

DISCOVERY AND VALIDATION OF A HIGH-DENSITY SUB-NEPTUNE FROM THE K2 MISSION

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Received 2016 January 27; revised 2016 July 11; accepted 2016 July 12; published 2016 October 10

ABSTRACT

We report the discovery of K2-56b, a high-density sub-Neptune exoplanet, made using photometry from Campaign 4 of the two-wheeled Kepler (K2) mission, ground-based radial velocity (RV) follow-up from HARPS and highresolution lucky and adaptive optics imaging obtained using AstraLux and MagAO, respectively. The host star is a bright (V = 11.04, K_s = 9.37), slightly metal-poor ([Fe/H] = -0.15 ± 0.05 dex) solar analogue located at $K_{*} = 0.928^{+0.05}_{-0.04}R_{\odot}$ and a mass of $R_{*} = 0.928^{+0.052}_{-0.04}R_{\odot}$ and a mass of $M_{*} = 0.961^{+0.032}_{-0.029}M_{\odot}$. A joint analysis of the K2 photometry and HARPS RVs reveal that the planet is in a \approx 42 day orbit around its host star, has a radius of $2.23^{+0.14}_{-0.11}R_{\odot}$, and a mass of $16.3^{+6.0}_{-6.1}M_{\odot}$. Although the data at hand put the planet in the region of the mass-radius diagram where we could expect planets with a pure rock (i.e., magnesium silicate) composition using two-layer models (i.e., between rock/iron and rock/ice compositions), we discuss more realistic three-layer composition models which can explain the high density of the discovered exoplanet. The fact that the planet lies in the boundary between "possibly rocky" and "non-rocky" exoplanets makes it an interesting planet for future RV follow-up.

Key words: planets and satellites: composition – planets and satellites: detection – planets and satellites: fundamental parameters - planets and satellites: terrestrial planets

1. INTRODUCTION

Since the discovery of the first rocky exoplanet (a term we use here to refer to planets with masses and radii consistent with MgSiO₃ and Fe compositions following Rogers 2015), CoRoT-7b (Léger et al. 2009; Queloz et al. 2009), effort has been made to find and study the formation, composition and evolution of these systems, since they resemble Earth in many ways. As most rocky planets are smaller than 1.6 R_{\oplus} , which correspond to masses of 6 M_{\oplus} (Weiss & Marcy 2014; Rogers 2015; Wolfgang & Lopez 2015), the discovery of those types of exoplanets is difficult due to the small signals that these radii and masses imply. In fact, in addition to CoRoT-7b, only nine planets with secure masses and radii (i.e., masses and radii with values more than 3σ away from zero) in this rocky regime exist to date: GJ1132 (Berta-Thompson et al. 2015), Kepler-36b (Carter et al. 2012), K2-3 d (Almenara et al. 2015; Crossfield et al. 2015), Kepler-93b (Dressing et al. 2015), Kepler-10b (Dumusque et al. 2015; Weiss et al. 2016), Kepler-23b (Ford et al. 2012; Hadden & Lithwick 2014), Kepler-20b (Fressin et al. 2012), Kepler-406b (Marcy et al. 2014), and Kepler-78b (Howard et al. 2013; Pepe et al. 2013; Sanchis-Ojeda et al. 2013; Grunblatt et al. 2015). All of these planets have radii smaller than ~1.6 R_{\oplus} , as has been empirically determined.

Although the sample of rocky planets is small, some interesting relationships suggest that some of these planets might have common properties (Weiss & Marcy 2014). Perhaps one of the most interesting relations was recently introduced by Dressing et al. (2015) which, considering planets with radii and mass measurements measured to better than 20%

precision, show that they follow a common iso-composition curve on the mass-radius diagram, along with Earth and Venus. This relation was recently revised by Zeng et al. (2016) to be a 74% rock and 26% Fe composition. This suggests that these small, rocky analogs of Earth might have similar compositions with small intrinsic scatter.

Here we report what could be an interesting addition to the picture of rocky worlds described above: a 2.23 R_{\oplus} exoplanet that falls just where a pure rock (i.e., magnesium silicate) composition is expected in the mass-radius diagram using twolayer models. Although this does not mean the planet has exactly this composition, its position on the diagram does makes it interesting due the fact that this has been used in previous works to divide the "non-rocky" and "possibly rocky" planets (Rogers 2015). The discovery is made in the context of a Chilean-based effort whose aim is to follow-up planetary candidates selected using data from the two-wheeled Kepler (K2) mission. K2 has proven to be very effective in the search for exoplanets, enabling a plethora of new discoveries of planets of different sizes, which are especially interesting due to the presence of several bright host stars in the sample that allow detailed follow-up characterization (see, e.g., Armstrong et al. 2015; Becker et al. 2015; Crossfield et al. 2015; Petigura et al. 2015; Sanchis-Ojeda et al. 2015; Vanderburg et al. 2015).

The paper is structured as follows. In Section 2 we present the data, which include the K2 photometry, archival, new, adaptive optics (AO) and lucky imaging of the target star, along with high-resolution spectra and radial velocities obtained with the HARPS spectrograph. Section 3 presents a joint analysis of the data and presents the derived parameters of the planetary



Figure 1. *K2* photometry (obtained from Vanderburg & Jonson 2014, upper panel) and long-term and outlier corrected version of the photometry (lower panel). The smooth, long-term variation observed in the original photometry was removed by a smoothed median-filter, depicted in the upper panel by a red solid line, which was used for outlier removal (see text). Two clear transit-like events can be seen on both versions of the photometry close to 2457070 and 2457110 BJD (indicated with red arrows). Note that the precision obtained for this lightcurve is ~55 ppm (rms) per point.

system. We discuss the results in Section 4 and present our conclusions in Section 5.

2. DATA

2.1. K2 Photometry

K2 photometry for our target was obtained by the Kepler spacecraft during Campaign 4. This field was observed between 2015 February and April and the data were released on September of the same year. We obtained the decorrelated versions of all the lightcurves in the campaign which were made publicly available for download by Vanderburg & Jonson (2014), using photometry with the optimal aperture, which in the case of our target star corresponded to a \approx 3 pixel radius around the target, or an aperture of $\approx 12''$ radius. We performed a transit search using a box least squares (Kovács et al. 2002) algorithm. Once a periodic signal is detected along with the best-fit depth, the transit event is flagged as a pontential planetary candidate if (1) the depth is at least 3σ larger than the average noise level of the lightcurve (denoted by σ) and (2) if there are three or more transit events. Initially, because of the latter requirement, the lightcurve of the target star was not flagged by our transit search pipeline. However, we also performed visual inspection of all the lightcurves, revealing this interesting candidate. In order to double check that this was indeed an astrophysical signal and not a spurious signal arising from the decorrelation method used to obtain the lightcurve, we also inspected the detrended lightcurves released by the Kepler

team using the PDC-MAP algorithm (Stumpe et al. 2012), and the same signal was observed at the exact same times as the signals observed in the Vanderburg & Jonson (2014) photometry. We were thus confident that the signal is of astrophysical origin, and proceeded to analyze the light curve.

A median filter with a 41 point (~20.5 hr) window was used to further filter long-term variations of this target. The resulting median filter was smoothed using a Gaussian filter with a fivepoint standard-deviation, and this smoothed light curve was used to normalize the light curve. Using this normalized lightcurve, an initial fit using our transit-fitting pipeline (see below) revealed a P = 41.7 day period for this candidate and a lightcurve whose shape resembled that of a planetary transit, with a duration consistent with that of a planetary companion. Using the parameters obtained from this initial fit, we removed outliers from the out-of-transit data, discarding any points deviating more than 3σ from the median flux. The resulting normalized version of this lightcurve is shown in Figure 1. No other significant signals were found in the photometry.

2.2. Reconnaissance Spectroscopy

A high-resolution spectrum of this target was taken on October 21 with the CORALIE spectrograph mounted on the 1.2 m Euler Telescope in La Silla Observatory in order to obtain rough spectral parameters of the stellar host, and define whether this was a giant or a dwarf star. Data were reduced and analyzed using the procedures decribed in Jordán et al. (2014).

Table 1 Radial Velocities Obtained with the HARPS Spectrograph along with Various Activity Indicators

BJD	RV	$\sigma_{\rm RV}$	BIS	$\sigma_{\rm BIS}$	$S_{H,K}$	$\sigma_{SH K}$	H_{α}	$\sigma_{H_{\pi}}$	He I	$\sigma_{H_{-}}$
(UTC)	$(m s^{-1})$	$(m s^{-1})$	$(m s^{-1})$	$(m s^{-1})$	(dex)	(dex)	(dex)	(dex)	(dex)	(dex)
2457329.63450	-20333.9	4.4	35.0	6.2	0.1748	0.0063	0.10151	0.00013	0.50230	0.00081
2457329.67362	-20340.1	3.6	28.9	5.0	0.1535	0.0050	0.10337	0.00013	0.50279	0.00081
2457329.72375	-20337.9	3.9	34.2	5.6	0.1864	0.0053	0.10367	0.00013	0.50146	0.00081
2457330.80181	-20343.1	2.6	22.6	3.7	0.1483	0.0035	0.10167	0.00013	0.50787	0.00082
2457331.63418	-20342.5	2.4	23.2	3.4	0.1551	0.0029	0.10171	0.00013	0.51233	0.00083
2457331.68695	-20338.4	2.0	11.0	2.8	0.1573	0.0026	0.10209	0.00013	0.50301	0.00081
2457332.64705	-20335.7	2.6	20.2	3.7	0.1549	0.0038	0.10236	0.00013	0.50221	0.00081
2457332.72713	-20338.4	2.0	12.9	2.9	0.1459	0.0025	0.10178	0.00013	0.50273	0.00081
2457336.65528	-20345.3	3.2	20.8	4.5	0.1701	0.0042	0.10397	0.00013	0.49984	0.00081
2457336.73328	-20339.8	3.6	9.5	5.1	0.1547	0.0047	0.10187	0.00013	0.49884	0.00081
2457339.70924	-20343.1	4.9	14.2	6.9	0.1985	0.0068	0.09939	0.00013	0.49982	0.00081
2457339.72063	-20339.2	4.1	31.1	5.8	0.1738	0.0058	0.10496	0.00013	0.50575	0.00082
2457340.69354	-20340.0	3.7	5.9	5.3	0.1833	0.0056	0.10217	0.00013	0.51486	0.00083
2457340.70475	-20336.6	3.1	23.9	4.3	0.1687	0.0044	0.10083	0.00013	0.50038	0.00081
2457341.74523	-20336.6	3.3	18.7	4.7	0.1658	0.0043	0.10536	0.00013	0.50213	0.00081
2457341.75600	-20335.3	3.2	25.4	4.5	0.1491	0.0043	0.10274	0.00013	0.50658	0.00082
2457348.80101	-20330.3	3.1	21.6	4.4	0.1858	0.0056	0.10339	0.00013	0.50277	0.00081
2457360.62435	-20337.2	2.2	14.8	3.2	0.1581	0.0029	0.10354	0.00013	0.50080	0.00081
2457360.63915	-20336.8	2.1	11.0	3.0	0.1585	0.0027	0.10237	0.00013	0.50273	0.00081
2457361.66418	-20337.3	3.1	30.7	4.4	0.1719	0.0042	0.10607	0.00013	0.50020	0.00081
2457361.67814	-20337.0	2.9	32.8	4.1	0.1533	0.0038	0.10231	0.00013	0.49660	0.00080
2457362.66191	-20331.0	2.2	15.4	3.1	0.1517	0.0031	0.10313	0.00013	0.49866	0.00081
2457362.67602	-20335.6	2.2	13.5	3.1	0.1575	0.0032	0.10479	0.00013	0.50121	0.00081

The analysis of the CORALIE spectra gave $T_{\rm eff} = 5600$ K, log $(g) = 4.4 \text{ dex}, \text{ [Fe/H]} = 0.0 \text{ dex} \text{ and } v \sin(i) = 2.5 \text{ km s}^{-1}$ which revealed that the star was a dwarf solar-type star. In addition, no secondary peak was seen on the cross-correlation function indicating no detectable spectroscopic binary. Because of this, the target was promoted to our list of planetary candidates despite the lack of high-resolution imaging needed to rule out potential blend events.

2.3. High Precision Radial Velocities with HARPS

High-precision radial velocities (RVs) were obtained from the HARPS spectrograph mounted on the 3.6 m telescope at La Silla between 2015 October and December in order to measure the reflex motion of the star due to the hypothetical planet producing the transit signal. The observations covered our predicted negative and positive quadratures, along with epochs in between, to probe possible long-term trends in the RVs indicative of a possible massive companion. A total of 23 spectra were taken with the simultaneous Thorium-Argon mode; the HARPS pipeline (DRS, version 3.8) was used to reduce these spectra and to obtain the (drift-corrected) radial velocities, which are calculated via cross-correlation with a G2V mask which is appropiate for the stellar type of the host (see Section 3.1). The typical precision was $\sim 3 \text{ m s}^{-1}$ for each individual RV measurement. For each spectrum, the bisector span, S-index, and the integrated flux of the H_{α} and He I lines were obtained to monitor the activity of the host star and study its influence on the RVs (Santos et al. 2010; Jenkins et al. 2011). The measured RVs, along with these various calculated activity indicators, are given in Table 1. Although the times are given in UTC, they were converted to TBD (which is the timescale used by Kepler) for our joint analysis, which we describe in Section 3.2.

2.4. Archival and New Imaging

Archival imaging was obtained from the STScI Digitized Sky Survey⁸ at the EPIC coordinates of our target. Data are from the Palomar Observatory Sky Survey (POSS). In Figure 2 we show the best images among the available archival images in terms of the measured FWHM. We show images taken at two epochs and with two filters: one obtained in 1995 using the RG610 filter (red⁹, 590–715 nm), taken by the POSSII-F and one using the RG9 filter (near-infrarred¹⁰, 700–970 nm) obtained in 1996 by the POSSII-N. For reference, we show the aperture used to obtain our K2 photometry (black circle, 12") along with circles with 5" (white solid line) and 2" (white dashed line) radii which are centered on the centroid of our target star, which was obtained by fitting a 2D Gaussian to the intensity profile.

New imaging was obtained using the Las Cumbres Observatory Global Telescope Network (LCOGT). Four images were taken using the SBIG camera with the Bessel R filter on UT 2015/12/27 from the Cerro Tololo Interamerican Observatory (CTIO). Our target star reached close-to saturation counts (~47,000 counts) in order to have enough photons to observe the close-by stars present in the POSS images. Figure 3 shows the resulting image obtained by median-combining our four images, along with the same circles as those drawn in Figure 2.

Given that the largest potential source of false-positive detections in our case comes from blended eclipsing binary systems mimicking a planetary transit event, we note that, since the depth of the observed transit is $\sim 0.05\%$, if a blended

⁸ http://stdatu.stsci.edu/cgi-bin/dss_form

Transmission curve available at http://www.cadc-ccda.hia-iha.nrc-cnrc. gc.ca/en/dss/TransmissionCurves/POSSII-F-IIIaF-RG610.txt. ¹⁰ Transmission curve available at http://www.cadc-ccda.hia-iha.nrc-cnrc.

gc.ca/en/dss/TransmissionCurves/POSSII-N-IVN-RG9.txt.



Figure 2. Archival imaging for our target at the coordinates given in the EPIC catalog obtained with different versions of POSS: (a) POSSII-F survey, taken with a red filter and (b) POSSII-N survey, taken with an infrared filter. The black circle indicates the aperture used for our K2 data. The white solid circle has a radius of 5" and the dashed circle a radius of 2" for illustration purposes; these are centered on the measured centroid of the target star. The red circle to the left of the target star marks an object which is ~8.2 mag fainter than the target in R (see text).



Figure 3. Modern imaging of our target obtained from LOCGT from CTIO using the SBIG camera with the R filter on 2015 December 27. Note that, although the circles have the same meanings as the ones in Figure 2, the scale here is different.

eclipsing binary system was responsible of the observed depth, then assuming a total eclipse of the primary (which is the worst case scenario; all other scenarios should be easier to detect), the eclipsed star would have to be ~8.23 mag fainter than our target star in the *Kepler* bandpass. We can confidently rule out such a bright star down to a distance of 9" of the target star with the POSSII and LCOGT images. For reference, the closest star to the left of the target star (indicated with a red circle) in Figures 2 and 3 is ~8.2 mag fainter than the target star in the *R* band. As can be seen on the images, a star that bright would be evident in the archival POSS images and/or on our new LCOGT images at distances larger than 9".

2.5. AO and Lucky Imaging

AO imaging was obtained using the MagAO+Clio2 instrument mounted at the Magellan Clay telescope in Las Campanas Observatory on December 6 using the K_s filter with the full Clio2 1024×512 pixel frames of the narrow camera (f/37.7). The natural guide star system was used and, because our target is relatively bright, it was used as the guide star. A total of 32 images with exposure times of 30 s each were taken in five different positions of the camera (nodding), all of them at different rotator offset angles. Due to a motor failure of the instrument, the nodding and rotation patterns were not able to cover the full $16'' \times 8''$ field of view around the star. However, it gave us enough data to rule out stars within a 2'' radius. We follow methods similar to those described in Morzinski et al. (2015) to reduce our images, which we briefly describe here; a Python implementation of such methods is available at Github.¹¹ First, the images are corrected by dark current but not flat fielded, because the flats show an uneven flux level as a result of optical distortions and not of intrinsic pixel sensitivities (see Section A.3 in Morzinski et al. 2015, for a detailed explanation of this effect). A bad pixel mask provided by Morzinski et al. (2015) is used to mask bad pixels. After these corrections are applied to each image, we obtain a median image using our 32 frames in order to get an estimate of the background flux, which we then subtract from each of the individual frames. In order to further correct for differences in the sky backgrounds of each image, we apply a 2D median filter with a 200 pixel ($\approx 3''$) window which takes care of largescale fluctuations of each image. The background-subtracted images are then merged by first rotating them to the true north (using the astrometric calibration described in Morzinski et al. 2015) and combined using the centroid of our target star (obtained by fitting a 2D Gaussian to the profile) as a common reference point between the images. Our resulting AO image, obtained by combining our 32 images, is shown in Figure 4. A

¹¹ https://github.com/nespinoza/ao-reduction

THE ASTROPHYSICAL JOURNAL, 830:43 (11pp), 2016 October 10



Figure 4. (Left) Adaptive optics image (log-scale) obtained with MagAO+Clio2 on 2015 December 6. The black dashed circle has a 2" radius for illustration and comparison with Figure 2; the gray circle marks a faint source found on our image, which was above our contrast limit but we identified as being of instrumental origin (see text). (Right) AstraLux Sur *i'*-band observations of our candidate on 2015 December 24. The inner black dashed circle indicates 2", while the outer black solid circle indicates 5" for comparison with Figure 2.

2D Gaussian fit to the target star gives a FWHM of 0."2, which we set as our resolution limit.

The limiting contrasts in our AO observations in the K_s band were estimated as follows. First, a 2D Gaussian fit to the target star was made and used to remove it from the image. Although a 2D Gaussian does not perform a perfect fit at the center, the fit is good enough for the wings of the point-spread function (PSF), which is our aim. Then, at each radial distance $n \times$ FWHM away from the target star, where n = 1, 2, ...,15 is an integer, a fake source was injected at 15 different angles. Sources with magnitude differences from 11 to 0 were injected in 0.1 steps, and a detection was defined if three or more pixels were 5σ above the median flux level at that position. The results of our injection and recovery experiments are plotted in Figure 5.

Only one source was detected at $\sim 2''$ from the target. The shape and position of this object is inconsistent with a speckle but is very faint: we measure a magnitude difference of $\Delta K_s = 9.8$ with the target, which is thus just above our contrast level at that position (see Figure 4, the source is indicated with a gray circle in the upper right). A careful assessment of the PSF shape, however, made it inconsistent with the object having the same PSF shape as our star. Comparing its PSF with known "ghosts" on the image, on the other hand, revealed that this source is not of astrophysical but of instrumental origin.

To search for companions at larger separations, lucky imaging was obtained with AstraLux Sur mounted on the New Technology Telescope at La Silla Observatory (Hippler et al. 2009) on 2015 December 24 using the *i'* band. Figure 4 shows our final image obtained by combining the best 10% images with a drizzle algorithm. Because the PSF shape obtained for our lucky imaging is complex and we already ruled out companions inside a 2" radius with Magellan+Clio2, and given that our objective with lucky imaging was to rule out companions at larger angular distances, we did not perform PSF substraction algorithms to obtain the 5σ contrasts at those distances. Instead, we used simple aperture photometry to



Figure 5. 5σ contrast curves obtained from our MagAO+Clio2 K_s band (black line) and AstraLux Sur *i*'-band (red line) observations of our candidate.

estimate the 5σ contrasts outside the 2" radius by performing a procedure similar to that described in Wöllert et al. (2015). In summary, we estimated the noise level in a 5×5 box at each radial distance at 15 different angles for distances larger than 2''from the estimated centroid of the image (where the contribution of the target star's PSF to the background level is low), and calculated the magnitude contrast by obtaining the flux of the target star using a 5 pixel radius around it and a 5 pixel radius about the desired distance from the star, where 5σ counts are summed to each pixel at that distance before performing the aperture photometry. Then, the magnitude contrast at a given distance is obtained as the average value obtained at the different angles. The resulting 5σ contrasts are presented in Figure 5. We study the constraints that our archival, new, AO and lucky imaging put on the false-positive probabilities and transit dilutions on the next section.

3. ANALYSIS

3.1. Stellar Properties

To obtain the properties of the host star, we made use of both photometric and spectroscopic observables of our target. For the former, we retrieved B, V, g, r and i photometric magnitudes from the AAVSO Photometric All-sky Survey (APASS, Henden & Munari 2014) and J, H and K photometric magnitudes from 2MASS for our analysis. For the spectroscopic observables, we used the Zonal Atmospherical Stellar Parameter Estimator (ZASPE, R. Brahm et al. 2016, in preparation) algorithm using our HARPS spectra as input. ZASPE estimates the atmospheric stellar parameters and $v \sin i$ from our high-resolution echelle spectra via a least-squares method against a grid of synthetic spectra in the most sensitive zones of the spectra to changes in the atmospheric parameters. ZASPE obtains reliable errors in the parameters, as well as the correlations between them, by assuming that the principal source of error is the systematic mismatch between the data and the optimal synthetic spectra, which arises from the imperfect modeling of the stellar atmosphere or from poorly determined parameters of the atomic transitions. We used a synthetic grid provided by R. Brahm et al. (2016, in preparation) and the spectral region considered for the analysis was from 5000 to 6000 Å, which includes a large number of atomic transitions and the pressure-sensitive Mg Ib lines. The resulting atmospheric parameters obtained through this procedure were $T_{\text{eff}} = 5766 \pm 99 \text{ K}$, $\log(g) = 4.5 \pm 0.08$, $[\text{Fe/H}] = -0.15 \pm 0.05$ and $v \sin(i) = 3.3 \pm 0.31 \text{ km s}^{-1}$. With these spectroscopic parameters at hand and the photometric properties, we made use of the Dartmouth Stellar Evolution Database (Dotter et al. 2008) to obtain the radius, mass, age and distance to the host star using isochrone fitting with the isochrones package (Morton 2015). We took into account the uncertainties in the photometric and spectroscopic observables to estimate the stellar properties, using the emcee (Foreman-Mackey et al. 2013) implementation of the affine invariant Markov Chain Monte Carlo (MCMC) ensemble sampler proposed in Goodman & Weare (2010) to explore the posterior parameter space. We obtained a radius of $R_* = 0.928^{+0.055}_{-0.040}R_{\odot}$, mass $M_* = 0.961^{+0.032}_{-0.029} M_{\odot}$, age of $3.3^{+1.9}_{-1.5}$ Gyr and a distance to the host star of $152.1^{+9.7}_{-7.4}$ pc. The distance to the star was also estimated using the spectroscopic twin method described in Jofré et al. (2015), which is independent of any stellar models. The values obtained were 158.3 \pm 5.4 pc when using 2MASS J band photometry and $160.0 \pm 5.7 \,\mathrm{pc}$ if H band photometry was used instead, where the stars HIP 1954, HIP 36512, HIP 49728 and HIP 58950 were used as reference for the parallax. Those values are in very good agreement with the value obtained from isochrone fitting. The stellar parameters of the host star are sumarized in Table 2.

3.2. Joint Analysis

We performed a joint analysis of the photometry and the radial velocities using the EXOplanet traNsits and rAdIal veLocity fittER, exonailer, which is made publicly available at Github.¹² For the transit modeling, exonailer makes use of the batman code (Kreidberg 2015), which allows the user to use different limb-darkening laws in an easy and efficient way. If chosen to be free parameters, the sampling of the limb-darkening coefficients is performed in an

Table 2Stellar Parameters of K2-56

Parameter	Value	Source
Identifying Information		
EPIC ID	210848071	EPIC
2MASS ID	03343623+2035574	2MASS
R.A. (J2000, h:m:s)	03h34m36 s 23	EPIC
Decl. (J2000, d:m:s)	20°35′57″23	EPIC
R.A. p.m. (mas yr^{-1})	36.7 ± 0.7	UCAC4
Decl. p.m. (mas yr^{-1})	-51.8 ± 1.3	UCAC4
Spectroscopic properties		
$T_{\rm eff}$ (K)	5766 ± 99	ZASPE
Spectral Type	G	ZASPE
[Fe/H] (dex)	-0.15 ± 0.05	ZASPE
$\log g_*$ (cgs)	4.5 ± 0.08	ZASPE
$v \sin(i) (\mathrm{km \ s}^{-1})$	3.3 ± 0.31	ZASPE
Photometric properties		
$K_{\rm p} ({\rm mag})$	11.04	EPIC
B (mag)	11.728 ± 0.044	APASS
V (mag)	11.038 ± 0.047	APASS
g' (mag)	11.352 ± 0.039	APASS
r' (mag)	11.872 ± 0.050	APASS
i' (mag)	10.918 ± 0.540	APASS
J (mag)	9.770 ± 0.022	2MASS
H (mag)	9.432 ± 0.022	2MASS
Ks (mag)	9.368 ± 0.018	2MASS
Derived properties		
$M_*~(M_{\odot})$	$0.961\substack{+0.032\\-0.029}$	isochrones+ZASPE
$R_*~(R_{\odot})$	$0.928\substack{+0.055\\-0.040}$	isochrones+ZASPE
$\rho_* ({\rm g}{\rm cm}^{-3})$	$1.70^{+0.20}_{-0.26}$	isochrones+ZASPE
$L_*(L_{\odot})$	$0.88^{+0.15}_{-0.12}$	isochrones+ZASPE
Distance (pc)	$152.1^{+9.7}_{-7.4}$	isochrones+ZASPE
Age (Gyr)	$3.34^{+1.95}_{-1.49}$	isochrones+ZASPE
	-1.49	

Note. Logarithms given in base 10.

informative way using the triangular sampling technique described in Kipping (2013). For the quadratic and squareroot laws, we use the transformations described in Kipping (2013) in order to sample the physically plausible values of the limb-darkening coefficients. For the logarithmic law we use the transformations described in Espinoza & Jordán (2016), which presents the sampling of the limb darkening parameters for the more usual form of the logarithmic law to allow for easier comparison with theoretical tables (if the geometry of the system is properly taken into account, see Espinoza & Jordán 2015). The code also allows the user to fit the lightcurve assuming either a pure white-noise model or an underlying flicker (1/f) noise plus white-noise model using the waveletbased technique described in Carter & Winn (2009). For the RV modeling, exonailer assumes Gaussian uncertainties and adds a jitter term in quadrature to them. The joint analysis is then performed using the emcee MCMC ensemble sampler (Foreman-Mackey et al. 2013).

For the joint modeling of the data set presented here, we tried both eccentric and circular fits. For the radial velocities, uninformative priors were set on the semi-amplitude, K, and the RV zero point, μ . The former was centered on zero, while the latter was centered on the observed mean of the RV data set. Note that our priors allow us to explore negative radial velocity amplitudes, which is intentional as we want to explore the possibility of the RVs being consistent with a flat line (i.e., K=0). Initially a jitter term was added but was fully consistent

¹² http://www.github.com/nespinoza/exonailer



Figure 6. Phase-folded photometry (gray points; circles the first transit, triangles the second transit) and best-fit transit lightcurve for the circular (red, solid line) and eccentric (red, dashed line) fits for our planet obtained from our joint analysis. Note that the difference in the lightcurve for both fits is very small.

with zero, so we fixed it to zero in our analysis. As for the noncircular solutions, flat priors were set on e and on ω instead of fitting for the Laplace parameters $e \cos(\omega)$ and $e \sin(\omega)$ because these imply implicit priors on the parameters that we want to avoid (Anglada-Escudé et al. 2013). For the lightcurve modeling, we used the selective resampling technique described in Kipping (2010) in order to account for the 30 min cadence of the K2 photometry, which has as a consequence the smearing of the transit shape. In order to minimize the biases in the retrieved transit parameters we fit for the limb darkening coefficients in our analysis (see Espinoza & Jordán 2015). To decide which limb-darkening law to use, we apply the method described in Espinoza & Jordán (2016) which, through simulations and given the lightcurves properties, aids in selecting the best limb-darkening law in terms of both precision and bias using a mean-squared error (MSE) approach. In this case, the law that provides the minimum MSE is the quadratic law, and we use this law to parametrize the limb-darkening effect. In addition, the K2 photometry is not good enough to constrain the ingress and egress times because only two transits were observed in long-cadence mode, which provides poor phase coverage; this implies that the errors on a/ R_* are rather large. Because of this, we took advantage of the stellar parameters obtained with our HARPS spectra, and derived a value for this parameter from them (see Sozzetti et al. 2007) of $a/R_* = 54.83^{+2.19}_{-3.16}$. This value was used as a prior in our joint analysis in the form of a Gaussian prior. We used the largest of the errorbars as the standard deviation of the distribution, which is centered on the quoted median value of the parameter.¹³ We tried both fitting a flicker-noise model and a white-noise model, but the flicker noise model parameters were consistent with no 1/f noise component, so the fit was finally obtained assuming white noise. 500 walkers were used to evolve the MCMC, and each one explored the parameter space in 2000 links, 1500 of which were used as burn-in samples. This gave a total of 500 links sampled from the posterior per walker, giving a total of 250,000 samples from the posterior distribution. These samples were tested to converge both visually and using the Geweke (1992) convergence test.

Figures 6 and 7 show close-ups to the phased photometry and radial velocities, respectively, along with the best-fit models for both circular (red, solid line) and non-circular (red, dashed line) fits obtained from our joint analysis of the data set. The lightcurve fits for both models are very similar, but in the RVs the differences are evident. In particular, the eccentric fit gives rise to a slightly smaller semi-amplitude than (yet, consistent with) the one obtained with the circular fit. For the eccentric fit, we obtain $e = 0.096^{+0.089}_{-0.066}$, $\omega = 53^{+17}_{-23}$ deg and a semi-amplitude of $K = 2.9^{+1.1}_{-1.0} \text{ m s}^{-1}$. For the circular orbit, we find a semi-amplitude of $K = 3.1^{+1.1}_{-1.1} \text{ m s}^{-1}$. Since the differences on the lightcurves are very small, we analyze the likelihood function of the RV data to compare the models and decide which is preferred by the data. We obtain that both models are indistinguishable, with both the AIC ($\Delta AIC = 2$) and BIC (Δ BIC = 2) values being ~2. We thus choose the simpler model of those two, which is the circular model, and report the final parameters using this as our final model.

The resulting parameters of our fit are tabulated in Table 3. It is interesting to note that the RV semi-amplitude is inconsistent with zero by almost 3σ . Moreover, we are confident that those variations do not arise from activity as all the correlation coefficients we calculate between our RVs and the different activity indexes given in Table 1 give correlation coefficients which are consistent with 0 at $\approx 1\sigma$, and all variations of the activity indices at the period and time of transit-center found for our target are consistent with flat lines. Interestingly, the radial-velocity semi-amplitude is large for a planetary radius of only $R_{\rm p} = 2.23^{+0.14}_{-0.11} R_{\oplus}$; the $K = 3.1^{+1.1}_{-1.1} \,{\rm m \, s^{-1}}$ semi-amplitude implies a mass of $M_{\rm p} = 16.3^{+6.0}_{-6.1} M_{\oplus}$, which at face value could be consistent with a rocky composition, a rare property for a Neptune-sized exoplanet such as K2-56b. We caution, however, that this interpretation has to be taken with care, as we have poor phase coverage on the "up" quadrature. We put these values in the context of discovered exoplanets of similar size in Section 4.

3.3. Planet Scenario Validation

To validate the planet scenario which we have implied in the previous sub-section, we make use of the formalism described

¹³ Performing a joint analysis with a large uniform prior on a/R_* spanning from $a/R_* \in (25, 70)$ gives a posterior estimate of $a/R_* = 55.92^{+5.64}_{-13.11}$ for this parameter, which is in excellent agreement with this spectroscopically derived value.



Figure 7. Phase-folded HARPS radial velocities (gray) and best-fit radial velocity models for both circular (red, solid line) and eccentric (red, dashed line) fits using our joint analysis. The light blue bands indicate regions that have been repeated for better visualization of the RV curve.

 Table 3

 Orbital and Planetary Parameters for K2-56

Parameter	Prior	Posterior Value		
Lightcurve parameters				
P (days)	$\mathcal{N}(41.68, 0.1)$	$41.6855\substack{+0.0030\\-0.0031}$		
$T_0 - 2450000 \text{ (BJD}_{\text{TDB}})$	N(7151.90, 0.1)	$7151.9021\substack{+0.0042\\-0.0047}$		
a/R_{\star}	N(54.83, 3.16)	$55.8^{+3.3}_{-3.3}$		
$R_{\rm p}/R_{\star}$	U(0, 0.1)	$0.02204\substack{+0.00058\\-0.00057}$		
<i>i</i> (deg)	U(80, 90)	$89.55_{-0.14}^{+0.17}$		
q_1	$\mathcal{U}(0, 1)$	$0.38^{+0.29}_{-0.16}$		
q_2	$\mathcal{U}(0, 1)$	$0.52\substack{+0.32\\-0.30}$		
σ_w (ppm)	J(50, 80)	$55.00_{-0.72}^{+0.73}$		
RV parameters				
$K ({ m m \ s}^{-1})$	N(0, 100)	$3.1^{+1.1}_{-1.1}$		
μ (km s ⁻¹)	$\mathcal{N}(-20.337, 0.1)$	$-20.33638\substack{+0.00073\\-0.00073}$		
е		0 (fixed)		
Derived parameters				
$M_{\rm p}~(M_{\oplus})$		$16.3^{+6.0}_{-6.1}$		
$R_{\rm p} \ (R_{\oplus})$	•••	$2.23^{+0.14}_{-0.11}$		
$\rho_{\rm p} \ ({\rm g \ cm^{-3}})$		$7.89^{+3.4}_{-3.1}$		
$\log g_{\rm p}$ (cgs)		$3.50\substack{+0.14\\-0.21}$		
a (au)		$0.241_{-0.017}^{+0.019}$		
$V_{\rm esc}~({\rm km~s^{-1}})$		$30.2^{+5.3}_{-6.2}$		
$T_{\rm eq}$ (K)				
Bond albedo of 0.0		546^{+19}_{-18}		
Bond albedo of 0.75		386^{+13}_{-12}		

Note. Logarithms given in base 10. $\mathcal{N}(\mu, \sigma)$ stands for a normal prior with mean μ and standard-deviation $\sigma, \mathcal{U}(a, b)$ stands for a uniform prior with limits a and b and $\mathcal{J}(a, b)$ stands for a Jeffrey's prior with the same limits.

in Morton (2012) as implemented on the publicly available vespa¹⁴ package. In short, vespa considers all the false-positive scenarios that might give rise to the observed periodic dips in the light curve and, using photometric and spectroscopic information of the target star, calculates the false-positive probability (FPP) which is the complement of the probability of

there being a planet given the observed signal. Because our archival and modern imaging presented on Section 2.4 rule out any companion at distances larger than 9" radius, we consider this radius in our search for possible false-positive scenarios using vespa, which considers the area around the target star in which one might suspect false-positives could arise. The algorithm calculates the desired probability as

$$\text{FPP} = \frac{1}{1 + f_{\text{p}}P},$$

where $f_{\rm p}$ is the occurrence rate of the observed planet (at the specific observed radius) and $P = L_{\rm TP}/L_{\rm FP}$, where TP indicates the transiting-planet scenario and FP the false-positive scenario, and each term is defined as $L_i = \pi_i \mathcal{L}_i$, where π_i is the prior probability and \mathcal{L}_i is the likelihood of the *i*th scenario. For our target, considering all the information gathered and the fact that no secondary eclipse larger than ≈ 165 ppm (i.e., 3σ) is detected, we obtain a value of P = 4288.79. As for the occurrence rate of planets like the one observed, we consider the rates found by Petigura et al. (2013) for planets between 2 and 2.83 R_{\oplus} with periods between 5 and 50 days orbiting solartype stars, which is 7.8%, i.e., $f_p = 0.078$. This gives us a falsealarm probability of FPP = 3×10^{-3} . Given that this probability is smaller than the usual 1% threshold (e.g., Montet et al. 2015), we consider our planet validated. We note that this FPP is an upper limit on the real FPP given our AO and luckyimaging observations. Both observations rule out an important part of the parameter space for blending scenarios between $0^{\prime\prime}_{...2}$ and 5'' from the star, which are the main source of falsepositives for our observations.

3.4. Transit Dilutions

As will be discussed in the next section, both the planet radius and mass puts K2-56 in a very interesting part of the mass-radius diagram. Therefore, it is important to discuss the constraints that our spectroscopic and new, AO and lucky imaging observations pose on possible background stars that might dilute the transit depth and thus cause us to underestimate the transit radius.

Given that the factor by which the planetary radius is changed by a collection of stars inside the aperture used to obtain the photometry of the target star is given by $\sqrt{1/F_{\%}}$, where $F_{\%}$ is the fraction of the total flux in the aperture added by the star being transited, we estimate that only stars with magnitude differences ≤ 2 are able to change the transit radius by magnitudes similar to the quoted uncertainties in Table 3. We note that such magnitude differences in the Kepler bandpass are ruled out from 0.2 to the aperture radius used to obtain the photometry for our target star: our AO and lucky imaging observations rule out companions of such magnitudes from 0.2' to 5'' (see Figure 5). On the other hand, stars with magnitude differences of that order should be evident on our retrieved archival and new images presented in Section 2.4, at least at distances of 5" from our target star, and up to and beyond the 12'' aperture used to obtain the K2 photometry. Given that the remaining unexplored area on the sky is very small (only 0."2 around our target star), and that a star of such magnitude should produce an evident peak on the crosscorrelation function on our high-resolution spectra, which is

¹⁴ https://github.com/timothydmorton/VESPA



Figure 8. Mass-radius relationship for planets with secure masses and radii (at the 3σ level, gray points) having masses less than $32 M_{\oplus}$ and radii less than $4 R_{\oplus}$. K2-56b is plotted in red, while solar system planets are plotted as colored circles (on the lower left Earth with blue, Venus with orange, and in the upper right Neptune in cyan and Uranus in dark blue). Theoretical two-layer mass-radius models from Zeng et al. (2016) are plotted with different colors; a 100% water composition is depicted in blue, a 100% rock (MgSiO₃) composition in brown and a 100% Fe composition in gray. The light blue dashed line indicates the best-fit composition of small rocky exoplanets obtained by Zeng et al. (2016) for reference (74% MgSiO₃, 26% Fe); the best-fit composition of K2-56b is that of 100% MgSiO₃.

not seen, we confidently consider that our derived transit radius is unaffected by dilutions of background field stars.

4. DISCUSSION

As mentioned in the previous section, the large mass $(M_{\rm p} = 16.3^{+6.0}_{-6.1}M_{\oplus})$ for the calculated radius $(R_{\rm p} =$ $2.23^{+0.14}_{-0.11}R_{\oplus}$) found for K2-56b is very interesting. Figure 8 compares K2-56b with other discovered exoplanets with radii less than 4 R_{\oplus} (~Neptune) and masses smaller than 32 M_{\oplus} (limits of theoretical models) as retrieved from exoplanets.eu except for the Kepler-10 planets, for which we use the masses obtained by Weiss et al. (2016), along with two-layer models obtained from Zeng et al. (2016). As can be seen, K2-56b spans a regime in radius at which most exoplanets have low densities and are composed of large amounts of volatiles (Rogers 2015). In particular, taking the mass-radius estimates for K2-56b at face value, the best-fit composition assuming a two-layer model for the planet is 100% MgSiO₃, i.e., a pure rock composition, positioning the planet in the boundary of "possibly rocky" and "non-rocky" planets. More realistic three-layer alternatives, however, can explain the observed radius and mass of the planet if a rock/Fe core has an added volatile envelope, composed either by water or H/He (see, e.g., the modeling for Kepler-10c in Weiss et al. 2016). If, for example, we assume an Earth-like interior composition for the planet (i.e., 74%) MgSiO₃ and 26% Fe) and again take the mass and radius estimates at face value, three-layer models obtained from Zeng et al. (2016) give a possible 0.2 R_{\oplus} water envelope for the planet (corresponding to 8% in mass). This thus gives a maximum radius for a possible H/He envelope, which would anyways produce a small layer of much less than a percent in mass, at least significantly smaller than the one modelled for Kepler-10c.

Given that the errors on the mass of K2-56b are large enough to be consistent with several compositions, a careful assessment must be made in order to explore its possible rocky nature. To this end, we follow the approach introduced by Rogers (2015) and compute p_{rocky} , the posterior probability that a planet is sufficiently dense to be rocky, which is defined as the fraction of the joint mass-radius posterior distribution that falls between a planet composition consistent with being rocky. A probably rocky planet, then, would have $p_{rocky} \sim 1$, while a planet with a density that is too low to be rocky would result in $p_{\text{rocky}} \sim 0$. The definition of "rocky planet" used in Rogers (2015), which we adopt in this work, is given by those planets spanning compositions between 100% rock and 100% Fe. Although this definition is based on simple two-layer models for the planetary composition, and in theory for a given point in the mass-radius diagram planets could have denser compositions with a gaseous envelope on top, we use this metric anyway in order to compare our newly discovered exoplanet in terms of the population of already discovered small planets. This is an

¹⁵ Data retrieved on 2015 December 23.



Figure 9. The posterior probability that a planet is sufficiently dense to be rocky, p_{rocky} , as a function of radius for all exoplanets with secure masses and radii (gray points), along with the estimated values for K2-56b (red point). The black dashed line shows the transition between rocky (to the left) and non-rocky (to the right of the diagram) planets, along with the 95% confidence band on this threshold (blue band).

important point to make, as p_{rocky} is actually an upper limit on the probability that a planet is indeed rocky. To compute this value and compare it to the population of exoplanets with secure masses and radii discovered so far, we use the models from Zeng et al. (2016). To sample from the posterior distributions given the posterior estimates published in the literature for the different exoplanets, we use the methods described in Appendix A of Espinoza & Jordán (2015) and assume these radii and masses are drawn from skew-normal distributions in order to use the asymmetric error bars published for those parameters, while we use the posterior samples of our MCMC fits described in Section 3.2 to sample from the posterior joint distribution of mass and radius of K2-56b. Our results are depicted in Figure 9, where we also indicate the threshold radius found by Rogers (2015) at which there is a significant transition between rocky and non-rocky exoplanets, with smaller exoplanets having in general rocky compositions and larger exoplanets having less dense compositions.

As evident in Figure 9, K2-56b is in an interesting position in this diagram. The closest exoplanet to K2-56b in this diagram is Kepler-20b, which has a radius of $1.91^{+0.12}_{-0.21}R_{\oplus}$, which is only 2σ away from the "rocky" boundary. K2-56b, on the other hand, is more than 5σ away from it. With a value of $p_{\text{rocky}} \sim 0.43$, K2-56b is the first Neptune-sized exoplanet to date with a large (compared to the typical Neptune-sized planet) posterior probability of being dense enough to be rocky.

The large mass obtained for K2-56b implies that if the planet ever had the chance to acquire an atmosphere, it should retain it. However, if the planet is indeed actually primarly composed of rock, given its small radius, a significant H/He envelope is unlikely in the usual settings of planet formation. Calculations using core accretion theory by Ikoma & Hori (2012), predict that if the mass of rock in the protoplanet is on the order of ~10 M_{\oplus} , even for disk dissipation timescales on the order of ~10 kyr an accretion of a ~1 M_{\oplus} H/He envelope should occur. Even in the case of a large opacity of the protoplanetary disk, a mass of rock similar to the one possible for K2-56b should imply at least this level of H/He accretion. Given the bulk composition and distance of K2-56b to its parent star, mass loss due to X-ray and extreme UV radiation from its parent star is unlikely. If this indeed is the primary composition of this planet, it might be possible that it formed at late stages in the protoplanetary disk, under conditions similar to those on transition disks (Lee & Chiang 2016) or that some external effect removed the accreted envelope from the planet. Recent studies on giant impacts, which predict efficient devolatilization mechanisms for super-Earths, might prove useful in explaining the lack of an extended atmosphere for K2-56b if the planet ever accreted a significant H/He atmosphere in the first place (Liu et al. 2015).

In terms of mass and radius, K2-56b is similar to both Kepler-131b (Marcy et al. 2014) and Kepler-10c (Weiss et al. 2016). Although both of them are probably non-rocky due to their low p_{rocky} (~0.1 and ~0.002 respectively), which is the main difference with K2-56b, they are also "warm" Neptune-sized planets just as K2-56b, with periods of 16 days and 45.29 days, respectively. The similarity in mass, radius and period between Kepler-10c and K2-56b, in fact, makes both of these planets excellent laboratories for comparison to put planet formation theories to the test.

Finally, it is interesting to mention that the sub-solar metallicity of the host star adds more weight to the growing evidence that low-mass planets tend to be found orbiting stars with a lower metallicity content (Mayor et al. 2009; Adibekyan et al. 2012) or at least they appear to show a lack of preference toward metal-rich stars (Jenkins et al. 2013; Buchhave & Latham 2015).

5. CONCLUSIONS

Using K2 photometry from Campaign 4 and a follow-up effort including radial velocities from the HARPS spectrograph, we have presented K2-56b, a planet with a radius $R_p = 2.23^{+0.14}_{-0.11}R_{\oplus}$ and mass of $M_p = 16.3^{+6.0}_{-6.1}M_{\oplus}$ orbiting a solar-type star. K2-56b lies in an interesting position in the mass-radius diagram, in the boundary between "possibly rocky" and "non-rocky" planets. Given the brightness of the host star (V = 11.04), K2-56b is amenable for future follow-up studies, which will enable a detailed study of its mass, and hence composition, that might be able to confirm whether K2-56b is in the "possibly rocky" or "non-rocky" regime on the mass-radius diagram.

We thank the referee for insightful comments that greatly improved this work. NE, JSJ and AJ would like to thank E. Pallé for his willingness to share time on Northern Hemisphere facilities for follow-up efforts. NE and RB are supported by CONICYT-PCHA/Doctorado Nacional. AJ acknowledges support from FONDECYT project 1130857 and from BASAL CATA PFB-06. NE, RB AJ and JC acknowledge support from the Ministry for the Economy, Development, and Tourism Programa Iniciativa Científica Milenio through grant IC 120009, awarded to the Millennium Institute of Astrophysics (MAS). JSJ acknowledges support from BASAL CATA PFB-06. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. It also made use of the SIMBAD database (operated at CDS, Strasbourg, France), NASA's Astrophysics Data System Bibliographic Services, and data

THE ASTROPHYSICAL JOURNAL, 830:43 (11pp), 2016 October 10

products from the Two Micron All Sky Survey (2MASS) and the APASS database and the Digitized Sky Survey. Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programmes 096.C-0499(A), 096.C-0417(A) and 096.D-0402(A).

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