Toi-5205b: A Jupiter transiting an M dwarf near the Convective Boundary

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(Received September 22, 2022)
Submitted to ApJ

ABSTRACT

We present the discovery of TOI-5205b, a transiting Jovian planet orbiting a solar metallicity M4V star, which was discovered using TESS photometry and then confirmed using a combination of precise radial velocities, ground-based photometry, spectra and speckle imaging. The host star TOI-5205 sits near the eponymous ‘Jao gap’, which is the transition region between partially and fully-convective M dwarfs. TOI-5205b has one of the highest mass ratio for M dwarf planets with a mass ratio of almost $0.3\%$, as it orbits a host star that is just $0.392 \pm 0.015 \, M_\odot$. Its planetary radius is $1.08 \pm 0.06 \, R_J$, while the mass is $1.08 \pm 0.06 \, M_J$. Additionally, the large size of the planet orbiting a small star results in a transit depth of $\sim 7\%$, making it one of the deepest transits of a confirmed exoplanet.

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orbiting a main-sequence star. The large transit depth makes TOI-5205b a compelling target to probe its atmospheric properties, as a means of tracing the potential formation pathways. While there have been radial velocity-only discoveries of giant planets around mid M dwarfs, this is the first transiting Jupiter with a mass measurement discovered around such a low-mass host star. The high mass of TOI-5205b stretches conventional theories of planet formation and disk scaling relations that cannot easily recreate the conditions required to form such planets.

**Keywords:** M dwarf stars, Radial Velocity, Extrasolar gaseous giant planets, Transits

1. INTRODUCTION

M dwarfs are the most common type of stars in the Galaxy (Henry et al. 2006; Reylé et al. 2021), and host a higher number of planets on average compared to FGK stars (Mulders et al. 2015). Yet due to their lower stellar (and disk) masses—and associated slower formation time scales—gas giants are expected to be infrequent around M dwarfs (Laughlin et al. 2004; Ida & Lin 2005). Recently, Burn et al. (2021) generated a synthetic planet population across a range of stellar masses and metallicities, to find that nominal scaling relations for disk properties and migration rates cannot reproduce the existence of gas giants for stellar masses \(< 0.5 \, M_\odot\).

New discoveries from the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014), have helped find numerous gas giants around M dwarfs despite their rarity (e.g.; Cañas et al. 2020; Jordán et al. 2022; Cañas et al. 2022; Kanodia et al. 2022), by observing millions of M dwarfs that are also bright enough for radial velocity (RV) mass measurements of transiting planet candidates (Stassun et al. 2018). Despite the enhanced detection signatures, the sample of confirmed transiting gas giants with precise mass measurements around M dwarfs consists of only < 10 planets. All of these transiting gas giants around M dwarfs orbit early M host stars, most of which are also metal-rich stars (Gan et al. 2022; Kanodia et al. 2022). These trends agree with the mass budget argument which necessitates massive stars (and disks) with high dust content to form the 10 \(M_\oplus\) cores (Pollack et al. 1996) in a timely manner before the disk dissipates. The alternative formation mechanism invokes disk instabilities for massive protoplanetary disks to form these gas giants more quickly (Boss 2006).

However, as we move from early M dwarfs towards the mid-M dwarfs, the internal structures of these stars change (Limber 1960). Around 0.35 \(M_\odot\), the partially convective M dwarfs (convective core + radiative envelope + convective outer envelope) transition to fully convective stars. This transition is associated with slow oscillations in stellar properties (radius, luminosity, etc.), which can potentially impact the orbital evolution of planets around these stars (VanderPlas 2018; Feiden et al. 2021). In this manuscript we present the discovery of the first\(^1\) transiting Jovian exoplanet orbiting a mid-M dwarf, which could also lie in this transition region – TOI-5205.

To characterize the host star and confirm the planetary nature of TOI-5205b, we use a combination of TESS and ground-based photometry (RBO, TMMT and APO/ARCTIC), high-contrast speckle imaging (WIYN/NESSI), precision RVs from the Habitable-zone Planet Finder spectrograph (HPF) and low-resolution optical spectra from the Low Resolution Spectrograph 2 (LRS2). In Section 2 we detail these observations, while in Section 3 we discuss the stellar parameters. Subsequently, in Section 4 we detail the data analysis, including the joint fitting of the photometry and RVs. In Section 5 we discuss the mass budget for protoplanetary disks that would be required to form such a massive planet, and place it in context of other planets around M dwarfs. Finally, we summarize our findings in Section 6.

2. OBSERVATIONS

2.1. TESS

TOI-5205 (TIC-419411415, Gaia DR3 1842656663520849024) is a mid-M dwarf observed by TESS in Sector 15 in Camera 1 from 2019 August 15 to 2019 September 11 at \(\sim 30\) minute cadence (Figure 2a), and Sector 41 in Camera 1 from 2021 July 23 to 2021 August 20 at \(\sim 10\) minute cadence (Figure 2b). The planet candidate was identified using the Quick Look Pipeline (QLP) algorithm developed by Huang et al.

\(^1\) We also note the recent discovery of the interesting TOI-1227 system, which hosts an inflated Jupiter-sized planet orbiting a very young (11 Myr) late M dwarf (0.17 \(M_\odot\)). However, this planet just has a mass upper limit of 0.5 \(M_J\), is still contracting, and will likely eventually shrink down to a super-Neptune (Mann et al. 2022).
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Figure 1. We overlay an 11 x 11 pixel footprint from TESS Sector 15 (blue grid) on a Pan-STARRS1 image from ∼2011 (Chambers et al. 2016). The TESS aperture is outlined in red and we highlight TOI-5205 with a star. Each TESS pixel is ∼21'' in size. The TESS observations of TOI-5205 are contaminated by the presence of background stars, thereby necessitating ground-based transits to constrain the true transit depth. (2020), under the ‘faint-star search’ (Kunimoto et al. 2022) with a period of ∼1.63 d.

We extract the light curve from the TESS full-frame images using using eleonor (Feinstein et al. 2019), which uses the TESScut\(^2\) service to obtain a cut-out of 31 × 31 pixels from the calibrated full-frame images centered on TOI-5205. The light curve is derived from the CORR\_FLUX values, in which eleonor uses linear regression with pixel position, measured background, and time to remove signals correlated with these parameters. The default aperture is a 2 × 1 pixel rectangle which does not include the target star. Instead, we set the aperturemode to ‘large’ in eleonor which uses a 3 × 3 pixel square aperture that includes the target star and obtains a combined differential photometric precision (CDPP) of ∼3850 and ∼4730 ppm for the two sectors respectively (Figure 2). The CDPP is formally the RMS of the photometric noise on transit timescales, and was originally defined for Kepler (Jenkins et al. 2010).

TOI-5205 is present in a crowded field with 10 stars located < 30'' away, with the closest star (TIC 1951446034) located about 4.2'' away and ∼1.7 magnitudes fainter in the TESS bandpass (Figure 1). Based on Gaia DR3 astrometry, TIC 1951446034 is not co-moving and is instead ∼30× more distant than TOI-5205 (∼2300 pc; Vallenari et al. 2022). The eleonor aperture includes many of these field stars, which present a significant source of dilution to the TESS light curve and necessitate ground-based follow up that can resolve these background stars. We discuss this dilution further in Section 4 where we include a dilution term while fitting the TESS photometry.

2.2 Ground based transit follow up

2.2.1 3.5 m ARC telescope

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\(^2\) https://mast.stsci.edu/tesscut/
We observed three transits of TOI-5205b 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) on the nights of 2022 April 22, 2022 July 3, and 2022 July 16. All these observations were conducted using quad-amplifier and fast readout mode using $4 \times 4$ on-chip binning mode to achieve a gain of $2 \text{e}^-$/ADU, a plate scale of $0.456''$/pixel, and a readout time of $2.7$ s. The relevant observation parameters are included in Table 1.

2022 April 22: We observed an ingress of TOI-5205b (Figure 3c) in SDSS $i'$ while the target was rising from an airmass of 1.41 to 1.16. To spatially resolve and separate out the background star ($\sim 4.2''$ away), we moderately defocus the star instead of using the engineered diffuser available on ARCTIC (Stefansson et al. 2017). These observations were conducted towards the end of the night, with the transit being interrupted by morning twilight. To prevent saturating the detector with the bright sky we used a short exposure time of 5 seconds. We processed the photometry using AstroImageJ (Collins et al. 2017) and the final reduction used a photometric aperture radius of 6 pixels ($2.74''$), an inner sky radius of 15 pixels ($6.8''$) and outer sky radius of 25 pixels ($11.4''$). This small innermost annulus separates TOI-5205 and the closest background star ($\sim 4.2''$). Furthermore, to verify the transit depth we also perform...
PSF photometry (instead of aperture photometry; following the routine described in Section 2.3), and obtain a comparable transit depth as that from the procedure followed above using aperture photometry.

**2022 July 3:** To check for chromaticity (Section A.4.2), we also observed TOI-5205b on 2022 July 3 (Figure 3d) in SDSS $g’$ while it was rising from an airmass of 2.35 to 1.45. Similar to the previous observation, we do not use a diffuser, and moderately defocus the star. The data was reduced using aperture photometry in AstroImageJ using the same annuli as above. We detrend this photometry with the Full Width Half Maximum (FWHM) of the target star across the night. The observation was interrupted due to increasing humidity and cloudy conditions, which forced us to stop observing shortly after transit midpoint.

**2022 July 16:** We obtained a full transit of TOI-5205b on 2022 July 16 (Figure 3g) while it was rising from an airmass of 2.69 to 1.01 in SDSS $i’$. During these observations the telescope secondary mirror had hardware issues that prevented us from using the focuser. This led to the stellar PSF changing by $\sim 2x$ during the night, which caused significant systematics in the photometry that had to be detrended out by the airmass and FWHM during the night. Due to the lack of focuser control, our PSF FWHM is much larger than on previous nights, necessitating larger aperture radii of 12, 18, and 25 pixels or 5.5, 8.2, and 11.4″ respectively. The large science aperture includes varying levels of contamination from the closest background star across the night. We therefore do not use this dataset to refine our transit depth, but only the ephemeris.

### 2.2.2. 0.6 m RBO

We observed a transit of TOI-5205b on 2022 May 10 (Figure 3e) using the 0.6m telescope at the Red Buttes Observatory (RBO) in Wyoming (Kasper et al. 2016). The RBO telescope is a f/8.43 Ritchey-Chrétien Cassegrain constructed by DFM Engineering, Inc.

The target rose from an airmass of 2.1 to 1.1. The observations were performed using the Bessell I filter with 2x2 pixel on-chip binning and exposure times of 240 s. The binned plate scale for RBO is 0.73″/pixel.

### 2.2.3. 0.3 m TMMT

We observed a transit on 2022 May 15 (Figure 3f) using the using the Three-hundred Millimeter (300mm) Telescope (TMMT; Monson et al. 2017) at Las Campanas Observatory in Chile. TMMT is a f/7.8 FRC300 from Takahashi on a German equatorial AP1600 GTO mount with an Apogee Alta U42-D09 CCD Camera, FLI ATLAS focuser, and Centerline filter wheel.

The target rose from an airmass of 4.88 at the start of observations to a minimum airmass of 1.67, and then set to an airmass of 1.69 at the end of observations. The observations were performed using Bessell I filter with 1x1 on-chip binning and exposure times of 180 s. In the 1x1 binning mode, TMMT has a gain of 1.35e/ADU, a plate scale of 0.194″/pixel, and a readout time of 6s.

Considering the dilution from the neighbouring companion, we use the RBO, TMMT, and third ARCTIC transits only to refine the ephemeris, and not to estimate the transit depth (shown in red in Figure 3).

### 2.3. Estimating JHK magnitudes using FourStar

We acquired near-infrared imaging using the FourStar Infrared Camera on the 6.5 m Magellan Baade telescope (Persson et al. 2013) during the night of 2022 July 13. The plate scale for FourStar is 0.16″ per pixel, while the seeing during observations was $\sim 0.9''$, which was useful to clearly separate the nearby background sources in a short 2.911 second exposure in the J, H and Ks filters. Each filtered observation used a 5-point dice-5 dither pattern and processed using a custom FourStar reduction package (FSRED). We used the daophot suite of programs to perform point-spread function (PSF) fitting photometry (Stetson 1987; Stetson & Harris 1988). The PSF photometry was compared to un-blended 2MASS stars in the field to determine the photometric zero-points in each filter. The final JHK magnitudes are listed in Table 3.

### 2.4. Speckle Imaging with NESSI at WIYN

To search for faint stellar companions or background sources that might have contributed to or diluted the detected transit signal, we acquired observations of TOI-5205 with the NN-EXPLORE Exoplanet Stellar Speckle Imager (NESSI; Scott et al. 2018) on the WIYN 3.5m telescope at Kitt Peak National Observatory on 5 May 2021. A sequence of 40 ms diffraction-limited images was taken in the Sloan $z'$ filter during the 9-minute observation, and these were then reconstructed following the procedures described by Howell et al. (2011). We detect no nearby sources with magnitudes brighter than $\Delta z'=4.0$ for separations $>0.3''$. The contrast curve and reconstructed speckle image are shown in Figure 4.

### 2.5. LRS2

To confirm the spectral type and stellar parameters for TOI-5205, we also observe the target using the Low Resolution Spectrograph 2 (LRS2; Lee et al. 2010; Chonis et al. 2016) on the Hobby-Eberly Telescope (HET; Ramsey et al. 1998) at McDonald Observatory, in West Texas. LRS2 is a low-resolution (R~1900) optical integral-field unit (IFU) spectrograph composed of
two arms that simultaneously observe two 6′′×12′′ fields of view separated by 100″. The blue arm (LRS2-B) consists of a pair of channels with spectral ranges of ∼3640–4670 Å and ∼4540–7000 Å, while the red arm (LRS2-R) is composed of two channels covering ∼6430–8450 Å and ∼8230–10560 Å. The LRS2-R data were obtained with a 1800 second exposure on 2022 June 11 (1.4″ seeing), while the LRS2-B data were taken on 2022 August 3 (1.6″ seeing) with the same exposure time.

The raw data were processed with Panacea\(^3\), an automated reduction pipeline for LRS2 written by G. Zeimann (Zeimann et al., in preparation). The initial processing includes bias-correction, wavelength calibration from arc lamps taken within 7 nights of the observation, fiber trace calculation from flat field exposures over ±7 nights, fiber normalization from twilight exposures over ±7 nights, fiber extraction, and an initial flux calibration from default response curves and measures of the mirror illumination as well as the the exposure throughput from guider images. After the initial reduction, we used LRS2Multi\(^4\), a python interface to perform advanced reduction steps and calibrations for Panacea products. Using LRS2Multi, we identified the target star, defined a 3.5″ aperture and used fibers beyond that aperture to build our sky model for each exposure. We subtracted the initial sky, and then constructed a principle component basis of 25 components with the residuals to further subtract sky residuals that occur from variable spectral point spread functions for each fiber. This is especially important for the LRS2-R channels. We extracted the target spectrum from the sky-subtracted frames and normalized the LRS2-B to the LRS2-R spectrum using a 100 Å window in the overlap between the two spectrographs. Noting that the default response may not be accurate enough for spectrophotometry, we reduced and calibrated standard stars from June-2021 through Aug-2022 and measured the average flux calibration correction. The response correction was smoothed by a median filter with a 250 pixel kernel and was applied to our extracted spectrum. The correction was relatively small and smoothly declining with a ∼10% positive correction in the blue and a ∼10% negative correction in the red. Finally, the telluric correction was chosen from three empirical models constructed from a dozen HR telluric standard stars. We note that the relative chromatic flux calibration should be good to ∼5% for ∼3700–10200 Å based on the standard star analysis above, with the exception of regions with strong telluric absorption and where individual channels overlap. The final LRS2 spectra was used to estimate the spectral type of the star (Figure 9, Section A).

2.6. Radial velocity follow-up with HPF

We started RV observations of TOI-5205 with HPF (Mahadevan et al. 2012, 2014) on 2022 April 20. HPF is a high resolution near-infrared (8080 – 12780 Å), fiber-fed (Kanodia et al. 2018) precision RV spectrograph with a stabilized environment (Stefansson et al. 2016). HPF is located at HET, which is a fixed-altitude telescope with a roving pupil design, and is fully queue-scheduled, where all the observations are executed by the HET resident astronomers (Shetrone et al. 2007). We correct for bias, non-linearity, cosmic rays, and calculate the slope/flux and variance images from the raw HPF data, using the algorithms described in the package HxRGproc (Ninan et al. 2018). We do not utilize simultaneous calibration using the near-infrared (NIR) Laser Frequency Comb for HPF (Metcalf et al. 2019) due to concerns about the impact of scattered calibration light given the faintness of our target. Instead, we obtain a wavelength solution for the target exposures by interpolating the wavelength solution from other LFC exposures on the night of the observations. This has been shown to enable precise wavelength calibration and drift correction with a precision of ∼30 cm s\(^{-1}\) per observation (Stefansson et al. 2020), a value much smaller than our expected per observation RV uncertainty (instrumental + photon noise) for this object of 22 m s\(^{-1}\) (in 969 s exposures, and 15 m s\(^{-1}\) in binned 30 minute exposures).

\(^{3}\) https://github.com/grzeimann/Panacea

\(^{4}\) https://github.com/grzeimann/LRS2Multi

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**Figure 4.** 5σ contrast curve for TOI-5205 observed from NESSI in the Sloan z′ filter showing no bright companions within 1.2″ from the host star. The z′ image is shown as an inset 1″ across.
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Figure 5. Left: Time series of RV observations of TOI-5205 with HPF (red). The best-fitting model derived from the joint fit to the photometry and RVs is plotted in blue, including the 16-84% confidence interval in lighter blue. The bottom panel shows the residuals after subtracting the model. Right: HPF RV observations phase folded on the best fit orbital period from the joint fit from Section 4. While we let the eccentricity float in this fit, the results are consistent with a circular orbit (Table 4).

Table 2. RVs (binned in ∼30 minute exposures) of TOI-5205. We include this table in a machine readable format along with the manuscript.

| BJD$_{TDB}$ | RV       | σ       | Instrument |
|------------|----------|---------|------------|
| (d)        | m s$^{-1}$ | m s$^{-1}$ |            |
| 2459689.97105 | -339.74  | 21.68   | HPF        |
| 2459690.96744 | 326.19   | 20.27   | HPF        |
| 2459698.96070 | 317.19   | 43.67   | HPF        |
| 2459701.93977 | -26.88   | 20.05   | HPF        |
| 2459712.90820 | -355.59  | 20.44   | HPF        |
| 2459713.90256 | 259.72   | 16.08   | HPF        |
| 2459718.89386 | 160.39   | 19.95   | HPF        |

To derive the RVs from the extracted spectra, we use the template-matching method (e.g., Anglada-Escudé & Butler 2012). This has been implemented under the SpEctrum Radial Velocity AnaLyser pipeline (SERVAL; Zechmeister et al. 2018), which has since been modified for HPF (Stefansson et al. 2020). Under this method, we first create a master template from the target star observations, and then determine the Doppler shift for each individual observation by moving it in velocity space, comparing it with the template, and minimizing the $\chi^2$ statistic. The master template is created using all of the HPF observations for TOI-5205, after masking out the telluric and sky-emission lines. The telluric regions are identified by a synthetic telluric-line mask generated from telfit (Gullikson et al. 2014), a Python wrapper to the Line-by-Line Radiative Transfer Model package (Clough et al. 2005). We use barycorrpy (Kanodia & Wright 2018) to perform the barycentric correction on the individual spectra, which is the Python implementation of the algorithms from Wright & Eastman (2014).

We obtained a total of 7 visits on this target between 2022 April 20 and 2022 May 19 (Figure 5). Each visit was divided into 2 exposures of 969 s each, where the median S/N of each HPF exposure was 40 per pixel at 1070 nm. The individual exposures were then combined by weighted averaging, with the final binned RVs being listed in Table 2.

3. STELLAR PARAMETERS

The stellar properties for TOI-5205 are crucial for understanding the system. Because it sits near this transition zone between fully and partially convective M dwarfs, the typical M dwarf scaling relations have additional scatter and often diverge. We have undertaken a thorough, multi-faceted approach to constraining the stellar properties and testing their robustness, the details of which are included in the Appendix. We summarize the main results here. From Gaia magnitudes and LRS2 spectra, we estimate a spectral subtype of M4 ± 1 for TOI-5205. From photometric relations we obtain an effective temperature of 3430 ± 54 K, solar metallicity, and a stellar radius of 0.394 ± 0.011 R$_\odot$. We then use a mass-radius relationship for M dwarfs to obtain a mass of 0.392 ± 0.015 M$_\odot$. We use H-α equivalent width measurements from LRS2 spectra and the lack of a detectable rotation period in the photometry to conclude that TOI-5205 is not an active star. Additionally, we rule out a number of false positive scenarios (such as background and hierarchical eclipsing systems) using a combination of archival images, HPF spectra, NESSI high contrast imaging, chromatic estimates of the transit depth. The procedure followed to perform this analysis and characterize the host star is explained in Appendix A.
Table 3. Summary of stellar parameters for TOI-5205

| Parameter | Description | Value | Reference |
|-----------|-------------|-------|-----------|
| **Main identifiers:** | | | |
| TOI | TESS Object of Interest | 5205 | TESS mission |
| TIC | TESS Input Catalogue | 419411415 | Stassun |
| Gaia DR3 | ... | 1842656663520849024 | Gaia DR3 |
| **Equatorial Coordinates and Proper Motion:** | | | |
| $\alpha_{2016}$ | Right Ascension (RA) | 20:55:04.96 | Gaia DR3 |
| $\delta_{2016}$ | Declination (Dec) | +24:21:39.54 | Gaia DR3 |
| $\mu_\alpha$ | Proper motion (RA, mas/yr) | 41.68 ± 0.02 | Gaia DR3 |
| $\mu_\delta$ | Proper motion (Dec, mas/yr) | 52.07 ± 0.02 | Gaia DR3 |
| $\pi$ | Parallax (mas) | 11.464 ± 0.026 | Gaia DR3 |
| $d$ | Distance in pc | 86.865 ± 0.05 | Anders |
| **Broadband photometry:** | | | |
| $G$ | $G$ mag | 14.903 ± 0.003 | Gaia DR3 |
| $g$ | PS1 g mag | 16.877 ± 0.008 | PS1 |
| $r$ | PS1 r mag | 15.694 ± 0.008 | PS1 |
| $i$ | PS1 i mag | 14.21 ± 0.01 | PS1 |
| $z$ | PS1 z mag | 13.55 ± 0.02 | PS1 |
| $y$ | PS1 y mag | 13.207 ± 0.005 | PS1 |
| $J$ | $J$ mag | 11.90 ± 0.02 | This work |
| $H$ | $H$ mag | 11.28 ± 0.02 | This work |
| $K_s$ | $K_s$ mag | 11.04 ± 0.02 | This work |
| **Derived photometry:** | | | |
| $A_G$ | Extinction in mag | 0.12 ± 0.02 | Anders |
| $M_G$ | Absolute $G$ mag | 10.09 ± 0.02 | Anders |
| **Stellar Parameters:** | | | |
| $T_{\text{eff}}$ | Effective temperature in K | 3430 ± 54 | This work |
| [Fe/H] | Metallicity | Solar | This work |
| $\log(g)^a$ | Surface gravity in cgs units | 4.84 ± 0.03 | This work |
| Sp Type$^b$ | Spectral Type | M4.0 ± 1.0 | This work |
| $R_*$ | Radius in $R_\odot$ | 0.394 ± 0.011 | This work |
| $M_*$ | Mass in $M_\odot$ | 0.392 ± 0.015 | This work |
| $L_*$ | Luminosity in $L_\odot$ | 0.0194 ± 0.0016 | This work |
| $\rho_*$ | Density in g/cm$^3$ | 9.0 ± 0.5 | This work |
| **Other Stellar Parameters:** | | | |
| $v \sin i_*$ | Rotational velocity in km/s | < 2 | This work |
| $\Delta RV$ | “Absolute” radial velocity in km/s | −65.9 ± 0.3 | This work |
| $U, V, W$ | Galactic velocities in km/s | −48.29 ± 0.12, −50.50 ± 0.27, 14.90 ± 0.07 | This work |
| $U, V, W^c$ | Galactic velocities (LSR) in km s$^{-1}$ | −37.19 ± 0.86, −38.26 ± 0.74, 22.15 ± 0.61 | This work |

References are: Stassun (Stassun et al. 2018), Gaia DR3 (Vallenari et al. 2022), PS1 (Chambers et al. 2016), Anders (Anders et al. 2022)

$^a$Using the $T_{\text{eff}}$ - $M_G$ relation from Rabus et al. (2019).

$^b$Spectral typing using relations based on Gaia colour (Kiman et al. 2019)

$^c$Using $R_*$ - $M_K$ relation from Mann et al. (2015, 2016).

$^d$Using $M_*$ - $R_*$ relation from Schweitzer et al. (2019).
3.1. Transition between partially and fully convective stars

M dwarfs with masses \( \sim 0.35 \, M_\odot \) have internal structures that transition from being partially convective (for the more massive stars) to fully convective (for the less massive ones; Limber 1958; Baraffe & Chabrier 2018). On the more massive end, the partially convective stars have convective cores and envelopes separated by a radiative zone. As these stars fuse \(^3\)He in the convective core, the \(^3\)He abundance rises with temperature when in nonequilibrium (Figure 2; Baraffe & Chabrier 2018), and causes the convective core to increase in radius, and ultimately merge with the outer convective envelope that has a lower \(^3\)He abundance (MacDonald & Gizis 2018; Feiden et al. 2021). This merger is accompanied by a sudden drop in the \(^3\)He abundance in the core, which reduces the reaction rate, causing the core to contract and separate from the envelope (Figure 5 from Feiden et al. 2021). When the core contracts, the temperature begins to rise again, producing an increase in the abundance of \(^3\)He, and an episodic cycling over Gyr timescales. Due to these repeated mergers and contractions, the abundance of the convective envelope increases until the core-envelope merger is not accompanied by a sudden decrease in abundance (and associated nuclear reaction rate). At this point, the star attains a fully convective steady state. The timescale to attain this fully convective state for stars in this transition zone depends on the mass and metallicity of the star (Kroupa & Tout 1997; Feiden et al. 2021). Unsurprisingly, these oscillations are accompanied by slow and small variations in the radius and luminosity of the star (van Saders & Pinsonneault 2012; MacDonald & Gizis 2018). This transition zone is also accompanied by an inflection in the mass-luminosity relation\(^5\) for M dwarfs as was noted by Kroupa et al. (1990) and Delfosse et al. (2000). As an aside, this feature in the mass-luminosity relation causes a local maxima in the slope, which can reproduce the additional scatter in the \( T_{\text{eff}} - R_\star \) relation for mid-M dwarfs in Mann et al. (2015).

Based on Gaia DR2, Jao et al. (2018) presented the discovery of the now eponymous gap near \( M_G \sim 10.2 \) in the Gaia colour-magnitude diagram (CMD; \( M_G \) vs. \( BP - RP \)). This is a narrow diagonal region with an under-density of stars, the width of which is a function of \( BP - RP \) colour (Jao & Feiden 2020). While the gap is associated with a 10–20\% decrement in the number of stars, it is hardly seen redwards of \( BP - RP \sim 2.7 \). Theoretical models have been used to approximately reproduce the properties of the gap in the CMD relying on the \(^3\)He instability, and attribute this under-density to the transition between partial and fully-convective M dwarfs (Feiden et al. 2021).

TOI-5205 lies near the gap based on the \( M_G, T_{\text{eff}} \) and mass estimates, and therefore sits near this transition zone between fully and partially convective M dwarfs. Theoretical evolution models that reproduce the gap in CMD space place this transition zone between 0.34–0.38 \( R_\odot \) (MacDonald & Gizis 2018; Baraffe & Chabrier 2018), which is slightly less than our radius estimate of TOI-5205 of 0.394 ± 0.011 \( R_\odot \) (Table 3). We consider that TOI-5205 could lie within this transition zone from the \(^3\)He instability, not just because of the 1-\( \sigma \) radius estimate, but also because of the systematic under-prediction of M dwarf radii by theoretical models when compared to observations. This is based on numerous studies of both single (interferometric measurements) and binary (eclipsing pairs) M dwarfs that find radius observations tend to be \( \sim 10\% \) larger than those predicted by theoretical evolutionary models (Ribas 2006; L´opez-Morales 2007; Spada et al. 2013; Feiden & Chaboyer 2014).

Due to the background companion at \( \sim 4'' \), we do not rely on the \( BP - RP \) estimates from Gaia, which are based on the prism spectra. Crevevey et al. (2022) mention that a CCD window of 3.5'\( '' \times 2.1'' \) is used while extracting the spectra, the orientation for which is quasi-random on the sky over different epochs. This could cause potential contamination from the background star in the prism spectra. Instead, if we use our estimated spectral type of M4, the relations from Kiman et al. (2019) suggest a \( BP - RP \) colour of 2.72 ± 0.13. This suggests that TOI-5205 sits near to the red extent of the ‘Jao gap’ (within 1-\( \sigma \)), and agrees with the stellar radius discussion in the previous paragraph. It is the first transiting Jovian exoplanet discovered around a mid-M dwarf, and one of the few well-characterized exoplanet hosts after LHS 1678 (Silverstein et al. 2022) that could lie near this gap. We discuss the potential implications of this association in Section 5.3.

4. JOINT FITTING OF PHOTOMETRY AND RVS

We perform a joint fit of the photometry and RVs using the python package exoplanet (Foreman-Mackey et al. 2021a) which relies on PyMC3, the Hamiltonian Monte Carlo (HMC) package (Salvatier et al. 2016). The HMC method has shown to be computationally efficient

\(^5\) Empirically this was first noticed as an increase in the stellar luminosity function for the local neighbourhood \( M_V \sim 11.5 \), which was then attributed to the combination of a smooth initial mass function, and an inflection in the mass-luminosity relationship due to this transition.
in spanning multi-dimensional parameter spaces to estimate parameter posteriors. The exoplanet package uses starry (Luger et al. 2019; Agol et al. 2020) to model the transits, and relies on the analytical models from Mandel & Agol (2002), and separate quadratic limb-darkening terms for each instrument. The limb-darkening priors use the reparameterization suggested by Kipping (2013) for uninformative sampling. We perform a joint fit with all the photometry and RVs, where we fit each phased transit (Figure 3) with separate limb-darkening coefficients. We also include a simple-white noise model in the form a jitter term for each photometry dataset. Our likelihood function for the TESS photometry includes a Gaussian Process (GP) kernel to model the quasi-periodic signal (Figure 2). This signal is discussed further in Appendix A.3.2.

We include a dilution term (Dil) in the photometric model to account for the presence of blended (or spatially unresolved) background stars in the TESS photometry. We assume that the higher spatial resolution ground-based photometry from the first two ARCTIC transits has no dilution, and therefore can be used to correct the TESS photometry. This dilution term is fit separately for individual TESS sectors, due to the different placement of the target and background stars on the camera pixels. We fit the dilution using a uniform prior from 0.1 to 1.5 to correct for potential overcompensation of the dilution term⁶. The dilution term (Dil) is used to inflate the planetary radius (Rₚ) estimate as shown below:

\[
R_{p,\text{true}} = \frac{R_{p,\text{TESS}}}{\sqrt{\text{Dil}}} \tag{1}
\]

The first two ARCTIC transits ( ingress in i', g') are used to estimate the true transit depth. The ARCTIC dataset from 2022 July 16 suffers from systematics due to wildly varying PSF FWHM from a malfunctioning focuser. This manifests as varying levels of contamination from the nearby star. We use this ARCTIC dataset along with the RBO and TMMT photometry to improve our ephemeris estimate.

Separate from the joint fit, we also use the ARCTIC dataset from 2022 July 16 to estimate the eccentricity using the photo-eccentric effect (Dawson & Johnson 2012), which relies on the transit duration and estimates and eccentricity of 0.11±0.32 0.08. This is consistent with the eccentricity obtained from the RV orbit (albeit a weaker limit), and suggests a circular orbit⁷. The precise photometry and duration estimate is then used to calculate a host star density assuming a circular orbit, to confirm the stellar parameters in Section A.2.

We model the RVs using a standard Keplerian model, allowing the eccentricity to float. We also include an RV offset and jitter term of HPF, along with a linear RV trend to account for long term drifts (both instrumental and astrophysical). We use scipy.optimize, to find the initial maximum a posteriori (MAP) parameter estimates, which uses the default BFGS algorithm (Broyden–Fletcher–Goldfarb–Shanno algorithm; Broyden 1970; Fletcher 1970; Goldfarb 1970; Shanno 1970). These parameter estimates are then used as the initial conditions for parameter estimation using “No U-Turn Sampling” (NUTS, Hoffman & Gelman 2014), implemented for the HMC sampler PyMC3, where we check for convergence using the Gelman-Rubin statistic (R ≤ 1.1; Ford 2006).

The final derived planet parameters from the joint fit are included in Table 4, with the phased RVs shown in Figure 5.

5. DISCUSSION

While gas giants are predicted to be rare and hard to form under the core-accretion framework (Laughlin et al. 2004; Ida & Lin 2005), they do exist around M dwarfs, as has been evinced by recent discoveries from transiting surveys⁸, especially TESS (Johnson et al. 2012; Hartman et al. 2015; Bayliss et al. 2018; Cañas et al. 2020; Jordán et al. 2022; Cañas et al. 2022; Kanodia et al. 2022). Due to the heterogeneous nature of this transiting sample, it is not straightforward to estimate the occurrence rate of such planets and compare them to population synthesis models or protoplanetary disk surveys.

So far all the discoveries of these transiting giant planets have been around early M dwarfs (M0 – M2), which are consistent with the simulations from Burn et al. (2021) that find that gas giants do not form for host stars < 0.5 M⊙. TOI-5205b defies this trend, as it orbits a mid-M dwarf host and has one of the largest mass

⁶ While this is not a problem for the eleonor reduction, occasionally the SPOC data can over-correct for dilution as shown for TOI-824 (Burt et al. 2020), especially in crowded fields.

⁷ This is unsurprising for a giant planet at such a short orbital period, which would have a circularization time scale of ~ Myr.

⁸ In addition to transit discoveries, there have been RV-only detections of gas giants around M dwarfs, e.g., Johnson et al. (2010); Wittamer et al. (2014); Astudillo-Defru et al. (2017); Trifonov et al. (2018); Feng et al. (2020); Morales et al. (2019); Quirrenbach et al. (2022). Some of these RV detected planets are around mid and late M dwarfs, but typically at longer orbital periods than the transiting planets (Schlecker et al. 2022).
### Table 4. Derived Parameters for the TOI-5205 System.

| Parameter                  | Units       | Value$^a$ |
|----------------------------|-------------|-----------|
| Orbital Period             | $P$ (days)  | 1.630757±0.000001 |
| Eccentricity               | $e$         | 0.020±0.010 |
| Argument of Periastron     | $\omega$ (radians) | -0.74±0.25 |
| Semi-amplitude Velocity    | $K$ (m s$^{-1}$) | 346±14 |
| Systemic Velocity          | $\gamma_{HPF}$ (m s$^{-1}$) | -28±11 |
| RV trend                   | $dv/dt$ (m s$^{-1}$ yr$^{-1}$) | 0.05±0.08 |
| RV jitter                  | $\sigma_{HPF}$ (m s$^{-1}$) | 14.7±16.6 |
| Transit Midpoint           | $T_C$ (BJD$_{TDB}$) | 2459443.4717±0.00019 |
| Scaled Radius              | $R_p/R_*$  | 0.2720±0.0043 |
| Scaled Semi-major Axis     | $a/R_*$   | 10.94±0.22 |
| Orbital Inclination        | $i$ (degrees) | 88.21±0.24 |
| Transit Duration           | $T_{14}$ (days) | 0.0583±0.0011 |
| Photometric Jitter$^c$     | $\sigma_{TESS\;S15}$ (ppm) | 2985±85 |
|                           | $\sigma_{TESS\;S41}$ (ppm) | 4241±50 |
|                           | $\sigma_{ARCTIC\;20220422}$ (ppm) | 5291±160 |
|                           | $\sigma_{RBO\;20220510}$ (ppm) | 865±947 |
|                           | $\sigma_{TMMT\;20220515}$ (ppm) | 15759±1364 |
|                           | $\sigma_{ARCTIC\;20220703}$ (ppm) | 3948±472 |
|                           | $\sigma_{ARCTIC\;20220717}$ (ppm) | 2716±120 |
| Dilution$^d$               | $D_{TESS\;S15}$ | 0.234±0.012 |
|                           | $D_{TESS\;S41}$ | 0.259±0.008 |
| Planetary Parameters       |             |           |
| Mass                       | $M_p$ (M$_\oplus$) | 343±18 |
|                           | $M_p$ (M$_J$) | 1.08±0.06 |
| Radius                     | $R_p$ (R$_\oplus$) | 11.6±0.3 |
|                           | $R_p$ (R$_J$) | 1.03±0.03 |
| Density                    | $\rho_p$ (g cm$^{-3}$) | 1.21±0.11 |
| Semi-major Axis            | $a$ (AU)   | 0.0199±0.0002 |
| Average Incident Flux$^g$  | $\langle F \rangle$ (10$^2$ W/m$^2$) | 0.67±0.06 |
| Planetary Insolation       | $S$ (S$_\odot$) | 49±4 |
| Equilibrium Temperature$^h$| $T_{eq}$ (K) | 737±15 |

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$a$ The reported values refer to the 16-50-84% percentile of the posteriors.

$b$ In addition to the Absolute RV from Table 3.

$c$ Jitter (per observation) added in quadrature to photometric instrument error.

$d$ Where $u_1 + u_2 < 1$, and $u_1 > 0$ according to Kipping (2013).

$e$ Dilution due to presence of background stars in TESS aperture, not accounted for in the eleanor flux.

$f$ We treat the dilution terms for RBO 20220510, TMMT 20220515, and ARCTIC 20220717 as nuisance parameters, since those datasets are used only to refine the ephemeris.

$g$ We use a Solar flux constant $= 1360.8$ W/m$^2$, to convert insolation to incident flux.

$h$ We assume the planet to be a black body with zero albedo and perfect energy redistribution to estimate the equilibrium temperature.
Figure 6. a) We show TOI-5205b (circled in green) in a mass-radius plane alongside other M dwarf planets (coloured by the stellar mass). We also include planets around FGK stars in the background, along with density contours for 0.3, 1, 3 g cm$^{-3}$. b) The radius-period plane is shown for the same sample of planets, but coloured by the equilibrium temperature. c) Planet-to-star mass ratio vs orbital period for planets with true mass (transiting; circle) and minimum mass (RV only; triangle) measurements. The planets are colour coded by the equilibrium temperature, the M dwarf planets are solid, whereas those orbiting FGK stars are shown in the background. TOI-5205b (circled in green) has the highest mass ratio for transiting M dwarf planets. The highest mass ratio M dwarf planet is GJ 3512 b at $\sim 200$ d (Morales et al. 2019).
ratio\(^9\) for M dwarf planets at 0.27%. It is a Jovian sized planet (Figure 6a) with an orbital period of \(\sim 1.6\) days (Figure 6b), and joins the current sample of \(\sim 10\) known transiting gas giants around M dwarfs. TOI-5205b is the first gas giant known to transit a mid-M dwarf, which also results in a transit depth \(\delta\) of \(\sim 7\%\). While we do not have precise constraints on the metallicity of the host star, photometric relations estimates suggest a host star metallicity close to solar ([Fe/H] = 0; Section A).

5.1. Planet Formation

In this section, we present a simple mass budget argument\(^10\) to estimate the minimum mass of the primordial protoplanetary disk in which this giant planet formed under the core-accretion paradigm, where models suggest that runaway gaseous accretion should initiate once a protoplanet has reached a solid core mass of \(\sim 10\) \(M_{\oplus}\) (Pollack et al. 1996). We calculate the heavy-element mass for TOI-5205b using the relations from Thorngren et al. (2016) to be \(\sim 60\) \(M_{\oplus}\) (or roughly 10x more metal-enriched than the host star), but also note that there is considerable scatter in their sample that can perhaps be attributed to the vagaries in planet formation and evolution. There are additional uncertainties due to the unknown heavy element composition, and uncertainties in the equation of state used for their model. As it stands, these models predict \(\sim 10\) \(M_{\oplus}\) of heavy elements locked up in the central core, with the rest (60 - 10 \(\sim 50\) \(M_{\oplus}\)) diffused in the H/He envelope.

The dust mass of the disk is typically estimated for mm sized dust particles in Class II disks using flux continuum measurements at \(\sim 850\) \(\mu\)m, which is then used to calculate the mass assuming a blackbody with typical temperatures of 20 K. We decompose the total dust mass in the disk as a product of the disk mass ratio and gas-to-dust ratio (Figure 7). The canonical disk mass scaling (ratio of disk to stellar mass) assumed is \(\sim 0.3\%\) based on a study of the Taurus region by Andrews et al. (2013), along with the gas-to-dust ratio of 70 – 100 ranging from solar to the interstellar medium (ISM; Bohlin et al. 1978). Following these scaling relations suggests a total of 4–5 \(M_{\oplus}\) of dust available for planet formation for TOI-5205, which would be insufficient to form a 10 \(M_{\oplus}\) core to start runaway gaseous accretion even with 100% planet formation efficiency\(^11\). Therefore in subsequent sections we discuss more realistic scaling values based on recent studies.

5.1.1. Disk mass scaling

Pascucci et al. (2016) suggest that the \(M_{\text{dust}} / M_{\ast}\) relation becomes steeper with age, and more so for low mass stars. If so, these traditional relations would likely underestimate the initial mass of M dwarf disks. Results from Ansdell et al. (2017) agree with this, where they find that (for a given stellar mass) the mass of dust present in a disk tends to decrease with age\(^12\). They also note a large dispersion in these scaling relations that are not attributed to measurement systematics, but rather intrinsic astrophysical variation (or diversity) in disk properties within populations.

Observations and simulations based on the Orion Nebula Cluster show that for massive optically-thick disks with fluxes > 10 mJy (Figure 13 from Eisner et al. 2018), the typical continuum flux-disk mass relations tends to under-predict the disk mass by up to an order-of-magnitude. However invoking disk stability arguments, the underestimate is probably less than that because depending on the surface density profile, disks can be \(\sim 10\%\) of the stellar mass before they are unstable. These massive optically thick disks (Flux \(\sim 10\) mJy, \(M_{\text{dust}} \sim 10 \sim 100\) \(M_{\oplus}\)) are seen around M dwarfs as well (Figure 10; Eisner et al. 2018); which is consistent with the typical scatter of \(\sim 1\) dex seen in these (\(M_{\text{disk}}/M_{\ast}\)) relations.

Studies suggest that planet formation is already underway for Class II disks (Greaves & Rice 2010; Najita & Kenyon 2014), and indeed that the primordial disk mass available for giant planet formation early in the disk lifetime (0.1 – 1 Myr) is likely much larger than than the masses measured for Class II disks, also evinced by measurements of the more massive Class I disks (Andrews & Williams 2005; Vorobyov 2011). Additionally, a lot of the solid mass for Class II disks can be locked up in planetesimals and planets, which the mm flux measurements would be insensitive to.

\(^9\) GJ 3512b has a larger mass ratio at 0.37%, but it does not transit and hence only a lower limit of its mass is available (Morales et al. 2019). Therefore only a lower limit of the mass is available.

\(^10\) Schlecker et al. (2022) discuss some of the other challenges in the formation of gas giants around low mass M dwarfs under the core accretion paradigm, beyond the mass budget discussed here.

\(^11\) In this section we refer to planet formation efficiency as the fraction of the total dust mass of the disk that is used to form TOI-5205b.

\(^12\) They show this using a comparative analysis of disks in five young star forming regions spanning ages from 1–2 to 5–10 Myr and fitting separate scaling relations to each and then comparing the slopes, thereby corroborating the results from Pascucci et al. (2016).
Figure 7. The mass budget of the dust present in the disk as a function of disk mass ratio (disk to star; y axis), and the gas-to-dust ratio (x axis). The black line is the contour corresponding to the estimated heavy-element mass for TOI-5205b of $\sim 60 M_\oplus$ based on relations from Thorngren et al. (2016). This indicates the disk properties required to form the planet even at 100% formation efficiency, i.e. if all the dust present in the disk could accumulate in TOI-5205b. A lower formation efficiency would imply an even larger disk dust mass. The red line shows the dust mass for a disk orbiting a mid-M dwarf as massive as TOI-5205 using the scaling relations from Ansdell et al. (2016) in the young (1 – 3 Myr) Lupus complex, while the region next to it shows the 1 $\sigma$ uncertainty. We also include a vertical line to show solar metallicity of $Z_\odot = 0.014$, or a gas-to-dust ratio of $\sim 71$. The heavy-element core for TOI-5205b (black line) is MUCH more massive than expected from scaling relations based on the Lupus complex.

Given the significant scatter that exists in these scaling relations$^{13}$, and the various factors that can be responsible for underestimating the primordial dust mass in disks as mentioned above, it is not entirely unreasonable to postulate a more massive disk around TOI-5205 than that predicted by the standard 0.3 % $M_{\text{disk}}/M_*$ scaling ratios for Class II disks. Indeed Andrews et al. (2013) do discuss the presence of outliers in their sample of disks in Taurus, which are anomalously massive at $\sim 10\%$ total disk-to-stellar mass.

5.1.2. Gas-to-dust ratio

While the correlation between Jovian planet occurrence and metallicity of the host star has been well established (Gonzalez 1997; Santos et al. 2001; Fischer & Valenti 2005; Ghezzi et al. 2010; Sousa et al. 2011), there is still considerable uncertainty in the gas-to-dust (inverse of metallicity) assumed in planet formation models. This is typically estimated by measuring the mass of the gas in the disk using CO lines, which is then

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$^{13}$ Both in observations pre-ALMA (in Taurus; Andrews et al. 2013), and then confirmed with ALMA — Lupus, (Ansdell et al. 2016), Chameleon I (Pascucci et al. 2016), Upper Sco (Barenfeld et al. 2016), and $\sigma$ Orionis (Ansdell et al. 2017) among others.
combined with dust mass measurements from mm continuum to obtain the gas-to-dust mass ratio.

The typical ISM estimate for the gas-to-dust ratio is \( \sim 100 \) (Bohlin et al. 1978), but a small sample of Taurus disks revealed a mean value closer to \( \sim 16 \) (Williams & Best 2014). In fact, Ausdell et al. (2016) find that for disks in Lupus, the ratio might even be closer to 10, which was then corroborated by Miotello et al. (2017). While these CO measurements could indicate a low gas-to-dust ratio, they could also be due to the selective loss of CO gas in the disk due to CO condensation, which would not apply to \( \text{H}_2 \). The latter was supported by Rosotti et al. (2017), who showed that the accretion rate versus disk mass relationship is consistent when the mass of the disk is estimated using a gas-to-dust ratio of \( \sim 100 \). Based on this they suggest that this ratio cannot be lower than by a factor of 2 from the canonical ISM value of 100. Most recently, Anderson et al. (2022) find that gas mass measurements of CO isotopologues extrapolated to \( \text{H}_2 \) can have significant uncertainties, often by many orders of magnitude, thereby severely underestimating the gas-to-dust ratio. All of this is to suggest that while the intrinsic gas-to-dust ratio for protoplanetary disks is hard to constrain, it should be within a factor of few of 100.

For a solar metallicity \( Z_{\odot} = 0.014 \) disk (gas-to-dust ratio of \( \sim 70 \)), we would require a disk that is about 3% total disk-to-stellar mass, to have the \( \sim 60 \, M_{\oplus} \) of heavy-elements estimated for TOI-5205b. While a detailed planet formation simulation is beyond the scope of this paper, Lin et al. (2018) suggest a maximum efficiency for giant planet formation under pebble accretion of \( \sim 10\% \), which would require a disk that is \( \sim 30\% \) in host star mass\(^{14}\).

5.1.3. Disk lifetimes (increasing efficiency of planet formation)

Apart from the low disk masses, the other issue with giant planet formation around M dwarfs is the longer orbital timescales (at a given separation) due to the lower host star mass. This results in a much slower growth rate for planetesimal formation (\( \sim 1 \) Myr), which must succeed in forming a massive enough core to initiate runaway accretion before the disk disperses.

The typical disk lifetime inferred by studying the incidence of disks in cluster of different ages is \( \sim 3 \) Myr, with an upper bound of \( \sim 10 \) Myr (Ribas et al. 2014). It has also been established that this lifetime scales with stellar mass, and while the disks around M dwarfs typically last longer (Carpenter et al. 2006), they still disperse within \( \sim 20 \) Myr (Pecaut & Mamajek 2016). Recently the discovery of very long-lived (\( \gtrsim 20 \) Myr), so called ‘Peter Pan’ disks has been reported around M dwarfs (Lee et al. 2020; Silverberg et al. 2020; Gaidos et al. 2022). Models suggest that the existence of these disks requires relatively high disk masses and very low external photoevaporation, similar to those found at the periphery of star-forming regions (Coleman & Haworth 2020). These longer-lived massive disks would offer more time for the formation of solid cores massive enough to initiate runaway gas accretion under the slower core-accretion paradigm.

5.1.4. Disk instability scenario

Previous studies use the positive correlation for giant planet occurrence with stellar mass and metallicity (Gonzalez 1997; Santos et al. 2001; Fischer & Valenti 2005; Ghezzi et al. 2010; Sousa et al. 2011) as evidence of core-accretion (Ida & Lin 2005; Thorngren et al. 2016; Ghezzi et al. 2018). However, this correlation with metallicity is only seen for \( M_p \lesssim 4 \, M_J \); while stars hosting more massive planets are on average closer to solar metallicity, or even metal-poor (Santos et al. 2017; Schlaufman 2018; Maldonado et al. 2019). This suggests a dichotomy in the formation mechanism centered at \( \sim 4 \, M_J \), with less massive objects classified as planets formed through core accretion, while more massive planets form through disk instability, similar to brown dwarfs and low-mass stars (Schlaufman 2018).

Even though the mass of TOI-5205b is \( < 4 \, M_J \), due to the large mass ratio for TOI-5205b we consider the disk instability scenario. Interestingly enough, this \( \sim 10\% \) disk mass regime discussed in the previous section is also the typical disk mass required to enable giant planet formation under the disk instability scenario either close-in (Boss 2006) or farther out (Boss 2011). Disk instability has been proposed as a faster (\( \sim 10^3 \) yr) alternative to the slower (\( \sim 1 \) Myr) core-accretion formation scenario for M dwarfs where the lower host star mass translates to longer orbital timescales at a given distance from the star (Laughlin et al. 2004). Under this mechanism a massive 10-20\% disk would have to be marginally unstable to start breaking up into lumps of gas and dust. These instabilities typically also require cooler temperatures, which warrants the formation of the planet at large orbital separations (ex-situ formation\(^{15}\)), followed

\(^{14}\) Conversely, if the actual heavy-element mass for TOI-5205b is lower than predicted by Thorngren et al. (2016) model, the required disk mass would scale down by the same factor.

\(^{15}\) See Helled et al. (2014); Dawson & Johnson (2018); Helled & Morbidelli (2021) for comprehensive reviews on giant planet formation.
by subsequent inward migration through disk migration (Kley & Nelson 2012) or high eccentricity excitation (Beaugé & Nesvorný 2012). Given the scope of current models, we cannot rule out disk instability as a potential formation mechanism for TOI-5205b.

Overall, we see two possible ways to explain the existence of this planet given current theories of planet formation – i) A ∼ 60 $M_\oplus$ solid heavy-element core: which would require a disk that is ∼ 3%–30% the mass of the host star (for 100% and 10% formation efficiency respectively), under which case both core-accretion and disk instability scenarios should be possible. ii) The interior models are biased and over-predict the solid core mass. Under the canonical core accretion scenario, this would suggest a core of 10 $M_\oplus$, and would need a disk that is ∼ 0.5% – 5% the mass of the host star (for 100% and 10% formation efficiency respectively).

5.2. Atmospheric characterization

Characterizing the atmosphere of TOI-5205b may provide clues needed to differentiate between formation mechanisms. Did it form via disk instability or core accretion, furthermore, under core accretion, did it form in-situ or farther out and then migrate inwards through disk or disk-free migration?

Assuming formation via core accretion, TOI-5205b is expected to have a super-stellar metallicity if it underwent disk migration, or either sub- or super-stellar metallicity if it underwent disk-free migration (Madhusudhan et al. 2014). If TOI-5205b is metal-enriched, and therefore likely formed via core accretion, the second question surrounds whether TOI-5205b formed in-situ or further out before migrating inwards. Multiple studies suggest that C/O ratios could provide some indication as to whether a planet formed inside or beyond various disk snowlines (e.g. Oberg et al. 2011; Madhusudhan et al. 2014). As molecules “freeze-out,” they remove those elements from the overall gas composition. When water freezes for example, it removes some of the overall oxygen from the gas increasing the C/O ratio beyond the water-ice line (Oberg et al. 2011). Similarly, Knierim et al. (2022) show that the ratio of refractory and volatile elements can depend on the migration history of the planet. While Dash et al. (2022) emphasizes there are degeneracies and assumptions that must be considered, such as post-formation bombardment, or sublimation of the core, C/O ratios may provide the first insights into where TOI-5205b originally formed.

Under the disk instability hypothesis, TOI-5205b would have formed from a collapse of a massive region of the protoplanetary disk prior to migrating inwards. Therefore, from a first approximation, it is assumed that its atmosphere should reflect that of the protoplanetary disk and its host star - i.e. should have the same metallicity and abundances as TOI-5205 (e.g. Helled & Bodenheimer 2010; Helled & Lunine 2014). However, recent works demonstrate that this initial picture may become complicated both by location of the initial collapse (Madhusudhan et al. 2014) or size of particles/objects accreted during this process (Helled et al. 2014). Hobbs et al. (2022) suggests that comparing abundances of various molecules, notably methane, carbon monoxide/dioxide and hydrogen cyanide, may be a useful method for distinguishing the two formation pathways. Even with these complications, discovering a solar or near-solar metallicity atmosphere (heavy element abundance of ∼1%) for TOI-5205b would hint at the potential for gravitational instability. In this scenario, the heavy-element mass estimated using the Thorngren et al. (2016) sample would be incorrect for TOI-5205b.

TOI-5205b is a compelling target scientifically, and with its 7% transit depth, it is also an object easily accessible with JWST observations. Even though it is a relatively cool (740 K) Jovian world, it still possesses a large Transmission Spectroscopy Metric (TSM) of ∼ 100 placing it in the second quartile of their giant planet sample (assuming a scale factor of 1.15) from Kempton et al. (2018). TOI-5205b also has one of the largest Emission Spectroscopy Metric (ESM) of any planet at ∼ 150, in part due to its $R_p/R_*$ and also its bright mid-M dwarf host (Figure 8).

We calculate model transmission and thermal emission spectra assuming 1×, 10×, and 100× solar metallicity. We then simulate JWST NIRSpec PRISM data using PandExo (Batalha et al. 2017) corresponding to the 1× solar cases, assuming two transits/secondary eclipses, respectively. The transmission spectra are calculated using Exo-Transit (Kempton et al. 2017). We predict that NIRSpec should significantly distinguish between each of the model transmission spectra, as a result of the smaller spectral feature amplitudes for the 100× Solar metallicity model and the onset of a CO2 feature in the 4–5 μm range between the 1× and 10× solar metallicity models. The model thermal emission spectra are generated using the self-consistent atmospheric model GENESIS (Gandhi & Madhusudhan 2017, 2019; Piette et al. 2020; Piette & Madhusudhan 2020). GENESIS calculates full line-by-line radiative transfer under the assumptions of radiative-convective equilibrium, hydrostatic equilibrium, and thermochemical equilibrium. Here, chemical equilibrium abundances are calculated using the analytic prescription of Heng & Tsai (2016). As shown in Figure 8, the 1×, 10×, and 100× Solar metallicity models are easily distinguishable in the
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Figure 8. a-b) We show the TSM and ESM for TOI-5205b with respect to other M dwarf gas giants, \( R_p > 8 \, R_{\oplus} \) (solid), while those orbiting FGK stars are in the background. TOI-5205b (circled in green) has a high TSM (\( \sim 100 \)) and ESM (\( \sim 150 \)) that make it an excellent target for atmospheric characterization to estimate the chemical composition of the planet.

c-d) Simulated transmission and thermal emission spectra for three different atmospheric metallicities, along with PandExo predictions for JWST NIRSPEC PRISM spectra for two transits and eclipses, respectively.

\( \sim 4-5 \, \mu m \) range due to the onset of an increasingly deep \( \text{CO}_2 \) feature as metallicity increases. Atmospheric characterization of TOI-5205b with both transmission and thermal emission spectroscopy is therefore a promising avenue to characterize its atmospheric metallicity and C/O ratio, and to place constraints on its formation and evolution.

5.3. Implications of association with ‘Jao gap’

As discussed in Section 3.1, the stellar properties of TOI-5205 indicate that it could lie in the transition region between partially and fully convective M dwarfs, i.e. the so-called ‘Jao gap’ (Jao et al. 2018), thereby being the second transiting planetary system to do so, after LHS 1678 (Silverstein et al. 2022).

Mid-M dwarfs in this region show small (up to \( \sim 10\% \)) and slow oscillations in radius and luminosity (Baraffe & Chabrier 2018; MacDonald & Gizis 2018; Feiden et al. 2021), the time-scale of which can vary with stellar mass, and is typically \( \sim \) Gyr. These variations in the internal structure of the host star change its mass distribution, its angular momentum, and hence rotation rate. Mullan & Houdebine (2020) note a transition between dynamo modes at similar spectral types, which corresponds to the onset of fully convective M dwarfs, and is accompanied by a drop in the strength of chromospheric emission. This could potentially affect the equilibrium temperature of the planet and impact its climate.

It is expected that short period exoplanets such as TOI-5205b should quickly (\( \sim \) Myr) circularize due to the tidal dissipation of energy within the planet (Goldreich & Soter 1966; Jackson et al. 2008). Furthermore, large planets around small stars in close-in orbits are expected to be in aligned orbits (see Figure 22 in Albrecht et al. 2022). If TOI-5205 b is in a well-aligned, circular orbit, the orbital decay could be governed by the excitation of
tides within the star. Ma & Fuller (2021) show that at short orbital periods the planet can lock into resonance with the tidally excited stellar gravity modes, especially for stars with convective cores. Not only do these modes change in frequency over time due to the evolution of the star, but also the tidal quality factor changes with age for different stellar types (Barker 2020). While the process of evolution for M dwarfs across the main-sequence is a slow process (Laughlin et al. 1997), the small and slow oscillations in the internal structure for TOI-5205 could play a role in the orbital properties of the planet.

We also note that the large transit depth makes it suitable for high-resolution transmission spectroscopy from the ground (as evinced by the large TSM and ESM; Section 5.2), similar to that performed for hot Jupiters. Given that we have a highly precise estimate of the RV semi-amplitude of the star, transmission spectroscopy could potentially be used to estimate the RV semi-amplitude of the planet (de Kok et al. 2013), at which point the system could be treated as a double-lined eclipsing binary to estimate model independent masses for both the planet and star (Russell 1912). This would offer an exciting opportunity to measure a model-independent mass for a mid-M dwarf near the ‘Jao gap’. The large mass ratio of the planet (∼0.3%) necessitates a disk that is ∼10% as massive as the host star, thereby stretching our current understanding of protoplanetary disks around M dwarfs. The typical scaling relations used to estimate disk properties are hard-pressed to reproduce the primordial disks that are massive enough to form such a planet. However there is significant scatter in disk dust mass measurements and scaling relations, which could still explain such massive planets around mid-M dwarfs.

TOI-5205b has a large transit depth of 7%, which makes it an excellent candidate for transmission and emission spectroscopy, both from the ground (high-resolution) and space (JWST). Atmospheric characterization could help constrain the metallicity of the planet and could offer clues about their formation history.

The large sample of M dwarfs being observed by TESS is already improving our understanding of planet formation around M dwarfs. While the first few discoveries were limited to the early M dwarfs, we are now starting to find that it is indeed possible to form these gas giants around mid-M dwarfs. As we go from a sample of these planets around solar-type stars to mid-M dwarfs, there is a unique opportunity to study planet formation at its extremes, spanning more than a 2x range in stellar mass, and 100x in luminosity!

APPENDIX

A. STELLAR CHARACTERIZATION

A.1. Spectral classification

- Template Matching (pyHammer): We classify the spectral sub-type for TOI-5205 with the LRS2 spectra using pyHammer (Roulston et al. 2020), which is based on The Hammer (Covey et al. 2007), and uses an empirical
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Figure 9. Comparing the LRS2 spectra with the empirical templates from pyHammer. In red we show the observed LRS2 spectra after response and telluric correction, while empirical templates from M3 – M6 are shown in different colours, while the vertical lines in the background denote the regions of significant telluric absorption. The increased noise (∼5%) in the measured spectrum around ∼9000 Å can be attributed to the telluric correction. We include the residuals in the lower plot and also the summed square errors (SSE) in the legend showing that the M5 template is the preferred one. We also plot the normalized fluxes based on the photometric magnitudes from PS1 (optical) and the J magnitude from FourStar with the horizontal errorbar depicting the bandpass. We do not include the H, K magnitudes from FourStar in this plot to focus on the optical spectra and template comparison.

- Spectral ratios: We also use the spectral ratios defined by Kirkpatrick et al. (1991) surrounding CaH, Ti I, Na I and Ca II, to obtain a spectral type of M3 – M4.5 based on the LRS2 spectra.
- Photometry relations: We also use relations from Kiman et al. (2019) to obtain a spectral type using the absolute G magnitude, which suggests an ∼M3.5 spectral type. Using the G – J relation from Figure 13 in Cifuentes et al. (2020) corroborates the M4 spectral type estimate for the given G – J colour of ∼3.

Considering the results from the template matching (M5) and colour relations, we adopt a spectral classification of M4.0 to which we ascribe an error of 1.0 sub-type.

A.2. Using Photometric Relations

We obtain $M_G$ of 10.09$^{+0.01}_{-0.03}$ from Anders et al. (2022), which takes into account extinction using estimates from multiple photometric surveys. Using Equation 11 from Rabus et al. (2019), we estimate a $T_{\text{eff}}$ from $M_G$ of 3430 K with an error of 54 K, where we propagate the error in $M_G$ to $T_{\text{eff}}$ and combining in quadrature with the scatter in the polynomial fit. We do note that our $T_{\text{eff}}$ estimate is on the hotter end of that expected for an M4 spectral type, however this is not too surprising given the uncertainty of 1 spectral type, and the considerable scatter in theoretical models for mid-type M dwarfs.

We use the empirically calibrated polynomial relations derived by Mann et al. (2015) to estimate the stellar radius. Given the large scatter in the $T_{\text{eff}}$ vs stellar radius relation (Figure 9 from Mann et al. 2015), we use the absolute $K_s$ magnitude – stellar radius relation instead, and adopt an error of ∼3% on the stellar radius based on their cross-validation results. The full transit obtained for TOI-5205b from the 3.5 m APO telescope on 2022 July 16 is used to obtain a density constraint on the star of 8.8 ± 0.4 g cm$^{-3}$, which is also consistent with the ∼0.39 $R_\odot$ obtained above. We also use $M_G$ along with the bolometric calculator$^{17}$ for the given $T_{\text{eff}}$ (Creevey et al. 2022), to obtain the

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$^{16}$ The empirical template is derived from the MaNGA Stellar Library (MaStar), which consists of well-calibrated optical spectra from SDSS IV (Yan et al. 2019). The relative calibration for this template is accurate to < 5%.

$^{17}$ https://www.cosmos.esa.int/web/gaia/dr3-bolometric-correction-tool
bolometric magnitude, luminosity, and subsequently a stellar radius of \( \sim 0.37 \pm 0.02 \, R_\odot \), which is consistent with our radius estimate using the relations from Mann et al. (2015).

Finally, we use the Stefan-Boltzmann law to obtain a stellar luminosity, and the empirically calibrated M-R relationship for main-sequence M dwarfs (Equation 6; Schweitzer et al. 2019) to obtain a stellar mass (Table 3). We also verify the stellar mass using photometric relations from Henry & McCarthy (1993); Delfosse et al. (2000); Benedict et al. (2016); Mann et al. (2019)\(^\text{18} \) and consistently obtain similar results to within 1-\( \sigma \).

Photometric relations from Bonfils et al. (2005), Schlaufman & Laughlin (2010) and Neves et al. (2012) give a metallicity of 0.02, 0.19 and 0.09 dex respectively, along with a typical uncertainty of 0.2 dex. Maldonado et al. (2020) note that photometric metallicities have systematically lower values than corresponding spectroscopic techniques. However due to the sparse sampling of the SpecMatch-Emp library in T\(_{\text{eff}}\)-[Fe/H] plane for mid-M dwarfs (Yee et al. 2016), and the potential covariance between these two quantities we do not have reliable metallicity estimates from SpecMatch-Emp for this mid-M dwarf. Instead, we adopt a qualitative estimate of solar metallicity for TOI-5205 (Table 3). See Passegger et al. (2022) for a detailed discussion of the complexities in metallicity determination for M dwarfs.

\[ \log(L_{bol}) = -\frac{\chi}{1 - \frac{F(\lambda)}{F_{pc}}} \]  

where \( \lambda_1 = 6560 \, \text{Å} \) and \( \lambda_2 = 6566 \, \text{Å} \). \( F_{pc} \) is the average of the median flux in the pseudo-continuum in the ranges from 6545 – 6559 Å, and 6567 – 6580 Å after removing a linear slope fit to that range seen in the pseudo-continuum surrounding the H\( \alpha \) line for late M dwarfs. In doing so, we measure a pEW(H\( \alpha \)) using the following equation:

\[ \text{pEW}(H\alpha) = \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{F(\lambda)}{F_{pc}} \right) d\lambda \]  

where we integrate over the limit from \( \lambda_1 = 6560 \, \text{Å} \) and \( \lambda_2 = 6566 \, \text{Å} \). \( F_{pc} \) is the average of the median flux in the pseudo-continuum in the ranges from 6545 – 6559 Å, and 6567 – 6580 Å after removing a linear slope fit to that range seen in the pseudo-continuum surrounding the H\( \alpha \) line for late M dwarfs. In doing so, we measure a pEW(H\( \alpha \)) using the statistical uncertainty accounting for the S/N of the observed spectrum.

To estimate \( \log(L_{H\alpha}/L_{bol}) \), we use the following equation,

\[ \log\left( \frac{L_{H\alpha}}{L_{bol}} \right) = \log \chi + \log(-\text{pEW}(H\alpha)) \]  

where \( \log \chi \) is the ratio of the flux in the continuum near H\( \alpha \) to the bolometric flux. We use estimate \( \chi \) following the methodology in Reiners & Basri (2008), which gives \( \chi \) as a function of stellar effective temperature for M dwarfs stars. In doing so, we obtain a \( \log(\chi) = -4.3 \), and \( \log(L_{H\alpha}/L_{bol}) = -4.4 \). From the sample of \( \log(L_{H\alpha}/L_{bol}) \) values in West et al. (2015), this value for TOI-5205 is suggestive of an M4 star that is not highly active.

A.3.2. Rotation Period Estimates

In Section 4, we describe the fitting of the TESS photometry from sectors 15 and 41 with separate stellar rotation kernels that return a rotation period of \( 3.7^{+1.3}_{-1.1} \) days from sector 15 and \( 4.3 \pm 0.6 \) days from sector 41. The kernel consists of two simple harmonic oscillator terms – one at the rotation period, with the second one at half the period. This observed period is also seen as a peak in a generalized Lomb Scargle (GLS) periodogram (Lomb 1976; Scargle 1982; Zechmeister & Kürster 2009) on the sector 41 photometry (after masking the transits of TOI-5205b) using its astropy implementation, and find a significant peak (20% False Alarm Probability) at \( \sim 4.4 \) days.

However, similar to TOI-3757 b (Kanodia et al. 2022), we see that this periodic signal is likely an artifact from the photometry reduction of the FFI. The signal is seen a few adjoining pixels in a 8x8 grid centered on the centroid for TOI-5205, which suggests that the signal is not astrophysical in origin. This is further corroborated by the lack of

\[ ^{18} \text{Mass-luminosity relations in the optical (M}_K\text{) from Henry & McCarthy (1993) and Benedict et al. (2016) give discrepant results with the M}_K\text{ mag relations due to the effect of the TiO and VO molecules, especially below 0.4 M}_\odot\text{ as discussed by Baraffe et al. (1998).} \]
detected rotational broadening in the HPF spectra, with which we can place a limit of \( v \sin i < 2 \text{ km s}^{-1} \) on the host star\(^{19}\). Furthermore, we also check the publicly available data from ASAS-SN (Kochanek et al. 2017) in V and g, and ATLAS (Tonry et al. 2018) in the cyan (420 – 650 nm) and orange (560 – 820 nm) bands using a GLS periodogram, and do not find any significant signals. We did not find any publicly available data from the Zwicky Transient Facility Data Release 12 (ZTF, Masci et al. 2019).

Based on the H-\( \alpha \) equivalent width estimate and lack of detectable photometric rotation signal for TOI-5205, we classify TOI-5205 as an inactive, old star.

A.4. Blended sources of contamination

The stellar density estimated assuming a circular orbit (8.8 \( \pm \) 0.4 g cm\(^{-3} \)) confirms the mid-M dwarf spectral type for the host (Section A.2). This also rules out the background eclipsing binary scenario around distant giant stars.

The speckle imaging from NESSI is used to resolve the presence of any objects down to a separation of 0.3" or about 27 AU (Figure 10). We then attempt to place constraints on unresolved stellar companions using HPF spectra, Gaia astrometry, archival imaging, photometry and the RVs.

A.4.1. Background objects

We look for background companions by comparing our observations of TOI-5205 from ARCTIC on 2022 April 22 (Section 2.2.1) with observations from the Palomar Observatory Sky Survey (POSS-1; Harrington 1952; Minkowski & Abell 1963) image taken on 1954 June 28. The POSS-1 plate images were taken with Eastman 103a-O spectroscopic plates without a filter and have a limiting magnitude of \( \sim \) 20. Over this period, TOI-5205 has had a proper motion of \( \sim 4.5" \), which is comparable to the PSF FWHM for the POSS-1 photographic plate observations. These archival observations rules out background companions that might be blended with TOI-5205 with a contrast of \( \Delta V \sim 4 \).

The closest companion seen in both images is TIC 1951446034, which is a resolved background star that is \( \sim 4" \) away and not co-moving.

A.4.2. Co-moving objects

We rule out the possibility of a system where TOI-5205b transits the primary, but is accompanied by a secondary stellar-mass companion orbiting the host star that is redder and fainter than TOI-5205 and would dilute the transit.

Assuming no unresolved companions, the transit depth (\( \delta_0 \)) for a planet with area \( A_p \) crossing a star with area \( A_1 \) and luminosity \( L_1(\lambda) \) is given by

\[
\delta_0 = \left( \frac{A_p}{A_1} \right) \frac{1}{L_1(\lambda)} = \frac{A_p}{A_1}
\]

Instead if there was an unresolved companion of later spectral type with luminosity \( L_2(\lambda) \), where \( L_2 < L_1 \):

\[
\delta(\lambda) = \left( \frac{A_p L_1(\lambda)}{A_1} \right) \frac{1}{L_1(\lambda) + L_2(\lambda)}
\]

\[
\delta(\lambda) = \delta_0 \left( \frac{L_1(\lambda)}{L_1(\lambda) + L_2(\lambda)} \right)
\]

\[
\delta(\lambda) \propto \frac{1}{1 + L_2(\lambda)/L_1(\lambda)}
\]

For \( \lambda_2 > \lambda_1 \),

\[
\frac{L_2}{L_1} \left( \lambda_2 \right) > \frac{L_2}{L_1} \left( \lambda_1 \right)
\]

i.e., \( \delta(\lambda_2) < \delta(\lambda_1) \)

We obtained precise multi-filter transit photometry from the 3.5 m ARC telescope (Figure 3) in the SDSS \( i' \) and \( g' \) filters. If there was a later spectral type unresolved companion (object 2) that was contaminating the photometry of

\(^{19}\) The corresponding equatorial velocity for a \( \sim 4.4 \) day rotation period would be \( \sim 3.7 \text{ km s}^{-1} \).
We show the limits placed on a blended secondary companion using three different methods. In green we show the constraints from speckle imaging (Section 2.4), in blue we show the limits from comparing transit depths in $g'$ and $i'$ (Section A.4.2). Given the short-observing baseline of the HPF RVs, the RV slope can only rule out massive companions with periods $<40$ days ($0.2$ AU), and are not shown here. Instead, the flux constraint from HPF spectra (yellow) order $5$ ($\sim 8700$ Å) is used to rule out stars more massive than $0.2$ $M_\odot$ within the HPF aperture ($0.85''$ radius $\sim 80$ AU) as long as they have velocity offsets $|\Delta v| > 5$ km s$^{-1}$. The dashed black line is the mass of the primary – TOI-5205.

the host star (object 1), it would result in different transit depths across different photometric bands. If we assume that we can compare the two transit depths (in $g'$ and $i'$) with a precision of $\epsilon$, where $\epsilon$ is a small number, then -

$$\frac{\delta(g')}{\delta(i')} = 1 + \epsilon$$  \hspace{1cm} (A9)

Then by this method we can rule out all objects with luminosity lesser than $L_2(\lambda)$,

$$\frac{L_2}{L_1}(g') \frac{L_2}{L_1}(i') = 1 + \epsilon$$  \hspace{1cm} (A10)

Using a separate dilution term for the ARCTIC transit in $g'$, we probe for chromaticity in the transit depth between $g'$ and $i'$, but find the depths to be consistent to $\sim 10\%$, i.e. $\epsilon \sim 0.1$. We then use the SDSS transmission curves for the two filters, and compare the flux within the bandpass using BT-Settl CIFIST theoretical stellar spectra for a range of stellar masses (Allard et al. 2011, 2012). We conclude that this method would be sensitive to transit depth variations for an unresolved companion cooler than $\sim 3100$ K or roughly $0.25$ $M_\odot$ (Figure 10).

If there was a secondary stellar-mass object present in the system, i.e. a hierarchical system, it would be a source of dilution that would suggest a radius larger than the $\sim 1$ $R_J$ estimated here. Due to the electron degeneracy pressure, objects around this size can range from Jovian planets to very low mass stars (M7-M8; Zapolsky & Salpeter 1969; Burrows et al. 2001). Therefore, if TOI-5205b had a larger radius (due to unaccounted dilution), it would have to be a late-type M dwarf or larger, which would make it at least 100x more massive than the $\sim 1$ $M_J$ we measure (Table 4).

Finally, we put additional constraints on the possibility of a bound stellar companion, as follows:

- Constraints from HPF spectra: We follow the procedure outlined in Kanodia et al. (2020) to place limits on any spatially unresolved stellar companion to TOI-5205 using the HPF spectra to quantify the lack of flux from a secondary object. We combine the spectra from a single epoch to obtain a higher S/N template for comparison, and then model the test spectra (TOI-3757) as a linear combination of a primary M dwarf (GJ 273) and a secondary companions (GJ 9066, GJ 1072, GJ 1111 and LSPM J0510+2714). The flux ratio between the secondary and primary star, $F$, is calculated as:

![Figure 10](image-url)
\begin{equation}
S_{\text{obs}} = A ((1 - x)S_{\text{primary}} + (x)S_{\text{secondary}})
\end{equation}
\begin{equation}
F = \frac{x}{1 - x}
\end{equation}

where \(S_{\text{obs}}\) is the observed spectrum, \(S_{\text{primary}}\) is the primary spectrum, \(S_{\text{secondary}}\) represents the secondary spectrum, and \(A\) is the normalization constant. For a given primary and secondary template, we (i) perform a \(\chi^2\) minimization to shift the secondary spectrum in velocity space, (ii) add this shifted secondary spectrum to the primary, and (iii) fit for the value of \(x\) (and \(A\)) that best fits the observed spectrum. We perform this for a range of spectral types for the secondary from M4.5 to M7 spanning velocity offsets of \(\pm 150 \text{ km s}^{-1}\). We place a conservative upper limit for a secondary companion of flux ratio < 0.2 or \(\Delta\text{mag} \simeq 1.8\) for \(|\Delta v| > 5 \text{ km s}^{-1}\), using HPF order index 5 spanning 8650 – 8770 Å. The lower limit coincides with HPF’s spectral resolution \((R \sim 55,000 \approx 5.5 \text{ km s}^{-1})\). At lower velocity offsets, the degeneracy between the primary and secondary spectra prevents any meaningful flux ratio constraints.

- Constraints from Gaia astrometry: Gaia DR3 (Vallenari et al. 2022) provides an additional astrometric constraint on the presence of unresolved bound companions using the re-normalized unit weight error (RUWE) metric. RUWE is sensitive to the change in the position of the primary target due to reflex motion caused by unresolved bound companions. For the single-star astrometric solution in use for Gaia DR3, this astrometric motion of the primary star around the center of mass would manifest as noise (Kervella et al. 2019), especially for orbital periods much shorter than the observing baseline for Gaia DR3 (~ 34 months). The commonly accepted threshold in literature for this is RUWE \(\gtrsim 1.4\), which correlates with the presence of a bound stellar companion in recent studies of stellar binaries (Penoyre et al. 2020; Belokurov et al. 2020; Gandhi et al. 2021). For TOI-5205, Gaia DR3 reports a RUWE of \(\sim 1.03\), which is in agreement with a single-star astrometric solution.

- Constraints from RVs: A joint fit of the photometry and RVs is used to estimate the planetary and system properties (Section 4). We also include a linear RV trend in the orbital solution while fitting the RVs. We estimate this to be consistent with 0, with an estimated RV trend \(~ 0.05^{+4.92}_{-5.08} \text{ m s}^{-1} \text{ yr}^{-1}\). Assuming a circular orbit for a unresolved companion star, the maximum at phase 0 (conjunction) and 180°, where the amplitude would be \(2\pi K/P\), where \(K\) is the RV-semi amplitude on the primary star due to a hypothetical secondary, and \(P\) is its orbital period. However, given our short observing period (~ 30 days), we use this to only constrain companions with a maximum orbital period of \(~ 60 \text{ days}\), or a semi-major axis of 0.2 AU.

A.5. Galactic kinematics

Using the systemic velocity from HPF and proper motion from Gaia DR3, we calculate the \(UVW\) velocities in the barycentric frame using GALPY (Bovy 2015)\(^{20}\). We provide these velocities in Table 3, including those in the local standard of rest using the offsets from Schönrich et al. (2010). Using the BANYAN tool (Gagné et al. 2018), we classify TOI-5205 as a field star in the thin disk with very high probability (> 99%; Bensby et al. 2014).

B. ACKNOWLEDGEMENTS

SK thanks Rocio Kiman for help with spectral typing using Gaia colours; Alycia J. Weinberger for illuminating discussions and references regarding protoplanetary disks around M dwarfs; Peter Gao for discussions regarding the atmospheric characterization of these planets and for proof-reading sections of this manuscript. SK acknowledges research support from Carnegie Institution of Science through the Carnegie Fellowship.

The Pennsylvania State University campuses are located on the original homelands of the Erie, Haudenosaunee (Seneca, Cayuga, Onondaga, Oneida, Mohawk, and Tuscarora), Lenape (Delaware Nation, Delaware Tribe, Stockbridge-Munsee), Shawnee (Absentee, Eastern, and Oklahoma), Susquehannock, and Walzhazhe (Osage) Nations. As a land grant institution, we acknowledge and honor the traditional caretakers of these lands and strive to understand and model their responsible stewardship. We also acknowledge the longer history of these lands and our place in that history.

\(^{20}\) With \(U\) towards the Galactic center, \(V\) towards the direction of Galactic spin, and \(W\) towards the North Galactic Pole (Johnson & Soderblom 1987).
These results are based on observations obtained with the Habitable-zone Planet Finder Spectrograph on the HET. We acknowledge support from NSF grants AST-1006676, AST-1126413, AST-1310885, AST-1310875, AST-1910954, AST-1907622, AST-1909506, ATI-2009889, ATI-2009982, AST-2108512, AST-1907622, and the NASA Astrobiology Institute (NNA09DA76A) in the pursuit of precision radial velocities in the NIR. The HPF team also acknowledges support from the Heising-Simons Foundation via grant 2017-0494. The Low Resolution Spectrograph 2 (LRS2) was developed and funded by the University of Texas at Austin McDonald Observatory and Department of Astronomy and by Pennsylvania State University. We thank the Leibniz-Institut für Astrophysik Potsdam (AIP) and the Institut für Astrophysik Göttingen (IAG) for their contributions to the construction of the integral field units. The Hobby-Eberly Telescope 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 HET collaboration acknowledges the support and resources from the Texas Advanced Computing Center. We thank the Resident astronomers and Telescope Operators at the HET for the skillful execution of our observations with HPF. 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.

The Low Resolution Spectrograph 2 (LRS2) was developed and funded by the University of Texas at Austin McDonald Observatory and Department of Astronomy and by Pennsylvania State University. We thank the Leibniz-Institut für Astrophysik Potsdam (AIP) and the Institut für Astrophysik Göttingen (IAG) for their contributions to the construction of the integral field units.

WIYN is a joint facility of the University of Wisconsin-Madison, Indiana University, NSF’s NOIRLab, the Pennsylvania State University, Purdue University, University of California-Irvine, and the University of Missouri. 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. Data presented herein were obtained at the WIYN Observatory from telescope time allocated to NN-EXPLORE through the scientific partnership of NASA, the NSF, and NOIRLab.

Deepest gratitude to Zade Arnold, Joe Davis, Michelle Edwards, John Ehret, Tina Juan, Brian Pisarek, Aaron Rowe, Fred Wortman, the Eastern Area Incident Management Team, and all of the firefighters and air support crew who fought the recent Contreras fire. Against great odds, you saved Kitt Peak National Observatory.

Some of the observations in this paper made use of the NN-EXPLORE Exoplanet and Stellar Speckle Imager (NESSI). NESSI was funded by the NASA Exoplanet Exploration Program and the NASA Ames Research Center. NESSI was built at the Ames Research Center by Steve B. Howell, Nic Scott, Elliott P. Horch, and Emmett Quigley.

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.

Computations for this research were performed on the Pennsylvania State University’s Institute for Computational and Data Sciences Advanced CyberInfrastructure (ICDS-ACI). This content is solely the responsibility of the authors and does not necessarily represent the views of the Institute for Computational and Data Sciences.

We acknowledge support from NSF grant AST-1907622 in the pursuit of precise photometric observations from the ground.

The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium.

Some of the data presented in this paper were obtained from MAST at STScI. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This work includes data collected by the TESS mission, which are publicly available from MAST. Funding for the TESS mission is provided by the NASA Science Mission directorate. This research made use of the (i) NASA Exoplanet Archive, which is operated by Caltech, under contract with NASA under the Exoplanet Exploration Program, (ii) SIMBAD database, operated at CDS, Strasbourg, France, (iii) NASA’s Astrophysics Data System Bibliographic Services, and (iv) data from 2MASS, a joint project of the University of Massachusetts and IPAC at Caltech, funded by NASA and the NSF.
This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and NASA’s Astrophysics Data System Bibliographic Services.

This research has made use of the Exoplanet Follow-up Observation Program website, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

The research was carried out (in part) at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

CIC acknowledges support by an appointment to the NASA Postdoctoral Program at the Goddard Space Flight Center, administered by USRA through a contract with NASA.

SK would like to acknowledge Theodora and Rafa for help with this project.

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

Facilities: Gaia, HET (HPF), APO (ARCTIC), WIYN 3.5 m (NESSI), Magellan (FourStar) RBO TESS, Exoplanet Archive

Software: ArviZ (Kumar et al. 2019), AstroImageJ (Collins et al. 2017), astroquery (Ginsburg et al. 2019), astropy (Robitaille et al. 2013; Astropy Collaboration et al. 2018), barycorrpy (Kanodia & Wright 2018), celerite2 (Foreman-Mackey et al. 2017; Foreman-Mackey 2018), daophot (Stetson 1987; Stetson & Harris 1988), eleanor (Fein- stein et al. 2019), exoplanet (Foreman-Mackey et al. 2021a,b), Exo-Transit Kempton et al. (2017), GENESIS (Gandhi & Madhusudhan 2017), HxRGproc (Ninan et al. 2018), ipython (Pérez & Granger 2007), lightkurve (Lightkurve Collaboration et al. 2018), matplotlib (Hunter 2007), numpy (Oliphant 2006), Panacea21, pandas (Mckinney 2010), PandExo (Batalha et al. 2017), PyMC3 (Salvatier et al. 2016), pyHammer (Roulston et al. 2020), scipy (Oliphant 2007; Virtanen et al. 2020), SERVAL (Zechmeister et al. 2018), starry (Luger et al. 2019; Agol et al. 2020), Theano (The Theano Development Team et al. 2016).

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