GJ 3929: High-precision Photometric and Doppler Characterization of an Exo-Venus and Its Hot, Mini-Neptune-mass Companion

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Received 2022 June 3; revised 2022 July 18; accepted 2022 July 21; published 2022 August 30

Abstract

We detail the follow-up and characterization of a transiting exo-Venus identified by TESS, GJ 3929b (TOI-2013b), and its nontransiting companion planet, GJ 3929c (TOI-2013c). GJ 3929b is an Earth-sized exoplanet in its stars’ Venus zone ($P_b = 2.616272 \pm 0.000005$ days; $S_b = 17.3^{+1.0}_{-0.7} S_{\oplus}$) orbiting a nearby M dwarf. GJ 3929c is most likely a nontransiting sub-Neptune. Using the new, ultraprecise NEID spectrometer on the WIYN 3.5 m Telescope at Kitt Peak National Observatory, we are able to modify the mass constraints of planet b reported in previous works and consequently improve the significance of the mass measurement to almost 4σ confidence ($M_b = 1.75 \pm 0.45 M_{\oplus}$). We further adjust the orbital period of planet c from its alias at $14.30 \pm 0.03$ days to the likely true period of $15.04 \pm 0.03$ days, and we adjust its minimum mass to $m \sin i = 5.71 \pm 0.92 M_{\oplus}$. Using the diffuser-assisted ARCTIC imager on the ARC 3.5 m telescope at Apache Point Observatory, in addition to publicly available TESS and LCOGT photometry, we are able to constrain the radius of planet b to $R_b = 1.09 \pm 0.04 R_{\oplus}$. GJ 3929b is a top candidate for transmission spectroscopy in its size regime (TSM = 14 ± 4), and future atmospheric studies of GJ 3929b stand to shed light on the nature of small planets orbiting M dwarfs.

Unified Astronomy Thesaurus concepts: Exoplanets (498); Mini Neptunes (1063); Super Earths (1655); Transmission spectroscopy (2133); Radial velocity (1332); Transits (1711)
1. Introduction

Transit photometry has become an extremely important technique for the characterization of exoplanets and has long been the most fruitful method for identifying candidates in the first place (Borucki et al. 2010). With the advent of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), we are in a new era of exoplanet detection around low-mass stars. Since the beginning of the TESS mission, over 5000 new exoplanet candidates have been discovered. Many identified candidates are false positives, however, and observations using different techniques are often required to accurately characterize orbital periods, rule out false-positive scenarios, detect longer-period or nontransiting companions, or measure additional parameters of an exoplanet (e.g., Kanodia et al. 2021; Weiss et al. 2021; Cañas et al. 2022; Lubin et al. 2022). Radial velocity (RV) observations are a particularly important follow-up method, as they allow for (1) independent confirmation of a transiting planet signal, (2) characterization of a planet’s mass, and (3) a search for nontransiting companion planets.

A transiting exoplanet candidate with a 2.6-day period was first identified by the TESS Science Processing and Operations Center (SPOC; Jenkins et al. 2016) pipeline around the nearby (15.822 ± 0.006) M dwarf GJ 3929 on 2020 June 19, then designated TOI-2013.01. Our team began follow-up observations using RV instruments and high-contrast imaging shortly after this announcement, with the intent to confirm the planetary nature of this system and refine the planetary parameters of the transiting candidate.

Kemmer et al. (2022) recently published an analysis of the system, placing constraints on its planetary parameters and validating its planetary nature, as well as discovering a second, nontransiting planet candidate during their analysis. Kemmer et al. (2022) were unable to precisely constrain the mass of the transiting planet \( (K/\sigma = 2.88) \), however, possibly due to the unanticipated existence of planet c.

Using precise RVs obtained with the NEID spectrograph on the WIYN31 3.5 m telescope at Kitt Peak National Observatory (KPNO), RVs taken with the Habitable Zone Planet Finder, and previously published CARMENES RV data, we were able to refine the mass measurements of both planets in the system. Using two ground-based transits obtained with the diffuse-assisted ARCTIC imager, in addition to publicly available TESS and LCOGT data, we refine the radius measurement of this system. Furthermore, our analysis concludes that the additional nontransiting planet candidate has a period of \( \sim 15 \) days, and we upgrade GJ 3929c from a candidate to a planet.

In Section 2, we give a summary of the data used in our analysis. In Section 3, we detail our estimation of the system’s stellar parameters. In Section 4, we detail the steps taken to measure planetary and orbital parameters and the investigation of an additional planet. In Section 5, we discuss our findings and the implications for the system. Finally, Section 6 summarizes our results and conclusions.

2. Observations

A summary of our observational data and key properties is given in Table 1.

2.1. TESS

GJ 3929 was observed by the TESS spacecraft between 2020 April 16 and June 8. These dates correspond to Sectors 24 and 25 of the TESS nominal mission. GJ 3929 was observed in CCD 1 of Camera 1 during sector 24 and CCD 2 of Camera 1 during sector 25. The TESS photometry was first reduced by SPOC. After initial processing, we used the pre-search data conditioning simple aperture photometry (PDCSAP; Stumpe et al. 2012) in our analysis. Data points flagged as poor quality are discarded before analysis. A plot of the TESS PDCSAP flux used in the analysis is shown in Figure 1.

2.2. Ground-based Photometric Follow-up

Ground-based follow-up can be a useful tool not only to validate the planetary nature of transiting signals but also to refine the measured parameters of transiting exoplanets. Here we detail the ground-based photometric follow-up for GJ 3929b.

2.2.1. ARCTIC

We observed three transits of GJ 3929b on the nights of 2021 February 26, 2021 April 30, and 2021 September 21, using the Astrophysical Research Consortium (ARC) Telescope Imaging Camera (ARCTIC; Huehnerhoff et al. 2016) at the ARC 3.5 m Telescope at Apache Point Observatory (APO). To achieve precise photometry on nearby bright stars, we used the engineered diffuser described in Stefansson et al. (2017). The air mass of GJ 3929 varied from 1.00 to 1.66 over the course of its observation on 2021 February 26. The observations were performed using a 30 nm wide narrowband Semrock filter centered at 857 nm (described in Stefansson et al. 2018) owing to moderate cloud coverage, with an exposure time of 33.1 s in the quad-readout mode with 2 × 2 on-chip binning. In the 2 × 2 binning mode, ARCTIC has a gain of 2 e/ADU, a plate scale of 0′′228 pixel−1, and a readout time of 2.7 s. We reduced the raw data using AstroImageJ (Collins et al. 2017). We selected a photometric aperture of 31 pixels (7′′07) and used an annulus with an inner radius of 70 pixels (15′′96) and an outer radius of 100 pixels (22′′8).

We also observed a transit of GJ 3929b on 2021 April 30. The air mass during observations varied between 1.00 and 1.51. The observations were performed using the same Semrock filter as described previously, with an exposure time of 45 s in the quad-readout mode with 2 × 2 on-chip binning. For the final reduction, we selected a photometric aperture of 33 pixels (7′′52) and used an annulus with an inner radius of 58 pixels (13′′22) and an outer radius of 87 pixels (19′′84). We observed a final transit of GJ 3929b on 2021 September 21. The air mass during observations varied between 1.21 and 3.22, and the resulting scatter in data points was >3 times the values of either previous ARCTIC night (rms20210226 = 1000 ppm; rms20210330 = 910 ppm; rms20210921 = 3400 ppm). Consequently, we chose not to use this final ARCTIC transit during analysis of planet b.

We checked for air-mass correlation on each night but found little evidence for any significant correlation. A plot of the ARCTIC transits used in our final analysis is visible in Figure 4.

2.2.2. LCOGT

We additionally use publicly available data taken by the Las Cumbres Observatory Global Telescope Network (LCOGT;
Brown et al. 2013. These data were obtained from the Exoplanet Follow-up Observing Program (ExoFOP) website.\textsuperscript{32} Two transits of GJ 3929b were obtained using the LCOGT. The first transit was obtained on 2021 April 10. Data were taken by both the SINISTRO CCDs at the 1 m telescopes of the McDonald Observatory (McD) and the Cerro Tololo Inter-American Observatory (CTIO). Both instruments have a pixel scale of 0.00389 pixel$^{-1}$ and a field of view (FOV) of $260 \times 260$. A second transit was obtained on 2021 April 15. These data were taken simultaneously in four different filters ($g', i', r', \text{and } z'$) with the Multi-color Simultaneous Camera for studying Atmospheres of Transiting exoplanets 3 camera (MuSCAT3; Narita et al. 2020) mounted on the 2 m Faulkes Telescope North at Haleakala Observatory (HAL). It has a pixel scale of 0.0027 pixel$^{-1}$, corresponding to an FOV of $9.01 \times 9.01$.

As outlined in Kemmer et al. (2022), high air mass caused the CTIO observations to exhibit higher scatter. In fact, both transits on 2021 April 10 exhibit much higher scatter ($\text{rms}_{\text{CTIO}} = 3300$ ppm; $\text{rms}_{\text{MCD}} = 2200$ ppm) than on 2021 April 15 ($\text{rms}_{g'} = 1010$ ppm; $\text{rms}_{i'} = 850$ ppm; $\text{rms}_{r'} = 910$ ppm; $\text{rms}_{z'} = 920$ ppm). Consequently, for the same reasons outlined in Section 2.2.1, we chose not to utilize either transit from 2021 April 10 in our final analysis.

The publicly available data were calibrated by the LCOGT BANZAI pipeline (McCully et al. 2018), and photometric data were extracted using AstroImageJ (Collins et al. 2017). The resulting photometric data are the same as those that were utilized in Kemmer et al. (2022).

2.3. High-contrast Imaging

High-contrast imaging can be important for ruling out false-positive scenarios. Kemmer et al. (2022) used high-resolution images obtained from the AstraLux camera (Hormuth et al. 2008) at the Calar Alto Observatory to rule out false-positive scenarios. They were able to rule out nearby luminous sources down to a $\Delta z' < 5.5$ at 1″. Here we detail our team’s adaptive

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Instrument & Date Range & rms & Average Error & Type \\
\hline
TESS & 2020 Apr 16–2020 Jun 8 & 1346 ppm & 1441 ppm & Photometry \\
ARCTIC & 2021 Feb 27–2021 Apr 30 & 1000 ppm & 734 ppm & Photometry \\
LCO & 2021 Apr 15 & 1522 ppm & 692 ppm & Photometry \\
CARMENES & 2020 Jul 30–2021 Jul 19 & 3.87 m s$^{-1}$ & 1.97 m s$^{-1}$ & RV \\
HPF & 2021 Aug 27–2022 Mar 11 & 8.81 m s$^{-1}$ & 8.42 m s$^{-1}$ & RV \\
NEID & 2021 Jan 6–2022 Jan 27 & 10.6 m s$^{-1}$ & 1.55 m s$^{-1}$ & RV \\
\hline
\end{tabular}
\caption{Summary of Observational Data}
\end{table}
optics (AO) follow-up of GJ 3929b and add to the evidence of a planetary explanation for the transit events.

2.3.1. ShARCS on the Shane Telescope

We observed GJ 3929 using the ShARCS camera on the Shane 3 m telescope at Lick Observatory (Srinath et al. 2014). GJ 3929 was observed using the $K_s$ and $J$ filters on the night of 2021 February 26. Instrument repairs prevented our observations from benefiting from Laser Guide Star (LGS) mode. Fortunately, GJ 3929 is sufficiently bright that LGS mode is helpful but not necessary. Further instrument repairs prevented our observations from using a dither routine to create mastersky images of GJ 3929. Instead, after a series of observations, we shifted several arcseconds to an empty region of sky and took images with the same exposure time for purposes of sky subtraction.

The raw data are reduced using a custom pipeline developed by our team (described in Beard et al. 2022). Using algorithms from Espinoza et al. (2016), we then generate a 5σ contrast curve as the final part of our analysis (Figure 2). We detect no companions at a $\Delta K_s = 4.85$ at 0"76 and $\Delta K_s = 9.75$ at 8"35. Additionally, we detect no companions at $\Delta \lambda = 4.54$ at 1"09 and $\Delta \lambda = 7.62$ at 8"99.

We note that observing conditions on 26 February 2021 were marginal. As a result of overcast conditions and poor seeing, the FWHM of the centroid in each reduced AO image was fairly large (0"77 and 1"11). Consequently, our final constraints on nearby luminous companions are not as tight as they might have been. However, our high-contrast images were taken in redder wave bands than the $\z$ filter used in Kemmer et al. (2022), and so we provide additional sensitivity toward detecting redder, cooler companions. In tandem, our results and those outlined in Kemmer et al. (2022) are consistent: we detect no nearby luminous companions as an explanation for the observed transit event.

2.4. Radial Velocity Follow-up

We obtained RVs of GJ 3929b in order to constrain the mass of the system and to independently confirm the planetary nature of the transiting planet. Here we detail the RV data acquired for the system GJ 3929.

2.4.1. The NEID Spectrometer on the WYI 3.5 m Telescope at KPNO

We obtained RVs of GJ 3929 using the new, ultraprecise NEID spectrometer (Schwab et al. 2016) on the WIYN 3.5 m telescope at KPNO. NEID is an environmentally stabilized (Stefansson et al. 2016; Robertson et al. 2019) fiber-fed spectrograph (Kanodia et al. 2018) with broad wavelength coverage (3800–9300 Å). We observed GJ 3929 in High Resolution (HR) mode with an average resolving power $R = 110,000$. The default NEID pipeline utilizes the cross-correlation function (CCF; Baranne et al. 1996) method to produce RVs. However, this method tends to be less effective on M dwarfs (e.g., Anglada-Escudé et al. 2012), and so we use a modified version of the SpEctrum Radial Velocity Analyser pipeline (SERVAL; Zechmeister et al. 2018) as described in Stefansson et al. (2021). SERVAL shifts and combines all observed spectra into a master template and compares this template with known reference spectra. We then minimize the $\chi^2$ statistic to determine the shifts of each observed spectrum. We mask telluric and sky emission lines during this process. A telluric mask is calculated based on their predicted locations using telfit (Gullikson et al. 2014), a Python wrapper to the Line-by-Line Radiative Transfer Model package (Clough et al. 2005).

We obtained 27 observations of GJ 3929 between 2021 January 6 and 2022 January 27. Our first two nights of observation for this system used three consecutive 900 s exposures, but we later changed our observation strategy to one 1800 s exposure per night. We obtained a median signal-to-noise ratio (S/N) of 44.8 in order 102 (λ = 4942 Å) of NEID for each unbinned observation. The median unbinned RV error bar is 1.18 m s$^{-1}$. The error bars are estimated from expected photon noise. A total of 23 nightly binned RVs were obtained, though four were discarded because the laser frequency comb stabilizer was not available on those nights, resulting in a less precise instrument drift solution that is insufficient for precision RV analysis. This left us with 19 nightly binned NEID RVs that were used in the analysis.

2.4.2. The Habitable Zone Planet Finder at McDonald Observatory

We observed GJ 3929 with the Habitable Zone Planet Finder (HPF; Mahadevan et al. 2012, 2014), a near-infrared (NIR: 8080–12780 Å), high-precision RV spectrograph. HPF is located at the 10 m Hobby–Eberly Telescope (HET) in Texas. HET is a fixed-altitude telescope with a rotating pupil design. Observations on the HET are queue scheduled, with all observations executed by the HET resident astronomers (Shevone et al. 2007). HPF is fiber-fed, with separate science, sky, and simultaneous calibration fibers (Kanodia et al. 2018), and has precise, millikelvin-level thermal stability (Stefansson et al. 2016).

We extracted precise RVs with HPF using the modified version of SERVAL Zechmeister et al. (2018) optimized for use for HPF data as described in detail in Stefansson et al. (2020). The RV reduction followed similar steps to those outlined in Section 2.4.1.

We obtained 18 observations of GJ 3929 with HPF over the course of six observing nights. These data were taken between 2021 August 27 and 2022 March 11. We obtained three consecutive exposures on each observing night, resulting in a median unbinned RV error of 7.15 m s$^{-1}$. Data taken on BJD = 2,459,649 were excluded from our analysis owing to poor weather conditions. Our data set then consists of five nightly binned HPF RVs. Due to the small quantity of the HPF data, we considered fits that did not utilize HPF data. We found that model results did not differ meaningfully whether HPF data were utilized or not, and we include them in our final model for completeness. HPF spectra were still used to derive stellar parameters, as outlined in Section 3.

2.4.3. CARMENES RVs

Our RV modeling also utilizes CARMENES RVs published in Kemmer et al. (2022). Kemmer et al. (2022) published 78 high-precision RVs as a part of their study of GJ 3929 using the CARMENES spectrograph (Quirrenbach et al. 2014). CARMENES is a dual-channel spectrograph with visible and NIR arms ($R_{\text{VIS}} = 94,600$; $R_{\text{NIR}} = 80,400$). CARMENES is located at the Calar Alto Observatory in Almería, Spain. RVs of GJ 3929 were taken between 2020 July 30 and 2021 July 19. Each observation lasted 30 minutes, with a median observation S/N of 74. Five RVs were discarded owing to a missing drift
correction in Kemmer et al. (2022), and we do so as well. This results in a final data set containing 73 RVs. These RVs were taken using the visible arm of CARMENES and have a median uncertainty of 1.9 m s\(^{-1}\).

3. Stellar Parameters

We followed steps outlined in Stefánsson et al. (2020) and Beard et al. (2022) to estimate \(T_{\text{eff}}\), \(\log g\), and [Fe/H] values of GJ 3929. The HPF-SpecMatch code is based on the SpecMatch-Emp algorithm from Yee et al. (2017) and compares the high-resolution HPF spectrum of the target star of interest to a library of high-S/N as-observed HPF spectra. This library consists of slowly rotating reference stars with well-characterized stellar parameters from Yee et al. (2017) and an expanded selection of stars from Mann et al. (2015) in the lower effective temperature range. Our analysis was run on 2022 March 3, and the library contained 166 stars during our run.

We shift the observed target spectrum to a library wavelength scale and rank all of the targets in the library using a \(\chi^2\) goodness-of-fit metric. After this initial \(\chi^2\) minimization step, we pick the five best-matching reference spectra. We then construct a weighted spectrum using their linear combination to better match the target spectrum. A weight is assigned to each of the five spectra according to its goodness of fit. We then assign the target stellar parameter \(T_{\text{eff}}\), \(\log g\), and [Fe/H] values as the weighted average of the five best stars using the best-fit weight coefficients. The final parameters are listed in Table 2. These parameters were derived from the HPF order spanning 8670–8750 Å, as this order is cleanest of telluric contamination. We artificially broadened the library spectra with a \(\sin i\) broadening kernel (Gray et al. 1992) to match the rotational broadening of the target star. We determined GJ 3929 to have a \(\sin i\) broadening value of \(<2\) km s\(^{-1}\).

We used EXOFASTv2 (Eastman et al. 2013) to model the spectral energy distributions (SEDs) of GJ 3929 and to derive model-dependent constraints on the stellar mass, radius, and age. EXOFASTv2 utilizes the BT-NextGen stellar atmospheric models (Allard et al. 2012) during SED fits. Gaussian priors were used for the 2MASS (\(JHK\)), Johnson (\(BV\)), and Wide-field Infrared Survey Explorer (WISE) magnitudes (W1, W2, W3, and W4; Wright et al. 2010). Our spectroscopically derived host star effective temperature, surface gravity, and metallicity were used as priors during the SED fits as well, and the estimates from Bailier-Jones et al. (2021) were used as priors for distance. We further include in our priors estimates of Galactic dust by Green et al. (2019) to estimate the visual extinction, though we emphasize that this is a conservative upper limit: GJ 3929 is fairly close to Earth and is likely to be foreground to much of the dust utilized in this estimate. We convert this upper limit to a visual magnitude extinction using the \(R_V = 3.1\) reddening law from Fitzpatrick (1999). Our final model results are consistent with those derived in Kemmer et al. (2022) and are visible in Table 2.

4. Analysis

Both photometry and RV data were essential for characterizing GJ 3929, as the system may have two or more planets, though we have only detected transits of planet b. First, in Section 4.1, we investigate the transiting planet using our photometric data. Next, we analyze the RV data of GJ 3929 in Section 4.2. Then, we search for additional transiting signals. Finally, in Section 4.5, we combine both data sets to reach our final conclusion.

4.1. Transit Analysis

A 2.6-day transit signal was originally identified by the MIT SPOC pipeline on 2020 June 19, then designated TOI-2013.01. Subsequently, Kemmer et al. (2022) confirmed the planetary nature of the signal in early 2022. We combine the TESS data with our follow-up transits in addition to other publicly available photometric data (detailed in Section 2.2) to further refine the measured parameters of the system.

4.1.1. Modeling the Photometry

We modeled GJ 3929’s photometry using the exoplanet software package (Foreman-Mackey et al. 2021a). First, we downloaded the TESS PDCSAP flux using lightkurve (Lightkurve Collaboration et al. 2018). We then performed a standard quality-flag filter, removing data points designated as of poor quality by the SPOC pipeline, and we median-normalized the TESS data. We then combined the TESS data with our normalized ARCTIC and LCOGT data for joint analysis.

Initial fits to ARCTIC and LCOGT data appeared to have a slight residual trend, and so in our adopted fit we detrended ARCTIC and LCOGT photometry before combining the data sets. We utilized the NumPy polyfit function to fit a line for purposes of detrending (Harris et al. 2020). This function performs a simple least-squares minimization to estimate the linear trend. This detrending was performed before modeling the data, as we found that including a detrending term in the model did not meaningfully improve our results, while increasing the complexity of our model.

We found it best to partition the photometric data into four regions of interest: the TESS data (which consist of two consecutive sectors), two different nights of ARCTIC data, and a night of LCOGT data. Due to the possibility of systematic offsets between nights and the distinct conditions during each night of ARCTIC observations, we choose to treat each ARCTIC night separately in our model. Furthermore, the LCOGT data were taken with four different filters. Consequently, we model each filter separately. For each instrument −filter combination, then, we adopt a unique mean and jitter term. The mean terms are additive offsets to account for potential systematic shifts between nights and are simply subtracted from all data points when fitting. The jitter terms are meant to model additional white noise not properly accounted for in the error bars of the data set and are added in quadrature with the error bars. Our model thus consists of seven total mean terms and seven jitter terms.

The physical transit model was generated using exoplanet functions and the starry light-curve package (Luger et al. 2019), which models the period, transit time, stellar radius, stellar mass, eccentricity, radius, and impact parameter to produce a simulated light curve. We adopt quadratic limb-darkening terms to account for the change in flux that occurs when a planet approaches the limb of a star (Kipping 2013). The two ARCTIC transits were taken using the same Semrock filter, and so we expect their limb-darkening behavior to be the same. Thus, we adopt the same limb-darkening parameters for each ARCTIC transit. We adopt distinct limb-darkening terms for the LCOGT data taken with the SDSS \(g’, i’, r’\), and \(z’\) filters. We note that this results in six pairs of limb-darkening terms, in contrast to seven separate jitter and mean terms, but is physically motivated.
Table 2
Summary of Stellar Parameters for GJ 3929

| Parameter | Description | Value | Reference |
|-----------|-------------|-------|-----------|
| **Main Identifiers:** | | | |
| TOI | TESS Object of Interest | 2013 | TESS mission |
| TIC | TESS Input Catalogue | 188589164 | TICv8 |
| GJ | Gliese-Jahreiss Nearby Stars | 3929 | Gliese-Jahreiss |
| 2MASS | | | 2MASS |
| Gaia DR3 | | | Gaia DR3 |
| **Equatorial Coordinates, Proper Motion and Spectral Type:** | | | |
| $\alpha_{2000}$ | R.A. (R.A.; deg) | 239.57754339(4) | Gaia DR3 |
| $\delta_{2000}$ | Decl. (decl.; deg) | 35.40815826(2) | Gaia DR3 |
| $\mu_x$ | Proper motion (RA; mas/yr) | $-143.28 \pm 0.07$ | TICv8 |
| $\mu_y$ | Proper motion (decl.; mas/yr) | $318.22 \pm 0.08$ | TICv8 |
| $d$ | Distance (pc) | $15.8 \pm 0.02$ | Bailer-Jones |
| **Optical and NIR magnitudes:** | | | |
| $B$ | Johnson $B$ mag | $14.333 \pm 0.008$ | TICv8 |
| $V$ | Johnson $V$ mag | $12.67 \pm 0.02$ | TICv8 |
| $g'$ | Sloan $g'$ mag | $15.161 \pm 0.006$ | TICv8 |
| $r'$ | Sloan $r'$ mag | $12.2405 \pm 0.0009$ | TICv8 |
| $i'$ | Sloan $i'$ mag | $10.921 \pm 0.001$ | TICv8 |
| $T$ | TESS magnitude | $10.270 \pm 0.007$ | TICv8 |
| **Spectroscopic Parameters:** | | | |
| $T_{\text{eff}}$ | Effective temperature in K | $3384 \pm 88$ | This work |
| $\text{[Fe/H]}$ | Metallicity in dex | $-0.02 \pm 0.12$ | This work |
| log($g$) | Surface gravity (cm s$^{-2}$) | $4.89 \pm 0.05$ | This work |
| **Model-dependent Stellar SED and Isochrone fit Parameters:** | | | |
| $M_*$ | Mass ($M_\odot$) | $0.313^{+0.027}_{-0.022}$ | This work |
| $R_*$ | Radius ($R_\odot$) | $0.32 \pm 0.01$ | This work |
| $L_*$ | Luminosity ($L_\odot$) | $0.0109^{+0.0005}_{-0.0004}$ | This work |
| $\rho_*$ | Density (g cm$^{-3}$) | $13.3 \pm 1.1$ | This work |
| Age | Gyr | $7.1^{+1.9}_{-1.1}$ | This work |
| $A_v$ | Visual extinction (mag) | $0.005 \pm 0.003$ | This work |
| $d$ | Distance (pc) | $15.822 \pm 0.006$ | This work |
| **Other Stellar Parameters:** | | | |
| $v \sin i_*$ | Rotational velocity (km s$^{-1}$) | <2 | This work |
| $\Delta RV$ | "Absolute" radial velocity (km s$^{-1}$) | $10.265 \pm 0.008$ | This work |
| $U, V, W$ | Galactic velocities (km s$^{-1}$) | $-21.05 \pm 0.04,10.85 \pm 0.06,14.66 \pm 0.08$ | Kemmer |

Note.

$^a$ Derived using the HPF spectral matching algorithm from Stefánsson et al. (2020).

References. TICv8 (Stassun et al. 2018), 2MASS (Cutri et al. 2003), Gaia DR3 (Gaia Collaboration et al. 2022j, in preparation), Bailer-Jones (Bailer-Jones et al. 2018), WISE (Wright et al. 2010), Kemmer (Kemmer et al. 2022).

Similar to Kemmer et al. (2022), we choose not to include a dilution term in our final model. GJ 3929 does not have many neighbors and is much brighter than all of them (Figure 3). GJ 3929 has an estimated contamination ratio of 0.000765, meaning that 0.08% of its flux is possibly from nearby sources (Stassun et al. 2019). This suggests that a dilution term is not necessary.

4.1.2. Inference

After constructing a physical transit model using `starry`, we compare it to the data after it has been adjusted to account for offsets, and we add our jitter parameters in quadrature with the error bars during likelihood estimation. Each free parameter is given a broad prior to prevent any biasing of the model, and we summarize the priors used in Table 4. The model is then optimized using `scipy.optimize.minimize` (Virtanen et al. 2020), which utilizes the Powell optimization algorithm (Powell 1998). This optimization provides a starting guess for posterior inference. We then used a Markov Chain Monte Carlo (MCMC) sampler to explore the posterior space of each model parameter. `exoplanet` uses the Hamiltonian Monte Carlo (HMC) algorithm with a No U-Turn Sampler (NUTS) for increased sampling efficiency (Hoffman & Gelman 2011). We ran 10,000 tuning steps and 10,000 subsequent steps and
assessed convergence criteria using the Gelman–Rubin (G-R) statistic (Ford 2006). We considered a chain well mixed if the G-R statistic was within 1% of unity. All the parameters in our model indicated convergence using this metric.

Our photometry-only fits are consistent with the joint fits adopted in Section 4.5. A final plot of the photometry, folded to the period of planet b, is visible in Figure 4.

4.2. Radial Velocity Analysis

4.2.1. Periodogram Analysis

We first used a Generalized Lomb–Scargle (GLS) periodogram (Zechmeister & Kürster 2009) to analyze the RVs of GJ 3929 and to identify any periodic signals. We estimate the analytical false-alarm levels and normalize the periodogram following the steps outlined in Zechmeister & Kürster (2009), which assume Gaussian noise. With this assumption, we scale the sample variance (and false-alarm levels) by \( \frac{1}{N - k - 1} \) in order to reproduce the population variance, which is the quantity of interest in our analysis. Consistent with Kemmer et al. (2022), we detected significant periodicities between 14 and 16 days. In contrast to Kemmer et al. (2022), however, we find that when including the new, more precise NEID RVs (median CARMENES RV error \( \sim 1.6 \times \) median NEID RV error), as well as our HPF RVs, the 15-day signal has grown in power relative to the 14-day signal, suggesting that it might be the true signal. Relative peak strengths of alias frequencies in a periodogram do not always indicate the true period, however, and we detail a more formal model comparison later in the section. A plot of the combined data set periodogram and periodograms on NEID and CARMENES only are visible in Figure 5. After the subtraction of the longer-period planet c, the signal of the 2.6-day planet b is clearly identifiable in the periodogram.

4.2.2. Modeling the RVs

We used the RadVel software package to analyze the RVs of GJ 3929 (Fulton et al. 2018). RadVel models an exoplanet’s orbit by solving Kepler’s equation using an iterative method outlined in Danby (1988). Each planetary orbit is then modeled by five fundamental parameters: the planet’s orbital period \( P \), the planet’s time of inferior conjunction \( T_i \), the eccentricity of the orbit \( e \), the argument of periastron \( \omega \), and the velocity semi-amplitude \( K \). We additionally include instrumental terms, \( \gamma \) and \( \sigma \), which account for systematic offsets between instruments and excess white noise.

We construct the RV model in a Bayesian context, encoding prior information about each parameter as a part of the model. Similar to the fits described in Section 4.1, we adopt broad priors on the free parameters of our model to prevent any bias in our results, the primary exception being that during RV-only fits we put tight priors on \( P_b \) and \( T_{\text{com,b}} \), as these are much more tightly constrained by transits than by RV fits. We emphasize, however, that our final adopted fit is a joint fit between RVs and transits, detailed in Section 4.5. Detailed prior information is available in Table 4.

4.2.3. Inference

In order to estimate the posterior probability of our model, we used an MCMC sampler to explore the posterior parameter space. RadVel utilizes the MCMC sampler outlined in Foreman-Mackey et al. (2013). We first used the Powell optimization method to provide an initial starting guess for each parameter (Powell 1998). We then ran 150 independent chains and assessed convergence using the Gelman–Rubin (G-R) statistic (Ford 2006). The sampling was terminated when the chains were sufficiently mixed. Chains are considered well mixed when the G-R statistic for each parameter is \( <1.03 \), the minimum autocorrelation time factor is \( \geq 75 \), the max relative change in autocorrelation time is \( \leq 0.01 \), and there are \( \geq 1000 \) independent draws. All of our considered models eventually satisfied these conditions.

We additionally considered the inclusion of a Gaussian process (GP; Ambikasaran et al. 2015) model to account for coherent stellar activity. Kemmer et al. (2022) identify a rotation period of \( \sim 120 \) days for GJ 3929. This value is derived from a combination of long-term photometry taken using the Hungarian Automated Telescope Network (HATNet; Bakos et al. 2004), the All-Sky Automated Search for SuperNovae (ASAS-SN; Shappee et al. 2014), and Joan Oró Telescope (TJO; Colomé et al. 2010) and periodogram analysis of the CARMENES H\(\alpha \) values. We use the combined H\(\alpha \) values from CARMENES and NEID to expand on this, plotted in Figure 6. While the maximum power occurs at a slightly shorter period than observed in Kemmer et al. (2022), we note that rotational variability is often quasi-periodic in nature and periodograms can have trouble distinguishing longer periods (Lubin et al. 2021). Our value observed here is still consistent with the previously reported value, and we make no amendment to the system’s rotation period.

The \( >100 \)-day rotation period of this system is consistent with a quiet, slowly rotating star, and we normally would not expect a large RV signal due to activity. However, Kemmer et al. (2022) found an RV fit that included a GP to be preferred to an RV-only fit, and so we proceed with a series of fits, some of which include...
Our fits utilize the quasi-periodic GP kernel owing to its flexibility and wide application in exoplanet astrophysics (e.g., Haywood et al. 2014; López-Morales et al. 2016). We also compared fits with the GP kernel that was adopted in Kemmer et al. (2022). Kemmer et al. (2022) utilized a combination of two simple harmonic oscillator (SHO; Foreman-Mackey 2018) kernels, outlined in more detail in Kossakowski et al. (2021). We refer to this as the double simple harmonic oscillator kernel (dSHO).

In order to explore the possibility of an additional planet in the GJ 3929 system and the plausibility of stellar activity interfering with RV signals, we perform a model comparison. Model

![Phase-folded transit fits to TESS data, ARCTIC data, and LCOGT data. We separate the 2021 April 15 transit taken with LCOGT by filter and label them accordingly. Using all of these data allows us to modify previous radius estimates of GJ 3929b.](image)

![GLS periodograms of the combined data set consisting of NEID, CARMENES, and HPF RVs, CARMENES data only, and NEID data only. Data have been adjusted for offsets. Middle: data after the subtraction of planet c, assuming the values derived in our final posterior fits. Bottom: GLS periodograms of data after the subtraction of planet b and planet c. We do not include a periodogram of HPF-only data owing to its sparseness.](image)
comparisons vary in the number of planets included, whether or not we include a GP to account for stellar noise and eccentric fits, and whether or not the second planet is modeled as the 14-day signal or the 15-day signal. A full table of our model results is provided in Table 3. Our analysis found that both the quasi-periodic and dSHO GPs perform similarly in model comparison, and so we only include the quasi-periodic results for brevity. When comparing models, we use the Bayesian information criterion (BIC; Kass & Raftery 1995) and the corrected Akaike information criterion (AICc; Hurvich & Tsai 1993). The BIC of each model can be used to estimate the Bayes factor (BF), a measure of preference for one model over another. Half the difference in BIC between two models is used to estimate the Schwarz criterion, which itself is an approximation of the log BF. The AICc is an approximation of the Kullback–Leibler information, another metric for ranking the quality of models (Hurvich & Tsai 1993).

Kass & Raftery (1995) suggest that a log10 BF > 2 (ln BF > 4.6) is decisive evidence for one model over another. For GJ 3929, our two-planet (∼15 days) model is preferred over the next best model, a two-planet GP (∼15 days), with a BF of 5.86 (RadVel estimates likelihoods using ln), suggesting a strong preference for the no-GP case. The AICc simply prefers the model that minimizes the AICc, which is also the two-planet model (∼15 days). Both methods of estimation are only asymptotically correct, but they are preferred by a wide enough margin and agree with one another. Consequently, we use these comparisons to justify selecting the two-planet model (∼15 days) without a GP as our best model.

A phase folded diagram of the RV model taken from our final joint fit is included in Figure 7.

4.3. An Additional Transiting Planet?

As elaborated further in Section 4.2 and detailed in Kemmer et al. (2022), GJ 3929 RVs show two strong periodicities between 14 and 16 days. Consistent with Kemmer et al. (2022), fitting either signal eliminates the other, suggesting that one is an alias of the other. Thus, we conclude that the two signals originate from a single source, though the true periodicity is originally unclear. Such a signal might be an additional planet, and if so, it may be transiting. Here we search the TESS photometry for signs of additional transiting exoplanets, with a particular emphasis on planets in this period range.

We use the TransitLeastSquares (TLS; Hippke & Keller 2019) Python package in order to search for additional periodic transit signals in the TESS light curves. Unlike a box-fitting least-squares (BLS) algorithm (Kovács et al. 2002), which is used frequently in transit searches, the TLS adopts a more realistic transit shape, increasing its sensitivity to transiting exoplanets, especially smaller ones. Initially, we recover GJ 3929b with a signal detection efficiency (SDE) > 35, a highly significant detection. Dressing & Charbonneau (2015) suggest that an SDE > 6 represents a conservative cutoff for a “significant” signal, though others adopt higher values (Siverd et al. 2012; Livingston et al. 2018). We then mask the transits of planet b and continue the investigation. Our second check highlights a significant signal

![Gj 3929 All Data H-Alpha Periodogram](image)

Figure 6. GLS periodogram of the Hα data taken by the CARMENES and NEID spectrographs. The only significant signal is at 116 days, which is most likely associated with the stellar rotation period identified in Kemmer et al. (2022). Neither of the planetary periods has any significant power in these data. We do not include HPF, as its bandpass does not include the Hα indicator.

| Fit            | Number of Free Parameters | BIC     | AICc   |
|----------------|---------------------------|---------|--------|
| 0 planet       | 4                         | 566.5757| 552.0607|
| 1 planet       | 7                         | 569.5241| 548.4207|
| 1 planet ecc   | 9                         | 578.4362| 553.4362|
| 1 planet GP    | 11                        | 574.0880| 545.0023|
| 2 planet (∼14 days) | 10                       | 560.2770| 533.0948|
| 2 planet (∼14 days) ecc (b) | 12               | 567.0928| 536.1688|
| 2 planet (∼14 days) ecc (c) | 12               | 562.6650| 531.7300|
| 2 planet (∼14 days) ecc (both) | 14             | 567.6228| 533.2274|
| 2 planet GP (∼14 days) | 14                     | 576.62   | 542.2246|
| 2 planet (∼15 days) | 10                       | 545.5826| 518.4004|
| 2 planet (∼15 days) ecc (b) | 12               | 552.2589| 521.3349|
| 2 planet (∼15 days) ecc (c) | 12               | 551.8569| 520.9229|
| 2 planet (∼15 days) ecc (both) | 14             | 560.8289| 525.8289|
| 2 planet GP (∼15 days) | 14                     | 557.3132| 522.9178|

Note. 

a Model comparison was performed on RV-only fits. This is motivated in Section 4.5.
at 13.9 days (SDE = 12.74), somewhat close to the suspected planetary signals from the RVs. However, analysis of the candidate transit event itself seems inconsistent. Using the nonparametric mass–radius relationship from mrexo (Kanodia et al. 2019), we estimate that planet c would have a radius of 2.26 \( R_\oplus \) using the minimum mass, and consequently a nongrazing transit depth of 4.19 ppt, more than 4 times as large as planet b. We caution that such mass–radius relationships are associated with a large uncertainty, though Figure 9 makes it clear that GJ 3929c should at least be larger than planet b. However, this “transit” observed by TLS at \( \sim 14 \) days has a depth of 0.24 ppt. It is possible that the transits of this candidate are grazing, resulting in an anomalously small transit depth. However, the durations of the transits of this signal are also much longer than expected, at 0.42 days. This not only is inconsistent with a grazing transit but also would be too long for any transit at this period. Finally, the estimated transit phase is totally inconsistent with the time of conjunction found in Kemmer et al. (2022). TLS finds a \( T_c = 2,459,867 \) BJD, while Kemmer et al. (2022) would have expected a \( T_c = 2,459,872 \) BJD (scaling back the time of conjunction reported). We thus conclude that this significant \( \sim 14 \)-day periodicity identified by the TLS package is not planet c and is most likely noise.

It is possible that planet c is transiting, but that its transits fell into TESS data gaps. In Figure 8, we highlight where the transits of planet c would occur relative to the TESS photometry. We identify no clear transit signals in the data.

We calculate 3\( \sigma \) and 5\( \sigma \) transit windows in Figure 8 by using our posterior period and time of conjunction values for planet c and back-propagating them using standard propagation of error. Consequently, from Figure 8, we can rule out nongrazing transits of planet c with 3\( \sigma \) confidence.

### 4.4. Candidate Planet, or Planet?

Kemmer et al. (2022) designated the 14-to-15-day signal a planet candidate. While no transit signal is clearly detected at this period, we can rule out most false-positive scenarios.

GJ 3929c might be a highly inclined binary or brown dwarf. While such a scenario cannot easily be ruled out, GJ 3929 has a Gaia RUWE value of 1.185, which is consistent with little astrometric motion (Gaia Collaboration et al. 2016, 2021; Lindegren & Dravins 2021). This suggests that a highly inclined binary scenario is unlikely.

Periodic or quasi-periodic RV signals can also be created by stellar magnetic activity. Our model comparison (Table 3) does not prefer a model that includes activity mitigation, and TESS photometry does not exhibit any obvious periodic variability (Figure 1). Furthermore, no strong signal near 14 or 15 days exists in the H\( \alpha \) indicator data (Figure 6). The candidate rotation period does show up very strongly in the H\( \alpha \) periodogram, however, and its value \( >100 \) days is far from either planet.

The \( \sim 15 \)-day signal associated with planet c is stable over the time baseline and across instruments, further suggesting a planetary explanation. Performing a two-planet fit (without a GP) on the CARMENES data, and doing the same with all data, yields consistent results (\( K_{\text{c,carmenes}} = 3.20 \pm 0.58 \) m s\(^{-1}\), \( K_{\text{c,all}} = 3.18 \pm 0.49 \) m s\(^{-1}\)). Planetary signals are expected to remain stable over any observational baseline, while activity-sourced signals increase or decrease in amplitude over time. This analysis provides additional evidence for the true period of planet c at \( \sim 15 \) days. Performing the same analysis on the \( \sim 14 \)-day signal yields a noticeable decrease in amplitude with the new RV data (\( K_{\text{c,carmenes}} = 2.64 \pm 0.63 \) m s\(^{-1}\), \( K_{\text{c,all}} = 2.38 \pm 0.52 \) m s\(^{-1}\)). While the two values are consistent, the 14-day signal appears more sensitive to the new data.

### 4.5. Joint Transit–RV Analysis

The final step of our analysis is the combination of the transit fits and RV fits into one complete, joint analysis. We adopt this model as our best, final model, as it is the most complete description of GJ 3929: it utilizes all data and characterizes both planets that are observed in this system, while also characterizing properties of planet b that can only be gleaned from photometry, especially its radius.

We performed a model comparison in Section 4.2, and we use that model comparison to select our preferred model, which is a two-planet model without the use of a GP. We performed this model comparison in the RV analysis rather than the joint analysis for one primary reason: all the free parameters of interest are primarily measured in the RVs. First, we were interested in deciding between a one- and two-planet model. The second planetary signal is only detected in the RVs; transit searches have been unsuccessful. Second, we wanted to differentiate between a 14- and 15-day period for planet c. Again, this signal is only represented in the RV data. Third, we wanted to justify the use of a GP. Our primary consideration for the use of a GP was in the RVs, as the photometries are quiet, as expected. A \( >100 \)-day rotation period would be unlikely to be observed in TESS PDCSAP flux, and the ground-based photometries are all far too short in baseline to be affected by a periodicity on even 1/100 of the rotation period’s timescale. Finally, we were interested in testing the veracity of eccentric models. Eccentricity, however, is much more strongly constrained by RVs than by photometry.

Our final, joint fit, then, was performed considering a two-planet model, where the second planet period is constrained between 15 and 16 days in order to prevent the MCMC chains from clustering around the alias at 14.2 days. The model is circular, and we do not adopt any GP to account for excess noise. We use the exoplanet software package in the joint fit, and the transits are modeled identically as described in Section 4.1. The RVs are modeled in exoplanet as well, with two Keplerian orbital solutions that model both photometric and RV data sets simultaneously. In particular, the period and time of conjunction of each planet are shared between the data sets, while other orbital parameters are typically constrained to one data set or another. A full list of the priors used in our model is available in Table 4.

We again use the HMC algorithm with a NUTS sampler for increased sampling efficiency. We again run 10,000 tuning steps and 10,000 subsequent posterior estimation steps. Our final transit fits are visible in Figure 4. Our final RV fit is visible in Figure 7. Finally, our posterior estimates for each model free parameter are listed in Table 5.

### 5. Discussion

We have refined the measured parameters for GJ 3929b (\( P_b = 2,616,235 \pm 0.000,000 \) days; \( R_b = 1.09 \pm 0.04 \) \( R_\oplus \); \( M_b = 1.75^{+0.44}_{-0.45} \) \( M_\oplus \); \( p_b = 7.3 \pm 2.0 \) g cm\(^{-3}\)) and GJ 3929c (\( P_c = 15.04 \pm 0.03 \) days; \( M \sin i_c = 5.71 \pm 0.94 \) \( M_\oplus \)).

GJ 3929 joins a growing list of M-dwarf systems that contain a short-period terrestrial planet, accompanied by a nontransiting, more massive planet (i.e., Bonfils et al. 2018). Additionally, the
possible existence of additional planetary companions cannot be ignored. M dwarfs in particular tend to have higher multiplicity of smaller exoplanets. Lu et al. (2020) used metallicity correlations when studying M-dwarf systems to estimate how much planet-forming material is present in an initial planetary disk. It is likely that a correlation exists between metallicity of the host star and the amount of planet-forming material in a disk, especially for late-type stars (Bonfils et al. 2005;
Johnson & Apps (2009). Lu et al. (2020) estimate only 9 $M_\oplus$ of material for forming planets in a metal-poor ([Fe/H] = −0.5) early M dwarf ($M_*=0.6 M_\odot$). While GJ 3929 is smaller ($M_*=0.32 M_\odot$) than this system, its metallicity is much closer to the Sun ([Fe/H] = −0.05), giving it ∼15 $M_\oplus$ of material to form planets, if we assume the disk-to-star mass ratio of 0.01 that Lu et al. (2020) adopt. The sum of the median mass of GJ 3929b ($1.75 M_\oplus$) and the median minimum mass of GJ 3929c ($5.70 M_\oplus$) are significantly less than this value, implying that planet c is significantly inclined and much more massive than we estimate, additional planets exist in the system, or the extra disk material was accreted onto the star.

We highlight the GJ 1132 system, characterized in Bonfils et al. (2018), for comparison with GJ 3929. GJ 1132b is also a short-period, Earth-sized rocky planet orbiting an M dwarf, with an additional nontransiting companion. GJ 3929b is denser than GJ 1132b, as seen in Figure 9, though its longer orbital period makes its RV semiamplitude a bit smaller. We include comparisons to this system further in the discussion to help frame GJ 3929 in the context of similar systems.

5.1. Planet b

GJ 3929b is an Earth-sized exoplanet, placing it below the radius gap for M dwarfs (Van Eylen et al. 2021; Petigura et al. 2022). Our mass and radius estimates allow us to constrain GJ 3929b’s bulk density and confirm its consistency with a composition slightly denser than Earth (Figure 9). Due to its proximity to its host star, GJ 3929b probably lost much of its atmosphere owing to X-ray and ultraviolet flux (Van Eylen et al. 2018). The addition of a nontransiting second planet in the system originally confounded our RV analysis of the system and further emphasizes the challenges discussed in He et al. (2021) relating to the mass measurement of transiting planets. Since more than half of the time the transiting planet in a system with nontransiting companions does not have the largest semiamplitude, initial follow-up can be confusing.

GJ 3929b is Venus-like ($S_0 = 17.3^{+0.3}_{-0.7}$), in that it resides in its host star’s Venus zone. This is defined as the boundary between the runaway-greenhouse inner edge of the habitable zone (Kopparapu et al. 2013) and an orbital distance that would produce 25 times Earth-like flux (Ostberg & Kane 2019).
Learning more about planets in the Venus zone is an important step toward discovering Earth twins. Spectroscopic observations of the solar system, for example, would have a hard time distinguishing between Earth and Venus, despite their drastically different surface environments (Jordan et al. 2021). GJ 3929b is an excellent planet for studying the differences in spectra for a system that is Venus-like, and for which we are certain that it is nothing like Earth.

Fortunately, GJ 3929b is amenable to atmospheric study with the James Webb Space Telescope (JWST; Gardner et al. 2006). Beyond learning more about exo-Venuses, studying the atmosphere of GJ 3929b could help reveal the evolutionary history of the system and shed light on planet formation models. GJ 3929b has an estimated Transmission Spectroscopy Metric (TSM; Kempton et al. 2018) of 14 ± 4, placing it in the top quintile of Earth-sized exoplanets amenable to JWST.
observations. The density of GJ 3929b does not suggest a thick atmosphere, though a thin atmosphere of outgassed volatiles, a thin atmosphere lacking in volatiles and consisting of silicates and enriched in refractory elements, and a no-atmosphere scenario are all plausible (Seager & Deming 2010).

In Figure 10, we highlight GJ 3929b’s TSM in the context of other small exoplanets. We include all exoplanets with sufficient information to calculate a TSM on the NASA Exoplanet Archive, though we caution that only exoplanets with \( > 3\sigma \) mass measurements are likely to see follow-up with JWST owing to a degeneracy in the interpretation of spectra (Batalha et al. 2019). GJ 3929b occupies a truly rare position in this space, as quality mass measurements are very challenging for planets of its size, and small planets with mass measurements are usually not very amenable to transmission spectroscopy. We highlight a few other small planets amenable to transmission spectroscopy. Besides the TRAPPIST-1 system (Agol et al. 2021), which is exceptional in most parameter spaces, few small planets are better for transmission spectroscopy than GJ 3929b. While GJ 1132b is a similar system to GJ 3929b and its TSM is slightly larger, GJ 3929b is brighter, making high-S/N measurements with JWST more likely, and making it more attractive for ground-based follow-up. On the other hand, GJ 367b is an ultra-short-period (USP) planet with a much higher TSM than GJ 3929b. However, its USP nature makes the existence of an atmosphere far less likely than for GJ 3929b, and further, any such atmosphere would likely exhibit very different chemistries from GJ 3929b, since its equilibrium temperature is more than 3 times hotter (\( T_{\text{eq,GJ367b}} = 1745 \pm 43 \) K; Lam et al. 2021).

5.2. Planet c

It is not clear whether or not GJ 3929c is a transiting exoplanet, though we detect no transits of this system in this study. Consequently, we cannot measure the radius of planet c, nor its bulk density.

The measured minimum mass of GJ 3929c suggests that it is at least a sub-Neptune in size when predicted from the mass–radius
relationship, and perhaps larger (Kanodia et al. 2019). M-dwarf systems consisting of a close-in, terrestrial exoplanet and longer-period sub-Neptunes are common occurrences (Rosenthal et al. 2021; Sabotta et al. 2021), though the brightness of GJ 3929 allows for a more detailed study than is often the case. GJ 3929 will not be observed by TESS during Cycle 5, though the success of the TESS mission suggests that it will likely continue for years longer. Additionally, the advent of future photometric missions (i.e., PLATO; Magrin et al. 2018) suggests that GJ 3929 will probably receive additional photometric observations in the future, and a transit of planet c may someday be identified.

5.3. Comparison to Kemmer et al. (2022)

The addition of HPF and NEID RV data, as well as diffuser-assisted ARCTIC data, have refined or changed various measured and derived parameters for each planet. Furthermore, our choice to use the ~15-day signal as the period of GJ 3929c has an additional effect on several of the qualities of the planet.

The period and transit time of planet b are fully consistent with those found in Kemmer et al. (2022), though the uncertainty is slightly larger in our case. This is most likely due to Kemmer et al. (2022)’s use of more transit data and in general modeling more transits of planet b. We prioritized higher-precision photometry and consequently opted not to use the SAINT-EX photometry or the additional LCO data utilized in Kemmer et al. (2022). Furthermore, our team did not have access to the transits obtained by the Observatorio de Sierra Nevada (OSN). Our additional ARCTIC photometry changed the radius measurement from 1.150 ± 0.04 R_{\oplus} to 1.09 ± 0.04 R_{\oplus}, though we note that these values are 1σ consistent.

The additional RVs did not shrink the formal 1σ error bars of the measured RV semi-amplitudes, but they did modify the mean posterior values, and the resulting K/σ of our mass measurements are improved. For planet b, Kemmer et al. (2022) found a mass of 1.21^{+0.42}_{-0.43} M_{\oplus}, and we find a mass of 1.75^{+0.44}_{-0.45} M_{\oplus}. Similarly for planet c, Kemmer et al. (2022) found a minimum mass of 5.27^{+0.74}_{-0.76} M_{\oplus}, while we measure a minimum mass of 5.71 ± 0.94 M_{\oplus}. We note, however, that changing the period of planet c likely played a role in this change as well, not merely the additional RVs.

Perhaps the most significant departure from Kemmer et al. (2022) is that our final model did not utilize a GP. In fact, this is probably the most significant contribution to the increased mass uncertainties in our fits. When utilizing a GP, our model does yield more precise mass uncertainties than those in Kemmer et al. (2022), which is expected owing to our inclusion of additional data. The increased amplitudes remain, however, suggesting that their difference is not related to the use of a GP. As shown in Table 3, we cannot justify the use of a GP in our final fit.

6. Summary

We use RVs from the NEID, HPF, and CARMENES spectrographs to characterize the transiting planet GJ 3929b and the probably nontransiting planet GJ 3929c. We use diffuser-assisted photometry from the ARCTIC telescope in combination with LCOGT and TESS photometry in order to improve the radius of GJ 3929b (R_b = 1.09 ± 0.04 R_{\oplus}), and we use RVs from CARMENES, NEID, and HPF to measure the mass of both planets (M_b = 1.75 ± 0.45 M_{\oplus}, M_c = 5.70 ± 0.92 M_{\oplus}). We conclude that GJ 3929 is a two-planet system with a 2.61626 ± 0.000005-day transiting exo-Venus that is highly amenable to transmission spectroscopy. GJ 3929c is a more massive planet orbiting with a period of 15.04 ± 0.03 days that is unlikely to transit.

This paper includes data collected by the TESS mission. Funding for the TESS mission is provided by NASA’s Science Mission Directorate.

The Hobby–Eberly Telescope (HET) is a joint project of the University of Texas at Austin, the Pennsylvania State University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly.

The authors thank the HET Resident Astronomers for executing the observations included in this manuscript.

We would like to acknowledge that the HET is built on Indigenous land. Moreover, we would like to acknowledge and pay our respects to the Carrizo & Comecrudo, Coahuiltecan, Caddo, Tonkawa, Comanche, Lipan Apache, Alabama-Coushatta, Kickapoo, Tigua Pueblo, and all the American Indian and Indigenous Peoples and communities who have been or have become a part of these lands and territories in Texas, here on Turtle Island.

These results are based on observations obtained with the Habitable-zone Planet Finder Spectrograph on the HET. The HPF team was supported by NSF grants AST-1006676, AST-1126413, AST-1310885, AST-1517592, AST-1310875, AST-1910954, AST-1907622, AST-1909506, ATU 2009889, ATU-2009982, AST-2108512, AST-2108801, AST-2108493, and AST-2108569 and the NASA Astrobiology Institute (NNA09DA76A) in the pursuit of precision RVs in the NIR. The HPF team was also supported by the Heising-Simons Foundation via grant 2017-0494.

This project was also supported by NSF grant AST-1909682.

Based on observations at Kitt Peak National Observatory, NSF’s NOIRLab (Proposal ID 2020B-0422; PI: A. Lin. Prop. ID 2021A-0385; PI: A. Lin. Prop. ID 2021B-0435; PI: S. Kanodia. Prop ID 2021B-0035; PI: S. Kanodia), managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. The authors are honored to be permitted to conduct astronomical research on Iolkam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham.

This paper contains data taken with the NEID instrument, which was funded by the NASA-NSF Exoplanet Observational Research (NN-EXPLORE) partnership and built by Pennsylvania State University. NEID is installed on the WIYN telescope, which is operated by the NSF’s National Optical-Infrared Astronomy Research Laboratory (NOIRLab), and the NEID archive is operated by the NASA Exoplanet Science Institute at the California Institute of Technology. NN-EXPLORE is managed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

We thank the NEID Queue Observers and WIYN Observing Associates for their skillful execution of our NEID observations.

This work was partially supported by funding from the Center for Exoplanets and Habitable Worlds. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University and the Eberly College of Science.
This research was supported in part by a Seed Grant award from the Institute for Computational and Data Sciences at the Pennsylvania State University.

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.

This research made use of exoplanet (Foreman-Mackey et al. 2021a, 2021b) and its dependencies (Astropy Collaboration et al. 2013; Kipping 2013; Salvatier et al. 2016; Theano Development Team 2016; Foreman-Mackey et al. 2017; Foreman-Mackey 2018; Astropy Collaboration et al. 2018; Luger et al. 2019; Kumar et al. 2019; Agol et al. 2020).

This research made use of Lightkurve, a Python package for Kepler and TESS data analysis (Lightkurve Collaboration, 2018).

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

This research has made use of the Exoplanet Follow-up Observation Program (ExoFOP; DOI: 10.26134/ExoFOP5) website, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

We include the RV data taken by our team (Tables 6 and 7). We include a corner plot of a few of our model parameters in Figure 11.

### Table 6

| BJD$\text{BJDTDB}$ (days) | RV (m s$^{-1}$) | $\sigma$ (m s$^{-1}$) | $S/N_{\text{int}}$ | H$_2$ Index | $\sigma$ H$_2$ Index |
|---------------------------|----------------|----------------------|-------------------|-------------|---------------------|
| 2,459,221.0168            | 7.4            | 1.8                  | 29.41             | 0.971       | 0.007               |
| 2,459,221.0275            | 1.66           | 1.63                 | 32.04             | 0.973       | 0.006               |
| 2,459,221.0384            | 1.05           | 1.69                 | 31.09             | 0.965       | 0.006               |
| 2,459,231.0107            | 4.72           | 10.47                | 5.51              | 1.049       | 0.046               |
| 2,459,231.0167            | 8.66           | 1.16                 | 43.58             | 0.956       | 0.004               |
| 2,459,231.0274            | 6.81           | 1.29                 | 40.16             | 0.956       | 0.005               |
| 2,459,231.0382            | 8.31           | 1.09                 | 46.21             | 0.956       | 0.004               |
| 2,459,322.8407            | 11.47          | 1.24                 | 43.41             | 0.939       | 0.004               |
| 2,459,327.8212            | 7.42           | 1.08                 | 49.62             | 0.941       | 0.004               |
| 2,459,363.9174            | 7.05           | 1.01                 | 51.56             | 0.946       | 0.004               |
| 2,459,384.7824            | 12.5           | 1.23                 | 42.22             | 0.947       | 0.004               |
| 2,459,385.7494            | 7.97           | 1.48                 | 36.59             | 0.957       | 0.005               |
| 2,459,411.8444            | 2.45           | 1.18                 | 44.79             | 0.944       | 0.004               |
| 2,459,413.763             | 6.47           | 1.03                 | 48.56             | 0.926       | 0.004               |
| 2,459,422.8348            | 3.12           | 1.09                 | 47.69             | 0.935       | 0.004               |
| 2,459,424.7787            | 3.12           | 1.9                  | 27.83             | 0.93        | 0.007               |
| 2,459,431.7429            | 8.28           | 1.0                  | 50.77             | 0.93        | 0.003               |
| 2,459,434.7056            | 0.66           | 1.25                 | 41.15             | 0.942       | 0.004               |
| 2,459,475.6962            | 8.87           | 1.33                 | 37.61             | 0.965       | 0.004               |
| 2,459,478.6923            | 2.94           | 1.02                 | 48.36             | 0.954       | 0.004               |
| 2,459,479.6223            | 0.1            | 0.85                 | 54.55             | 0.947       | 0.003               |
| 2,459,481.6797            | 6.08           | 1.57                 | 31.97             | 0.957       | 0.006               |
| 2,459,498.5889            | 1.54           | 0.84                 | 56.35             | 0.953       | 0.003               |
| 2,459,590.0301            | 6.89           | 0.86                 | 54.54             | 0.945       | 0.003               |

**Note.** We do not include the five NEID RVs with failed drift solutions.
Table 7
HPF RVs of GJ 3929

| BJD\textsubscript{TDB} (days) | RV (m s\textsuperscript{-1}) | \(\sigma\) (m s\textsuperscript{-1}) | S/N\textsubscript{18} |
|-----------------------------|-----------------------------|-----------------------------|------------------|
| 2,459.088.6272             | \(-16.43\)                  | 4.98                        | 210.68           |
| 2,459.088.6349             | \(-5.87\)                   | 4.84                        | 214.31           |
| 2,459.088.6426             | \(-3.77\)                   | 5.17                        | 202.62           |
| 2,459.222.0314             | \(-3.74\)                   | 5.48                        | 189.58           |
| 2,459.222.0392             | 1.12                        | 5.03                        | 206.82           |
| 2,459.222.0470             | \(-4.42\)                   | 5.05                        | 207.29           |
| 2,459.233.0037             | 1.42                        | 7.62                        | 135.48           |
| 2,459.233.0117             | 6.38                        | 7.79                        | 133.86           |
| 2,459.233.0195             | 12.04                       | 7.54                        | 140.42           |
| 2,459.271.8998             | 20.83                       | 6.97                        | 151.17           |
| 2,459.271.9076             | 4.8                         | 6.51                        | 162.75           |
| 2,459.271.9154             | 3.63                        | 7.21                        | 146.2            |
| 2,459.296.8246             | 9.54                        | 9.38                        | 114.91           |
| 2,459.296.8327             | 0.5                         | 7.96                        | 136.29           |
| 2,459.296.8403             | 6.47                        | 7.1                         | 147.33           |
| 2,459.649.8572             | \(-14.68\)                  | 13.81                       | 82.09            |
| 2,459.649.8652             | 8.43                        | 13.75                       | 83.03            |
| 2,459.649.8719             | 4.25                        | 25.37                       | 49.05            |

Figure 11. We include a corner plot of a few key parameters generated during our joint fit. At the top of each column is a histogram of each parameter’s values during the MCMC process, marginalized over other parameters.
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