A Novel Method to Determine Precise Stellar Radii and Temperatures of Low Mass Stars Using JWST Transits and Occultations

The Problem

The masses, radii, and temperatures of planets depend directly on the same quantities as those of their host stars. Often the limiting factor for determining precise planetary parameters is our knowledge of their host stars. The higher the precision we can achieve measuring these stars the better we will be able to understand climates, habitability, formation, and evolution of individual stellar systems, as well as generally develop more detailed theoretical models for stellar atmospheres and evolution. This is the case for all planet hosting stars but is most apparent for low mass host stars because they are most difficult to measure. These stars, such as M-dwarfs, have been understood to be critical targets in the search for Earth-like planets.

What is an Exoplanet?

Exoplanets are planets outside of our solar system

One way we detect these planets using the transit method, which occurs when an exoplanet passes in front of its star and creates a dip in light

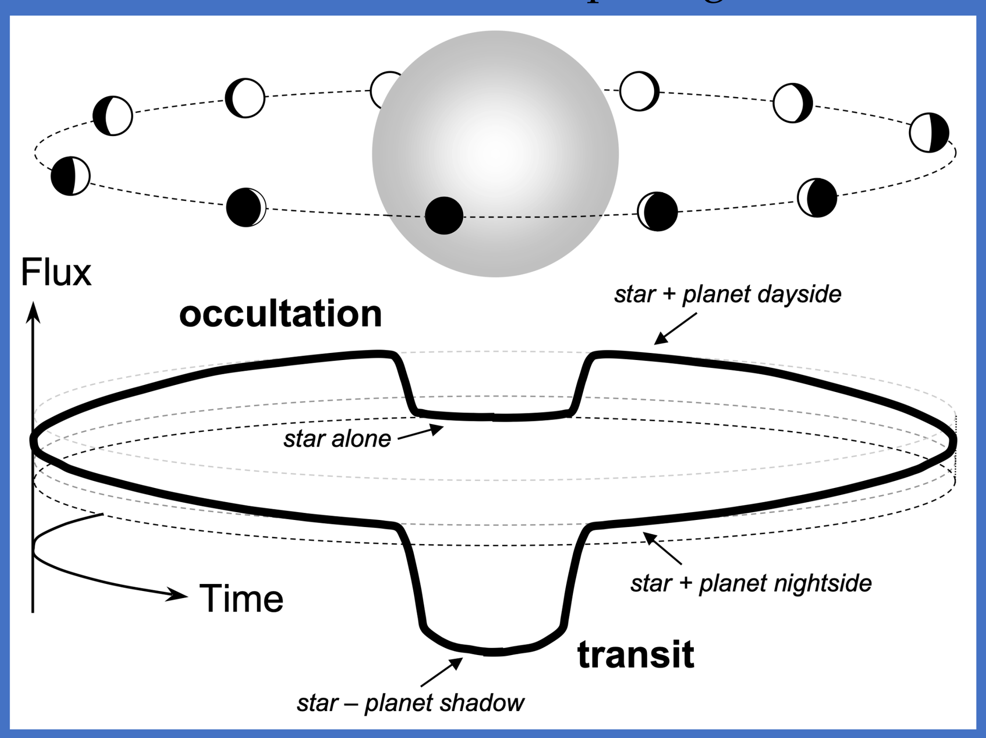


Fig. 1: An illustration of a transit and occultation. **[Credit: Winn 2010]**

Low Mass Stars

M-dwarfs are small stars that have a mass between 8% to 70% of the mass of our sun

These stars are our best hope of finding other life within the next 30 years and critical in the search for habitability; Planets like Earth are far easier to detect around small stars

The Big Issue: Low mass stars are not well understood

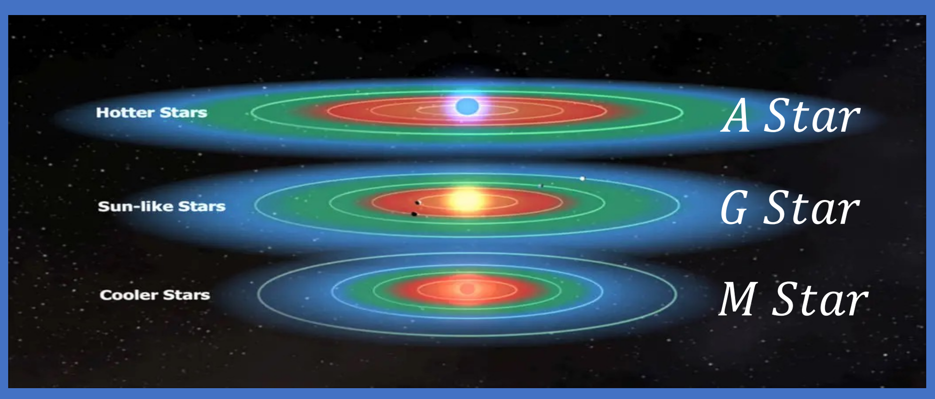


Fig. 2: The habitable zone, represented in green, is where liquid water (thought to be a requirement of life) is permitted to exist. **[Credit: NASA/Kepler Mission/Dana Berry]**

James Webb Space Telescope (JWST)

- The Solar System's best telescope
- With a primary mirror size of 6.5 m (21.3 ft) and located in space, JWST's data is far more precise and reliable
- JWST was designed to look at atmospheres- **I used the data in a way it was not originally intended**

Fig 3: A full scale replica of JWST, with NASA employees standing by for scale. **[Credit: NASA.gov]**

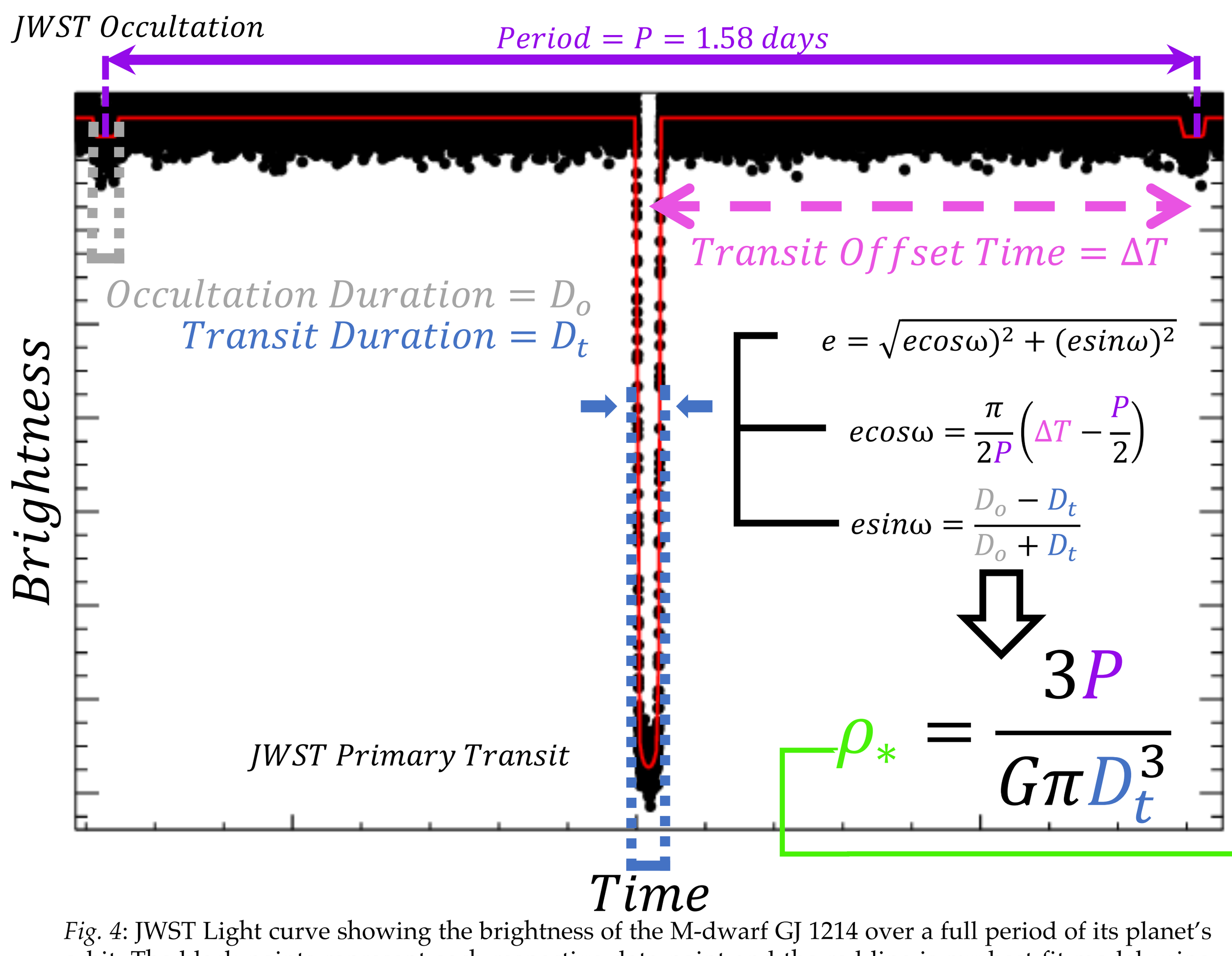


Fig. 4: JWST Light curve showing the brightness of the M-dwarf GJ 1214 over a full period of its planet's orbit. The black points represent each respective data point and the red line is my best-fit model using EXOFASTv2. **[Credit: This work]**

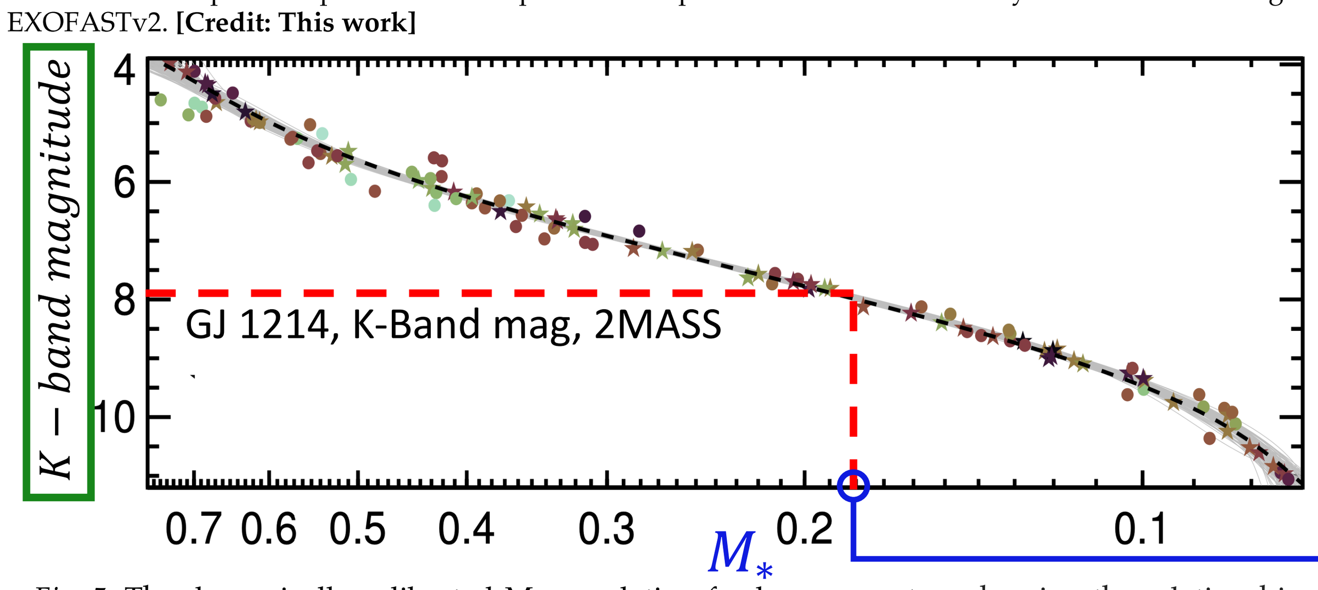
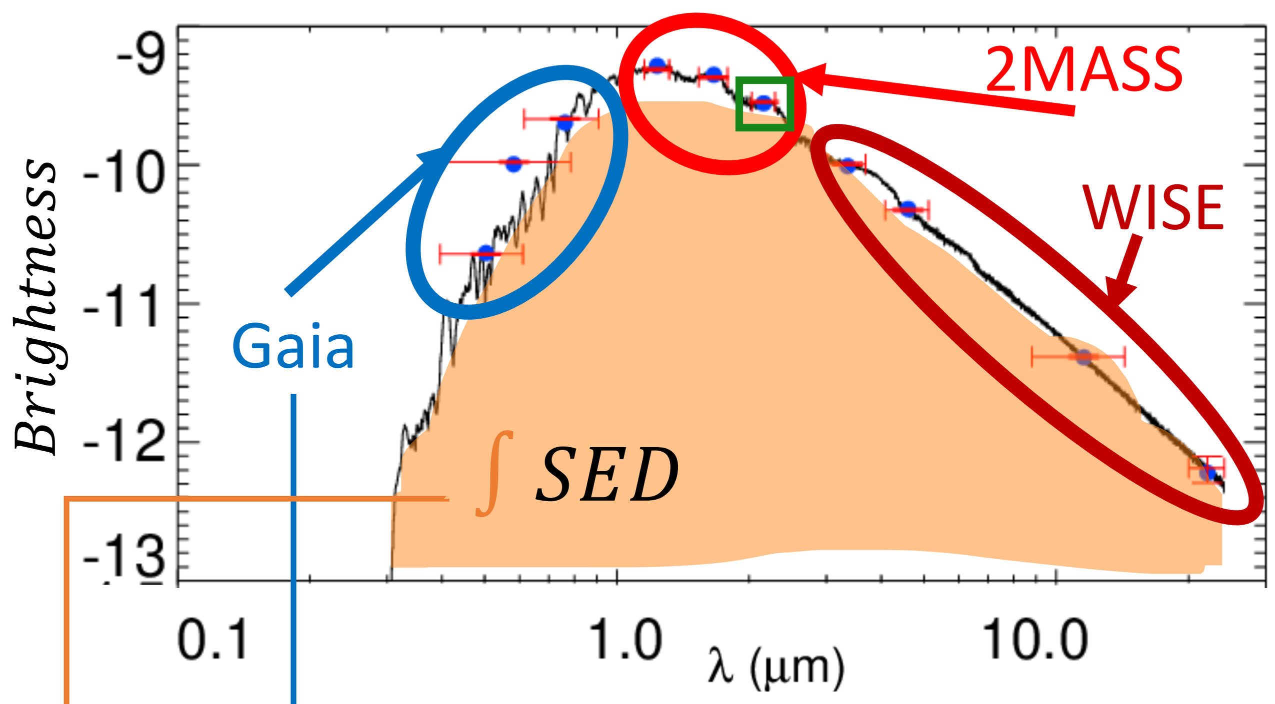
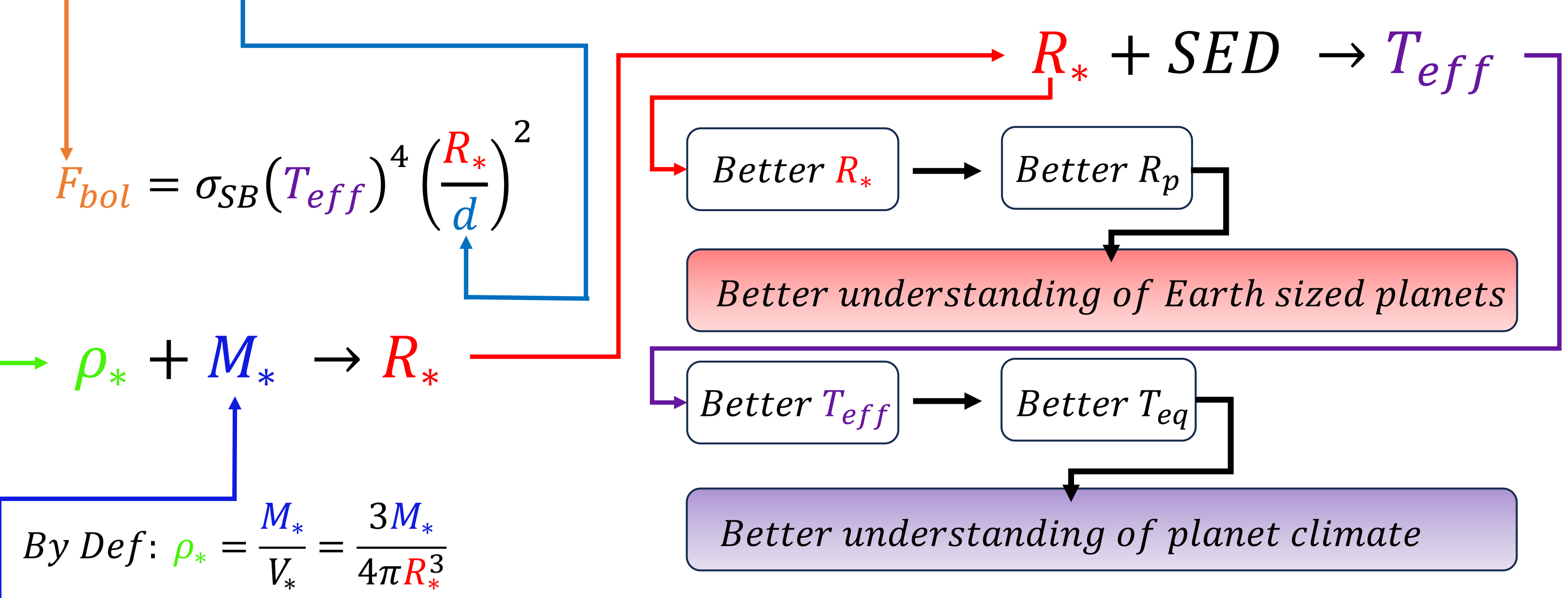


Fig. 5: The dynamically calibrated Mann relation for low mass stars showing the relationship between a star's K-band magnitude and its mass. **[Credit: Mann et al. 2019]**



Bolometric Flux → F_{bol}
Effective Temp. → T_{eff}
Distance → d

Fig. 6: The SED (Spectral Energy Distribution) for GJ 1214 of brightness versus wavelength in microns. The blue points represent my best-fit model using EXOFASTv2. **[Credit: This work]**



Findings: 3x Better Than Any Previous Result

Notably, my analysis dramatically improves the precision for R_* (3.27×), T_{eff} (2.33×), and ρ_* (4.89×) compared to the next best result by Cloutier et al. (2021).

The improved stellar parameters propagate to improved precision in the planetary parameters, including the radius R_p (1.59×) and the equilibrium temperature, T_{eq} (2.50×), which is critical for understanding exoplanets, their climates, and habitability.

Parameter	Description	This Work	Cloutier et al. (2021)	Improvement[1]
Stellar Parameters:				
M_*	Mass ($M_\odot$)	$0.1820^{+0.0042}_{-0.0041}$	0.178 ± 0.010	2.41
R_*	Radius ($R_\odot$)	$0.2162^{+0.0025}_{-0.0024}$	0.215 ± 0.008	3.27
ρ_*	Density (cgs)	$25.41^{+0.62}_{-0.71}$	$25.4^{+3.5}_{-3.0}$	4.89
$T_{\rm eff}$	Effective Temperature (K)....	3101 ± 43	3250 ± 100	2.33
Planetary Parameters:				
P	Period (days)	$1.580404531^{+0.000000018}_{-0.000000017}$	$1.58040433 \pm 0.00000013$	7.43
R_P	Radius ($R_\oplus$)	$2.733^{+0.033}_{-0.031}$	$2.733^{+0.050}_{-0.052}$	1.59
M_P	Mass ($M_\oplus$)	$8.41^{+0.36}_{-0.35}$	8.17 ± 0.43	1.21
e	Eccentricity 95% Upper Limit	< 0.019	< 0.063	3.32
$T_{\rm eq}$	Equilibrium temperature[6] (K).	567.0 ± 7.6	596 ± 19	2.50

[1] The improvement is calculated as the average error bar from Cloutier et al. (2021) divided by the average error bar from our analysis.

Tab. 1: A summary of the key system properties from my work, alongside a comparison with the next best analysis published in the literature by Cloutier et al., 2021. See Mahajan, et. al. (2024) for a comprehensive list of parameters. **[Credit: This work}**

Future Applications

- GJ 1214 is an archetype for super-Earths around M-dwarfs; **precise constraints contribute to a deeper understanding of habitability, planet formation, and stellar evolution for all other M-dwarf planetary systems**
- My method is immediately applicable to six additional low mass stars currently available in the JWST archive, adding ~25% to the total number of precisely measured low mass stars to better understand habitable planets
- Only 29 low mass stars are constrained to the precision I have achieved for GJ 1214. These 29 stars anchor our understanding of all other ~100 million cataloged M-dwarfs
- A larger sample size of anchor stars means creating a relation for understanding all M-dwarfs that is applicable to the ~100 million low mass star targets

References

Mahajan et al., 2024, ApJL, accepted (arXiv:2402.05991) [This work]
Cloutier, et., al., 2021, AJ, 162, 174
Eastman, et. al., 2019, (arXiv:1907.09480)
Mann, et. al., 2019, AJ, 871, 63
Winn, et. al., 2010, "Exoplanets", (arXiv:1001.2010)

[Credit: NASA.gov]