Studying the Fundamental Stellar Mass-Radius Relation in Low Mass Binaries Identified in Kepler-MARVELS Survey Data

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Project J85 (RRI)

Research Background

Motivation

- Stars are the building blocks of our universe
- Stellar evolution answers questions like: When will Earth be destroyed? How and when were planets formed?
- Calculations of eclipsing binary orbits and ellipses allow stellar mass and radius to be determined
- Limited accuracy (~30% error) for stellar mass-radius relation[1]
- Limited data on low-mass stars around and below 1 solar masses
- Lack of research and extracted radial velocities for eclipsing binaries

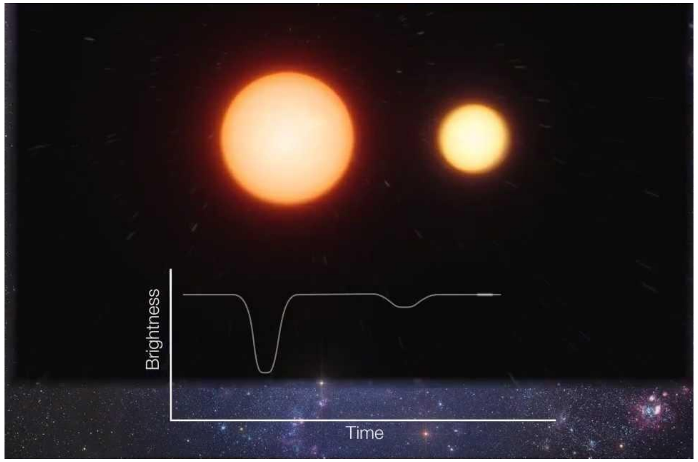


Figure 1: Eclipsing binary transit observed through brightness

Objectives

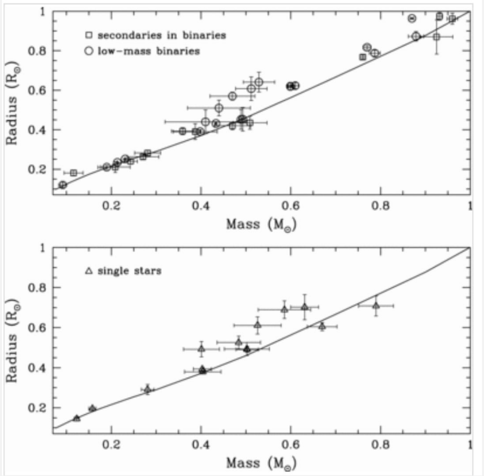
- Develop a new method by combining Cross-correlation fitting with Monte-Carlos Method and a widget (allowing for simple fitting), eliminating lengthy manual work
- Collect stellar information from on-line databases and derive stellar masses and radii for both primary and secondary of binaries
- Fit transit and orbit fits of 8 eclipsing binary targets to determine radius and mass ratios of the primary to the secondary star
- Propose a more accurate stellar mass-radius relationship for low-mass stars (with 33% more data)
- More easily study stellar evolution, stellar formation, and estimate the ages of stars

Significance of This Research

- Find a clearer trend for the stellar mass-radius relation for low mass stars (< 1 solar masses)
- Discover rare star systems with eclipsing binaries
- Mass allows prediction of how long a star will live
- Can more accurately predict lifetime of low-mass stars and planets, for example, Pluto (6.58×10^{-9} solar masses)
- Derive accurate parameters for each eclipsing binary, especially the mass and radius ratios
- Mass-radius relation is the fundamental law to understand the universe's building block: stars.

Summary of Selected Literature Research

2007 Mercedes López-Morales[1]



- ➢ All the current mass -radius measurements of main-sequence stars below 1 solar mass.
- ➢ Techniques used Include measuring X-ray fluxes
- ➢ Errors as large as 30%, the result for masses below 0.35 solar masses is misleading
- ➢ Related radius to metallicity of stars
- ➢ Proposed trend for stellar mass-radius relation

2012 Fleming, Scott W., et al[2]

- ➢ "A Long-Period Benchmark Eclipsing Binary From MARVELS"
- ➢ Early study of an eclipsing binary
- ➢ Discovered detached eclipsing binary and calculated more accurate parameters
- ➢ First binary for future study of several long-period eclipsing binaries
- ➢ Doppler technique, spectroscopic binaries, radial velocity
- ➢ Calculated mass ratio for the eclipsing binary
- ➢ Studied only 1 eclipsing binary, limited data, still work needed to be done
- ➢ Measurement of the mass ratio to within 1%

My Research vs Previous Research Work

- ➢ Many eclipsing binaries exist in outer space, however, few have radial velocities extracted (making them hard to study)
- ★ **Studied 8 low-mass eclipsing binaries with their radial velocities already extracted, allowing the measurement of both their masses and radii, which are key information for studying stellar structure and their evolution**
- ➢ Parameters (mass and radius) have been calculated for an eclipsing binary utilizing the doppler technique
- ★ **Accurately derived and calculated (through fitting) parameters including period, eccentricity, primary and secondary mass and radii, mass ratio, radius ratio, and more through the MCMC Solver technique and method**
- ➢ Low mass stars below 1 solar mass lack fundamental stellar mass-radius, let alone low mass eclipsing binaries
- ★ **Plotted and included extra data points of the stellar mass-radius relationship, allowing further study of stellar evolution**

Overview of Method and Techniques Used in this Work

1. Chose 8 Eclipsing Binaries

- ➢ Kepler/MARVELS databases
- ➢ Only with radial velocities extracted
- ➢ Picked targets with some contrasting periods to confirm or deny Kepler or MARVELS data
- ➢ Low-mass
- ➢ SDSS-III MARVELS
- ➢ Noted by their KIC numbers

2. Normalization and Transit Fitting

- ➢ Python program
- ➢ Doppler Shift
- ➢ Keplerian Fitting
- ➢ Calculated period, mass ratio, eccentricity
- ➢ Markov Chain Monte-Carlo Method (MCMC solver), random sampling to obtain numerical results

3. Binary Orbit Fitting

- ➢ Python program
- ➢ Calculated and extracted parameters including radius ratio, radial velocity
- ➢ Cross-correlation fitting (CCF)
- ➢ Radial velocity extraction
- ➢ Spectroscopic Binaries (SB1 and SB2)

4. Plot Stellar Mass-Radius Relationship

- ➢ Mass ratio and radius ratio from program
- ➢ Low-mass eclipsing binary data
- ➢ Also plotted primary mass vs primary radius, secondary mass vs secondary radius
- ➢ Plot with graph from López-Morales 2007

5. Observe Trend

- ➢ Found new, more accurate trend for stellar mass-radius relationship
- ➢ Low-mass eclipsing binaries, especially below 1 solar mass
- ➢ Linear vs exponential fits

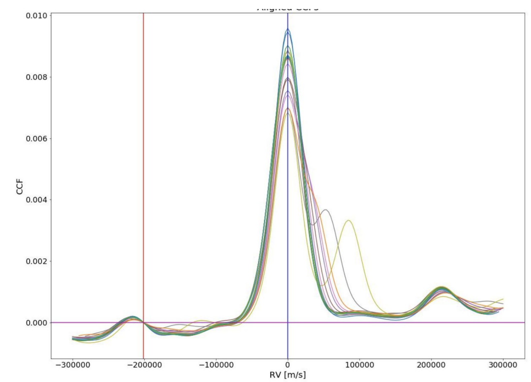


Figure 1: Cross-correlation fitting method

Challenges and Solutions in My Research Work

➢ Lot of data was difficult to normalize (steps 2 and 3)

1. Created a new method, transit and orbit fitting utilizing the MCMC solver and Cross-Correlation fitting

➢ High activity on background binaries (steps 2 and 3)

2. No solution since they are background binaries, but radial velocity was still extracted with eccentricity and period

Fitting Results of Three Spectroscopic Binaries I

Binary: 11922782

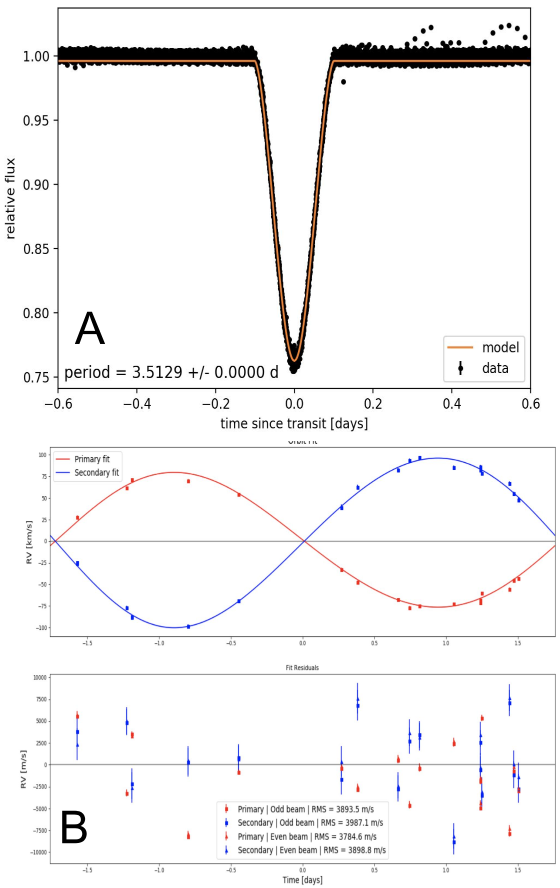


Figure 1: A and B describe eclipsing binary 11922782. There is an accurate fit for both the transit and also the binary orbit. Period accuracy is improved to the thousandths digit compared to previous data. New parameters also calculated, allowing study of stellar evolution.

3120320

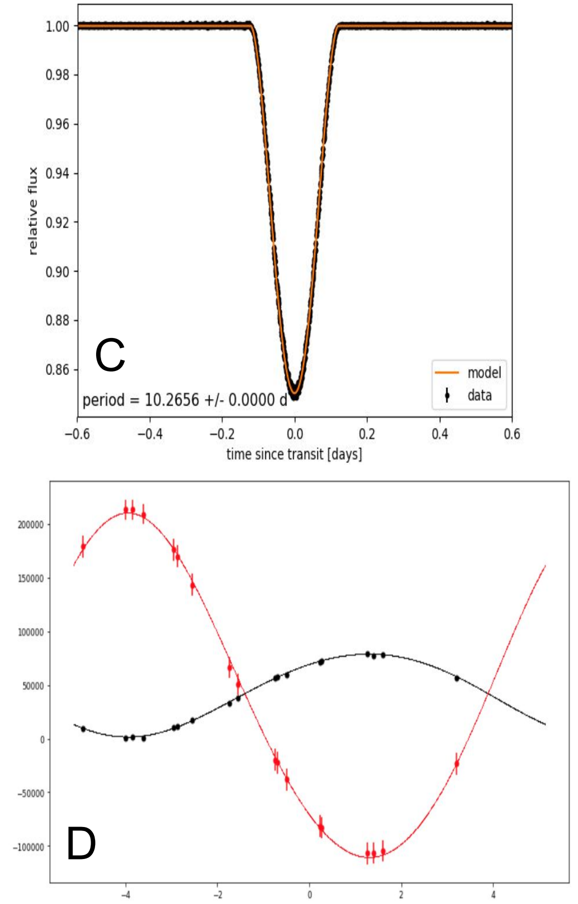


Figure 2: C and D describe eclipsing binary 3120320. There is an accurate fit for both the transit and the binary orbit. Improved period accuracy from previously believed (from MARVELS) 10.2 days to 10.3 days.

5630212 (SB1)

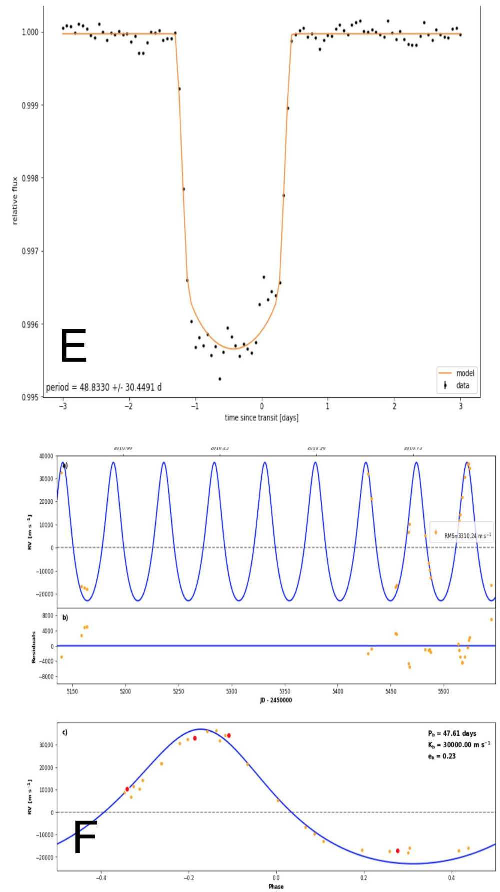


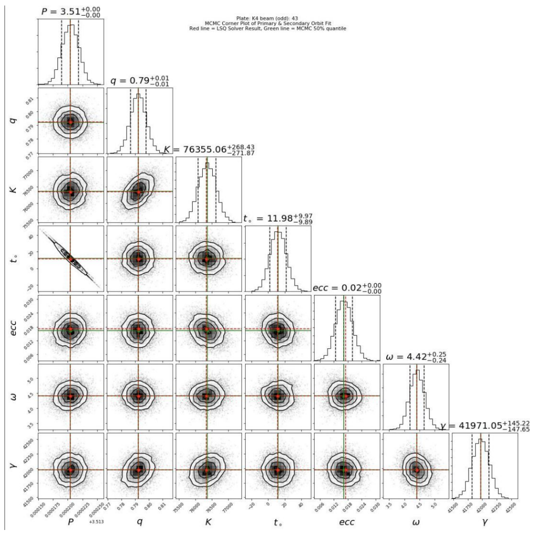
Figure 3: E and F describe eclipsing binary 5630212. Due to high activity which can be seen in the F fit, the data is difficult to normalize, causing this target to be only nicely fit as an SB1

Results and Discussions

- Figures A and B: period of 3.51 days (agreeing with Kepler and MARVELS database)
- Figures C and D: period of 10.27 days (agreeing with Kepler and MARVELS database)
- Figures E and F describe **single spectroscopic binary** (SB1), period: 47.6 days (agreeing with Kepler and MARVELS)
- **More accurately derived periods and other parameters** of these stars (compared to Kepler and MARVELS databases)
- Proposed new period for target KIC5630212
- Better understanding of stellar evolution and formation, better estimates for ages of low-mass stars

Fitting Results of Three Spectroscopic Binaries II

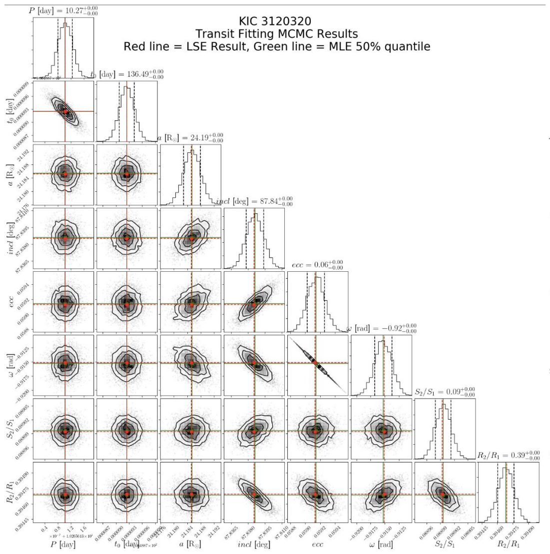
Binary: 11922782



$\gamma = 41971.052^{145.224}_{-147.647}\ m/s$	$t_0 = 133.787^{1.2E-05}_{-1.1E-05}$ day
$\omega = 4.419^{0.247}_{-0.236}\ rad$	$P = 3.513^{4.8E-08}_{-4.8E-08}$ day
$\mathrm{ecc} = 0.016^{0.004}_{-0.004}$	$R_2/R_1 = 0.616^{0.003}_{-0.003}$
$\mathrm{t}_0 = 11.983^{9.974}_{-9.885}\ day$	$u_{1a} = -0.001^{5.8E-05}_{-1.9E-04}$
$\mathrm{K} = 76355.062^{268.434}_{-271.869}\ m/s$	$u_{1b} = 1.264^{0.011}_{-0.017}$
$\mathrm{q} = 0.792^{0.006}_{-0.006}\ M_p/M_s$	$u_{2a} = -0.005^{2.4E-04}_{-5.6E-04}$
$\mathrm{P} = 3.513^{0.000}_{-0.000}\ day$	$u_{2b} = 1.509^{0.018}_{-0.032}$
	$S_2/S_1 = 0.482^{6.5E-04}_{-3.8E-04}$
	$a = 11.661^{0.018}_{-0.013}\ R_\odot$
	$b = 0.721^{0.003}_{-0.003}$
	$R_2 = 0.925^{0.004}_{-0.004}\ R_\odot$
	$incl = 84.670^{0.023}_{-0.021}$ rad

Figure 1: Corner plot (with parameters of period, mass ratio, eccentricity, and more) for binary 11922782. Also, variables more clearly listed above.MARVELS and Kepler periods of 3.512 vs 3.513. My research shows Kepler data more accurate for this target.

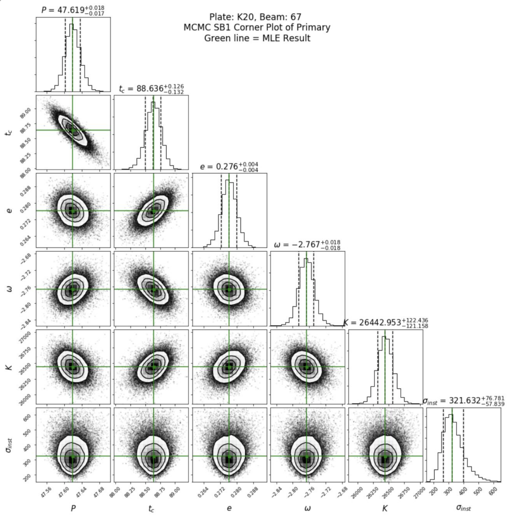
3120320



parameter	value
per1	10.2625
tc1	114.7
e1	0.07663
w1	-3.4
k1	40000
dvdt	0
curv	0
gamma	42000
jit	0.01

Figure 2: Corner plot (with parameters of period, mass ratio, eccentricity, and more) for binary 3120320. Also, variables more clearly listed above. This eclipsing binary's period matches the period from Kepler and MARVELS.

5630212 (SB1)



	parameter	mean	mean_error	high_error	low_error
1	per1	47.61890	0.01719	0.01765	0.01672
2	tc1	88.63567	0.12961	0.12611	0.13311
3	e1	0.27623	0.00368	0.00370	0.00367
4	w1	-2.76725	0.01850	0.01869	0.01830
5	k1	26443.00327	122.32783	122.37076	122.28489
6	jit	321.60007	67.95255	77.52432	58.38079

Figure 3: Corner plot (with parameters of period, eccentricity, and more) for binary 5630212. Also, variables more clearly listed above. Errors for parameters are also listed, which are later plotted in the stellar mass-radius relationship. This target represents an SB1.

Results and Discussion

- ➢ Target KIC5630212 is a single-lined spectroscopic binary (SB1)
- ➢ Smooth shapes in corner plot mean estimates for parameters were sampled sufficiently, providing accurate likelihood and error estimates.
- ➢ Periods from corner plot and variable chart or list match periods from Kepler and MARVELS, further supporting the accuracy of the other variables (such as mass ratio and eccentricity)
- ➢ **For the first time, I calculated new parameters** for these three eclipsing binaries, including their **mass and radius ratios**

Fitting Results: Trinary and Background Binaries

Trinary (SB3): 11244501

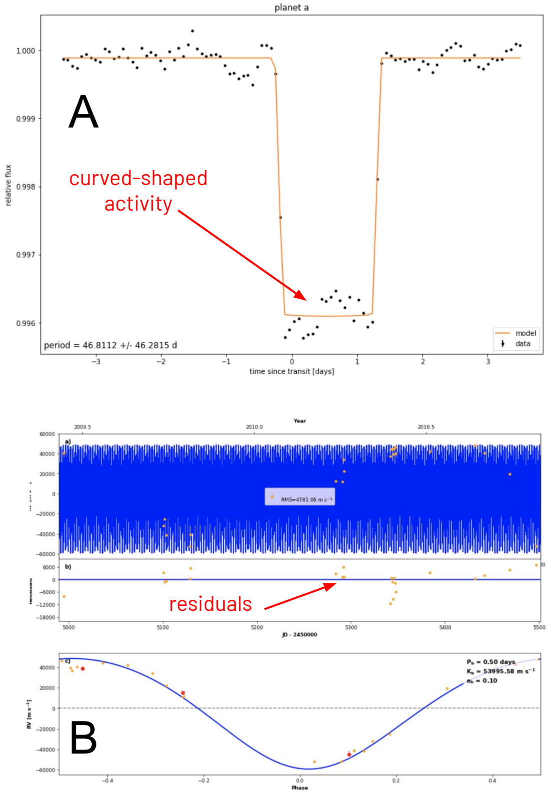


Figure 1: A and B describe a trinary star system (three gravitationally bound stars). A special program was utilized for this fit. A binary orbit fit is inapplicable for trinary systems. The extra radial velocity seen in the residual of B and extra activity in the transit of A are evidence of this. Additionally, there are three peaks in the CCF, further evidence of a trinary system.

Background binary: 3459199

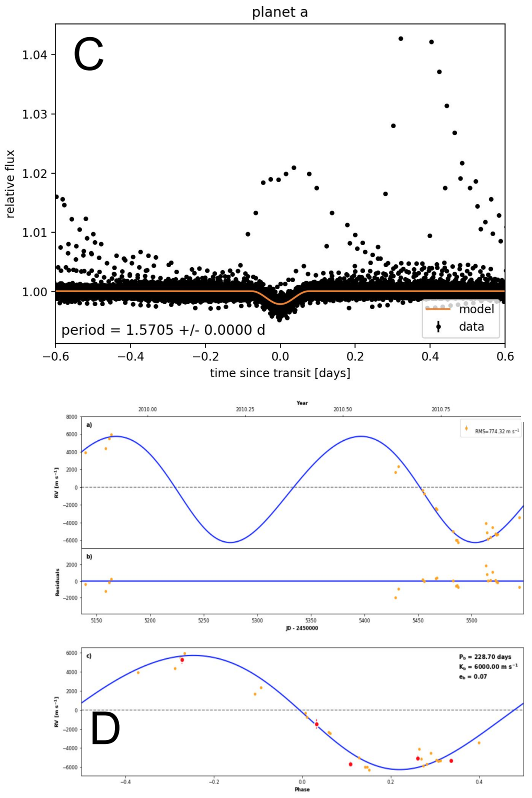


Figure 2: C and D describe a background binary. Extra activity in figure C and D suggest so. Background binaries are unable to fit as double-line spectroscopic binaries (SB2's). However, their transit was still fit, deriving the period, and the radial velocity was still extracted. MARVELS had no period for this target, allowing my contribution of new data.

Background binary: 8478994

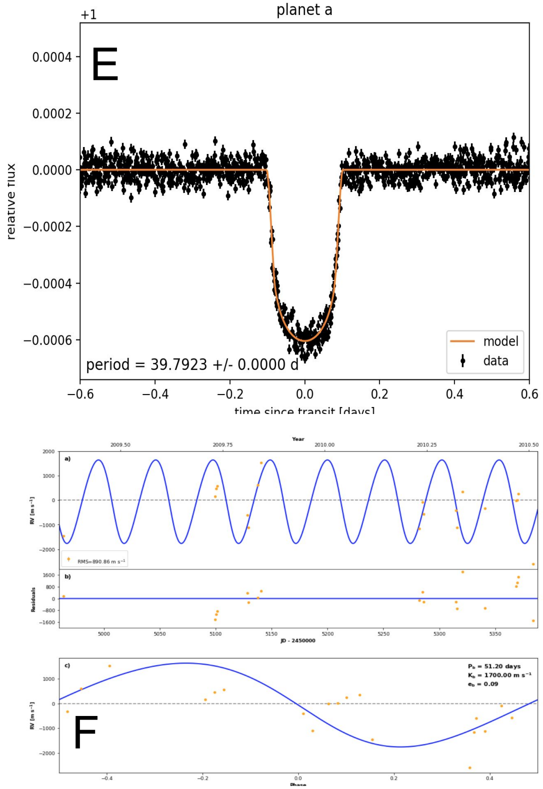


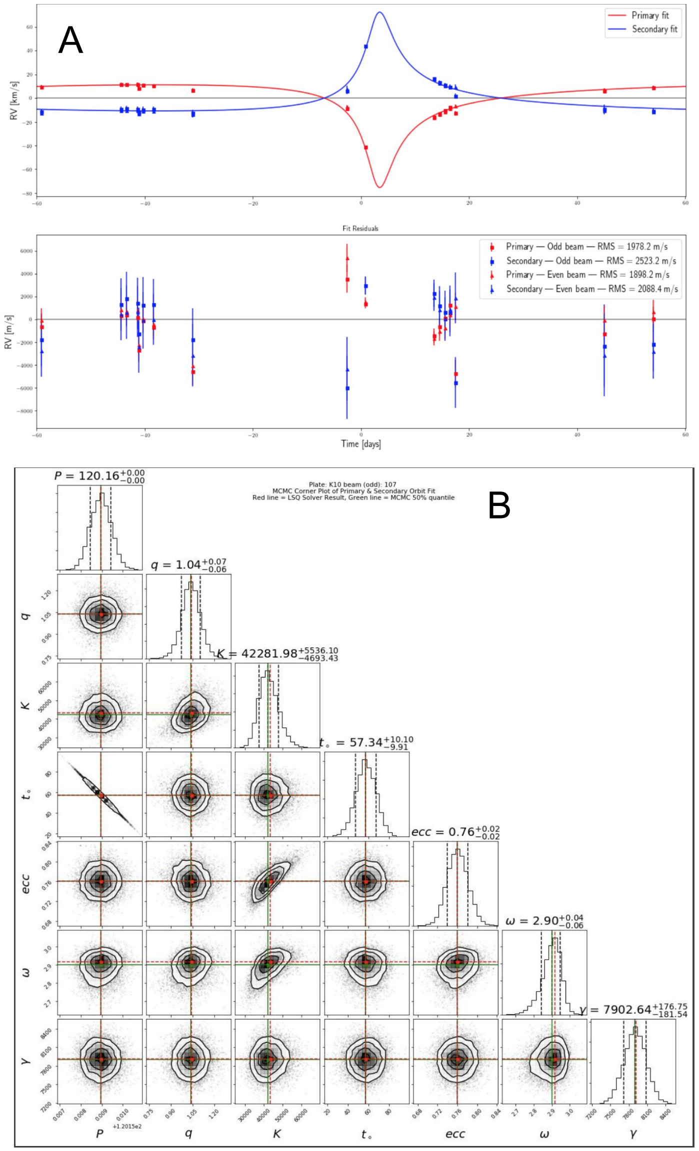
Figure 3: E and F describe a background binary. Figure F is a poor fit due to the high amount of activity in the radial velocity plot However, the transit has a clean fit with a period of around 39.79 days. This is in contrast to the period of around 50 days from Kepler and MARVELS, respectively. Thus, my clean fit significantly improves the accuracy of the period parameter.

Results and Discussions

- **I first combined** MCMC solver with Cross-correlation fitting and the doppler technique (in the Python program) to **successfully and accurately extract the radial velocities and parameters** of background binaries and trinaries whilst fitting their transits
- Using my method, background binaries can be clearly distinguished from false positives
- Targets KIC3459199 and KIC8478994 are background binaries as proven through their **different periods**
- I was able to observe a **high amount of activity** in the radial velocity and transit fit, suggesting Target KIC11244501 is a trinary.

Fitting Results of Special Star Systems

Binary with heartbeat star: 9163796



Figures 1a and b: Binary orbit of binary with heartbeat stars and corner plot with

Background binary with brown dwarf: 8848288

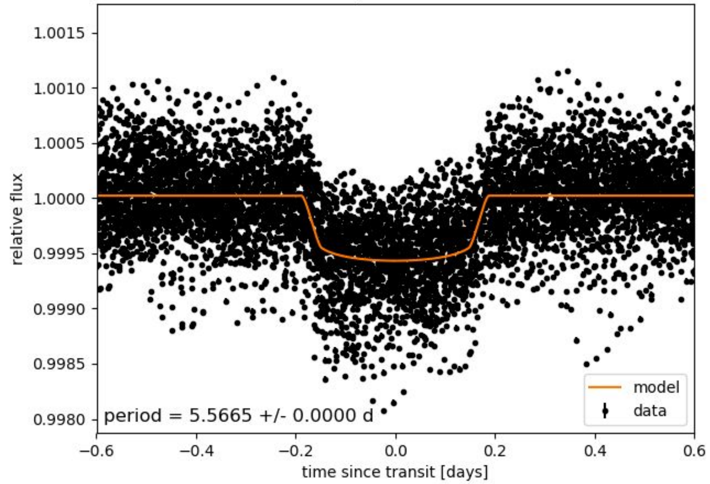


Figure 2: Transit fit of background binary target with brown dwarf. Data covers large range of relative flux.

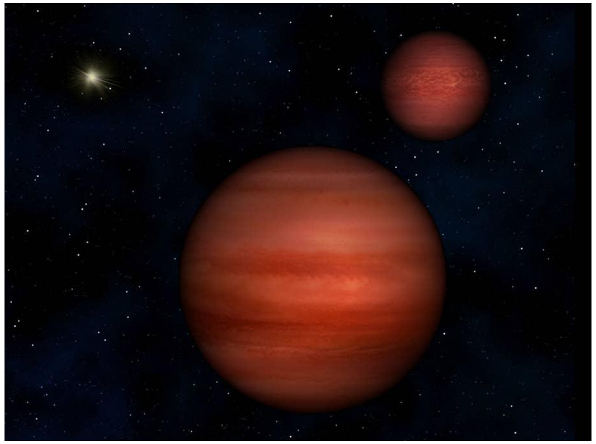


Figure 3: Artists' conception of binary with brown dwarf, similar to what target KIC8848288 looks like

Results, Findings, and Discussion

- As of March 2020, **there had been only one** double-lined spectroscopic binary (SB2) eclipsing binary brown dwarf system known , **second background binary with brown dwarf system discovered in the world so far to the best of my knowledge**
- In a heartbeat star binary system, each star rotates in a highly elliptical orbit and the distance between the primary and secondary stars varies drastically throughout its orbit
  - Thus, the fluctuation in relative flux creates the look of a heartbeat signal when plotted
- Oddly shaped orbit fit suggests heartbeat star system
- Deeper study into these rare star systems will allow astronomers to learn more about our universe and how it functions

Results of Stellar Mass-Radius Relation I

Primary and Secondary Masses and Radii of Three Binary Targets, Including Ratios

KIC Target ID	Mass Ratio	Radius Ratio	Mass Primary (M⊙)	Mass Secondary (M⊙)	Radius Primary (R⊙)	Radius Secondary (R⊙)	System Type
9163796	1.037	1.015	1.39	1.34	6.227	6.32	binary w/hearbeat star
5630212	0.921	0.784	0.58	0.534	0.584	0.458	binary (sb_1)
3120320	0.513	0.395	1.15	0.59	1.42	0.56	binary
11922782	0.798	0.616	1.03	0.822	1.798	1.108	binary

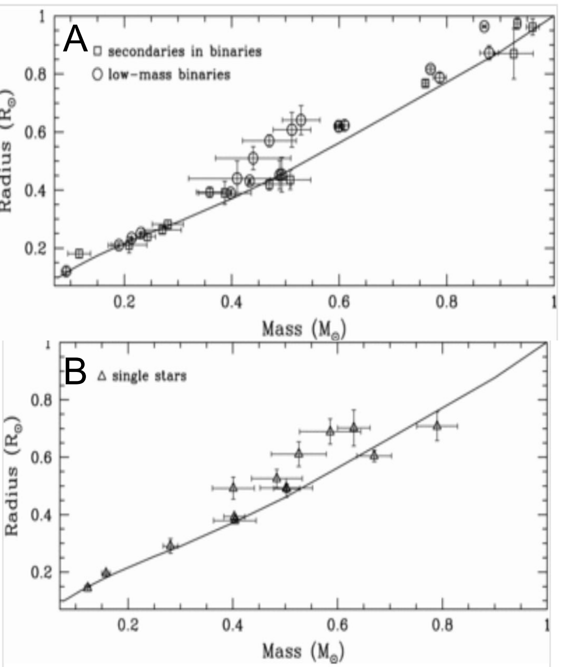


Figure 1: Previous mass-radius relationship plot for low mass stars below 1 solar mass (Lopez-Morales 2007). A exhibits all radii and mass (primary and secondary for binaries) whereas B presents single star targets. The wide error bars depict high variation in data.

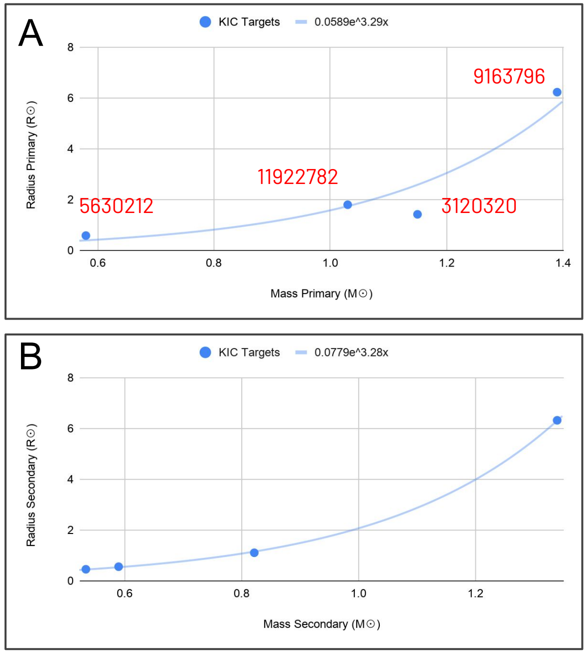


Figure 2: Graph A exhibits the primary mass versus the radius whereas Graph B presents the secondary. B seems to follow a clear trend. The two fit equations both have e raised to around 3.28 or 3.29 power, suggesting a trend in nature.

Results, Findings, and Discussion

- Stellar primary and secondary mass and ratios calculated for binary targets
  - Mass and radius ratios derived from fit (new method: MCMC solver and CCF)
  - Primary mass/radius from Vizier (Nolan 2018)
- **Plotted stellar mass-radius relationship** for low-mass binary targets (with Lopez-Morales 2007 plot) with error bars
- **Found more accurate trend** for primary versus secondary radius, primary versus secondary mass, and mass ratio versus radius ratio
- Exponential trend, with e raised to the power or around 3.3 in both cases
- First report of mass and radius ratio for all eight targets
- My new accurate data, allows better study of stellar evolution and formation
- Better estimates for ages or life span of low-mass stars

Results of Stellar Mass-Radius Relation II

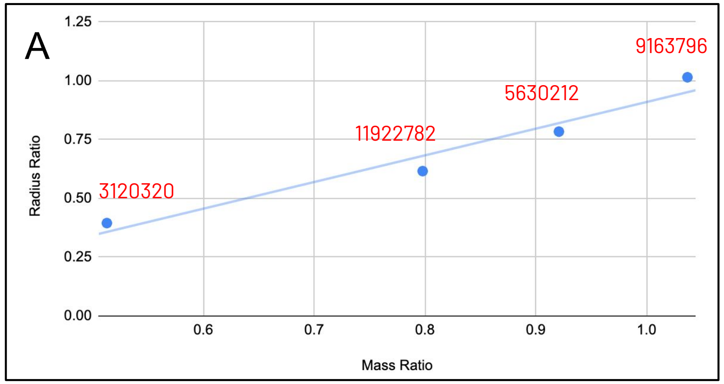


Figure 1: Mass ratio versus the radius ratio for the four eclipsing binary targets. The ratios display a more accurate linear trend, suggesting a linear relationship between the ratios

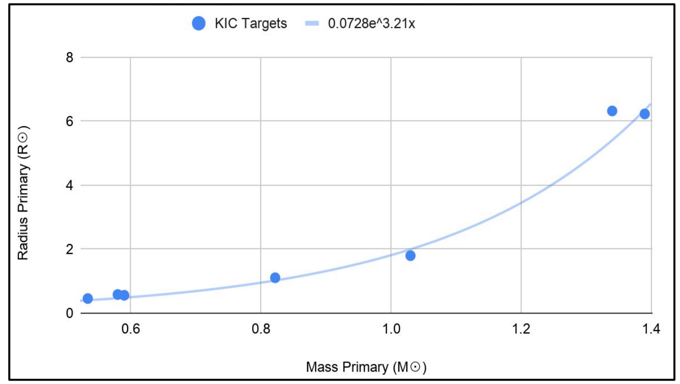


Figure 2: Primary and secondary masses versus primary and secondary radii. An exponential trend is observed. It is raised to the power of around 3.2 again, similar to before.

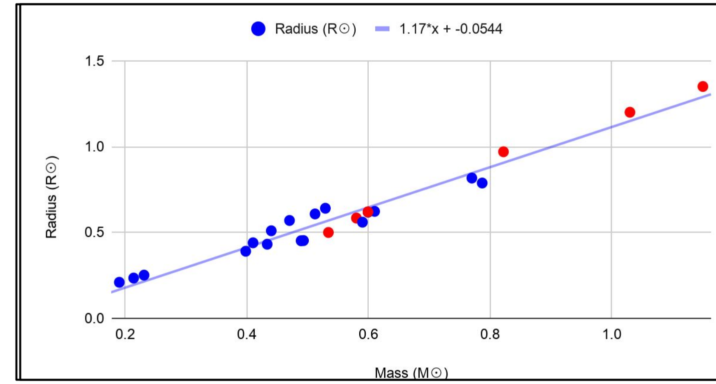


Figure 3:: My data combined with data from Lopez-Morales 2007. The data shows a clearer trend for the fundamental stellar-mass radius relationship for low mass stars

$$K_* = \frac{8.95\,\mathrm{cm\,s^{-1}}}{\sqrt{1-e^2}} \frac{M_P \sin i}{M_\oplus} \left(\frac{M_* + M_P}{M_\odot}\right)^{-2/3} \left(\frac{P}{\mathrm{yr}}\right)^{-1/3}$$

Equation 1: Equation for calculating secondary mass (Fischer) utilizing parameters extracted from radial velocity fitting

Mass-Radius Relation Process

- ➢ Calculated secondary mass by inputting formula from Fischer into Python program
- ➢ Primary mass, mass ratio, radius ratio, and primary and secondary radii were solved through fitting programs
- ➢ Plotted results, discovered that there is a common trend between the different targets
- ➢ Linear trend when plotting mass and radius ratios

Results, Findings, and Discussion

- ➢ Common trend in comparing primary and secondary masses and radii of an exponential fit to the power of around 3.2
- ➢ Linear fit when plotting mass versus radius ratio
- ➢ Before plot from had best fit line equation of 1.01x + 0.023[1], now I propose a more accurate trend of 1.17*x - 0.0544
- ➢ First time compiling stellar mass-radius relation for these eight eclipsing binary targets
    - ○ Typically is time consuming and data is difficult to normalize using usual method, due to high activity in data from light
    - ○ Through many different attempts, I developed a method utilizing cross-correlation fitting and the monte-carlos method along with widgets to adjust parameters, simplifying this difficult task from laborious manual work to automatically completed by a computer
- ➢ A more accurate trend for low-mass eclipsing binaries is identified (providing around 33% more data), allowing more accurate estimates of stars

Conclusions, Achievements, and Future Work

Conclusions

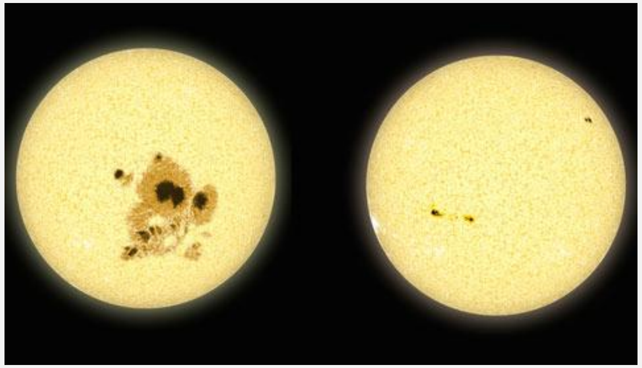
- Trinary (SB3): KIC11244501
- Background binary: KIC3459199, KIC8478994
- Binary: KIC11922782 (SB2), KIC3120320 (SB2), KIC5630212 (SB1)
- Binary with heartbeat star: KIC9163796
- Background binary with brown dwarf: KIC8848288
- Calculated periods from fit matched MARVELS and Kepler databases, proving that other parameters extracted must be accurate too
- Calculated mass ratio q through binary orbit fits and secondary mass by utilizing the mass ratio formula
  - Primary masses found from Vizier database
- Calculated radius ratio through transit fitting, program outputs radius ratio along with secondary radius
- Included more data for low-mass eclipsing binaries

Achievements

- I found a new trend for low-mass targets comparing mass and radius, providing 33% more new data
- I developed a MCMC + CCF method which allows people to tell mass/radius of low-mass star without tedious, time consuming manual work which often needs a ton of methods to complete
- I discovered rare star systems (trinaries, binary with heartbeat stars, and brown dwarf binary)
- I improved the accuracy of parameters for eclipsing binaries in Kepler and MARVELS (sometimes even by around 10 days)
- Our knowledge on stellar evolution enhanced for low-mass eclipsing binaries through improvement of stellar mass-radius relationship estimates
- My work strengthens future astronomers' knowledge on star evolution and formation, allowing us to answer puzzling questions about our universe

Future Work

- Analyze more eclipsing binaries to improve accuracy of trend
- Study star spots discovered on one of the stars



- Find location of star spots through program
- Analyze special star systems and attempt to fit with a new special fitting program
  - Heartbeat star system
  - Trinary
  - Eclipsing binary with brown dwarf
- Complete research papers
- Continue improving my method, possibly implement artificial intelligence

References

[1] Lopez-Morales, Mercedes. “On the Correlation between the Magnetic Activity Levels, Metallicities, and Radii of Low-Mass Stars.” The Astrophysical Journal, vol. 660, no. 1, 2007, pp. 732–739., doi:10.1086/513142.

[2] Fleming, Scott W. A Long-Period Benchmark Eclipsing Binary From MARVELS, Jan. 2012.

[3] Gilster, Paul. “A Rare Brown Dwarf Eclipsing Binary.” Centauri Dreams - Imagining and Planning Interstellar Exploration, 11 Mar. 2020 ,www.centauri-dreams.org/2020/03/11/a-rare-brown-dwarf-eclipsing-binary/.

[4] Aliçavuş, Fahri, and Faruk Soydugan. “Precise Analysis of Two Kepler Detached Eclipsing Binary Stars KIC 3327980 and KIC 10156064.” 2017, doi:10.1063/1.4976435.

[5] Hoyman, B, and Ö Çakırlı. “High-Resolution Spectroscopy of Detached Solar-Type Eclipsing Binaries Observed during the Kepler K2 Mission.” Monthly Notices of the Royal Astronomical Society, vol. 493, no. 2, 2020, pp. 2329–2338., doi:10.1093/mnras/staa439.

[6] Beers, Timothy C. “The Chemo-Dynamical History of the Milky Way as Revealed by SDSS/SEGUE.” Proceedings of the International Astronomical Union, vol. 5, no. S265, 2009, pp. 453–460., doi:10.1017/s1743921310001250.

[7] Fischer, D. A., et al. “Exoplanet Detection Techniques.” Protostars and Planets VI, 2014, doi:10.2458/azu_uapress_9780816531240-ch031.

[8] Torres, G., et al. “Accurate Masses and Radii of Normal Stars: Modern Results and Applications.” The Astronomy and Astrophysics Review, vol. 18, no. 1-2, 2009, pp. 67–126., doi:10.1007/s00159-009-0025-1.

[9] Morales, Juan Carlos, et al. “THE EFFECT OF MAGNETIC ACTIVITY ON LOW-MASS STARS IN ECLIPSING BINARIES.” The Astrophysical Journal, vol. 718, no. 1, 2010, pp. 502–512., doi:10.1088/0004-637x/718/1/502.

[10] Morris, Brett M., et al. “The Starspots of HAT-P-11: Evidence for a Solar-like Dynamo.” The Astrophysical Journal, vol. 846, no. 2, 2017, p. 99., doi:10.3847/1538-4357/aa8555.

[11] Maxted, P. F., et al. “Precise Mass and Radius Measurements for the Components of the Bright Solar-Type Eclipsing Binary Star V1094 Tauri.” Astronomy & Astrophysics, vol. 578, 2015, doi:10.1051/0004-6361/201525873.

[12] Fleming, Scott W., et al. “ECLIPSING BINARY SCIENCE VIA THE MERGING OF TRANSIT AND DOPPLER EXOPLANET SURVEY DATA—A CASE STUDY WITH THE MARVELS PILOT PROJECT AND SuperWASP.” The Astronomical Journal, vol. 142, no. 2, 2011, p. 50., doi:10.1088/0004-6256/142/2/50.

[13] Stassun, Keivan G., et al. “Accurate Empirical Radii and Masses of Planets and Their Host Stars with Gaia Parallaxes.” The Astronomical Journal, vol. 153, no. 3, 2017, p. 136., doi:10.3847/1538-3881/aa5df3.

[14] Maxted, P. F., and R. J. Hutcheon. “Discovery and Characterisation of Long-Period Eclipsing Binary Stars from Kepler K2 Campaigns 1, 2, and 3.” Astronomy & Astrophysics, vol. 616, 2018, doi:10.1051/0004-6361/201732463.

[15] Moya, Andy, et al. “Empirical Relations for the Accurate Estimation of Stellar Masses and Radii.” The Astrophysical Journal Supplement Series, vol. 237, no. 2, 2018, p. 21., doi:10.3847/1538-4365/aacdae.

[16] Stassun, Keivan G., and Guillermo Torres. “ECLIPSING BINARY STARS AS BENCHMARKS FOR TRIGONOMETRIC PARALLAXES IN THEGAIAERA.” The Astronomical Journal, vol. 152, no. 6, 2016, p. 180., doi:10.3847/0004-6256/152/6/180.

[17] Del Burgo, C, and C Allende Prieto. “Testing Models of Stellar Structure and Evolution – I. Comparison with Detached Eclipsing Binaries.” Monthly Notices of the Royal Astronomical Society, vol. 479, no. 2, 2018, pp. 1953–1973., doi:10.1093/mnras/sty1371.