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K2-98 b: A 32-M⊕ NEPTUNE-SIZED PLANET IN A 10-DAY ORBIT TRANSITING AN F8 STAR

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ABSTRACT

We report the discovery of K2-98 b (EPIC 211391664 b), a transiting Neptune-sized planet monitored by the K2 mission during its campaign 5. We combine the K2 time-series data with ground-based photometric and spectroscopic follow-up observations to confirm the planetary nature of the object and derive its mass, radius, and orbital parameters. K2-98 b is a warm Neptune-like planet in a 10-day orbit around a V=12.2 mag F-type star with $M_* = 1.074 \pm 0.042 \, M_\odot$, $R_*=1.314^{+0.083}_{-0.048} \, R_\odot$, and age of $5.2^{+1.2}_{-1.0}$ Gyr. We derive a planetary mass and radius of $M_p = 32.2^{+8.1}_{-6.1} \, M_\oplus$ and $R_p = 4.3^{+0.3}_{-0.2} \, R_\oplus$. K2-98 b joins the relatively small group of Neptune-sized planets whose both mass and radius have been derived with a precision better than 25%. We estimate that the planet will be engulfed by its host star in $\sim$3 Gyr, due to the evolution of the latter towards the red giant branch.

Keywords: planets and satellites: detection — planets and satellites: individual: K2-98 b (EPIC 211391664 b) — stars: fundamental parameters

1. INTRODUCTION

The transit of an exoplanet in front of its host star provides us with valuable information about its size. When combined with radial velocity (RV) measurements (e.g., Mayor & Queloz 1995) or transit timing variations (TTVs, e.g., Ford et al. 2011), transit photometry gives us access to the geometry of the orbit, enabling the measurement of the true mass of the planet, of its radius, and consequently of its mean density. Masses, radii, densities, and orbital parameters are fundamental “ingredients” to study the internal structure, composition, dynamical evolution, tidal interaction, architecture, and atmosphere of exoplanets (e.g., Winn & Fabrycky 2015; Hatzes 2016).

The space-based photometry revolution of CoRoT (Baglin et al. 2006) and Kepler (Borucki et al. 2010) has given us access to the small-radius planet domain ($R_p \lesssim 6 \, R_\oplus$, i.e., Neptune- and Earth-sized planets), a regime that is not easily accessible from the ground. Neptune-like planets ($2.0 \lesssim R_p \lesssim 6.0 \, R_\oplus$,
10 ≤ M_p ≤ 40 M_⊕ Borucki et al. 2011) are of special interest as they mark the transition from Super-Earths to larger planets with higher volatile content, more akin to the icy giants in our solar system. However, our knowledge of these planets is still quite limited. Although Kepler has found that ∼26% of Sun-like stars in our Galaxy host small planets with orbital period shorter than 100 days (Marcy et al. 2014), determinations of masses with a precision of ∼25% – or better – have been possible only for a few dozen Neptune-like planets1. This is because of the small RV variations induced by such planets and the faintness of most of the Kepler host stars (V > 13 mag), which makes them not suitable for precise RV follow-up observations.

In its extended K2 mission, Kepler is surveying different stellar fields located along the ecliptic, performing 80-day-long continuous observations of 10 000–20 000 stars per campaign. K2 data products have no proprietary period and are released to the community typically three months after the end of each campaign, enabling immediate follow-up observations. The K2 mission is an unique opportunity to gain knowledge of transiting Neptune-sized planets (e.g., Espinoza et al. 2016; David et al. 2016). K2 is targeting a number of bright dwarfs (V ≤ 12 mag) higher than the original Kepler mission (Howell et al. 2014). This is a definite advantage for any RV follow-up observations.

As part of the KEST, ESPRINT, and PICK2 collaborations (Cochran et al. 2015; Grziwa et al. 2015; Sanchis-Ojeda et al. 2015; Johnson et al. 2016; Nespral et al. 2016), we have recently started a RV follow-up program that aims at confirming Neptune-sized candidates detected by the K2 mission and at measuring their masses via high-precision RV follow-up observations. We herein report the discovery of K2-98 b (EPIC 211391664 b), a transiting Neptune-sized planet in a 10-day orbit around a relatively bright (V = 12.2 mag) solar-like star photometrically monitored by the K2 mission during its Campaign 5. We combine the K2 photometry with ground-based follow-up observations to assess the planetary nature of the transiting object and derive its mass. We note that K2-98 b has been recently identified as a planet candidate by Pope et al. (2016) and Barros et al. (2016), but has not previously been confirmed. We are the first team to confirm and characterize in detail this planetary system.

The paper is organized as follows: in Sect. 2 we present the K2 photometry, and in Sect. 3 and 4 our ground-based photometric and spectroscopic follow-up, respectively. Sect. 5 reports on the characterization of the host star. Sect. 6 describes the joint RV and photometric analysis. Results, discussion, and conclusion are given in Sect. 7 and 8.

2. K2 LIGHT CURVE

K2 Campaign 5 observations began on 27 April 2015 UT and lasted until 10 July 2015 UT2. During the observations the boresight of the Kepler spacecraft was pointed at coordinates α = 08h40m38s, δ = +16°49′47″. A total of 26 054 light curves were simultaneously acquired by K2; 25 850 in long cadence mode (∼30 minute integration time) and 204 in short cadence mode (∼1 minute integration time).

In this work, we use the light curves extracted by Vanderburg & Johnson (2014)3. They were the only publicly available light curves at the time we started the detection of transiting planet candidates in K2 Field 5. We search the light curves for transit signals using the DST algorithm (Cabrera et al. 2012) and the EXOTRANS pipeline (Grziwa et al. 2012). DST and EXOTRANS have been applied extensively to both CoRoT (Carpano et al. 2009; Cabrera et al. 2009; Erikson et al. 2012; Carone et al. 2012; Cavarroc et al. 2012) and Kepler (Cabrera et al. 2014; Grziwa & Pätzold 2016) data. All transit detection algorithms search for a pattern in the data and use statistics to assess whether a signal is present in the data or not. When compared to widely used algorithms such as, e.g., Box Least Squares (BLS; Kovács et al. 2002), DST uses an optimized transit shape, with the same number of free parameters as BLS, and an optimized statistic for signal detection. EXOTRANS uses a combination of the wavelet based filter technique VARLET (Grziwa & Pätzold 2016) and the BLS detection algorithm. VARLET was developed to reduce both stellar variability and data discontinuities. EXOTRANS calculates the Signal Detection Efficiency (SDE) for every light curve when the BLS algorithm is used. The Generalized Extreme Value (GEV) distribution is used to calculate the SDE threshold (Grziwa et al. 2012). We consider all light curves with a SDE value higher than the SDE threshold for further inspection (about 4% of the sample).

Both DST and EXOTRANS identify a periodic transit-like signal associated with the target EPIC 211391664. The star was proposed for K2 observations by programs GO5007 (P.I.: J. Winn) and GO5029 (P.I.: D. Charbonneau). For brevity we will hereafter refer to the star and its transiting planet as K2-98 and K2-98 b, respectively.

The target passes all of the tests that we carry out to

1 As of June 2016; source: exoplanet.org.
2 See http://keplerscience.arc.nasa.gov/k2-fields.html.
3 Publicly available at https://www.cfa.harvard.edu/-avanderb/allk2c5obs.html.
identify likely false positives with the DST and EXOTRANS pipelines. These tests were regularly used during the CoRoT mission. Briefly, we stack and fit even and odd transits separately using the Transit Analysis package TAP (Gazak et al. 2012). We find neither significant odd-even transit depth variations, nor ellipsoidal variability/tidal deformation signatures in the light curve, both typically observed in eclipsing binaries. We find also no shallow secondary eclipses that might suggest an eclipsing binary scenario. Possible secondary eclipses are simulated using the detached eclipsing binary light curve fitter (DEBI; Devor 2005) we first described in Pätzold et al. (2012). Similar tests are performed using the DST pipeline and are described in Cabrera et al. (2009) and Cabrera et al. (2012). Large photometric variation in phase with the candidate orbital period is a hint for a possible binary. Such variations are also not found, and so we proceed to more detailed fitting of the light curve, as well as high-resolution imaging, reconnaissance spectroscopy, and RV observations (Sect. 3 and 4).

We also search the K2 light curve of K2-98 for additional transit signals, but none are found. The main identifiers, optical and infrared magnitudes, and proper motions of this star are listed in Table 2.

3. FASTCAM HIGH-RESOLUTION IMAGING

We observed K2-98 on 17 May 2016 with the FASTCAM lucky imaging camera (Oscoz et al. 2008) mounted on the 1.5m Carlos Sánchez Telescope of Teide Observatory in Tenerife (Spain). To account for the low altitude of the object at the time of our observation, we used a relatively long exposure time of 300 milliseconds and acquired a total of 5,000 images. The integration time of 300 milliseconds does not completely freeze the atmosphere, but this duration was necessary to collect enough light to detect faint objects. We selected the 300 best images, i.e., those with the highest Strehl ratio, and processed the data using the COELI algorithm (Cagigal et al. 2016a). COELI provides a map of the temporal covariance between the intensity of K2-98 and the intensity of the remaining pixels (Fig. 1). This removes the speckled halo surrounding the host star and creates a dark ring-shaped region around it, which is the zone where the algorithm is more sensitive to the presence of faint objects (Cagigal et al. 2016b). COELI also reinforces in this zone those pixels whose intensity follows the same temporal fluctuations as K2-98, which can only happen when the pixels contain an object. We estimate that in the ring-shaped region, at distances of 0.5–1.7”, there are no background objects brighter than $V \approx 19$ mag (i.e., $\Delta V \approx 7$ mag).

The final image shows the target to be isolated except for the detection of an object located 1.9” South-East of K2-98. The detected object is located just outside the dark ring-shaped region, in a zone where COELI provides relatively poor contrast and small spots show arbitrarily amplified noise. Nevertheless, due to being rather bright, we consider the source as a secure detection, and estimate it to be 50±10 times fainter (4.2±0.2 mag) than the main target. The distance of 1.9” between the target and the faint object is less than the sky-projected size of the Kepler/K2 CCD pixel (∼4”). We therefore assume that the light from the faint object contributes with a fraction of 1/(50±10) to the measured flux of K2-98 and correct the K2 light curve accordingly prior to performing the joint analysis presented in Sect. 6.

No additional contaminants are identified. The DSS images reveal that the next closest star with a brightness comparable to the target is a ∼3.5-mag fainter object.

| Table 1. Main identifiers, magnitudes, and proper motion of K2-98. |
| Parameter | Value | Source |
|-----------|-------|--------|
| **Main Identifiers** | | |
| EPIC | 211391664 | EPIC |
| UCAC | 508-047859 | EPIC |
| 2MASS | 08255719+1130402 | EPIC |
| $\alpha$(J2000.0) | $08^h05^m57.189^s$ | EPIC |
| $\delta$(J2000.0) | $+11^\circ30^\prime40.12^\prime\prime$ | EPIC |

| **Magnitudes** | | |
| $B$ | 12.646±0.030 | EPIC |
| $V$ | 12.166±0.030 | EPIC |
| $g$ | 12.313±0.030 | EPIC |
| $r$ | 12.031±0.030 | EPIC |
| $J$ | 11.124±0.022 | 2MASS |
| $H$ | 10.905±0.025 | 2MASS |
| $K$ | 10.869±0.028 | 2MASS |
| W1 | 10.823±0.023 | WISE |
| W2 | 10.856±0.020 | WISE |
| W3 | 10.678±0.108 | WISE |
| W4 | 8.258 | WISE |

| **Proper motions** | | |
| $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $-15.4 \pm 2.3$ | UCAC2 |
| $\mu_\delta$ (mas yr$^{-1}$) | $-8.8 \pm 1.5$ | UCAC2 |

Note—Values of fields marked with EPIC are taken from the Ecliptic Plane Input Catalog, available at http://archive.stsci.edu/k2/epic/search.php. Values marked with UCAC2, 2MASS, and WISE are from Zacharias et al. (2004), Cutri et al. (2003), Cutri & et al. (2013), respectively. The WISE W4 magnitude is an upper limit.
that is located at ∼42′′ East of K2-98, which is too large to produce any relevant influence onto the K2 light curve of K2-98.

4. SPECTROSCOPIC FOLLOW-UP OBSERVATIONS

We took 2 reconnaissance spectra of K2-98 with the Harlan J. Smith 2.7m Telescope and the Tull Coudé Spectrograph (Tull et al. 1995) at McDonald Observatory. The Tull spectrograph covers the entire optical spectrum (3450–9800 Å) at a resolving power of R≈60,000. We used exposure times of 1800 seconds, which resulted in a signal-to-noise ratio (SNR) of ∼30 per pixel at 5500 Å. We derived a first estimate of the spectroscopic parameters by using our code Kea that compares observed high-resolution spectra to a large library of synthetic models (Endl & Cochran 2016). For the first spectrum we obtain the following parameters: $T_{\text{eff}} = 5880 \pm 107$ K, $\log g = 3.81 \pm 0.31$ (cgs), [Fe/H] = $-0.06 \pm 0.07$ dex and a $v \sin i = 8.8 \pm 0.3$ km s$^{-1}$. For the second observation: $T_{\text{eff}} = 5820 \pm 116$ K, [Fe/H] = $-0.03 \pm 0.08$ dex, $\log g = 4.00 \pm 0.35$ (cgs) and a $v \sin i = 8.7 \pm 0.4$ km s$^{-1}$. We also measure an absolute RV of 76.7 ± 0.2 km s$^{-1}$ by cross-correlating the data with spectra of the RV standard star HD 50692 (Udry et al. 1999).

We also acquired 4 high-resolution spectra (R≈67,000) in November 2015 and January 2016 using the FIbre-fed Échelle Spectrograph (FIES; Frandsen & Lindberg 1999; Telting et al. 2014) mounted at the 2.56m Nordic Optical Telescope (NOT) at Roque de los Muchachos Observatory (La Palma, Spain). We adopted the observing strategy described in Buchhave et al. (2010) and Gandolfi et al. (2013, 2015), i.e., we took 3 consecutive exposures of 1200 seconds per observation epoch – to remove cosmic ray hits – and acquired long-exposed (Texp≈35 seconds) ThAr spectra immediately before and after the three sub-exposures – to trace the RV drift of the instrument. We reduced the data using standard IRAF and IDL routines. The signal-to-noise ratio (SNR) of the extracted spectra is ∼30 per pixel at 5500 Å. Radial velocity measurements were derived via multi-order cross-correlation with the RV standard star HD 50692 – observed with the same instrument set-up as K2-98. They are listed in Table 2 along with the full-width at half maximum (FWHM) and bisector span (BIS) of the cross-correlation function (CCF).

We also acquired 8 high resolution spectra using the HARPS (R≈115,000; Mayor et al. 2003) and HARPS-N spectrographs (R≈115,000; Cosentino et al. 2012) mounted at the ESO-3.6m telescope at La Silla observatory (Chile) and the 3.58m Telescopio Nazionale Galileo (TNG) at the Roque de los Muchachos Observatory (La Palma, Spain), respectively. The observations were performed between December 2015 and May 2016, setting the exposure times to 1800–3600 seconds depending on the sky condition. We monitored the Moon background light using the second fiber and reduced the data with the dedicated HARPS and HARPS-N data reduction software pipeline. The SNR of the extracted spectra is SNR=35–45 per pixel at 5500 Å. Radial velocities (Table 2) were extracted by cross-correlation with a G2 numerical mask (Baranne et al. 1996; Pepe et al. 2002).

We search for possible correlations between the RVs...
and the CCF FWHM, as well as between the RVs and CCF BIS. By combining all the three data sets, we derive for the RV and BIS data a Pearson correlation coefficient of -0.36 with a p-value of 0.25, while for the RV and FWHM measurements we obtain a Pearson correlation coefficient of -0.32 with a p-value of 0.31. The lack of significant correlations at a 0.05 confidence level provides further evidence that the observed RV variations are caused by the orbital motion of the planet rather than stellar activity. It also excludes the presence of an unseen stellar contaminant whose CCF is blended with than stellar activity. It also excludes the presence of an unseen stellar contaminant whose CCF is blended with

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Compared with the discussion given in Valenti & Fischer (2005), we find the errors quoted there to be representative of what can currently be achieved when calculating synthetic spectra in order to fit high resolution, high SNR spectra.

We obtain stellar parameters from the FIES, HARPS, HARPS-N consistent to within 1-sigma uncertainties. Our final adopted values for $T_{\text{eff}}$, $\log g_*$, [M/H], and $v \sin i_*$ are the weighted means of the values produced by the three co-added spectra and the quoted errors are the 1-σ standard deviation. They are also consistent within 2-σ with the preliminary values derived from the 2 reconnaissance spectra taken at McDonald observatory (Sect. 4). We note that the $v \sin i_*$ estimates obtained from the Tull spectroscopic data using KEA should be regarded as upper limits as they do not account for the line broadening induced by the macroturbulent velocity (Endl & Cochran 2016).

We determine stellar mass, radius, and age by combining the effective temperature $T_{\text{eff}}$ and metallicity [M/H] with the mean density $\rho_*$ obtained from the transit light curve modeling (Sect. 6). We compare the position of the host star on a $\rho_*$-versus-$T_{\text{eff}}$ with a fine grid of evolutionary tracks. The latter are computed ad hoc for this work using the FRANEC code (Tognelli et al. 2011), setting the same configuration as for the Pisa stellar evolution data base for low-mass stars 5 (Dell'Omodarme et al. 2012). We adopt the mixing-length parameter $\alpha_{\text{ml}} = 1.74$, which is our solar calibrated value for the heavy element mixture of the Sun by Asplund et al. (2009). We account for microscopic diffusion by means of the routine developed by Thoul et al. (1994). The final grid contains tracks in the mass range 0.90-1.30 $M_\odot$, with a step of 0.01 $M_\odot$, computed for five different couples of initial metallicity $Z$ and helium abundance $Y$, namely, (0.006, 0.260), (0.008, 0.265), (0.010, 0.268), (0.011, 0.271), (0.012, 0.273), and (0.013, 0.274). We find that evolutionary models with initial metal content between $Z=0.011$ and $Z=0.013$ reproduce the current photospheric metallicity. With a mass of $M_*=1.074 \pm 0.042$ $M_\odot$, radius of $R_* = 1.311^{+0.048}_{-0.045}$ $R_\odot$ and an age of $5.2^{+1.2}_{-1.0}$ Gyr (Table 3), K2-98 is a slightly evolved star leaving the main sequence. Based on the calibration of

5 Available at http://astro.df.unipi.it/stellar-models/.
 Straizys & Kuriliene (1981) for dwarf stars, the effective temperature of the star translates into a F8V spectral type. The stellar mass and radius imply a surface gravity of $\log g_\ast = 4.23^{+0.03}_{-0.05}$ (cgs), which agrees within 1-$\sigma$ with the value of $\log g_\ast = 4.35 \pm 0.10$ (cgs) derived from the co-added spectra.

We check the K2 data for evidence of rotational modulation. The lack of significant periodic and quasi-periodic photometric variation prevents us from estimating the stellar rotation period. Assuming that the star is seen equator-on, the projected rotational velocity $v\sin i_\ast = 6.1 \pm 0.5$ km s$^{-1}$ and stellar radius $R_\ast = 1.311^{+0.034}_{-0.048} R_\odot$ imply a rotational period of $P_{\text{rot}} = 10.9^{+1.0}_{-0.8}$ days.

Following the technique described in Gandolfi et al. (2008), we use the magnitudes listed in Table 2 and our spectroscopic parameters to estimate the interstellar extinction and distance to the star. We find that the light of K2-98 suffers a negligible reddening ($A_v = 0.05 \pm 0.05$ mag) and the star is located at a distance $d = 435^{+40}_{-20}$ pc from the Sun.

6. JOINT RV-TRANSIT MODELING

We perform the joint modeling of the photometric and spectroscopic data using the code pyaneti, a Python/ Fortran software suite that finds the best fitting solution using Markov Chain Monte Carlo (MCMC) methods based on Bayesian inference (Barragán et al., in preparation). The code implements ensemble sampling with affine invariance for a larger coverage of parameter space (Goodman & Weare 2010).

The photometric data included in the joint analysis are subsets of the whole K2 light curve. We select $\sim$13 hours of data points centered on each of the 7 transits observed by K2. We de-trend the individual transits using a second-order polynomial locally fitted to the $\sim$16 out-of-transit points per transit (8 points per side). The final data set contains 180 photometric points. The modeled RV data set contains the 12 measurements listed in Table 2.

The radial velocity model is given by a Keplerian orbit and an offset term for each systemic velocity (see, e.g., Perryman 2014). We fit for the systemic velocity $\gamma_j$ (as measured by the $j^{\text{th}}$ instrument), the RV semi-amplitude variation $K$, the transit epoch $T_0$, the period $P_{\text{orb}}$, the eccentricity $e$, and the argument of periastron of the star’s orbit $\omega$ measured from the ascending node to its periastron.

The transit model follows the quadratic limb-darkened law of Mandel & Agol (2002). We account for the K2 long integration ($T_{\text{exp}} = 29.425$ minutes) by supersampling the transit model with 10 sub-samples per long cadence data (Kipping 2010). For the linear $u_1$ and quadratic $u_2$ limb darkening coefficients, we use the $q_1 = (u_1 + u_2)^2$ and $q_2 = u_1^2 (2 (u_1 + u_2)^{-1}$ parameterization described in Kipping (2013). The fitted transit parameters are $T_0$, $P_{\text{orb}}$, $e$, $\omega$, $q_1$, $q_2$, scaled semi-major axis $a/R_\ast$, planet-to-star radius ratio $R_p/R_\ast$, and impact parameter $b$.

We use the Gaussian likelihood

$$L = (2\pi)^{-n/2} \left[ \prod_{i=1}^{n} \sigma_i \right] \exp \left[ -\frac{\sum_{i=1}^{n} (D_i - M_i)^2}{2 \sigma_i^2} \right] ,$$

where $n = n_{\text{tr}} + n_{\text{RV}}$ is the number of transit and RV points, and $\sigma_i$ is the error associated to each data point $D_i$, and $M_i$ is the model associated to a given data point $D_i$.

We fit for both a circular and an eccentric model. The joint modeling is carried out running 500 independent chains with uninformative uniform priors in the wide ranges $P_{\text{orb}} = [10.1, 10.2]$ days, $T_0 = [2457145.7, 2457146.3]$, $b = [0, 1]$, $a/R_\ast = [5, 100]$, $R_p/R_\ast = [0.005, 0.2]$, $K = [0.001, 1.0]$ km s$^{-1}$, and $\gamma_j = [1, 100]$ km s$^{-1}$. For the circular model we set $e = 0$ and $\omega = 90$ deg, while for the eccentric fit we set uninformative uniform priors between the limits $e = [0, 1]$ and $\omega = [0, 360]$ deg. For $q_1$ and $q_2$ we set uninformative uniform priors in the range $[0, 1]$ to sample a physical solution for the limb darkening coefficients (Kipping 2013).

We check the chain convergence by comparing the “between-chain” and “within-chain” variance using the Gelman-Rubin statistics. The burning-in phase used 25 000 additional iterations with a thin factor of 50, leading to a final number of 500 independent points for each chain, i.e., 25 000 independent points for each fitted parameter.

An initial global fit to the data yields the parameterized limb darkening coefficients $q_1 = 0.27^{+0.29}_{-0.12}$ and $q_2 = 0.47^{+0.26}_{-0.24}$ which corresponds to $u_1 = 0.47^{+0.14}_{-0.17}$ and $u_2 = 0.03^{+0.36}_{-0.21}$. As described in Csizmadia et al. (2013), the large uncertainties arise from the shallow transit depth ($\sim 0.1\%$), the small number of data points ($\sim 180$) and transits (7), and the K2 long integration time ($\sim 30$ minutes). We thus choose to constrain the limb darkening coefficient interpolating the table of Claret & Bloemen (2011) and assuming conservative 20% error bars. We stress that the system parameters derived with uninformative priors on the limb darkening coefficients are consistent to within 1-$\sigma$ uncertainties with those obtained by constraining $u_1$ and $u_2$.

7. RESULTS AND DISCUSSION

Figure 2 shows the folded transit light curves and phase-folded RV curve, along with their best fitting models. The parameter estimates and error bars are

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6 The transit duration is $\sim 5$ hours.
listed in Table 3. They are taken as the median and the 68% central interval of the final posterior distributions (Gregory 2010). Our results are consistent with the transit parameters derived by Pope et al. (2016) and Barros et al. (2016).

Our RV measurements do not allow us to constrain the eccentricity of the system. A fit for an eccentric orbit yields $0.19^{+0.17}_{-0.11}$ with a significance of only about 1-σ. In order to further check whether the non-zero eccentricity solution is significant or not, we run an F-test and calculate the p-value, i.e., the probability that the apparent eccentricity could have arisen if the underlying orbit were circular (Lucy & Sweeney 1971). In doing so we take into account the number of fitted parameters – both for the circular and eccentric model –, the number of measurements and their uncertainties, and the residuals from the best fitting circular and eccentric solution. We find a p-value of 0.87, which is much higher than the 0.05 significance threshold suggested by Lucy & Sweeney (1971) to prefer $e \neq 0$ over $e = 0$. We therefore conclude that the nonzero best fitting eccentricity obtained with models where $e$ is allowed to vary is not significant. Moreover, we find that the circular (DOF=153) and eccentric (DOF=151) models provide very similar minimum χ² values of ~152. The difference of the Bayesian information criterion is ∆BIC=10 between the two models, implying that the circular model is favored. We therefore adopt the circular model as the one that better describes our data. We note that the derived system parameters for a non-zero eccentricity are consistent to within 1-σ uncertainties with those derived assuming a circular orbit.

K2-98 b has a mass of $M_p = 32.2 \pm 8.1 \, M_{\oplus}$ and a radius of $R_p = 4.3^{+0.2}_{-0.3} \, R_{\oplus}$, consistent with a density of $2.15^{+0.67}_{-0.90} \, g \, cm^{-3}$. These parameters are calculated adopting the stellar mass and radius derived in Sect. 5 and listed in Table 3. Figure 3 shows the position of K2-98 b in the mass-radius diagram for Neptune-sized planets.

Assuming a minimum mass solar nebula (MMSN), the isolation mass (Schlichting 2014) of a planet at 0.093 AU is $\sim 0.004 \, M_\odot$, which is significantly lower than the mass of K2-98 b. In order to form K2-98 b in situ, a disk

![Figure 2](image1.png)

**Figure 2.** Left panel: Transit light curve folded to the orbital period of K2-98 b and residuals. The red points are the K2 data and their error bars. The solid line mark the re-binned best fitting transit model. Right panel: Phase-folded FIES (blue circles), HARPS-N (green diamonds) and HARPS (red triangles) RV measurements of K2-98 and best fitting circular orbit (solid line), following the subtraction of the systemic velocities as measured from each instrument.

![Figure 3](image2.png)

**Figure 3.** Mass-radius diagram for Neptune-sized planets ($2.0 \lesssim R_p \lesssim 6.0 \, R_{\oplus}$) whose both mass and radius have been determined with a precision of at least $\sim 25\%$ (Exoplanet Orbit Database, as of June 2016; Han et al. 2014). The red circle marks the position of K2-98 b. The green diamond and blue square show the position of Neptune and Uranus, respectively. The solid and dashed lines mark the Earth (5.5 g cm$^{-3}$) and Neptune (1.6 g cm$^{-3}$) isodensity curves.
The tidal evolution of the planet will become important in the future – after \(~3\) Gyr from now – due to the increase of the stellar radius and rotational period of the star, leading to a rapid decay of the planet’s orbit (Fig. 4, middle panel).

The amount of angular momentum in the orbit is insufficient to synchronize the rotation of the star, so the present approximately synchronous state cannot be maintained. Damiani & Lanza (2015) showed that other systems having host stars with an effective temperature around 6100 K show a rather wide distribution of the ratio of the orbital period to the stellar spin period, even in the case of more massive planets, thus supporting the conclusion that the present approximate synchronicity is probably coincidental.

Finally, we consider the possibility that the planet was initially significantly closer to the star when the latter reached the ZAMS and was pushed outwards by the action of tides because angular momentum was transferred from the stellar spin to the orbit, provided that the rotational period of the star was shorter than the orbital one. We find that also this scenario is unlikely. As an illustrative case, we show in Fig. 4 two integrations...
for the planet initially at an orbital period of 2.5 days, corresponding to a semi-major axis of 0.037 AU. This is the minimum orbital period for observed Neptune-mass planets around main-sequence stars (cf. Fig. 4 of Valsecchi et al. 2014) that we choose in order to maximize the strength of the tidal interaction. Since the star was initially rotating faster than the planet, the tidal interaction was initially pushing the planet outwards, in particular for $Q'_\star = 10^5$ (Fig. 4, middle panel). However, the fast rotational braking of the star led soon to a rotation period longer than the orbital period. Since the amount of orbital angular momentum was too small to maintain the synchronous state, the final fate of the planet was to fall towards the star under the action of tides within a few Gyrs\(^7\). This scenario would account for the significant dearth of Neptune-like planets with orbital periods below 2-4 days (see, e.g., Szabó & Kiss 2011; Mazeh et al. 2016).

The tidal evolution of the system further supports an inward migration scenario for K2-98 b, from the outer region of the system to its current position.

8. CONCLUSIONS

We confirm the planetary nature of K2-98 b and derive the system parameters. Our results are based on photometric data from the K2 space mission combined with high-precision Tull, FIES, HARPS, and HARPS-N RV measurements and lucky imaging. K2-98 b is a transiting Neptune-sized planet in a 10-day-orbit around an F8 V leaving the main sequence. It has a mass of $M_p = 32.2 \pm 8.1 \, M_\oplus$ and a radius of $R_p = 4.3^{+0.3}_{-0.2} \, R_\oplus$, translating into a mean density of $2.15^{+0.67}_{-0.60} \, g \, cm^{-3}$. K2-98 b joins the still relatively small number of Neptune-size planets (~20 objects) whose mass and radius have been determined with a precision better than 25%.

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\(^7\) We note that assuming a different initial orbital period leads to qualitatively similar scenarios. If the initial orbital period of the planet is shorter than 2.5 days (i.e., $a_0 < 0.037$ AU), tidal push is stronger, but for a shorter time interval before the rotation period of the star becomes longer than the orbital period, after which the orbit decays faster. If the planet is further out ($P_{\text{orb}} > 2.5$ days and $a_0 > 0.037$ AU), tides are weaker, but they can act longer before the direction of the evolution of the semi-major axis is reversed and the planet falls into the star.
The limb-darkening coefficient parameterization follows Kipping (2013). The estimates have been obtained assuming micro and macroturbulent velocities from the calibration equations of Bruntt et al. (2010) and Doyle et al. (2014), respectively.

The adopted Sun and Earth units follow the recommendations from the International Astronomical Union (Prsa et al. 2016). The limb-darkening coefficients $q_1$ and $q_2$ are $0.40 \pm 0.05$ and $0.26 \pm 0.05$, respectively.

Systemic velocity $\gamma_{\text{HARPS}}$ (km s$^{-1}$) is $76.7479 \pm 0.0022$.

The spectroscopic analysis gives $\log g_\star = 4.35 \pm 0.10$ (cgs).

**Table 3. Stellar and Planetary Parameters.**

| Parameter | Value |
|-----------|-------|
| Orbital period $P_{\text{orb}}$ (days) | $10.13675 \pm 0.00033$ |
| Transit epoch $T_0$ (BJD$_{\text{TDB}}-2450000$) | $7145.9807 \pm 0.0012$ |
| Scaled semi-major axis $a/R_\star$ | $15.388^{+0.543}_{-1.192}$ |
| Scaled planet radius $R_p/R_\star$ | $0.0304^{+0.0004}_{-0.0003}$ |
| Impact parameter, $b$ | $0.27^{+0.17}_{-0.14}$ |
| Parameterized limb-darkening coefficient $q_1$ | $0.40 \pm 0.05$ |
| Parameterized limb-darkening coefficient $q_2$ | $0.26 \pm 0.05$ |
| Eccentricity $e$ | $0$ (fixed) |
| Radial velocity semi-amplitude variation $K$ (m s$^{-1}$) | $9.1 \pm 2.3$ |
| Systemic velocity $\gamma_{\text{HARPS}}$ (km s$^{-1}$) | $76.6116 \pm 0.0029$ |
| Systemic velocity $\gamma_{\text{HARPS-N}}$ (km s$^{-1}$) | $76.7417 \pm 0.0026$ |

**Derived parameters**

| Parameter | Value |
|-----------|-------|
| Semi-major axis of the planetary orbit $a$ (AU) | $0.0943^{+0.0061}_{-0.0052}$ |
| Transit duration $\tau_{14}$ (hours) | $5.03^{+0.05}_{-0.04}$ |
| Transit ingress/egress duration $\tau_{12} = \tau_{34}$ (hours) | $0.16^{+0.03}_{-0.01}$ |
| Orbit inclination along the line-of-sight $i_0$ (°) | $89.0^{+0.5}_{-0.7}$ |

**Stellar parameters**

| Parameter | Value |
|-----------|-------|
| Star mass $M_\star$ ($M_\odot$) | $1.074 \pm 0.042$ |
| Star radius $R_\star$ ($R_\odot$) | $1.311^{+0.083}_{-0.048}$ |
| Surface gravity log $g_\star$ (cgs)$^b$ | $4.25^{+0.07}_{-0.05}$ |
| Mean density $\rho_\star$ (g cm$^{-3}$) | $0.66^{+0.07}_{-0.12}$ |
| Star age (Gyr) | $5.2^{+1.2}_{-1.0}$ |
| Spectral type$^c$ | F8 V |
| Effective temperature $T_{\text{eff}}$ (K) | $6120 \pm 80$ |
| Iron abundance [Fe/H] (dex) | $-0.2 \pm 0.1$ |
| Nickel abundance [Ni/H] (dex) | $-0.1 \pm 0.1$ |
| Silicon abundance [Si/H] (dex) | $-0.1 \pm 0.1$ |
| Calcium abundance [Ca/H] (dex) | $-0.1 \pm 0.1$ |
| Sodium abundance [Na/H] (dex) | $-0.0 \pm 0.1$ |
| Magnesium abundance [Mg/H] (dex) | $-0.0 \pm 0.1$ |
| Microturbulent velocity $v_{\text{mic}}$$^c$ | $1.3 \pm 0.1$ |
| Macroturbulent velocity $v_{\text{mac}}$$^d$ | $3.7 \pm 0.6$ |
| Projected rotational velocity $v \sin i_*$ | $6.1 \pm 0.5$ |
| Distance $d$ (pc) | $435^{+40}_{-20}$ |
| Visual interstellar extinction $A_v$ (mag) | $0.05 \pm 0.05$ |

**Planetary parameters**

| Parameter | Value |
|-----------|-------|
| Planet mass $M_p$ ($M_\oplus$) | $32.2 \pm 8.1$ |
| Planet radius $R_p$ ($R_\oplus$) | $4.3^{+0.3}_{-0.2}$ |
| Planet density $\rho_p$ (g cm$^{-3}$) | $2.13^{+0.67}_{-0.60}$ |
| Equilibrium temperature $T_{\text{eq}}$ (K) | $1102^{+13}_{-20}$ |

Note—The adopted Sun and Earth units follow the recommendations from the International Astronomical Union (Prsa et al. 2016).

$^a$ The limb-darkening coefficient parameterization follows Kipping (2013). The estimates have been obtained assuming $u_1 = 0.33 \pm 0.06$ and $u_2 = 0.30 \pm 0.06$ for the linear and quadratic limb-darkening coefficients (Claret & Bloemen 2011), adopting 20% conservative error bars.

$^b$ Stellar surface gravity log $g_\star$ as measured from the global fit and evolutionary tracks. The spectroscopic analysis gives log $g_\star = 4.35 \pm 0.10$ (cgs).

$^c$ Based on the spectral type vs. effective temperature calibration of Straizys & Kuriliene (1981) for dwarf stars.

$^d$ Micro and macroturbulent velocities from the calibration equations of Bruntt et al. (2010) and Doyle et al. (2014), respectively.
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