Three Pre-Main-Sequence Eclipsing Binaries in the Orion Nebula Cluster

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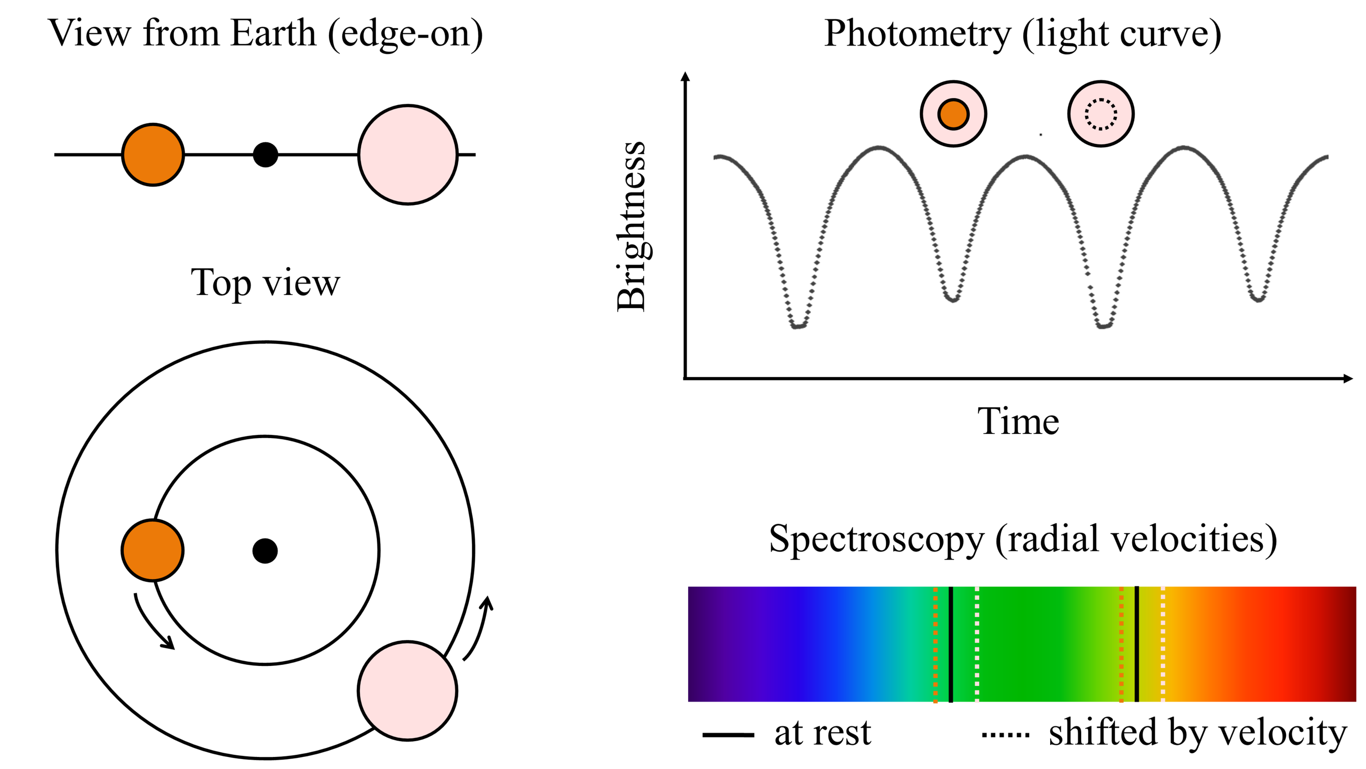
Abstract

There is still much that is not known about the earliest stages of stellar evolution. Pre-main-sequence (PMS) stars are highly dynamic objects, and their internal structures change rapidly as they accrete material and contract towards the main sequence. To ensure that theoretical PMS models are properly calibrated, it is important to test them against a dense grid of PMS objects with well-measured properties. Eclipsing binaries (EBs) are especially useful probes of stellar evolution models because their high inclination and close separation allows for the radii, masses, and effective temperatures of both stars to be constrained via photometric and spectroscopic analysis. Previous work by Morales-Calderón+2012 contributed to PMS model calibration efforts by providing an initial characterization of six PMS EBs in the Orion Nebula Cluster. We present further constraints on the properties of three of these systems and discuss implications for theoretical PMS models.

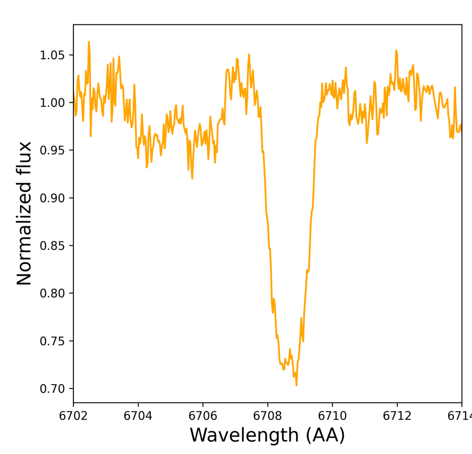
Measuring the Parameters of Eclipsing Binary Systems

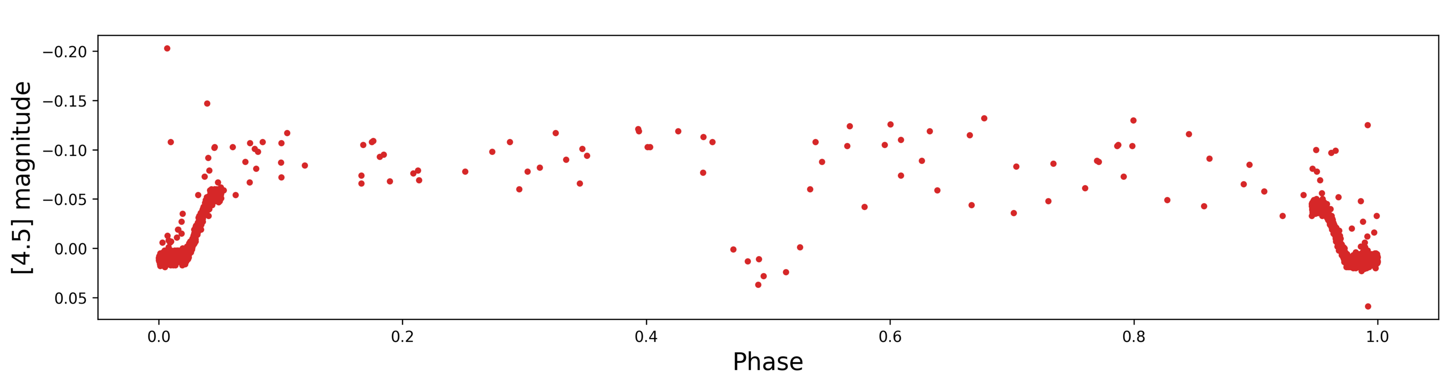
In an eclipsing binary system, two stars are gravitationally bound to orbit a shared center of mass. To measure the masses, radii, and effective temperatures of the individual stars in the system, two types of data are needed. **Photometric data** (usually depicted as a light curve) measures how the total brightness of the system changes over time. The dips in the light curve correspond to points where one of the stars in the system has eclipsed the other star, and the sizes of these dips can be used to determine the sizes of the stars. **Spectroscopic data** measures the spectrum of the system, where it is possible to see spectral lines from the presence of different elements in the stars' atmospheres. Sometimes the spectrum will display two sets of lines (one for each star); sometimes one star dominates the spectrum and only one set of lines is visible. In either case, as the stars move, these lines appear redshifted or blueshifted by an amount proportional to the stars' radial velocities. By taking several spectra at different times and modeling the changes in the radial velocities, it is possible to determine the masses of the stars.



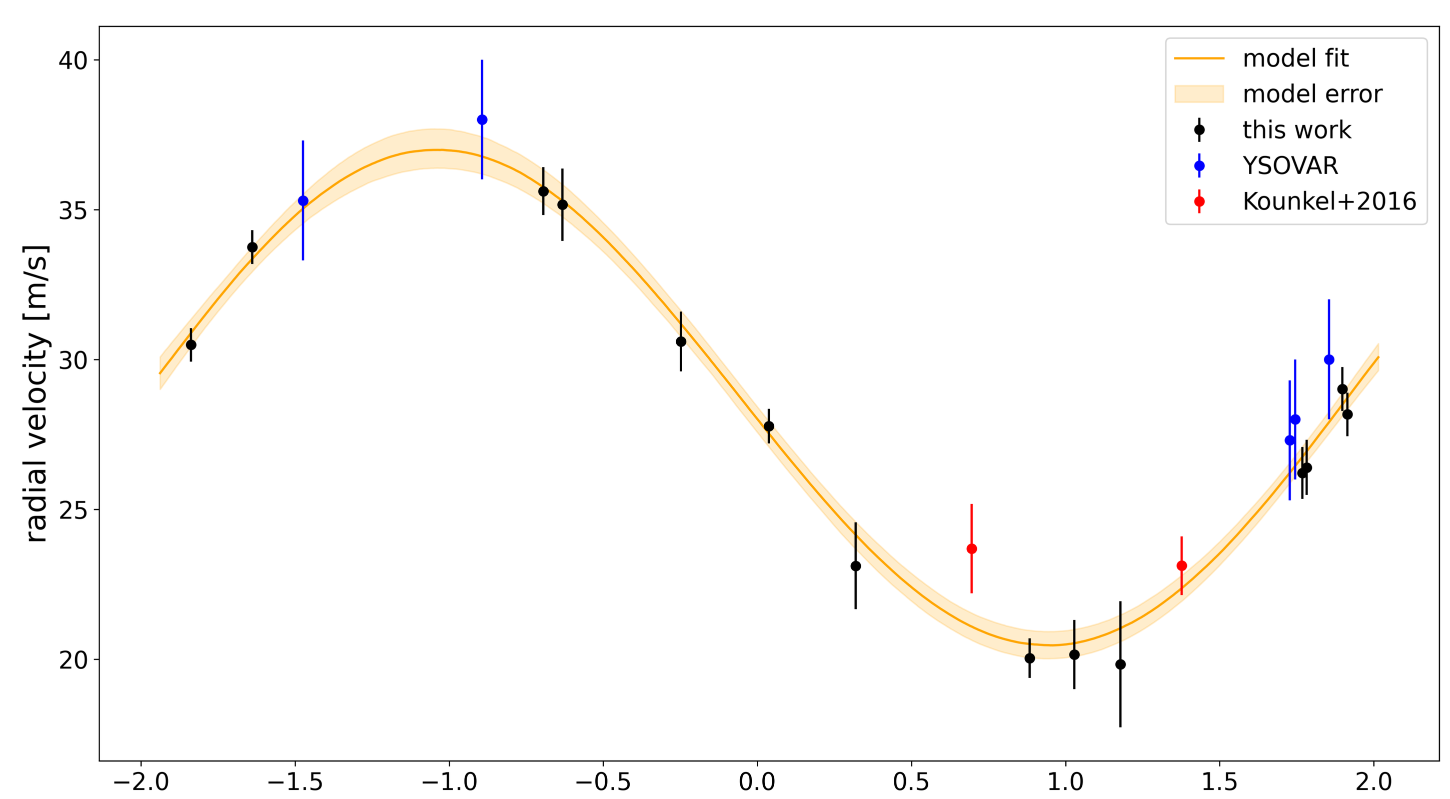
Ori3227 (ISOY J0535-0447)

We have a total of 14 Keck HIRES spectra and 4 light curves (I, J, Spitzer [4.5], and Spitzer [3.6]) for Ori3227. The system is a single-lined eclipsing binary, as shown in the example Li line at right. Both the primary and secondary eclipses are clearly visible in the light curves, with the best example being the Spitzer [4.5] curve (shown below). Morales-Calderón+2012 measured a period of 3.905625 days for this system, which we have been able to confirm with a Lomb-Scargle periodogram analysis. We also measured the radial velocities of the system for each spectral epoch by performing cross-correlation analysis on several spectral regions and averaging the results.



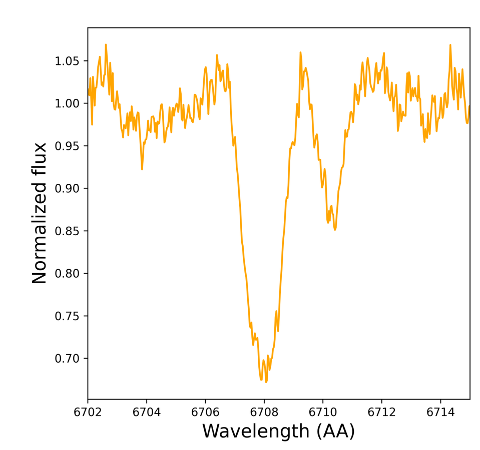


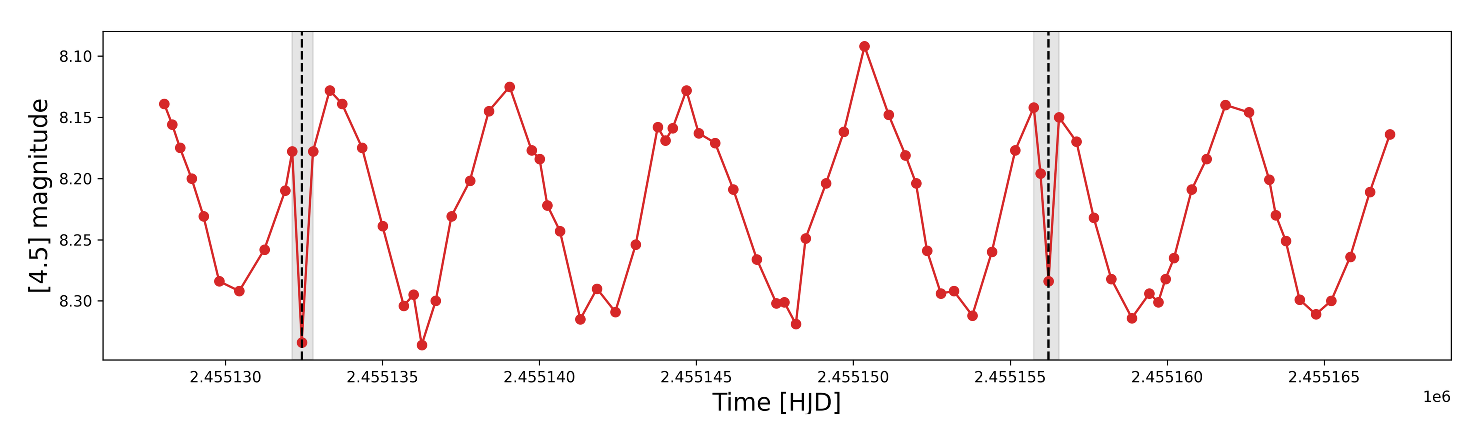
Additional radial velocities were available in Morales-Calderón+2012 and Kounkel+2016. We used the `exoplanet` package (Foreman-Mackey+2021) to fit all available measurements. The radial velocities and the resulting fit are shown below. We obtain a zeropoint velocity of 28.689 ± 0.232 km/s and a semimajor amplitude of 8.301 ± 0.416 km/s.



Ori40003 (ISOY J0535-0525)

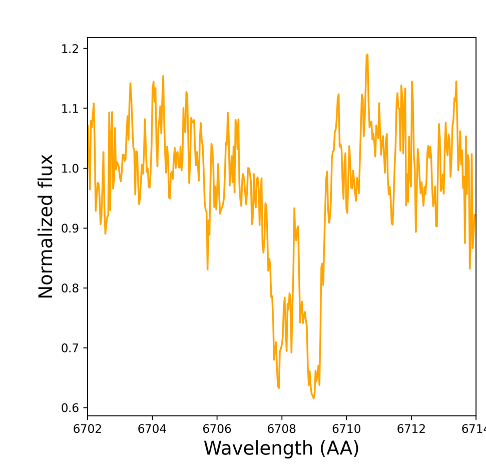
We have a total of 14 Keck HIRES spectra and 4 light curves (I, J, Spitzer [4.5], and Spitzer [3.6]) for Ori40003. The system is a double-line eclipsing binary, as shown in the example Li line at right. Morales-Calderón+2012 do not provide a period for this system. Lomb-Scargle periodogram analysis recovers a rotational period of 5.75129534 days; the only indication of the orbital period is the presence of two eclipses in the Spitzer light curves (shown below) which are ~24 days apart. RV measurements for this system are currently in progress.

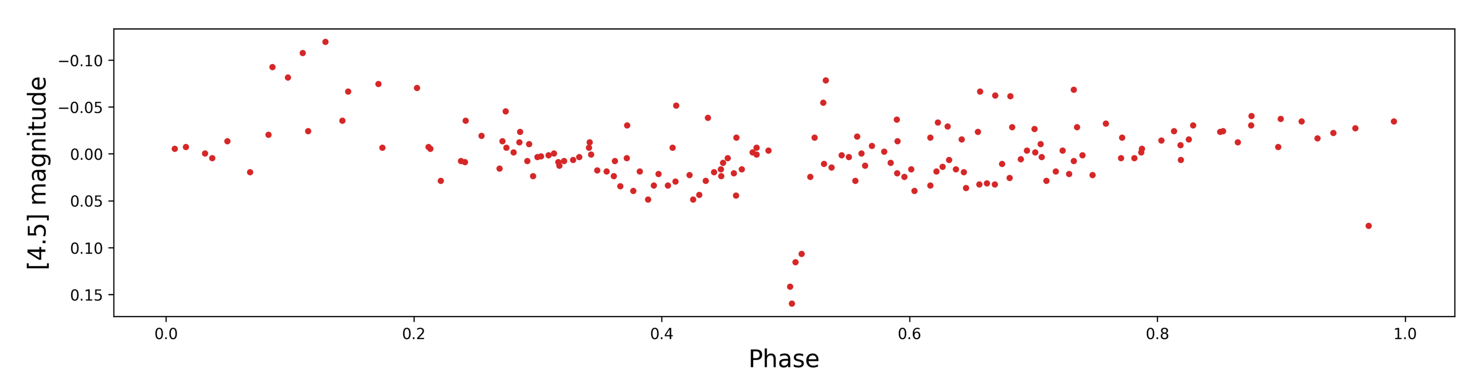




Ori40134 (ISOY J0535-0523)

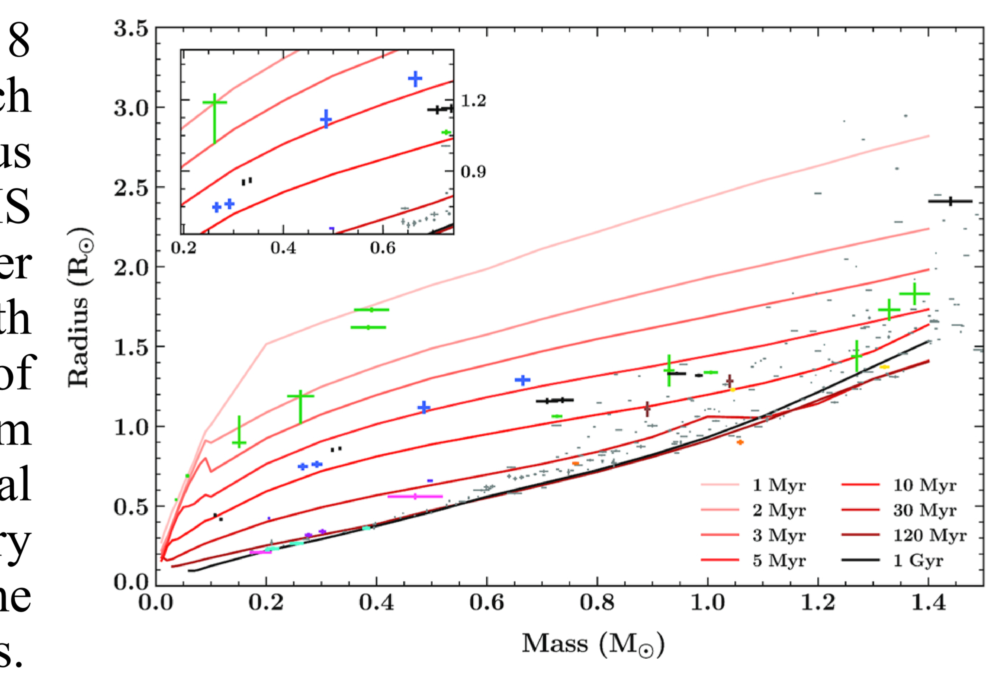
We have a total of 12 Keck HIRES spectra and 6 light curves (I, Spitzer [4.5], and Spitzer [3.6] from our own efforts; and J, H, and K obtained via private communication with Tom Rice) for Ori40134. The system is a double-lined eclipsing binary, as shown in the example Li line at right. Morales-Calderón+2012 measure a tentative period of 20.485 days, but we have not been able to confirm this with Lomb-Scargle periodogram analysis. RV measurements for this system are currently in progress.





Implications for Stellar Evolution Models

Shown here is Figure 8 from Gillen+2020, which displays the mass-radius relation of known PMS EBs (at the time the paper was written) along with theoretical models of stellar evolution from Baraffe+2015. Additional PMS EBs are necessary to refine and ensure the accuracy of these models.



Though the results of my work are preliminary, possible contributions from each of the three systems studied here are as follows:

Ori3227: The fact that only one set of lines is visible in the spectra implies that one member of the system is much smaller than the other. Preliminary fitting of the RV curve appears to confirm this result. Morales-Calderón+2012 notes that the smaller member of this system may be a brown dwarf, which would be an exciting result given that there are only a few known objects in that mass regime.

Ori40134: An RV solution will be necessary to fully characterize this system, but Morales-Calderón+2012 note that the long period may mean the system is not spun up by tidal effects, a rarity among PMS EBs. If this is confirmed, this system will provide an important test of the relationship between magnetic fields, rotation, and stellar radii.

Ori40003: Both an RV solution and a more accurate period estimate will be necessary to fully characterize this system. If the long period is confirmed, this system may be an additional example of an EB with radii that have not been inflated by tidal effects.

Though additional work is required to constrain the parameters of these systems, it is clear that they will constitute an important addition to the current census of PMS EBs and the mass-radius models shown above.

Key References

[1] Morales-Calderón, M.; Stauffer, J.R.; Stassun, K.G.; et al. (2012). "YSOVAR: Six pre-main-sequence eclipsing binaries in the Orion Nebula Cluster." *The Astrophysical Journal*, no. 753 (2).

[2] Foreman-Mackey, D.; Luger, R.; et al. (2021). "*exoplanet*: Gradient-based probabilistic inference for exoplanet data and other astronomical time series." *Journal of Open Source Software*, no. 6 (62).

[3] Gillen, E.; Hillenbrand, L.A.; et al. (2020). "Mon-735: a new low-mass pre-main-sequence eclipsing binary in NGC 2264." *Monthly Notices of the Royal Astronomical Society*, no. 495 (2).