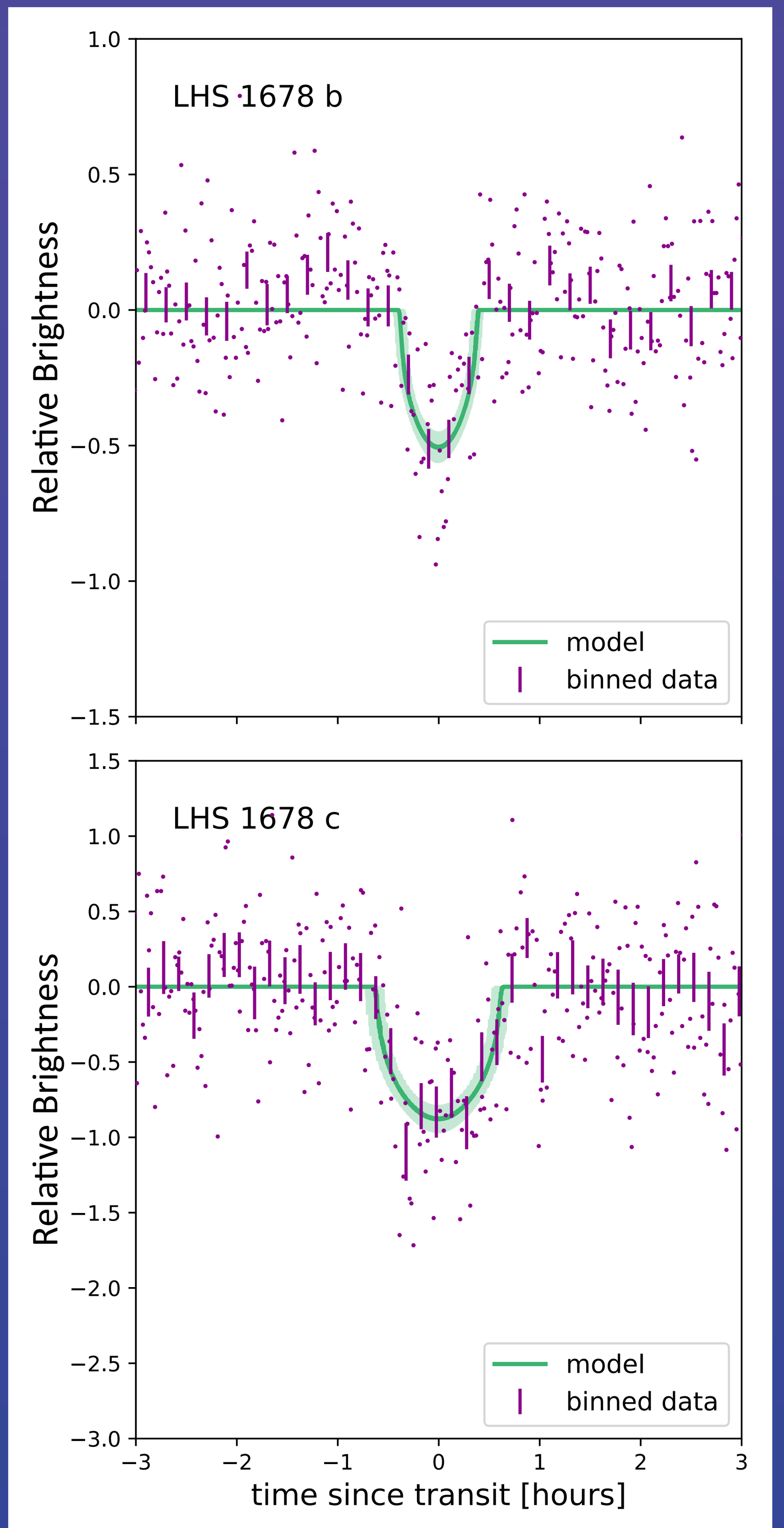
Star Properties

Star Property	Value	Method/Reference
Mass	0.345 ± 0.014 $M_\odot$	Benedict+2016 Eq. 11
Effective Temperature	3490 ± 50 K	Silverstein+ in prep
Radius	0.329 ± 0.010 $R_\odot$	Silverstein+ in prep
V magnitude	12.48 ± 0.03	Winters+2015
K magnitude	8.27 ± 0.03	2MASS (Cutri+2003)
Parallax	50.28 ± 0.02 mas	*Gaia* DR2 (G.C.+ 2016)
Total Galactic Motion	94.6 ± 0.4 km s^{-1}	Combined *Gaia* DR2 PM + HARPS & CHIRON RV
Rotation Period	64 ± 22 days	Newton+2017 Eq. 7
Spectral Type	M2.0 V	RC Spec (Henry+2002)
Metallicity	subsolar	various indicators
Age	4-9 Gyr	Engle+2018 Eq.s 1, 2

Planet Properties

Property	LHS 1678 b	LHS 1678 c	TOI-696.03
Radius ($R_\oplus$)	0.696 ± 0.044	0.982 ± 0.064	0.915 ± 0.085
Orbital Period (d)	0.860	3.694	4.965
Semi-major Axis (AU)	0.013 ± 0.001	0.033 ± 0.002	0.040 ± 0.001
Insolation Flux ($S_\oplus$)	93.2 ± 9.3	13.5 ± 1.3	9.1 ± 0.3
HARPS 2-σ Mass Upper Limit ($M_\oplus$)	0.35	1.4	-
forecaster Mass Estimate ($M_\oplus$)	0.276	0.940	0.72
TSM (Kempton+2018)	30.2	15.2	-
ESM (Kempton+2018)	3.9	2.0	-

TESS Phase-folded Light Curves



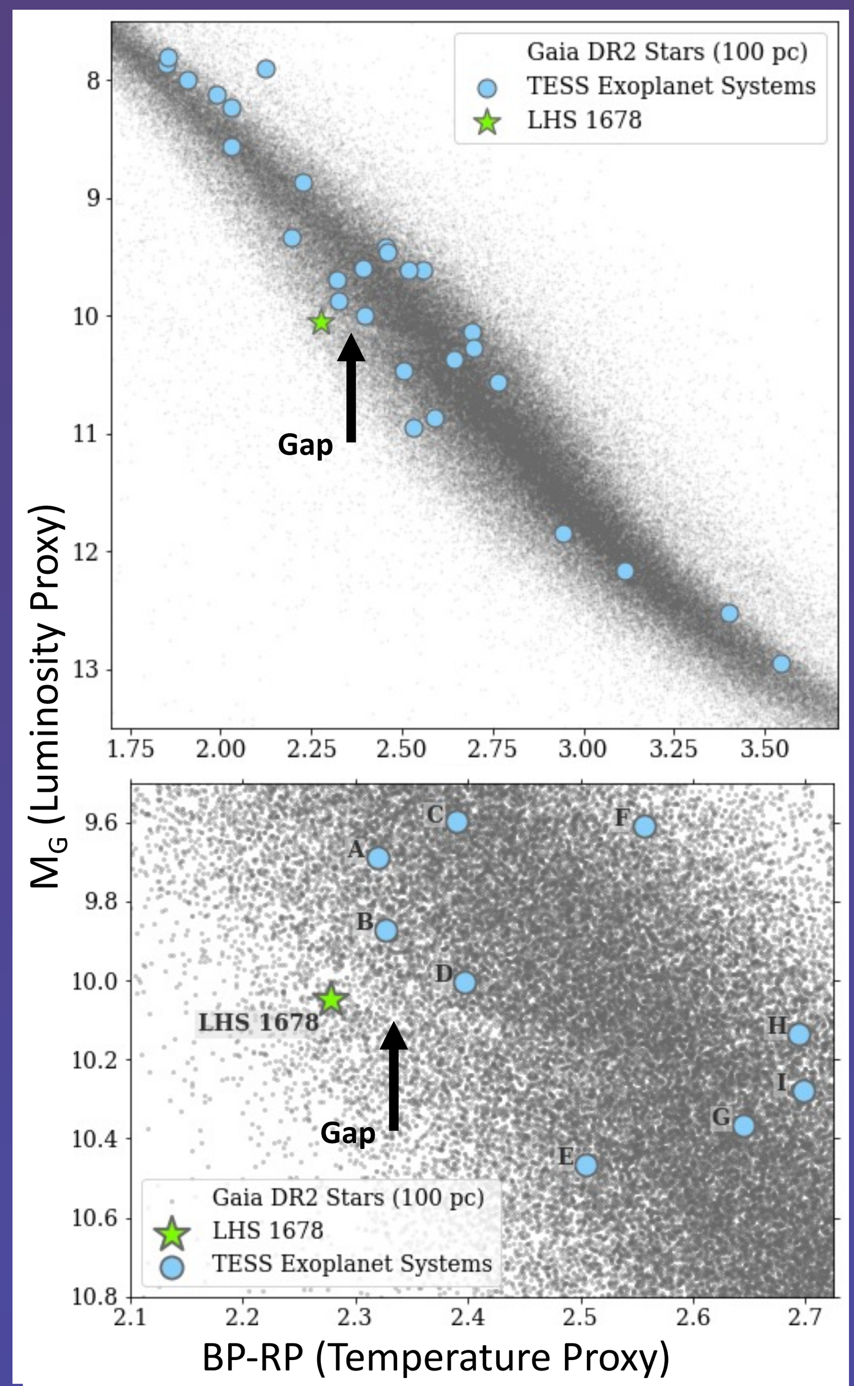
TESS data folded around the planets' periods. Overlaid for planets b and c are transit models measured via a MCMC analysis performed simultaneously on Sector 4 and 5 TESS data, ground-based light curves, and HARPS radial velocities. The shading in green corresponds to the 1-sigma range of models consistent with the data.

For more, look out for Silverstein et al. 2021 submitted

with, e.g., details on follow-up observations via TFOP and vetting & validation using *DAVE* (Kostov+2019b), *QATS* (Carter & Agol 2013, Kruse+2019), *TLS* (Hippke & Heller 2019a,b), and *vespa* (Morton 2015). Also details on planet b and c properties derived using *PyMC3* (Salvatier+2016), *forecaster* (Chen & Kipping 2017), *exoplanet* (Foreman-Mackey 2018), and *lightkurve* (Lightkurve Collaboration+ 2018). Additional details also on finding and characterizing TOI-696.03, following work in, e.g., Vanderburg+2016 and Huang+2020a,b, and using software such as *TESS-plots* (https://github.com/mkunimoto/TESS-plots).

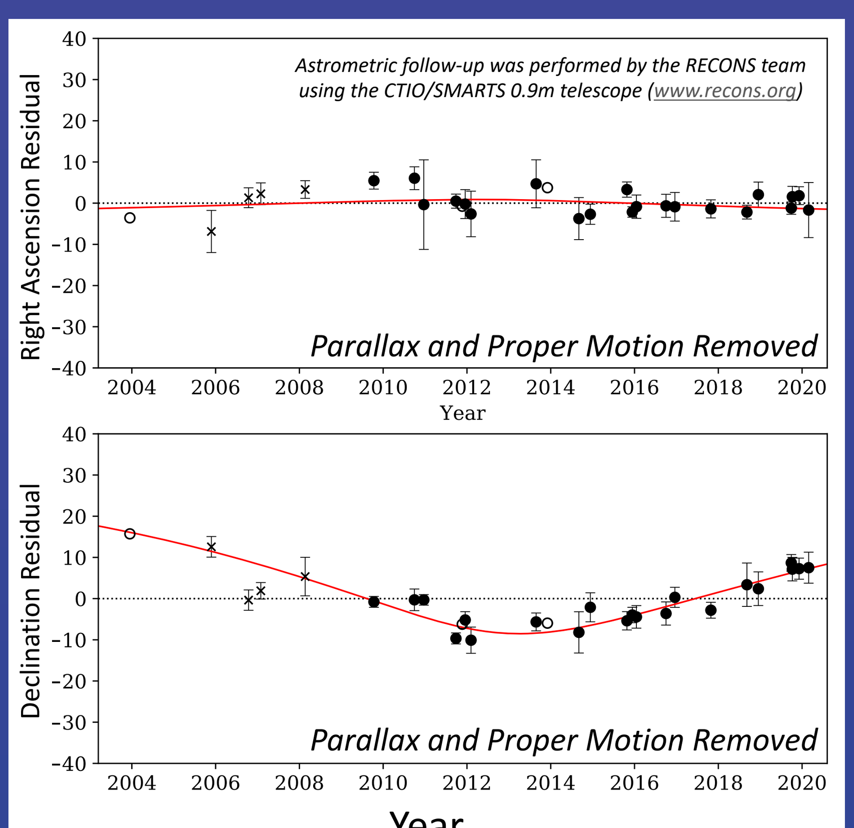
Ongoing Mysteries and Exciting Discoveries

Star Slowly Expanded & Contracted for 100s of Millions of Years What did this do to the planets?



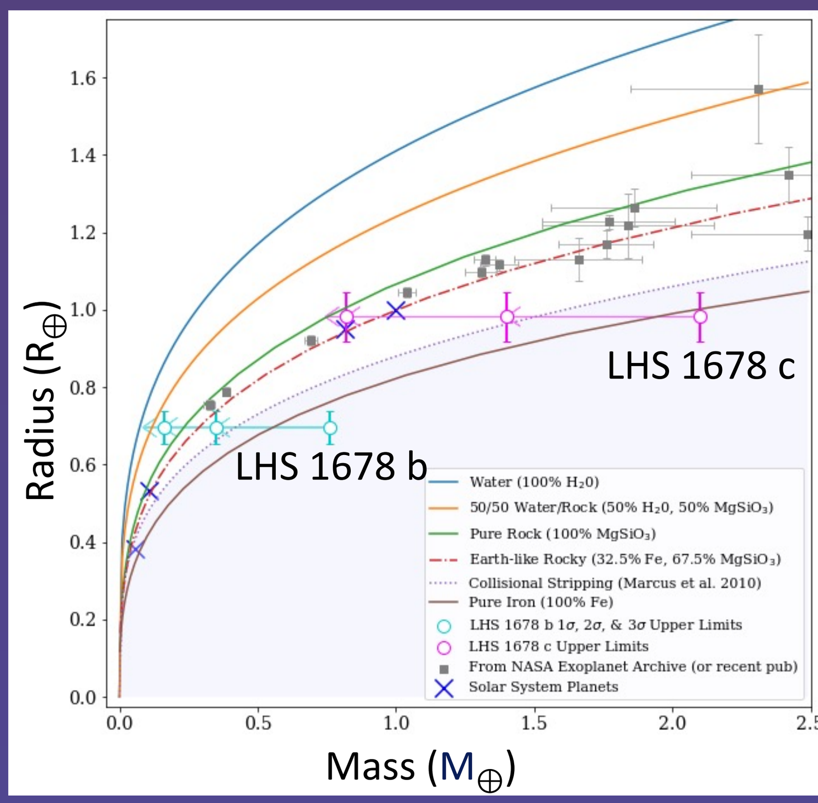
In the above HR diagram, the star's position just below the *Gaia* gap (Jao et al. 2018) indicates that it is fully convective and likely spent ~10^8-10^9 Gyr moving back and forth across the gap before settling below it (Baraffe & Chabrier 2018). **The effects of the associated change in stellar radius on exoplanet formation and evolution is currently unknown.** This is one of just a handful of exoplanet systems in/near the gap.

Brown Dwarf (?) Companion Found using 16 Years of Astrometry Data



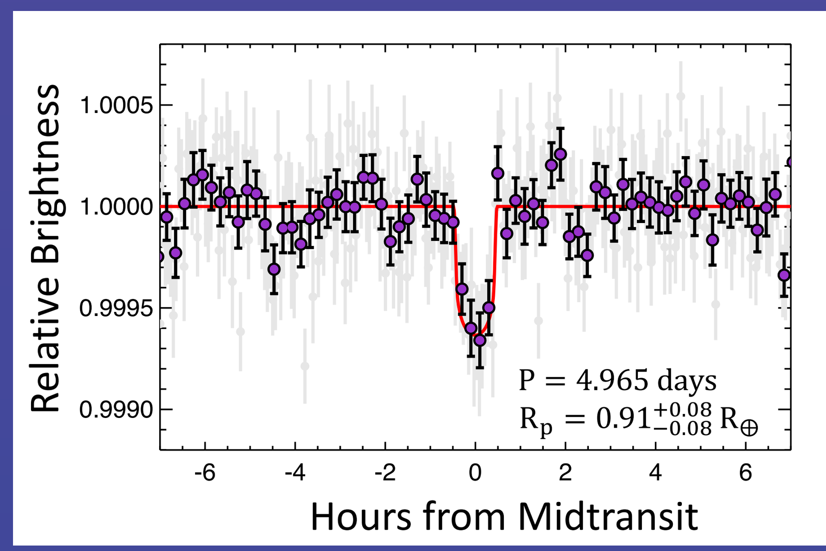
The periodic motion in Declination is caused by a **brown-dwarf-mass companion** or smaller with an **orbital period on the order of decades.** It is only detectable because of the long-term, 16-year dataset (Jao+2005). How many exoplanet systems have hidden companions? The companion may eclipse the host star and **orbit in the same plane as the exoplanets**, joining a small but growing set of systems useful in studying star and planet formation.

LHS 1678 as a Venus Analog? Need to measure mass…



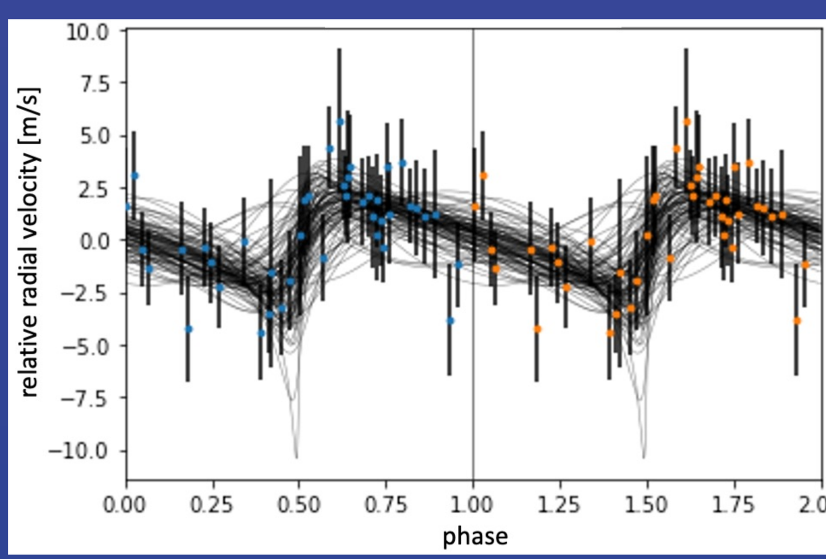
LHS 1678 b and c mass upper limits, the solar system objects, planets with known masses (exoplanetarchive.ipac.caltech.edu), and lines of constant density (Zeng+ 2019). The 1-σ mass upper limit of LHS 1678 c overlaps with Venus – perhaps we have a **Venus-density planet in the Venus zone**! This is useful for studying Venus & the runaway greenhouse effect. But first we must measure mass using an instrument such as ESPRESSO on VLT (Pepe+2010, Suárez-Mascareño+2020).

Candidate Third Planet TOI-696.03



TESS data folded on the candidate 3rd planet's period. Plotted in red is the MCMC best-fit model of TOI-696.03 using TESS multi-Cycle data from Sectors 4, 5, 31, and 32. Ground-based follow-up data are needed to confirm and validate the planet, which is **near 4:3 resonance** with LHS 1678 c.

42-Day Signal: Rotation? New Planet?



We identify a 42-day period signal in the HARPS RV data (Astudillo-Defru+ 2017b) using a Lomb-Scargle periodogram with ~5% false alarm probability. Plotted is the full phase-folded dataset and a Keplerian orbit model. This signal could be caused by **the rotation of the star or a longer-period planet.**