Physical Parameters of KID 6131659, a Low-Mass, Double-Lined Eclipsing Binary

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Credits

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  • AST-0808145
  • AST-0850564 (REU grant to San Diego State)

• Kepler Guest Observer Program

• Kepler Science Team, W. J. Borucki, D. G. Koch et al.
Organization of Talk

• Binary stars
  – How binaries are detected
  – What information they provide
• Low-mass stars
• The Kepler mission
• KID 6131659 Results
• Conclusions and Future Work
Binary Stars

- After the invention of the telescope (around 1609) it was quickly found that some stars that appear single to the naked eye appear double in the telescope:
  - Mizar (ζ Uma), Riccioli 1650
  - q Ori, Huygens 1656
  - a Cru, Fotenay 1685
  - a Cen, Richaud 1689
  - g Vir, Bradley 1718
  - Castor (α Gem), Pound 1719
  - 61 Cygni, Bradley 1753

Image Courtesy: Ian Morison
Binary Stars

- After the invention of the telescope (around 1609) it was quickly found that some stars that appear single to the naked eye appear double in the telescope:

- At first they were just thought to be two stars whose positions on the sky happened to be close.

- In 1767, John Michell showed statistically that the closeness was not due to chance, and that most pairs represent real physical pairs.
Ways to Identify Binaries

• Visual
  • Observe (possibly with a telescope) two stars very close to each other orbiting

• Astrometrics
  • Observe one star's motion through space being altered by an unseen companion

• Spectroscopy
  • Observe one or both star's spectra shifting in response to the other

• Eclipses
  • Observe a decrease in light as one star eclipses the other
Visual Binaries
Astrometric Binaries

- As stars in binaries move through space relative to Earth, they do not do so in a straight line.

- Even if one of the stars is substantially brighter than the other, if the dimmer star has an equal or greater mass, its existence can be inferred by its effects on the brighter star.

Spectroscopic Binaries

- Recall that radial velocities can be measured from Doppler shifts in the spectral lines:

- Here are two spectra of Castor B, taken at two different times. The shift in the lines due to a change in the radial velocity is apparent.
Spectroscopic Binaries

• In some cases, you can see both stars in the spectrum.

• In most cases, you can only see one star changing its radial velocity in a periodic way.

• When you can see both stars, it is called a “double-lined” spectroscopic binary
Spectroscopic Binaries

- The radial velocity of each star changes smoothly as the stars orbit each other.
- These changes in the radial velocity can be measured using high resolution spectra.
Center of Mass

For two objects orbiting a common center of mass, \( m_1 r_1 = m_2 r_2 \)

Also, note that velocity of the star is proportional to the distance to the center of mass since a star further from the COM has a greater distance to cover in the same amount of time. This implies \( m_1 v_1 = m_2 v_2 \), or \( m_1 / m_2 = v_2 / v_1 \)

The ratio of the velocities is inversely proportional to the mass ratio. Also, the same is true for radial velocities.
If you can see both stars in the spectrum, then you may be able to use Doppler shifts to measure the radial velocities of both stars. This gives you the mass ratio of both stars regardless of the viewing angle (e.g. nearly face-on, nearly edge-on, etc.). However, you cannot get the total mass just spectroscopically.
Eclipsing Binaries

• In 1783, John Goodricke showed that the variations in Algol were periodic: it gets about 2 magnitudes fainter than normal every 68.8 hours. Two possible reasons:
  • Algol had an unseen body in orbit about it with a period of 68.8 hours.
  • Algol had dark spots which came into view every 68.8 hours.

• H. C. Vogel showed in 1890 that Algol was a spectroscopic binary with a period of 68.8 hours. The primary was receding just before eclipse, and approaching just after eclipse.
Eclipsing Systems and Stellar Radii

- The relative radii is related to much light is blocked, and for how long.
- This also depends on the separation of the two stars.
Eclipsing Systems and Stellar Radii

- The relative radii can be found by studying looking at the length of the eclipse

- The ratio of the eclipse duration will be related to the ratio of radii

Image from Nick Strobel's Astronomy Notes (http://www.astronomynotes.com)
Accurate Masses and Radii From Binary Stars

- Double-lined eclipsing binaries offer the best-known and best-tested means of measuring stellar masses and radii.
  - Generally need RV curves of both stars to constrain masses.
    - Need luminosities to be similar to within a factor of a few.
    - Need relative Doppler shifts > resolving power.
  - Generally need mutual eclipses to constrain radii.
    - Need two or more bandpasses, if only single bandpass is available then $R_1 + R_2$ is constrained, not $R_1$ and $R_2$ separately.
    - “Third light” causes systematic errors.

- There are around 100 well-studied systems with main-sequence stars.

- Since the stars can be assumed to be coeval, one can test evolutionary models.
The stars form a tight sequence. This provides a test for stellar models.

For a main-sequence star, high mass means high luminosity...  
...while low mass means low luminosity.
Eclipsing Binaries

- Models for solar type stars (between about 1 and 3 solar masses) generally work well

Pols et al. (1997)

Figure 2. Comparison of the best-fitting isochrones to the observational data for YZ Cas [24], in case of the STD (solid lines) and OVS models (dashed lines). The left panel shows the mass–radius diagram, and the right panel log $T_{\text{eff}}$ versus log $R$, which is equivalent to the HR diagram (lines of constant luminosity running diagonally). The ZAMS is shown as a dash-dotted line.
• Models for low-mass stars (between about 0.3 and 0.8 solar masses) generally DON’T work well.
Low Mass Stars

• Low-mass stars with good radius measurements are generally larger than predicted by evolutionary models.
• The disagreement can be 5-15%.
• Kraus et al. (2011) added a few systems where the disagreement is less.
• Ribas (2006) notes that the models do tend to accurately predict the mass-luminosity relationship.
• The combination of these two facts means that the temperature must be the exact amount lower than the models predict to result in the same luminosity.
• This implies that the models are accurately modeling the stellar interior, but are having problems with the stellar atmosphere.
Observational Limitations

- Low mass stars are inherently hard to observe
- Low intrinsic luminosities require more powerful telescopes to detect spectral lines
- Both stars must be low mass, or the high mass star will overpower the lower mass star
- Double-lined eclipsing binaries are rare, and difficult to find
- Need perfect orientation
- Need long continuous observations to detect eclipses

All well studied low mass double-lined eclipsing binaries as of 2005 (Ribas 2005)
Low-Mass Stars

- The sample contains short-period binaries (less than 3 days with most a day or less)
  - Tidal forces causes the stars to rotate faster
  - Faster rotation leads to increased stellar activity
  - ???
  - The stars get “puffed up”

- To test this theory, we need long-period binaries
  - The stars should be slowly rotating
  - The stellar activity should be reduced
  - The theory predicts that these stars should match theoretical predictions (e.g. the mass-radius relationship)
The Kepler mission

• The Kepler telescope is a 0.95 meter reflecting mirror with a field of view of 105 square degrees.

• It points at the same field because it's in an Earth trailing orbit

• 150,000 stars are observed continuously

• Has incredible photometric precision and stability
Kepler Eclipsing Binaries

- The Prsa et al. (2011) catalog contains 1832 binaries identified in the *Kepler* Q0 and Q1 data
- Nearly complete light curves (duty cycle of 90% or better)
  - Can easily find long-period systems
- Very precise light curves (much better than mmag in most cases)
  - Can easily assess the stellar activity level

- There are dozens of candidate systems with low-mass stars (Coughlin et al. 2011)
Kepler Eclipsing Binaries

KID 10935310 (P=4.1289 d)

KID 8736245 (P=5.0705 d)

KID 9821078 (P=8.4296 d)
Kepler Eclipsing Binaries

KID 5731312 (P=7.9445 d)

KID 2719873 (P=17.2749 d)

KID 6131659 (P=17.5255 d)

Scaled counts/cadence

Time (BJD−54,000)
Kepler Eclipsing Binaries

- Sample of 9 low-mass binaries, three are spot-free
  - Want deep primary eclipses, low crowding values
  - Want KIC $T_{\text{eff}} < 5500$

- Ground-based follow-up
  - HET echelle spectroscopy ($R=30,000$), about 60 observations
  - Photometry from MLO 0.6m and 1.0m, 39 nights covering primary or secondary eclipses

- Results
  - One spectroscopic triples
  - Two single-lined systems
  - One good system – KID 6131659
Binary Complications

• Earlier, I discussed how to get mass and radius ratios from double-lined eclipsing binaries

• However, the combined masses and radii (and thus individual masses and radii) are a bit more complicated to get

• They depend on various factors, including the inclination and eccentricity of the orbit. Although they can be calculated analytically for the non-eccentric, inclination=90° case, for other cases, there is no analytic solution to the orbit

• In addition, the presence of background stars in the field of view can add further ambiguity
ELC

• ELC is a code developed to efficiently search the parameter space of a binary system.

• For a binary, there are a number of unknown parameters, including the masses and radii of the stars, the inclination of the system towards Earth, the eccentricity of the orbits, the temperatures of the stars, the presence of a third light, etc.

• ELC takes values for all of these parameters and then produces a corresponding light curve and/or radial velocity curve.

• These can then be compared with the actual observed light curve and compared to see how good the parameter values were.
Machine Learning

- ELC also has machine learning algorithms, including genetic algorithms and Markov chains that search the parameter space to find the parameters that best match the observed light curve.

- Since different machine learning algorithms have different strengths and weaknesses, they are typically used subsequently to eventually converge on the best values.
Initial Steps

- Detrend and scale
- Divided into period long segments
- Gives uncertainties
ELC tries to use various computational shortcuts where possible to calculate values analytically rather than doing numerical integration.

For our first runs, we treated the stars as perfect spheres, ignoring gravitational distortions, and simpler limb-darkening laws.

We also set eccentricity to be equal to zero to run in analytic mode to get a reasonable first guess.

Then, we used those answers as a starting point to run again, this time allowing a non-zero eccentricity, and distorted stars and doing numerical integration to produce our final values.
### Results

<table>
<thead>
<tr>
<th>Param</th>
<th>Min</th>
<th>Max</th>
<th>Best Fit</th>
<th>1-σ</th>
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<tbody>
<tr>
<td>$T_{\text{conj}}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>$\text{arg}$</td>
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<td>$t_{1}$</td>
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<td>5800</td>
<td>5762.86</td>
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<tr>
<td>$t_{3}$</td>
<td>4000</td>
<td>5700</td>
<td>4888.80</td>
<td>11.38</td>
</tr>
</tbody>
</table>

- Very small, but non-zero eccentricity, inclination
- There is a third light ($t_{3}$) that has been corrected for
- Uncertainties in general are tiny
Results (continued)

- Masses and radii have incredibly low uncertainties
- Barring some sort of systematic error
- Rotational velocities are unresolved in the spectra (less than 18 km/s)
- Values here assuming synchronous
- As was expected for long period system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
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<tr>
<td>r1</td>
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<td>m2</td>
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<td>r2</td>
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<tr>
<td>VRot2</td>
<td>1.878875</td>
<td>0.000354</td>
</tr>
</tbody>
</table>
Results

\[ M_1 = 0.93 \, M_{\text{sun}} \], \; R_1 = 0.89 \, R_{\text{sun}}, \; \quad M_2 = 0.69 \, M_{\text{sun}}, \; R_2 = 0.65 \, R_{\text{sun}} \quad \text{Errors < 2%} \]
Results

![Graph showing the relationship between radius and mass for different ages (1.0 Gyr, 2.0 Gyr, 4.0 Gyr, and 8.0 Gyr). The graph includes markers for various stars, such as KOI 126, YY Gem, CM Dra, V568 Lyr, UV Psc, CG Cyg, RW Lac, RX J0239.1-1028, GU Boo, 2MASS J05162881+2607387, and HS Aur.]
Results

![Graph showing the relationship between mass and radius over different ages (1.0 Gyr, 2.0 Gyr, 4.0 Gyr, 8.0 Gyr). The graph includes symbols and markers for various stars like KID 6131659, KOI 126, YY Gem, CM Dra, V568 Lyr, RX J0239.1-1028, GU Boo, UV Psc, 2MASS J05162881+2607387, CG Cyg, CU Cnc, RW Lac, and HS Aur.]
Conclusions and Future Work

• Low mass stars in long-period binaries with low stellar activity seem to fit evolutionary models much better
  • Have already seen hints from Kraus et al. (2011) and Coughlin et al. (2011)

• Future work
  • Can continue to use long-term Kepler coverage to measure robust uncertainties as more data is publicly released (e.g. will have dozens more eclipses)
  • Do a few more systems in addition to KID 6131659
  • Carefully correlate activity levels and other properties to radius excess
  • Better understand the process in which magnetic activity causes the star to expand
Thanks!

• To my advisor: Jerome Orosz
• To my committee: Jerome Orosz, Douglas Leonard, and William Welsh
• To my collaborators: Jerome Orosz, William Welsh, Gur Windmiller, Trevor Gregg, Tara Fetherolf, Richard Wade
• To all of you: for coming!