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ZTFJ0038+2030: a long period eclipsing white dwarf and a substellar companion

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ABSTRACT

In a search for eclipsing white dwarfs using the Zwicky Transient Facility lightcurves, we identified a deep eclipsing white dwarf with a dark, substellar companion. The lack of an infrared excess and an orbital period of 10 hours made this a potential exoplanet candidate. We obtained high-speed photometry and radial velocity measurements to characterize the system. The white dwarf has a mass of $0.50 \pm 0.02\,\mathrm{M}_\odot$ and a temperature of $10900 \pm 200\,\mathrm{K}$. The companion has a mass of $0.059 \pm 0.004\,\mathrm{M}_\odot$ and a small radius of $0.0783 \pm 0.0013\,\mathrm{R}_\odot$. It is one of the smallest transiting brown dwarfs known and likely old, $\gtrsim 8\,\mathrm{Gyr}$. The ZTF discovery efficiency of substellar objects transiting white dwarfs is limited by the number of epochs and as ZTF continues to collect data we expect to find more of these systems. This will allow us to measure period and mass distributions and allows us to understand the formation channels of white dwarfs with substellar companions.

Keywords: editorials, notices — miscellaneous — catalogs — surveys

1. INTRODUCTION

Substellar objects mainly consist of hydrogen gas and are not massive enough to fuse hydrogen in their core ($M \lesssim M_{\mathrm{HBL}} \approx 0.07\,\mathrm{M}_\odot$; $73\,\mathrm{M}_{\mathrm{jup}}$). Substellar objects have masses in the range of $\sim$0.3–$73\,\mathrm{M}_{\mathrm{jup}}$ and are generally divided into two classes: brown dwarfs and giant exoplanets. There is no clear separation based on mass, but the distinction is based on the formation history (see Burrows et al. 2001 for an extended discussion). The formation of a brown dwarf is the same as that of more massive main-sequence stars: they are formed by gravitational instabilities in gas clouds and have elemental abundances similar to that of the interstellar medium. On the other hand, giant planets are formed by core accretion in a disk around a protostar, and have an enhanced metal abundance compared to the host star. Transit studies (e.g. Carmichael et al. 2021), radial velocity studies (e.g. Shahaf & Mazeh 2019), and microlensing observations (e.g. Han et al. 2016; Poleski et al. 2017) of main-sequence stars show that substellar objects exist in orbits of $\sim 1\,\mathrm{AU}$. The mass distribution suggests that there are two distinct populations, giant planets with masses $\lesssim 30\,\mathrm{M}_{\mathrm{jup}}$, and brown dwarfs with masses $\gtrsim 60\,\mathrm{M}_{\mathrm{jup}}$, with a gap in between, the brown dwarf desert (Marcy & Butler 2000; Grether & Lineweaver 2006; Sahlmann et al. 2011; Ma & Ge 2014).

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However, recent discoveries by TESS shows that substellar objects do span the entire mass-range (Carmichael et al. 2020).

At the end of their life, main sequence stars go through a red-giant phase, which significantly affects nearby substellar companions (see Grunblatt et al. 2018, for giant planets around red giants). If a substellar companion is in a close enough orbit ($\approx$ 200–1000 $R_\odot$, 1–5 AU for RGB and AGB giants), the system forms a common-envelope (Ivanova et al. 2013). While more massive objects (brown dwarfs and low mass red dwarfs) are known to survive this process and end up as a short period binary (Casewell et al. 2018, 2020b,a), lower mass substellar companions are predicted to merge during a common-envelope event or get evaporated as soon as the hot white dwarf emerges from the common envelope (Soker 1998; Nelemans & Tauris 1998; Bear & Soker 2011). However, recent work (Lagos et al. 2021) suggest that giant planet can survive common envelope evolution. There are also alternative pathways to form short-period white dwarfs–planets systems, including the formation of second-generation planets from gas around the white dwarf (e.g. Perets 2010), or capture and/or inward migration of distant planets (e.g. Stephan et al. 2020).

There are many indications that short-period white dwarf–planet systems do exist: dust discs have been observed around white dwarfs (e.g. Zuckerman & Becklin 1987); the detection of heavily polluted white dwarfs (Koester et al. 2014); transiting debris around WD 1145+017 (Vanderburg et al. 2015) and other white dwarfs (Vanderbosch et al. 2020; Guidry et al. 2020); and white dwarf WD J0914+1914 which shows accreting material of a Neptune-like composition (Gänsicke et al. 2019).

There have been many searches for exoplanets transiting white dwarfs, e.g. Faedi et al. (2011); Fulton et al. (2014); van Sluijs & Van Eylen (2018); Dame et al. (2019); Rowan et al. (2019), but all of them did not find any candidates. In addition, Van Grootel et al. (2021) searched for exoplanets around bright SdB stars, but were also only able to put an upper limit to the planet occurrence rate. Vanderburg et al. (2020) discovered a white dwarf with a substellar companion with an orbital period of 1.4 days (WD J0914+1914). After carefully analysing optical and infrared lightcurves of the grazing eclipse, they conclude that the companion is a giant planet with a mass of $\lesssim 14 M_{\rm jup}$.

The discovery of the giant planet candidate around WD J0914+1914, which is bright and nearby, suggests that there are more eclipsing white dwarfs with (low mass) substellar companions. Because the white dwarf is small and hot, eclipses of substellar companions around white dwarfs are deep, and eclipses are the best method to detect these systems (e.g. Bell 2020; Agol 2011a). However, eclipses alone are not sufficient to determine the nature of the object. The radius of substellar objects is almost invariant of their mass for masses between 1 Jupiter mass and 0.07$M_\odot$brown dwarfs (Hatzes & Rauer 2015), which means the optical eclipse is identical for a Jupiter mass-object and a brown dwarf. However, the tidal disruption period is a function of density (Rappaport et al. 2013, 2021), which means that we can determine (using mass-radius models) what the *minimum* mass is. High mass substellar objects have a high density and can exist in orbital periods as short as 80 minutes, but low mass, low-density Jupiter-like objects exceed their Roche radius at periods as long as 9 hours and can only exist at longer periods.

In this paper, we present the discovery and characterization of ZTFJ003855.0+203025.5 (ZTFJ0038+2030), an eclipsing white dwarf with a substellar companion with an orbital period of 10 hours. To identify the eclipses, we used the Zwicky Transient Facility lightcurves (Graham et al. 2019; Bellm et al. 2019; Masci et al. 2019; Dekany et al. 2020). The system was identified in a search for deep eclipsing white dwarfs. We searched the combined PSF-photometry and alert photometry lightcurves of white dwarfs (Gentile Fusillo et al. 2019) for deep eclipses and identified the period using the BLS algoritm (Kovács et al. 2002). For more details, see van Roestel (2021) and Van Roestel (2021b) (in prep). ZTFJ0038+2030 showed a complete eclipse in the g and r band and the eclipse duration is short, consistent with that of a substellar object. It also showed no excess luminosity in the *Gaia* HR-diagram and no infrared excess in Pan-STARRS colors. Because of these properties, we prioritised it for followup observations to determine the nature of the companion.

We obtained followup photometry and spectroscopy (Section 2), which we used the characterize the system (Section 3). We present the mass, radius, and temperature measurements in Section 4. We compare this binary system with other white dwarfs with substellar companions, and discuss the implications of this discovery for future searches for giant exoplanets around white dwarfs with ZTF. We end with a summary.

2. FOLLOWUP DATA

2.1. *CHIMERA fast cadence photometry*

We obtained high-speed photometry in the g and z filters using CHIMERA (see Table 2). CHIMERA (Harding et al. 2016) is a dual-channel photometer that uses frame-transfer, electron-multiplying CCDs mounted on

Table 1. Brightness of ZTFJ0038+2030 in different bands. Gaia eDR3 data was used (Brown et al. 2020b), with the geometric distance from Bailer-Jones et al. (2021). '^{V}' indicates that the magnitudes are in the Vega system, other magnitudes are in the AB-system.

RA	$00^h38^m55.0^s$
Dec	$20°30'26.1''$
G^V	17.70
BP^V	17.76 ± 0.01
RP^V	17.63 ± 0.01
parallax	7.19 ± 0.11 mas
distance	$138.3^{+1.7}_{-1.9}$ pc
GALEX FUV	20.37 ± 0.24
GALEX NUV	18.58 ± 0.06
ZTF-g	17.70 ± 0.02
ZTF-r	17.78 ± 0.03
ZTF-i	17.95 ± 0.03
PS-g	17.705 ± 0.005
PS-r	17.786 ± 0.002
PS-i	17.931 ± 0.006
PS-z	18.093 ± 0.005
PS-y	18.18 ± 0.02
WISE-$W1^V$	17.87 ± 0.11
WISE-$W2^V$	17.63 ± 0.29

the Hale 200-inch (5.1 m) Telescope at Palomar Observatory (CA, USA). The pixelscale is 0.28 arcsec/pixel (unbinned). We used the conventional amplifier and used 2x2 binning on most nights to reduce the readout noise. Each of the images was bias subtracted and divided by twilight flat fields. We used the ULTRACAM pipeline to do aperture photometry (Dhillon et al. 2007). We used an optimal extraction method with a variable aperture of 1.5 the FWHM of the seeing (as measured from the reference star). A differential lightcurve was created by simply dividing the counts of the target by the counts from the reference star. Timestamps of the images were determined using a GPS receiver.

2.2. *ESI*

We used the Echellete Spectrograph and Imager (ESI, Sheinis et al. 2002) mounted at KeckII to obtain medium-resolution spectra ($R \approx 6000$). CuAr arc exposures were taken at the beginning of the night. The spectra were reduced using the *MAKEE*[1] pipeline following the standard procedure: bias subtraction, flat fielding, sky subtraction, order extraction, and wavelength calibration.

[1] http://www.astro.caltech.edu/~tb/ipac_staff/tab/makee/

2.3. *Archival photometry*

To be able to study the spectral energy distribution, we obtained photometry data from multiple other survey telescopes (see Table 1): *Gaia* eDR3 (Brown et al. 2020a), *Galex* (Bianchi et al. 2017), Pan-STARRS (Chambers et al. 2016), and *WISE* (Marocco et al. 2020). We used zero points for each of the filters to convert the magnitudes to a flux.

3. ANALYSIS

3.1. *Ephemeris*

We determine the ephemeris by measuring the mid-eclipse time from the CHIMERA g lightcurve. We then use the best model from the Chimera g data and use it fit all ZTF data. In addition, we noticed that there is one non-detection on 2012-11-1 in Palomar Transient Factory data (out of 94 observations). We add this epoch with half the eclipse duration as uncertainty as a prior ($BJD_{TDB} = 2456232.8854 \pm 0.0018$). This results in an ephemeris of:

$$BJD(TDB) = 2459045.985194(2) + 0.431\,920\,8(14) \quad (1)$$

3.2. *Spectra and radial velocity amplitude*

The spectra show a typical DA white dwarf spectrum with broad Balmer absorption lines. No features from the brown dwarf can be seen, including any Balmer emission due to irradiation (e.g. Parsons et al. 2018).

Radial velocities of the ESI spectra were measured by fitting a Gaussians, Lorentzians, and polynomials to the hydrogen lines to cover the continuum, line, and line core of the individual lines using the *FITSB2* routine (Napiwotzki et al. 2004). The procedure is described in full detail in Kupfer et al. (2020, 2017a,b). We fitted the wavelength shifts compared to the rest wavelengths using a χ^2-minimization.

To determine the radial velocity semi-amplitude of the white dwarf (K_1), we fit the radial velocity measurements using a sinusoid with a fixed period and zero phase based on the ephemeris determined from the ZTF data. The two remaining free parameters are the amplitude (K_1) and a systematic velocity (γ). We use the *emcee* Foreman-Mackey et al. (2013) to determine the best value and uncertainty: $K_1 = 24.2 \pm 1.4$ km/s (Fig. 2).

3.3. *Spectral energy distribution*

To determine the white dwarf temperature, we fit the observed spectral energy distribution with white dwarf models (see Fig. 1). We use a grid of DA white dwarf

Table 2. Summary of the followup observations

Date	UT	Tele./Inst.	N_{exp}	Exp. time (s)	Wavelength
2020-07-15	11:22 - 11:57	P200/CHIMERA	400	5.0	g
2020-07-15	11:22 - 11:57	P200/CHIMERA	400	5.0	z
2020-07-21	12:18 - 12:39	Keck/ESI/Echellete	2	600	4000 - 10000Å
2020-09-12	12:17 - 12:38	Keck/ESI/Echellete	2	600	4000 - 10000Å
2020-09-12	14:16 - 14:37	Keck/ESI/Echellete	3	600	4000 - 10000Å

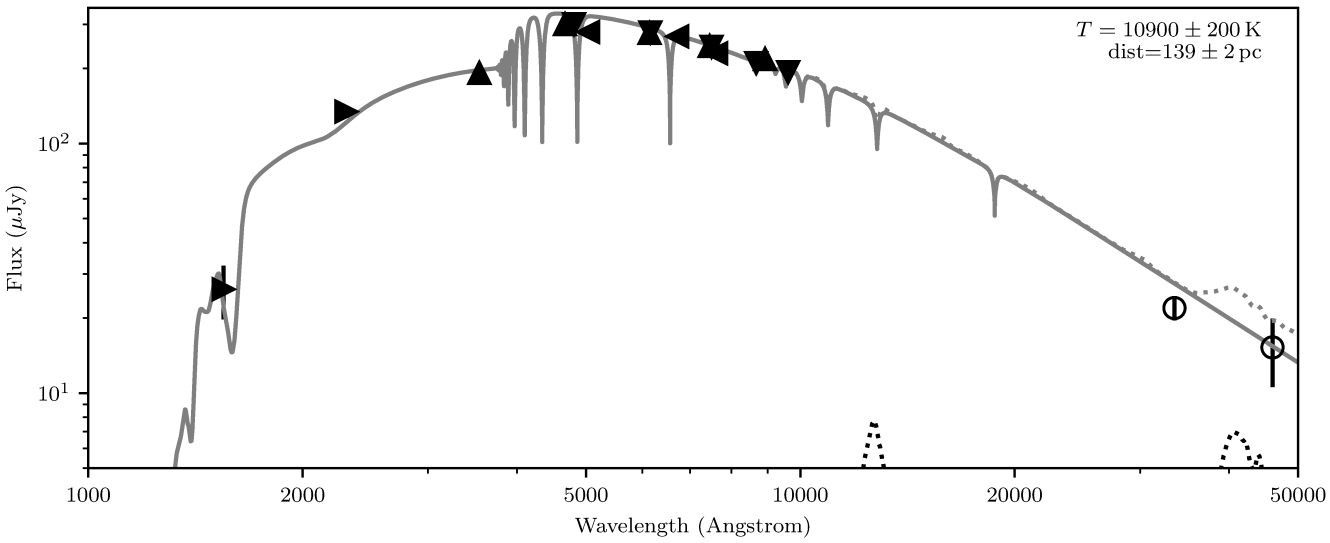

Figure 1. The spectral energy distribution of the system. Markers show *Galex*, *Gaia* DR3, Pan-STARRS, median ZTF *gri*, and *WISE* data. Open markers indicate data not used to constrain the fit. The grey solid line shows the best-fit DA white dwarf model. The dotted line shows the SED of the best-fit DA model with a 900 K brown dwarf model added.

models by Koester (2009) and use bilinear interpolation to be able to generate a model for any temperature and surface gravity value. We use the extinction law by Fitzpatrick (1999) to account for any dust extinction. To compare the model spectra with the data, we convolve the model spectra with the filter response curves[2] (Rodrigo et al. 2012; Rodrigo & Solano 2020). We use Gaussian priors on the parallax using the *Gaia* eDR3 data, the radius estimate from the lightcurve, and an E_{BV} value from Pan-STARRS extinction estimates (Green et al. 2018). We again use *emcee* to estimate the best-fit values and uncertainties. Using this method, we estimate the white dwarf temperature to be: $T_{\rm WD} = 10900 \pm 200$ K (Fig. 1).

3.4. *Lightcurve modelling*

We modelled the high cadence lightcurves using the package *ellc* (Maxted 2016). We use a spherical star to model the white dwarf, and use a Roche-lobe geometry for the companion. The free parameters for this model are the mid-eclipse time (t_0), inclination (i), mass-ratio (q), the radii divided by the semi-major axis of both objects ($r_{1,2} \equiv R_{1,2}/a$), the semi-major axis (a), and the surface brightness ratio ($J_{g,z}$).

We used a number of fixed parameters in the binary model. First, we use the orbital period obtained from the ZTF data (Section 3.1). For limb-darkening of the white dwarf we the values for T=10 000 K and $\log(g) = 8.0$ as calculated by (Claret et al. 2020).

In addition, we imposed two restrictions on the white dwarfs. The first is that it cannot be smaller than a zero-temperature white dwarf. The second constrain is a Gaussian prior on the white dwarf radius relative to the white dwarf M-R relation with an uncertainty of 5%. We use the approximation of the mass-radius relation of Eggleton from Rappaport et al. (1989). As a final constraint, we use a Gaussian prior on the radial velocity amplitude (K_1) of the white dwarf (see Section 3.2).

To find most probable parameter values and uncertainties, we again use *emcee*.

[2] http://svo2.cab.inta-csic.es/theory/fps/

4. RESULTS

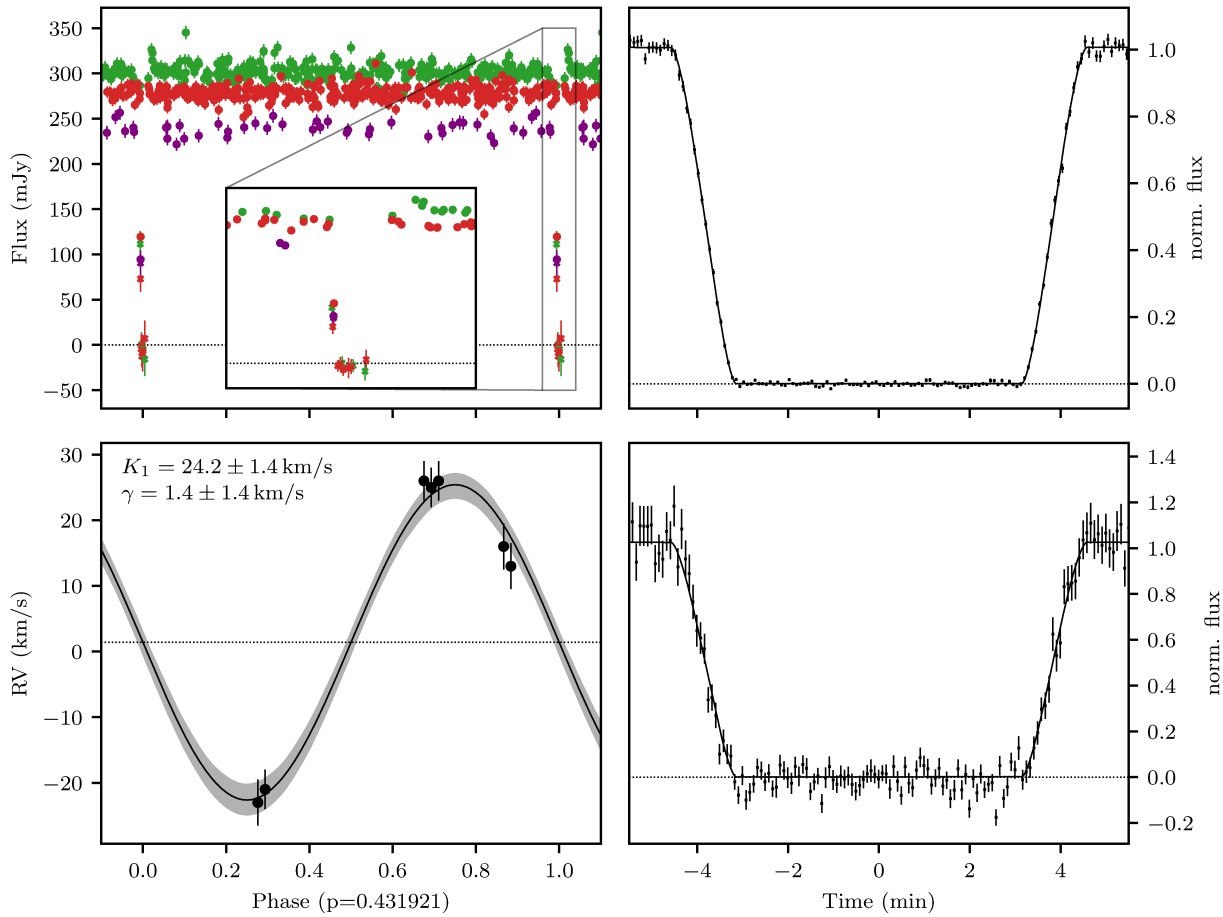

Figure 2. The top left panel shows the ZTF *gri* data (green, red, purple) folded to the period. The bottom left panel shows the ESI radial velocity measurements. The best-fit radial velocity curve is overplotted, with in grey the the 1-standard deviation, and the dotted line indicates the systematic velocity. The right two panels show the CHIMERA g (top) and z data (bottom) with the best-fit *lcurve* model overplotted.

We measured the binary properties by analysing the spectral energy distribution, ZTF lightcurves, phase-resolved spectroscopy, and high cadence g- and z-band lightcurves. The results are summarized in Table 4 and the posterior of the lightcurve modelling is shown in the appendix (Fig. 4).

The mass of the companion, which is mostly set by the radial velocity semi-amplitude measurement, is $M_2 = 0.0593 \pm 0.004 M_\odot$, and a radius of $R_2 = 0.0783^{0.0013}_{-0.0011} R_\odot$. This is consistent with a brown dwarf. Using the z-band surface brightness ratio, we estimate that the temperature of the brown dwarf is $\lesssim 1550$ K.

The mass of the white dwarf is $0.50 \pm 0.02\,M_\odot$, which is typical for a white dwarf (Kepler et al. 2007). The white dwarf radius ($R_1 = 0.01429 \pm 0.00020\,R_\odot$) is consistent with the white dwarf M-R relation, which is what we enforced with a prior. The temperature of the white dwarf is $T_1 = 10900 \pm 200$ K.

The orbital separation of the binary system is $a = 1.987 \pm 0.027 R_\odot$ and the inclination of this system is $i = 89.71 \pm 0.13°$. The corresponding impact parameter is $b \lesssim 0.18$.

5. DISCUSSION

5.1. *The nature of the substellar companion*

In Fig. 3, we plot the mass and radius of the companion, and compare it to models by Marley et al. (2018). The measured mass and radius agree with models of 10 Gyr old brown dwarfs with $Z \gtrsim 0$ abundances. The models predict a temperature of ∼800–900 K, which is well below the upper limit we determined from the z-band surface brightness ratio. In Fig. 1 we plot the best fit white dwarf spectrum with the spectrum of a 900 K brown dwarf added. Such a low temperature is consistent with the lack of any excess emission in the *WISE* bands. If we assume a solar abundance or lower, the age of the brown dwarf (and therefore the system) is $\gtrsim 8$ Gyr.

Compared to other substellar objects that are eclipsing white dwarfs, the mass and radius do not stand out

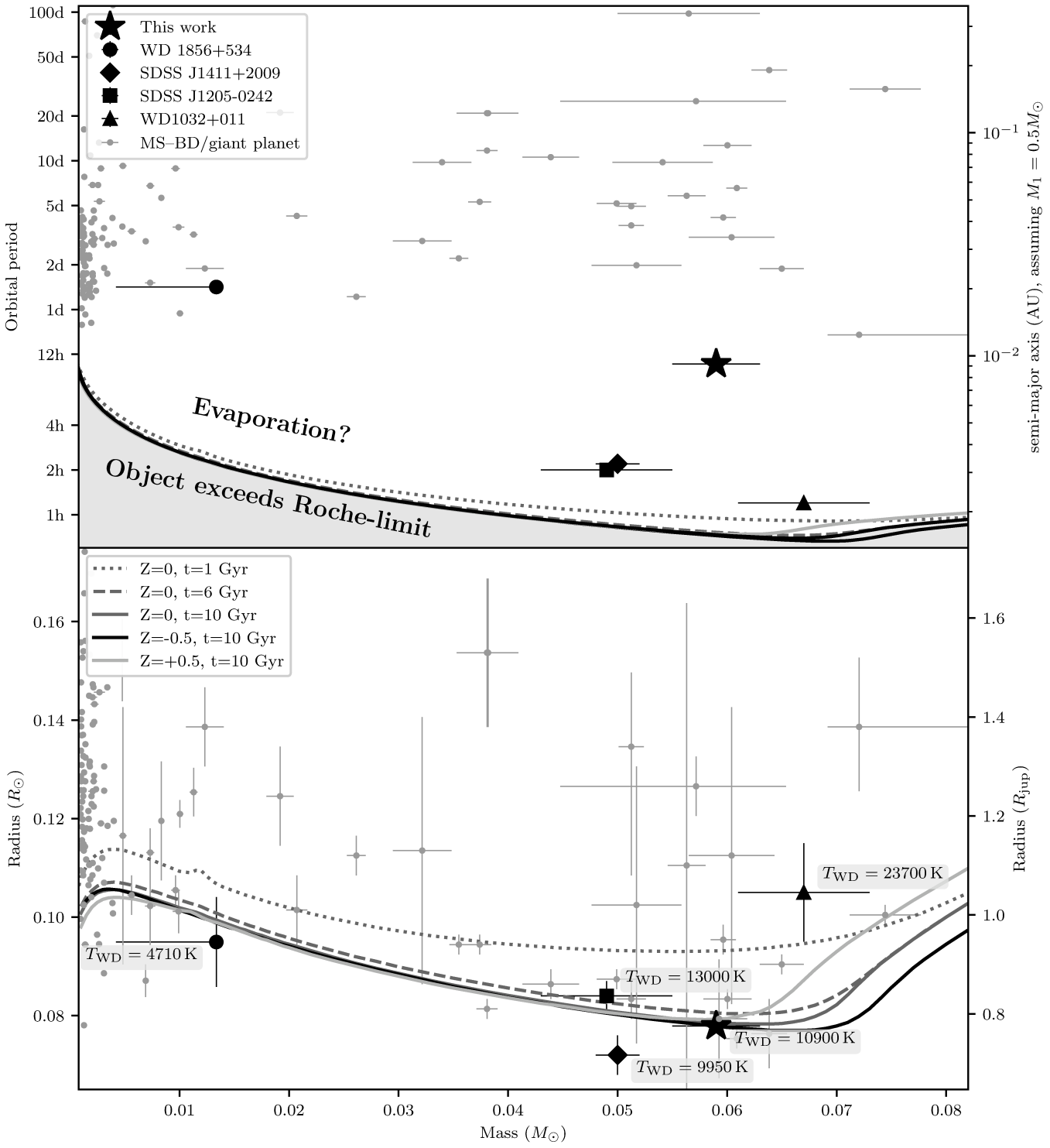

Figure 3. The characteristics of substellar companions that are eclipsing white dwarfs (black markers). The parameters of the other eclipsing white dwarfs with substellar companions are taken from Vanderburg et al. (2020), Casewell et al. (2020b), Parsons et al. (2018), Littlefair et al. (2014). Grey points show brown dwarfs and giant planets around other stellar types taken Carmichael et al. (2021) and Chen & Kipping (2017). The top panel shows the orbital period versus the mass. The lower-left region is off-limits as the object would exceeds the Roche-limit (Rappaport et al. 2013). Low-mass objects close to hot white dwarfs are also affected by photo-evaporation (Soker 1998; Nelemans et al. 2004; Bear & Soker 2011). The bottom panel shows the radius versus the mass. The white dwarf temperature is indicated next to each marker. Models are taken from Marley et al. (2018). Uncertainties for low mass objects are omitted for clarity.

Table 3. The binary parameters are determined by modelling the lightcurves using *ellc*. The top section lists model parameters, the bottom part shows derived parameters. We fixed the orbital period (^{f}), and for the radius of the white dwarf (R_1) and radial velocity amplitude (K_1) we used a prior (^{p}). We use the 95% percentile to determine upperlimits.

p^f (d)	0.431 920 8 (14)
t_0 ($\mathrm{BJD_{TBD}}$)	2459045.985194(2)
q	$0.1167^{+0.0075}_{-0.0068}$
i (°)	$89.71^{+0.12}_{-0.13}$
r_1	$0.007195^{+0.000075}_{-0.000078}$
r_2	$0.03934^{+0.00033}_{-0.00019}$
a ($\mathrm{R_\odot}$)	$1.987^{+0.030}_{-0.022}$
J_g	$\lesssim 0.000035$
J_z	$\lesssim 0.00014$
M_1 ($\mathrm{M_\odot}$)	$0.505^{+0.024}_{-0.018}$
M_2 ($\mathrm{M_\odot}$)	$0.0593^{+0.0036}_{-0.0039}$
R_1^p ($\mathrm{R_\odot}$)	$0.01429^{+0.00022}_{-0.00017}$
R_2 ($\mathrm{R_\odot}$)	$0.0783^{+0.0013}_{-0.0011}$
$\log(g_1)$ (cgs)	$7.832^{+0.013}_{-0.013}$
$\log(g_2)$ (cgs)	$5.425^{+0.02}_{-0.03}$
K_1^p (km/s)	$24.4^{+1.4}_{-1.4}$
K_2 (km/s)	$208.4^{+3.7}_{-2.9}$
$\overline{\rho}_2$ ($\mathrm{g/cm^3}$)	174^{+9}_{-11}

and are similar to other brown dwarfs. This object does stand out because of its orbital period, which at 10 hours is an order of magnitude larger than the three other known brown dwarfs orbiting white dwarfs. This means that the amount of irradiation by the white dwarf is relatively low. Using a simple blackbody approximation (Littlefair et al. 2014), we estimate that the temperature of the brown dwarf is only increased by ∼50 K due to irradiation by the white dwarf. This fact, and the systems relative brightness, make this system a good prototype system for long period white dwarf brown dwarf systems.

5.2. *Formation history*

Since the companion is a brown dwarf and not a giant planet, standard common envelope evolution can explain the formation of this system. Given that the mass the white dwarf is $\geq 0.47\,\mathrm{M_\odot}$ the white dwarf has very likely a CO core (see e.g. Marigo 2013 and also Parsons et al. 2017 for observational evidence) which allows for two formation scenarios. In the first scenario, the white dwarf could have formed during a common envelope phase on the Asymptotic Giant branch (AGB) after helium core exhaustion. The second scenario is that the common envelope happened at the tip of the Red giant branch (RGB), just after the helium flash (Han et al. 2003) which would result in a white dwarf with a mass close to $0.47\,\mathrm{M_\odot}$. In that scenario the white dwarf would have after the common envelope evolved into a hot subdwarf (sdB) and appeared as an HW Vir system before it evolved into a white dwarf with a brown dwarf companion after helium exhaustion in the sdB. Several sdB + brown dwarf systems are known, although typically seen with shorter orbital periods (e.g. Geier et al. 2011; Schaffenroth et al. 2015, 2018, 2019).

The initial to final mass relation for the white dwarfs suggests that the white dwarf progenitor was approximately a 1–2 $\mathrm{M_\odot}$ main-sequence star. This corresponds to a main-sequence lifetime of 10–2 Gyr (Catalán et al. 2008; Marigo 2013; Cummings et al. 2018). The cooling age of the white dwarf is approximately ∼400 Myr (Koester 2009). This is consistent with the age estimate based on the brown dwarf radius.

The white dwarf will slowly cool down and the period will slowly decrease due to gravitational wave radiation. It will take ∼135 Gyr to reach an orbital period of ∼40 minutes (Rappaport et al. 2021), at which point the white dwarf will be ∼1000 K. Roche-lobe overflow will commence and system becomes a cataclysmic variable (Littlefair et al. 2003). The accretion flow will heat up the white dwarf again while the period increases. This will slowly drain the brown dwarf and the system ends up as a 'period-bouncer'; a very low accretion rate CV with an orbital period of ≈90 minutes (e.g Pala et al. 2018).

5.3. *Implications for searches for giant planets transiting white dwarfs with ZTF*

Here, we briefly discuss the detection efficiency of our search and the occurrence rate of white dwarfs with transiting substellar objects. A detailed simulation is beyond the scope of this paper and we limit ourselves to an order of magnitude estimate only.

To find ZTFJ0038+2030 we searched the ZTF lightcurves of the *Gaia* white dwarf catalog by Gentile Fusillo et al. (2019) which contains 486 641 candidate white dwarf over the entire sky. There are 129 148 white dwarf brighter than 20 mag with more than 80 epochs in their ZTF lightcurve. Based on the number of epochs in these lightcurves, we estimate an average recovery efficiency of 15-25% (simply the probability of getting 7-5 in-eclipse points). We note that we recovered the other three eclipsing WD-BD systems in Fig. 3.

With the discovery of ZTFJ0038+2030 and the discovery by Vanderburg et al. (2020), there are now two known long-period ($\gtrsim 10$ h) transiting substellar objects around a white dwarfs; the first most likely a giant planet and the second most likely a brown dwarf. This

suggests that, at longer orbital periods, the occurrence rate is the same order of magnitude. More systems need to be found and characterized in order to determine the mass distribution and determine which of the formation channels are important in the formation of these objects.

Currently, the ZTF detection efficiency is limited by the number of epochs available per white dwarf. As more epochs are obtained, ZTF will be able to identify narrower eclipses, which means that longer period systems can be identified. Based on the recovery efficiency of ZTFJ0038+2030 we estimate that ZTF will find another $3-6$ similar objects as it keeps on accumulating more data. Other surveys like *Gaia*, ATLAS, and BlackGEM can be used to find similar systems over the whole sky. In the near future, the Vera C. Rubin observatory (Ivezič et al. 2019) will find many more white dwarfs with exoplanets, possibly down to earth-sized objects (Agol 2011b).

6. SUMMARY AND CONCLUSION

Using ZTF photometry, and *Gaia* and Pan-STARRS data, we discovered an eclipsing binary composed of a white dwarf and a substellar companion with an orbital period of 10 hours. We used follow-up photometry and spectroscopy to measure the binary parameters. This shows that the substellar companion is an $\gtrsim$ 8Gyr old brown dwarf with a mass of $0.06M_{\odot}$, and the white dwarf a $0.50M_{\odot}$, CO white dwarf. The system is relatively bright, and a good prototype system where the brown dwarf suffers minimal irradiation. It is also a useful target for eclipse timing to find circum-binary objects (e.g. NNser, Marsh et al. 2014) as brown dwarf are not expected to show eclipse time variations due to Applegate's mechanism (Applegate 1992; Bours et al. 2016).

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Based on observations obtained with the Samuel Oschin Telescope 48-inch and the 60-inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project. ZTF is supported by the National Science Foundation under Grant No. AST-1440341 and a collaboration including Caltech, IPAC, the Weizmann Institute for Science, the Oskar Klein Center at Stockholm University, the University of Maryland, the University of Washington, Deutsches Elektronen-Synchrotron and Humboldt University, Los Alamos National Laboratories, the TANGO Consortium of Taiwan, the University of Wisconsin at Milwaukee, and Lawrence Berkeley National Laboratories. Operations are conducted by COO, IPAC, and UW.

Based on observations obtained with the 200-inch Hale Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project. The Hale telescope is operated by the Caltech Optical Observatories.

Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France. This research made use of NumPy (Harris et al. 2020); matplotlib, a Python library for publication quality graphics (Hunter 2007); SciPy (Virtanen et al. 2020); Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2018, 2013a).

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The Pan-STARRS1 Surveys (PS1) have been made possible through contributions of the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation under Grant No. AST-1238877, the University of Maryland, and Eotvos Lorand University (ELTE).

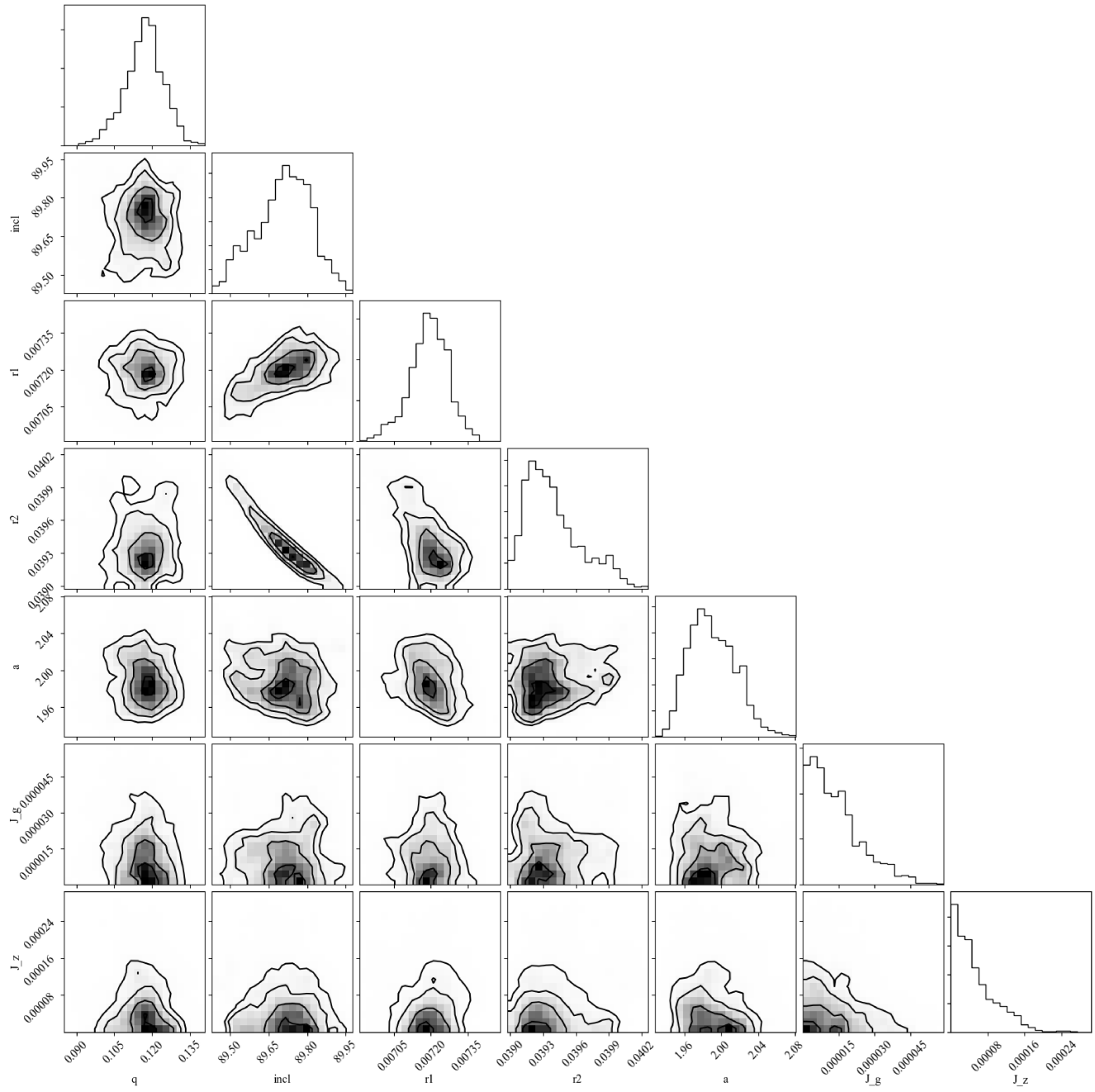

Figure 4. The posterior distribution of the fit to the lightcurve data using *ellc* and *emcee*.

Facilities: P48(ZTF), P200:5.0m (CHIMERA), Keck2:10m (ESI),

Software: astropy (Astropy Collaboration et al. 2013b), Makee, ellc (Maxted et al. 2014), scipy, emcee (Foreman-Mackey et al. 2013)

APPENDIX

A. APPENDIX INFORMATION

REFERENCES

Agol, E. 2011a, 25, conference Name: Telescopes from Afar. http://adsabs.harvard.edu/abs/2011tfa..confE..25A

—. 2011b, The Astrophysical Journal Letters, 731, L31. http://adsabs.harvard.edu/abs/2011ApJ...731L..31A

Applegate, J. H. 1992, The Astrophysical Journal, 385, 621. http://adsabs.harvard.edu/abs/1992ApJ...385..621A

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013a, A&A, 558, A33

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013b, Astronomy and Astrophysics, 558, A33. http://adsabs.harvard.edu/abs/2013A%26A...558A..33A

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, The Astronomical Journal, 161, 147. http://adsabs.harvard.edu/abs/2021AJ....161..147B

Bear, E., & Soker, N. 2011, Monthly Notices of the Royal Astronomical Society, 414, 1788. http://adsabs.harvard.edu/abs/2011MNRAS.414.1788B

Bell, K. J. 2020, 357, 37, conference Name: IAU Symposium Place: eprint: arXiv:1911.07889. http://adsabs.harvard.edu/abs/2020IAUS..357...37B

Bellm, E., Kulkarni, S., & Graham, M. 2019, 233, 363.08, conference Name: American Astronomical Society Meeting Abstracts #233. http://adsabs.harvard.edu/abs/2019AAS...23336308B

Bianchi, L., Shiao, B., & Thilker, D. 2017, 230, 24, arXiv: 1704.05903 [astro-ph.GA] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2017ApJS..230...24B tex.eid: 24

Bours, M. C. P., Marsh, T. R., Parsons, S. G., et al. 2016, Monthly Notices of the Royal Astronomical Society, 460, 3873. http://adsabs.harvard.edu/abs/2016MNRAS.460.3873B

Brown, A. G. A., Vallenari, A., Prusti, T., & Bruijne, J. H. J. d. 2020a, Astronomy & Astrophysics, doi:10.1051/0004-6361/202039657, publisher: EDP Sciences. https://www.aanda.org/articles/aa/abs/forth/aa39657-20/aa39657-20.html

Brown, W. R., Kilic, M., Bédard, A., Kosakowski, A., & Bergeron, P. 2020b, The Astrophysical Journal Letters, 892, L35. http://adsabs.harvard.edu/abs/2020ApJ...892L..35B

Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Reviews of Modern Physics, 73, 719. http://adsabs.harvard.edu/abs/2001RvMP...73..719B

Carmichael, T. W., Quinn, S. N., Mustill, A. J., et al. 2020, The Astronomical Journal, 160, 53. http://adsabs.harvard.edu/abs/2020AJ....160...53C

Carmichael, T. W., Quinn, S. N., Zhou, G., et al. 2021, The Astronomical Journal, 161, 97. http://adsabs.harvard.edu/abs/2021AJ....161...97C

Casewell, S. L., Debes, J., Braker, I. P., et al. 2020a, arXiv e-prints, 2010, arXiv:2010.07398. http://adsabs.harvard.edu/abs/2020arXiv201007398C

Casewell, S. L., Littlefair, S. P., Parsons, S. G., et al. 2018, Monthly Notices of the Royal Astronomical Society, 481, 5216. http://adsabs.harvard.edu/abs/2018MNRAS.481.5216C

Casewell, S. L., Belardi, C., Parsons, S. G., et al. 2020b, Monthly Notices of the Royal Astronomical Society, 497, 3571. http://adsabs.harvard.edu/abs/2020MNRAS.497.3571C

Catalán, S., Isern, J., García-Berro, E., & Ribas, I. 2008, Monthly Notices of the Royal Astronomical Society, 387, 1693. https://doi.org/10.1111/j.1365-2966.2008.13356.x

Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560, arXiv: 1612.05560 [astro-ph.IM] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2016arXiv161205560C tex.eid: arXiv:1612.05560

Chen, J., & Kipping, D. 2017, The Astrophysical Journal, 834, 17. http://adsabs.harvard.edu/abs/2017ApJ...834...17C

Claret, A., Cukanovaite, E., Burdge, K., et al. 2020, Astronomy and Astrophysics, 634, A93. http://adsabs.harvard.edu/abs/2020A%26A...634A..93C

Cummings, J. D., Kalirai, J. S., Tremblay, P.-E., Ramirez-Ruiz, E., & Choi, J. 2018, The Astrophysical Journal, 866, 21, arXiv: 1809.01673. http://arxiv.org/abs/1809.01673

Dame, K., Belardi, C., Kilic, M., et al. 2019, Monthly Notices of the Royal Astronomical Society, 490, 1066. http://adsabs.harvard.edu/abs/2019MNRAS.490.1066D

Dekany, R., Smith, R. M., Riddle, R., et al. 2020, Publications of the Astronomical Society of the Pacific, 132, 038001. http://adsabs.harvard.edu/abs/2020PASP..132c8001D

Dhillon, V. S., Marsh, T. R., Stevenson, M. J., et al. 2007, Monthly Notices of the Royal Astronomical Society, 378, 825. http://adsabs.harvard.edu/abs/2007MNRAS.378..825D

Faedi, F., West, R. G., Burleigh, M. R., Goad, M. R., & Hebb, L. 2011, Monthly Notices of the Royal Astronomical Society, 410, 899. http://adsabs.harvard.edu/abs/2011MNRAS.410..899F

Fitzpatrick, E. L. 1999, Publications of the Astronomical Society of the Pacific, 111, 63. http://adsabs.harvard.edu/abs/1999PASP..111...63F

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, 125, 306, arXiv: 1202.3665 [astro-ph.IM] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2013PASP..125..306F

Fulton, B. J., Tonry, J. L., Flewelling, H., et al. 2014, The Astrophysical Journal, 796, 114. http://adsabs.harvard.edu/abs/2014ApJ...796..114F

Geier, S., Heber, U., Tillich, A., et al. 2011, 1331, 163, conference Name: Planetary Systems Beyond the Main Sequence Place: eprint: arXiv:1012.3839. http://adsabs.harvard.edu/abs/2011AIPC.1331..163G

Gentile Fusillo, N. P., Tremblay, P.-E., Gänsicke, B. T., et al. 2019, 482, 4570, arXiv: 1807.03315 [astro-ph.SR] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2019MNRAS.482.4570G

Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, 131, 078001, arXiv: 1902.01945 [astro-ph.IM] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2019PASP..131g8001G

Green, M. J., Marsh, T. R., Steeghs, D. T. H., et al. 2018, Monthly Notices of the Royal Astronomical Society, 476, 1663. https://ui.adsabs.harvard.edu/abs/2018MNRAS.476.1663G/abstract

Grether, D., & Lineweaver, C. H. 2006, The Astrophysical Journal, 640, 1051. http://adsabs.harvard.edu/abs/2006ApJ...640.1051G

Grunblatt, S. K., Huber, D., Gaidos, E., et al. 2018, The Astrophysical Journal, 861, L5, publisher: American Astronomical Society. https://doi.org/10.3847/2041-8213/aacc67

Guidry, J. A., Vanderbosch, Z. P., Hermes, J. J., et al. 2020, arXiv e-prints, 2012, arXiv:2012.00035. http://adsabs.harvard.edu/abs/2020arXiv201200035G

Gänsicke, B. T., Schreiber, M. R., Toloza, O., et al. 2019, Nature, 576, 61. http://adsabs.harvard.edu/abs/2019Natur.576...61G

Han, C., Jung, Y. K., Udalski, A., et al. 2016, The Astrophysical Journal, 822, 75. http://adsabs.harvard.edu/abs/2016ApJ...822...75H

Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, doi:10.1046/j.1365-8711.2003.06451.x. https://arxiv.org/abs/astro-ph/0301380v1

Harding, L. K., Hallinan, G., Milburn, J., et al. 2016, Monthly Notices of the Royal Astronomical Society, 457, 3036. https://ui.adsabs.harvard.edu/abs/2016MNRAS.457.3036H/abstract

Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Nature, 585, 357. https://doi.org/10.1038/s41586-020-2649-2

Hatzes, A. P., & Rauer, H. 2015, The Astrophysical Journal Letters, 810, L25. http://adsabs.harvard.edu/abs/2015ApJ...810L..25H

Hunter, J. D. 2007, Computing In Science & Engineering, 9, 90

Ivanova, N., Justham, S., Chen, X., et al. 2013, Astronomy and Astrophysics Review, 21, 59. http://adsabs.harvard.edu/abs/2013A%26ARv..21...59I

Ivezić, v., Kahn, S. M., Tyson, J. A., et al. 2019, The Astrophysical Journal, 873, 111. http://adsabs.harvard.edu/abs/2019ApJ...873..111I

Kepler, S. O., Kleinman, S. J., Nitta, A., et al. 2007, Monthly Notices of the Royal Astronomical Society, 375, 1315. https://doi.org/10.1111/j.1365-2966.2006.11388.x

Koester, D. 2009, Astronomy & Astrophysics, 498, 517. http://www.aanda.org/10.1051/0004-6361/200811468

Koester, D., Gänsicke, B. T., & Farihi, J. 2014, Astronomy and Astrophysics, 566, A34. http://adsabs.harvard.edu/abs/2014A%26A...566A..34K

Kovács, G., Zucker, S., & Mazeh, T. 2002, 391, 369, arXiv: astro-ph/0206099 [astro-ph] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2002A&A...391..369K

Kupfer, T., van Roestel, J., Brooks, J., et al. 2017a, The Astrophysical Journal, 835, 131. http://adsabs.harvard.edu/abs/2017ApJ...835..131K

Kupfer, T., Ramsay, G., Roestel, J. v., et al. 2017b, The Astrophysical Journal, 851, 28, publisher: American Astronomical Society. https://doi.org/10.3847/1538-4357/aa9522

Kupfer, T., Bauer, E. B., Marsh, T. R., et al. 2020, The Astrophysical Journal, 891, 45. http://adsabs.harvard.edu/abs/2020ApJ...891...45K

Lagos, F., Schreiber, M. R., Zorotovic, M., et al. 2021, Monthly Notices of the Royal Astronomical Society, 501, 676. http://adsabs.harvard.edu/abs/2021MNRAS.501..676L

Littlefair, S. P., Dhillon, V. S., & Martín, E. L. 2003, Monthly Notices of the Royal Astronomical Society, 340, 264. http://adsabs.harvard.edu/abs/2003MNRAS.340..264L

Littlefair, S. P., Casewell, S. L., Parsons, S. G., et al. 2014, Monthly Notices of the Royal Astronomical Society, 445, 2106. http://adsabs.harvard.edu/abs/2014MNRAS.445.2106L

Ma, B., & Ge, J. 2014, Monthly Notices of the Royal Astronomical Society, 439, 2781. http://adsabs.harvard.edu/abs/2014MNRAS.439.2781M

Marcy, G. W., & Butler, R. P. 2000, Publications of the Astronomical Society of the Pacific, 112, 137. http://adsabs.harvard.edu/abs/2000PASP..112..137M

Marigo, P. 2013, 281, 36, conference Name: Binary Paths to Type Ia Supernovae Explosions. http://adsabs.harvard.edu/abs/2013IAUS..281...36M

Marley, M., Saumon, D., Morley, C., & Fortney, J. 2018, Sonora 2018: Cloud-free, solar composition, solar C/O substellar atmosphere models and spectra (Zenodo), doi:10.5281/zenodo.1309035

Marocco, F., Eisenhardt, P. R. M., Fowler, J. W., et al. 2020, arXiv e-prints, 2012, arXiv:2012.13084. http://adsabs.harvard.edu/abs/2020arXiv201213084M

Marsh, T. R., Parsons, S. G., Bours, M. C. P., et al. 2014, Monthly Notices of the Royal Astronomical Society, 437, 475. https://doi.org/10.1093/mnras/stt1903

Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, 131, 018003, arXiv: 1902.01872 [astro-ph.IM] tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/2019PASP..131a8003M

Maxted, P. F. L. 2016, Astronomy and Astrophysics, 591, A111. http://adsabs.harvard.edu/abs/2016A%26A...591A.111M

Maxted, P. F. L., Serenelli, A. M., Marsh, T. R., et al. 2014, Monthly Notices of the Royal Astronomical Society, 444, 208. http://adsabs.harvard.edu/abs/2014MNRAS.444..208M

Napiwotzki, R., Karl, C. A., Lisker, T., et al. 2004, Astrophysics and Space Science, 291, 321. http://adsabs.harvard.edu/abs/2004Ap%26SS.291..321N

Nelemans, G., & Tauris, T. M. 1998, Astronomy and Astrophysics, 335, L85. http://adsabs.harvard.edu/abs/1998A%26A...335L..85N

Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2004, Monthly Notices of the Royal Astronomical Society, 349, 181, publisher: Oxford Academic. https://academic.oup.com/mnras/article/349/1/181/3101554

Pala, A. F., Schmidtobreick, L., Tappert, C., Gänsicke, B. T., & Mehner, A. 2018, Monthly Notices of the Royal Astronomical Society, 481, 2523. http://adsabs.harvard.edu/abs/2018MNRAS.481.2523P

Parsons, S. G., Gänsicke, B. T., Marsh, T. R., et al. 2017, Monthly Notices of the Royal Astronomical Society, 470, 4473. http://adsabs.harvard.edu/abs/2017MNRAS.470.4473P

—. 2018, Monthly Notices of the Royal Astronomical Society, 481, 1083. http://adsabs.harvard.edu/abs/2018MNRAS.481.1083P

Perets, H. B. 2010, arXiv e-prints, 1001, arXiv:1001.0581. http://adsabs.harvard.edu/abs/2010arXiv1001.0581P

Poleski, R., Udalski, A., Bond, I. A., et al. 2017, Astronomy & Astrophysics, 604, A103, publisher: EDP Sciences. https://www.aanda.org/articles/aa/abs/2017/08/aa30928-17/aa30928-17.html

Rappaport, S., Putney, A., & Verbunt, F. 1989, 345, 210, tex.adsnote: Provided by the SAO/NASA Astrophysics Data System tex.adsurl: https://ui.adsabs.harvard.edu/abs/1989ApJ...345..210R

Rappaport, S., Sanchis-Ojeda, R., Rogers, L. A., Levine, A., & Winn, J. N. 2013, The Astrophysical Journal Letters, 773, L15. http://adsabs.harvard.edu/abs/2013ApJ...773L..15R

Rappaport, S., Vanderburg, A., Schwab, J., & Nelson, L. 2021, arXiv e-prints, arXiv:2104.12083. https://ui.adsabs.harvard.edu/abs/2021arXiv210412083R/abstract

Rodrigo, C., & Solano, E. 2020, 182, conference Name: XIV.0 Scientific Meeting (virtual) of the Spanish Astronomical Society. http://adsabs.harvard.edu/abs/2020sea..confE.182R

Rodrigo, C., Solano, E., Bayo, A., & Rodrigo, C. 2012, IVOA Working Draft 15 October 2012, doi:10.5479/ADS/bib/2012ivoa.rept.1015R. http://adsabs.harvard.edu/abs/2012ivoa.rept.1015R

Rowan, D. M., Tucker, M. A., Shappee, B. J., & Hermes, J. J. 2019, Monthly Notices of the Royal Astronomical Society, 486, 4574. http://adsabs.harvard.edu/abs/2019MNRAS.486.4574R

Sahlmann, J., Ségransan, D., Queloz, D., et al. 2011, Astronomy and Astrophysics, 525, A95. http://adsabs.harvard.edu/abs/2011A%26A...525A..95S

Schaffenroth, V., Barlow, B. N., Drechsel, H., & Dunlap, B. H. 2015, Astronomy and Astrophysics, 576, A123. http://adsabs.harvard.edu/abs/2015A%26A...576A.123S

Schaffenroth, V., Geier, S., Heber, U., et al. 2018, Astronomy and Astrophysics, 614, A77. http://adsabs.harvard.edu/abs/2018A%26A...614A..77S

Schaffenroth, V., Barlow, B. N., Geier, S., et al. 2019, Astronomy and Astrophysics, 630, A80. http://adsabs.harvard.edu/abs/2019A%26A...630A..80S

Shahaf, S., & Mazeh, T. 2019, Monthly Notices of the Royal Astronomical Society, 487, 3356. http://adsabs.harvard.edu/abs/2019MNRAS.487.3356S

Sheinis, A. I., Bolte, M., Epps, H. W., et al. 2002, Publications of the Astronomical Society of the Pacific, 114, 851. http://adsabs.harvard.edu/abs/2002PASP..114..851S

Soker, N. 1998, The Astronomical Journal, 116, 1308. http://adsabs.harvard.edu/abs/1998AJ....116.1308S

Stephan, A. P., Naoz, S., & Gaudi, B. S. 2020, arXiv e-prints, 2010, arXiv:2010.10534. http://adsabs.harvard.edu/abs/2020arXiv201010534S

Van Grootel, V., Pozuelos, F. J., Thuillier, A., et al. 2021, arXiv:2104.10462 [astro-ph], arXiv: 2104.10462. http://arxiv.org/abs/2104.10462

van Roestel, J. 2021

van Sluijs, L., & Van Eylen, V. 2018, Monthly Notices of the Royal Astronomical Society, 474, 4603. http://adsabs.harvard.edu/abs/2018MNRAS.474.4603V

Vanderbosch, Z., Hermes, J. J., Dennihy, E., et al. 2020, The Astrophysical Journal, 897, 171. http://adsabs.harvard.edu/abs/2020ApJ...897..171V

Vanderburg, A., Johnson, J. A., Rappaport, S., et al. 2015, Nature, 526, 546. http://adsabs.harvard.edu/abs/2015Natur.526..546V

Vanderburg, A., Rappaport, S. A., Xu, S., et al. 2020, Nature, 585, 363, arXiv: 2009.07282. http://arxiv.org/abs/2009.07282

Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261

Zuckerman, B., & Becklin, E. E. 1987, Nature, 330, 138. http://adsabs.harvard.edu/abs/1987Natur.330..138Z