Eclipsing Binary Stars as Astrophysical Laboratories

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I would like to split this talk into two parts. First, I will explain my own research interests, eclipsing binary stars, and give you some idea why astrophysicists and astronomers find them to be so valuable. They play an important role in understanding the nature and evolution of stars. I also want to share with you some of the research that students and I are doing here at Juniata College on eclipsing binary star systems.

My research interests lie in observational astronomy. Students and I work at telescopes taking images and observing the stars themselves. When we look at the night sky, I think most people see it as a symbol of constancy, permanence, and eternity — never changing, always the same year after year. In fact, many stars, hundreds of thousands of stars, are not constant. They change their brightness over time, and they are called variable stars. These cycles of variability can range in period from seconds to years or even decades. Variable stars come in all sorts of flavors and types. You have probably heard of a supernova, a really dramatic type of variable star. But the type I am interested in falls under the category of extrinsic variables, because the variability is not a part of a star itself. The stars in the system are not changing in brightness, but the system as a whole is changing in brightness. So the change in brightness is not intrinsic to the star, but belongs to the system.

Many of the stars in our galaxy come in pairs, or even multiples — triplets and quadruplets. Estimates vary, but most people agree that half or more — let's say 50–70% — is the estimate for how many stars you see in the sky that are actually parts of binary systems. Most of these binary stars are fairly close to each other. So when we see them in the sky, most of the eclipsing binary pairs are much too far away to distinguish or resolve into two stars. They appear to our eyes, with our low resolution, as a single star. Even with powerful telescopes, the stars we study here at Juniata are not resolvable into individual stars. You can only tell they are binaries because of their eclipsing nature.

To say it the right way, a binary star system is a gravitationally bound pair of stars that orbit around their center of mass. You could also say they orbit each other. The center of mass in this image is the red cross in the center (Figure 1). These stars happen to be following elliptical orbits, but stars in binary pairs can also follow circular orbits. They have to orbit in the same plane. In this image, we are

looking down on the plane of the orbits, and you'll notice that these stars never block each other. You will always see both stars all the time. If you were observing this binary system, it would give off a constant amount of light, even though the stars would change position.
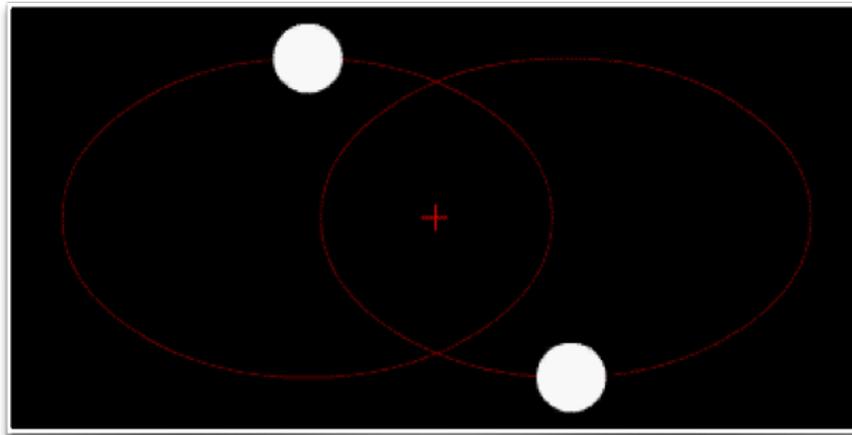
Figure 1. Two stars in a binary star system orbiting a common center of mass (red cross). (Public domain, http://en.wikipedia.org/wiki/Binary_star#mediaviewer/File:Orbit5.gif)

If you imagine taking this view and tilting it, so that instead of looking at it from above, you are looking at it from the side, you have changed the angle of inclination. Then twice per orbit, one star will block the other star (Figure 2). First, star A will block star B, and then B will block A, and it happens over and over again. That is an eclipsing binary star system. The inclination angles of binary star systems are completely random, and just a few percent of them are at the right inclination to exhibit eclipses.

How do we tell that? Again, it's very hard to see the individual stars — to resolve them. We most often just see a single point of light. But we can measure the brightness of the star system. When the stars are side by side, you see the light from both stars at the same time. When one crosses in front of the other, you get a dip in the amount of light you receive — it will dim. This dimming could range from a few percent to maybe ten, twenty, or thirty percent. In other words, it is anywhere from really hard to tell to really easy to tell.

We usually have two different dips, because most often the stars are two different temperatures, and they are emitting different amounts of light. When the brighter star is blocked, you get a bigger dip, and when the dimmer star is blocked, you get a shallower dip. We call them primary and secondary eclipses. And this repeats over and over again. What we are looking at here is a sketch of the light curve, which is a plot of the brightness versus time (Figure 2).
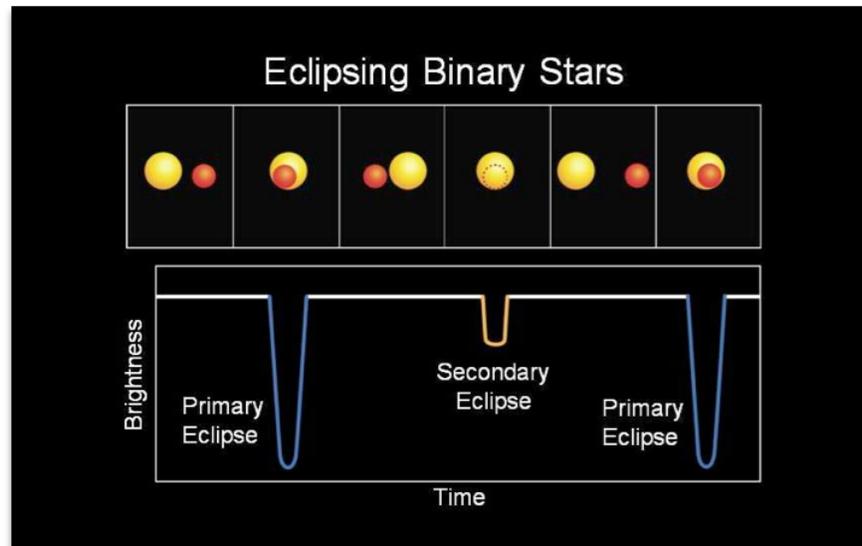
Figure 2. Representation of a light curve for an eclipsing binary star system (bottom) as it depends on the positions of the two stars in the system (top). (Public domain, http://en.wikipedia.org/wiki/Variable_star#mediaviewer/File:Light_curve_of_binary_star_Kepler-16.jpg)

One well-known binary star is Algol. It is in the constellation Perseus, which is high in the sky in the winter. It is visible any evening we don't have clouds, which is about once a month this time of year. Algol happens to have a period of about 2.8 days. It's a neat project to try to predict when the eclipse will happen. If you watch Algol compared to the stars around it, you can actually see its brightness dim. It takes a few hours to go through that dimming and brightening process. In the course of an evening, you can watch the whole eclipse with your own eyes.

Algol was the first known eclipsing binary star, discovered in the 1600s. Actually, I just read a suggestion that the Egyptians might have known about Algol and its period. That's an interesting study that we don't have time to go into, but they have a cycle in their calendar that corresponds to the period of Algol or a multiple of the period of Algol, suggesting that they might have known about that thousands of years ago.

Perseus is best known for slaying the Gorgon Medusa. And so from the 1600s, there are beautiful pictures with Medusa's head being held here, and one of her eyes is Algol (Figure 3). Every few days the severed head winks at you in a deliciously creepy kind of way. That has nothing to do with astrophysics — just a neat connection there to history and mythology.
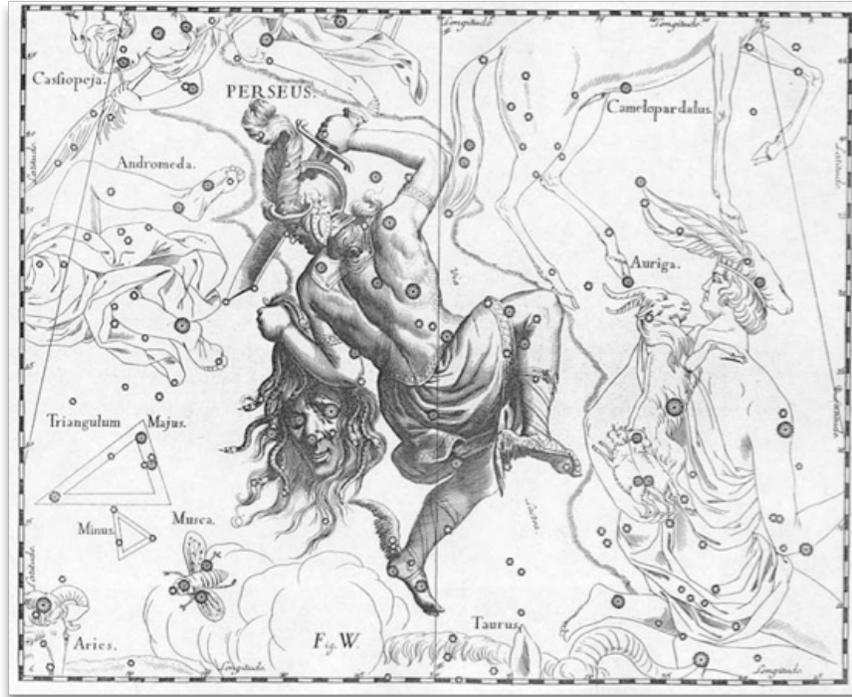
Figure 3. An illustration of the constellation Perseus by Johannes Hevelius (1689). (Public domain, http://commons.wikimedia.org/wiki/File:Perseus_Hevelius.jpg)

Now I want to get to the astrophysical laboratory side of the talk. What do I mean by that? Maybe it goes without saying that we can't do experiments on stars. You can't build a star in the laboratory and poke it, prod it, or change it to see what happens. It's just impossible. So we have to rely on the galaxy to provide the experimental data for us. Thankfully, there are millions of eclipsing binaries out there in all sorts of shapes and sizes and flavors. We have lots of examples, and they have proven to be very valuable to astrophysics.

When you observe a single star, a non-binary and isolated star, like our Sun, and you observe it from a distance, the only thing that you can detect is starlight, which will tell you how bright the star is. One way to figure out how bright a star is involves taking an image of the star using a telescope and camera and then using a computer program that measures the brightness of the star. The brightness of the star is related to its luminosity — how much energy it gives off each second. Alternatively, you can take the starlight and pass it through a prism. You get beautiful spectra, which are full of information. The first and most important thing you can learn is the temperature of the star.

$$L = 4\pi\sigma R^2 T^4$$

Equation 1. The Stefan-Boltzmann law relating the luminosity L, the temperature T, and the radius R.

So we have the star's luminosity and temperature. Great! That's important information. We can go a step further: from the Stefan-Boltzmann law (Equation 1), we can get the radius of the star as well. The Stefan-Boltzmann law tells us that the luminosity of the star is the product of a bunch of constants times the radius of the star squared, times the surface temperature raised to the fourth power. If your measurements of the star tell you the luminosity and the temperature, then you can calculate the radius of the star. Now we have three key pieces of information about the star.

I couldn't give a talk about astrophysics without introducing the Hertzsprung-Russell diagram (Figure 4). There's a lot going on in the diagram, but what we are seeing is a plot of luminosity on one axis and temperature on the other. Traditionally, the cool stars are drawn over to the right and the hot stars to the left — backwards, but that's just a historical accident. Every star has a place on the Hertzsprung-Russell diagram. In the upper right corner are giants and super giants, like Betelgeuse and Rigel, which are both in Orion, which is high in the sky right now. You can also see Polaris, a yellow giant star, towards the upper right. Vega and Sirius and other ones you might have heard of are in the middle. It is hard to tell from this graph, but the diagonal lines represent the radius. So, for example, when we look at Sirius we can read off its luminosity, its temperature, and its radius right from that diagram. It is all right there in a compact two-dimensional form. The Hertzsprung-Russell diagram has been fundamental to astrophysics; filling it out, exploring it, and understanding it has really pushed along the understanding of how stars work.

What we are missing here is the mass of the stars. Using spectroscopic techniques and the Doppler shift in the light (the shift in the frequency of the light as the stars move), we can derive the velocity of the stars, or how fast they're moving in their orbits. This technique was developed for binary stars and used to discover extra solar planets — yet another important contribution of eclipsing binary stars! If we use Newton's law of gravitation and Kepler's third law of planetary motion, after lots of derivation we get a couple of equations involving the mass ratio and the sum of the masses of the binary stars. We have two equations and two unknowns, so we can solve for each mass independently. We can calculate the star masses quite accurately, to within a few percent. This is almost the only way to measure individual star masses. For a single star out there on its own in space, we can tell its luminosity, radius, and temperature, but there is no way to tell its mass because it is not interacting with anything. So eclipsing binary stars are key to determining star masses, and that is probably the centerpiece of their importance to astrophysics.
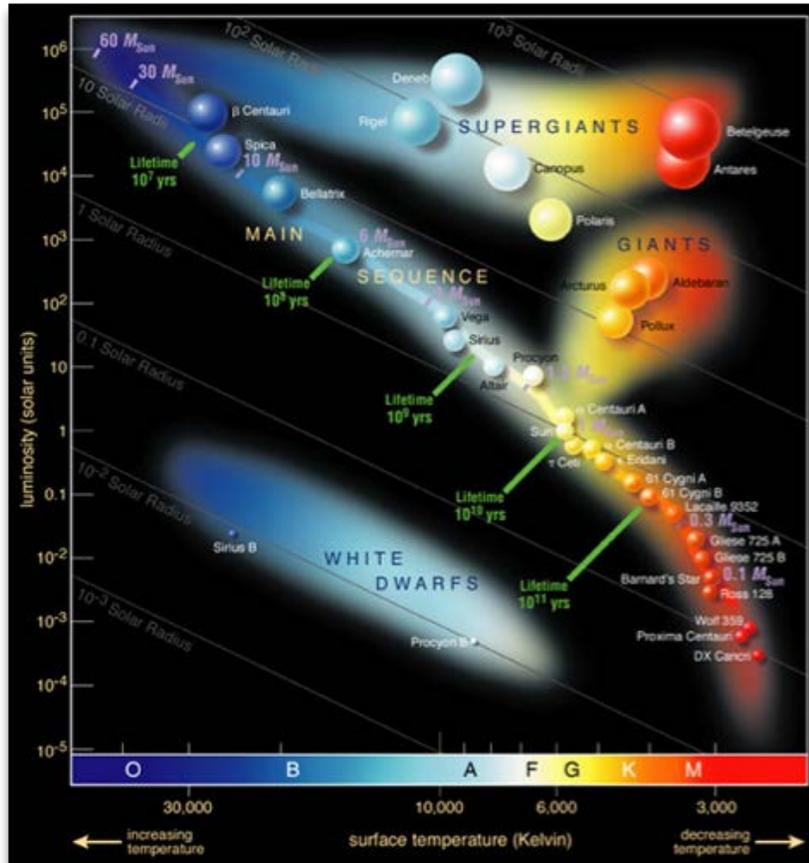
Figure 4. The Hertzsprung-Russell diagram plots stellar luminosity versus star surface temperature. (Creative commons, http://en.wikipedia.org/wiki/Hertzsprung–Russell_diagram#mediaviewer/File:Hertzsprung-Russel_StarData.png)

For example, once the individual masses of binary stars were calculated using this method, it was found that there is a clear-cut, almost linear relationship between luminosity and mass. So in practice, you can choose any old star, whether it is isolated or not, measure its luminosity with telescopes, and then read the mass from a graph of mass versus luminosity. So when we say we know a star's mass, what we really mean is that we know its luminosity, and we use this relationship, which came from studies of eclipsing binary stars, to get its mass.

A star's mass tells you just about everything you need to know about it. If we know a star's mass, we can determine all of its other properties — its surface temperature, luminosity, and lifetime. Stars' lifetimes depend on their mass. In short, the more massive a star is, the more it squeezes gravitationally, and the hotter its core gets, and the faster fusion takes place in the core, and the faster it uses up the hydrogen fuel that powers stars. When the fuel is used up, the star's life is over. The more massive a star is, the more luminous it is, the hotter it is, and the shorter it lives.

To put this in a different way, all stars begin as clouds of gas and dust in space. From those clouds of gas and dust, material coalesces. As it contracts, it heats up. It eventually gets hot enough for nuclear fusion to take place in the core, and the star is born. There are distinct evolutionary tracks on the Hertzsprung-Russell diagram for low-mass stars and for high-mass stars. Low-mass stars eventually swell into red giant stars, and then they shed their outer layers as a planetary nebula and leave a white dwarf at the center. A high-mass star also swells up into a giant, but it explodes as a supernova and its core becomes either a neutron star or a black hole. A star's mass determines its life cycle.

An astrophysicist would say that stellar evolution is very well understood. (This is evolution in the sense of a single star's evolution through its life, not in the sense of Darwinian evolution of a species.) It has been worked on for over a hundred years. You tell me what a star's mass is and I'll tell you what the rest of its lifetime is going to be. Remember that the masses only come from the studies of eclipsing binary stars. That's one way that eclipsing binary stars are astrophysical laboratories. They allow us to derive the important parameters, as you might in a laboratory. It's a bit of an old story now, but its importance to astrophysics cannot be overstated.

I am going to turn back now to eclipsing binary stars in particular. This is just a reminder that eclipsing binary stars are two stars orbiting in such a way that one blocks the other as you see it from Earth (Figure 2). Again, this is a light curve, which plots brightness versus time. That's really the first level of experimental work. If there is an eclipsing binary star we are curious about, we have to measure its light curve and then we go from there. Light curves are different for different eclipsing binary stars, and each curve reflects the shape of the stars in the system.

What we have in Figure 5 is a diagram of two stars. The curves are equipotential surfaces, or lines of equal gravitational potential energy. In other words, it is like two gravitational wells with the stars sitting in the bottoms, a little bit like two valleys side by side. This figure eight is like a road that runs around the mountains at a fixed altitude. It defines a surface of constant gravitational potential. The stars are down there in the valleys, a little bit like lakes in mountain valleys.
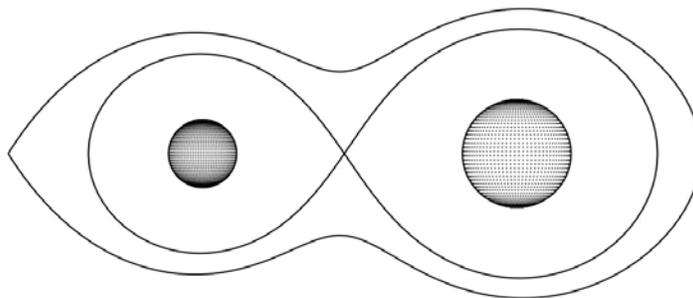
Figure 5. A model of the eclipsing binary star EE Pegasi. The curves around the two spherical stars are equipotential surfaces, known as Roche lobes.

Let's extend this metaphor a little more. When you fill up the lakes in the bottoms of those valleys, you will get lakes that are more or less circular if the valleys are circular in shape. The water will sit in the bottoms of the valleys and not move, in the same way that stars remain in the bottoms of their gravitational potential wells. This figure eight is called a Roche lobe after Édouard Roche, the mathematician who derived the formula for it. And the center point is important: this Lagrangian point is a point of equal potential between the two stars. If you balanced a piece of matter right there, it would be perfectly balanced between the two stars. In the same way, if you had a rock at the center point of a figure eight mountain road with a valley dropping off in each direction, the rock could sit there in a state of equilibrium.

In an experimental light curve (Figure 6), each dot represents one measurement of the eclipsing binary's brightness. Here it is plotted as flux, the total amount of light hitting the detector. The primary minimum is easily recognizable, as is the secondary minimum. The solid line is just the best fit to the data. This light curve tells me right away that the stars must be well separated from each other because first there is the primary eclipse, then a long time of no eclipse, and then the secondary eclipse. These stars must therefore be well separated, or detached, as we say in the lingo. Also, the difference in the depths of the minima tells me that the two stars are at very different temperatures. This is called an Algol type, after the star Algol, because it looks like Algol's light curve.
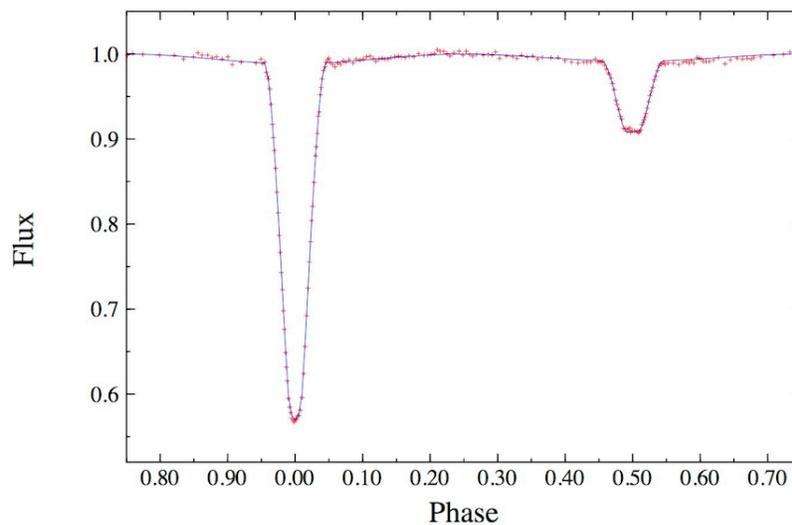
Figure 6. The light curve of the star EE Pegasi. Experimental data are shown as red crosses, and the best fit model is shown as a blue line.

As mentioned earlier when talking about stellar evolution, when a star run out of its nuclear fuel, it begins to swell up into a red giant. It is like a lake filling up a valley. The star begins to grow in size, it

begins to fill the Roche lobe, and eventually it gets to the point where the lake fills the valley and starts to reach that overflow point, the road between the two valleys. Here is a binary star system with one ordinary star and one red giant star (Figure 7, left). The red giant star's shape is determined by the Roche lobe — by the potential well it is in. Just like the surface of that lake would be a teardrop shape, the star is a teardrop shape. And what is really neat is that any material that overflows the gravitational well can end up rolling down the other hill and into the other star. Mass can actually transfer from one star to the other, leading to changes in the light curve. Now we have a more rounded-out eclipse maximum and the values of the two minima are closer to being equal (Figure 7, right).
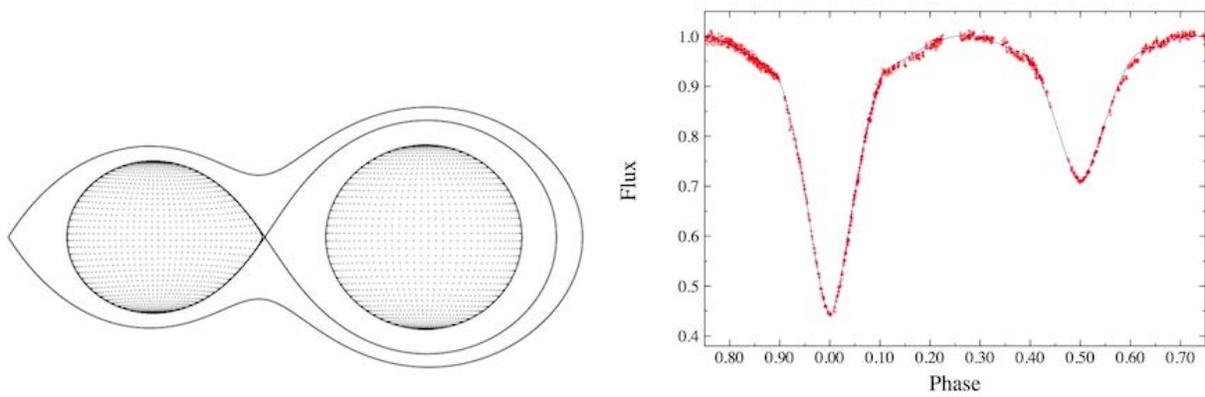
Figure 7. The model (left) and light curve (right) for eclipsing binary star MR Cygnii. This is an example of a semidetached binary star system.

As this process continues, the second star swells up and fills its Roche lobe, and we get what we call a contact binary (Figure 8). In a contact binary, both stars fill the Roche lobes, maybe even overflow them, and they are essentially merging together. They equilibrate to the same temperature, so the difference in the values of the two minima of the light curve is not as great. Also, because the stars are so close to each other, they are almost always in eclipse. Therefore, you get a kind of W-shape in the light curve. Figure 8 is what you might see if you were looking at the star system from only one hundred million miles away. They really are touching – kissing, so to speak, and sharing material between them. One of my students refers to these as "space peanuts." But these are star-sized objects like our sun — two of them literally touching and whipping around two or three times a day. They are really dramatically energetic systems.
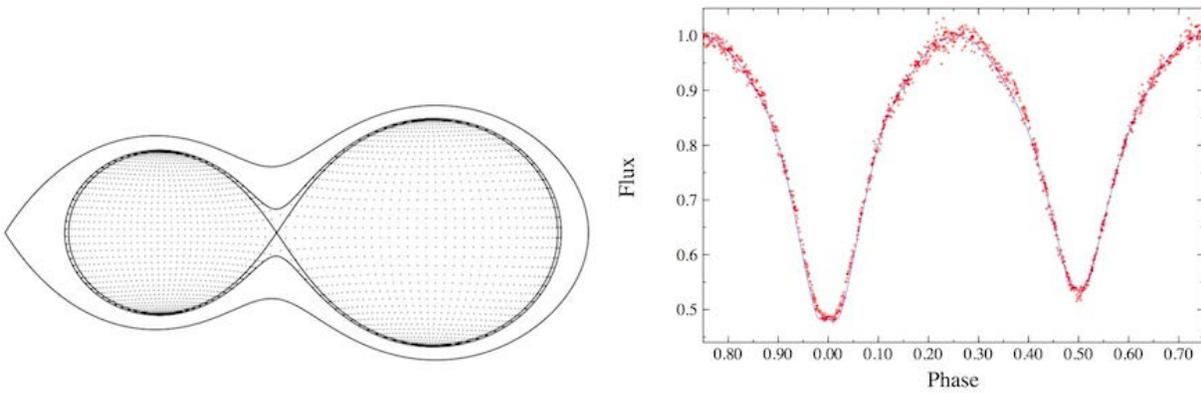
Figure 8. The model (left) and light curve (right) for eclipsing binary star AB Andromedae. This is an example of a contact binary star system.

Typical rates of mass transfer between binary stars are something like one Earth mass per year — the total amount of mass equal to that of the Earth every year, for millions of years. Fortunately, stars have billions of Earth masses worth of material, so they don't really notice it until a long time has gone by. Still, one star in the system is losing mass and the other star is gaining mass. Imagine an astrophysicist who has done a calculation for all of these individual stars at a fixed mass, and then tell that astrophysicist to do it again if a star's mass changes over time. That is where we are in 2014. This is the big topic in stellar astrophysics: trying to model stars whose mass is changing over time. The star starts off as a low-mass star and gains mass over its lifetime. It is going to have a very different evolution than one that remained a low-mass star all of its life. That's not something that we can get into now, but this is another area where eclipsing binary stars are astrophysical laboratories. When mass transfer or sharing mass is involved, the behavior of the stars is going to be different than detached binary systems or individual stars, which are more or less on their own, left up to their own devices over time.

I now want to tell you a little bit about a project that I am working on with students at Juniata College. (I have another project with students as well, but I don't have time to go over both projects, so I am going to give one short shrift, and I apologize for that.) The project I want to tell you about begins with the idea that if two stars are side by side, we would expect to get a certain amount of light from them. Let's say they are detached stars, for example, and we receive the maximum amount of light possible because there is no eclipse going on. When the stars move through half an orbit and switch position, we should get the same amount of light from them. We are seeing the other side of the stars. Because the stars are just big glowing spheres, we should expect the same amount of light. So the second maximum — the other maximum — should be the same height, representing the same brightness (Figure 9). And that is what every model of eclipsing binary stars tells us, although in reality it doesn't happen that way.
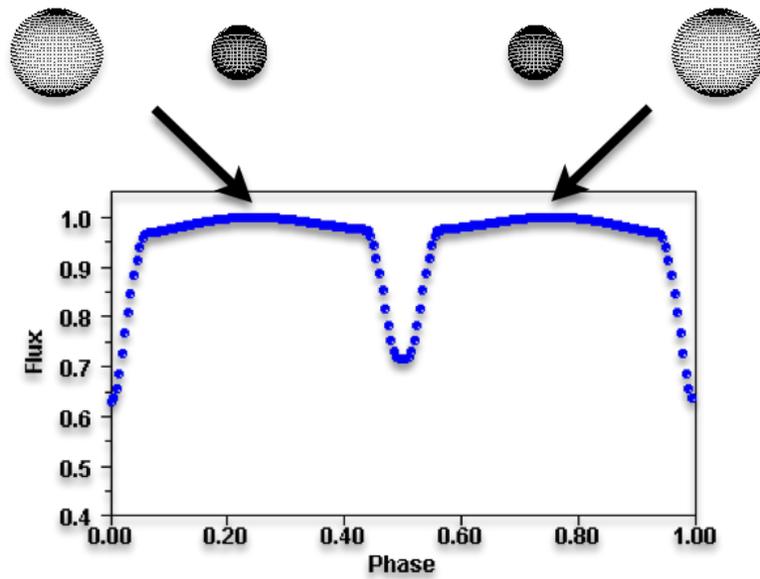
Figure 9. A light curve of an eclipsing binary star system. The arrows indicate maximum light when the two stars are in a side-by-side position.
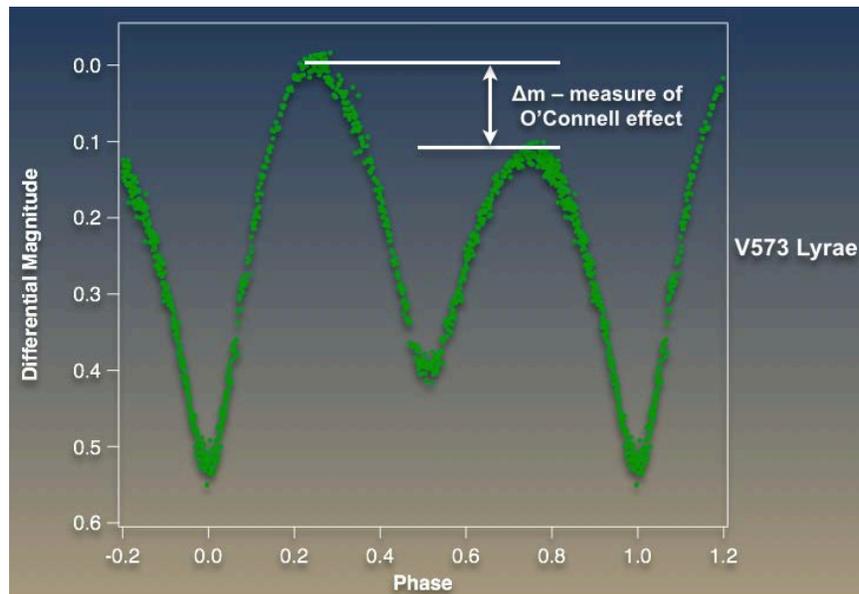
Figure 10. A light curve of the eclipsing binary star system V543 Lyrae.

Some eclipsing binary stars have very different primary and secondary maxima for some mysterious reason (Figure 10). This is referred to as the O'Connell effect, after the person who first talked about it and described it. Delta–m is the difference in the brightness of the maxima of the light curve. Delta-m equal to zero is the case when the primary and secondary maxima are of equal height; the bigger delta-m is, the bigger the difference in those two maxima. As I said, it is a little mysterious. There has to

be something different about one side-by-side configuration and the opposite side-by-side configuration. There is a difference in the observation, so there has to be some physical origin for it. We know that stars can have star spots, which are dimmer and cooler regions of the star. There are some very magnetically active stars that have extreme star spots on them. Our sun is magnetically active and has what we could consider a mild case of sunspots. Star spots appear on stars not exactly at random, but in locations that are unpredictable, and they last for a while. Then they go away and new ones appear.

Let's imagine there are no star spots visible in one side-by-side orientation, but there are star spots visible in the other. Those cooler star spots are less luminous because of their lower temperature, and so we would see less light from the side of the stars that have the star spots on them. That is a perfectly sensible and perfectly reasonable hypothesis, except that we know about star spots best from our sun, which is an isolated star. We can extrapolate from it to other isolated stars, but it is not so clear what happens in binary stars — how the magnetic fields that create the star spots develop and behave, especially if those stars are really close to each other and interacting. In a sense, then, all bets are off and we are back to the drawing board in understanding magnetic phenomena and star spots. So saying star spots are the cause is great. It explains it. But saying that we understand how star spots develop, how they evolve, how long they live, and so on in binary stars — no one has really done that yet.

During mass transfer, the gas that leaves one star forms a gas stream that lands on the other star and possibly forms a hot spot. The mass impact heats up the star, so that hot spot is on one side of the star. There might be a hot spot visible in one side-by-side configuration, making the binary system a lot brighter than in the other side-by-side configuration, where the hot spot is hidden. That is another possible explanation for the O'Connell effect. A third possibility is that binary stars might be surrounded by gas and dust. Dust has the effect of blocking starlight, so in one side-by-side configuration there may be a lot of dust blocking the stars, making them appear very dim, but in the other side-by-side configuration with not so much dust, they may appear brighter. That is yet another way of looking at asymmetry to explain the O'Connell effect.

One way to tackle this problem is by first observing binary stars that exhibit the O'Connell effect, measuring it, and contributing to overall the body of knowledge about these kinds of stars. How do we do that? We do that with telescopes and cameras. Here is our telescope in our observatory at Juniata (Figure 11). We attach to it a fancy and expensive digital camera and take lots of images over time. We analyze them, measure the star's light curve, and hopefully publish our results.

We also share time on the telescope at Lowell Observatory in Flagstaff, Arizona, and we make several research trips there every year. Here is the big telescope, a thirty-one inch telescope — it's pretty cool (Figure 12). We don't actually sit at the telescope. Instead, we have a nice warm, comfortable room with a kitchenette and couches, and we kick back and let the telescope do its thing. We take the images

through different filters. We rotate a set of filters one at a time in front of the camera lens in order to sample different parts of the star spectrum, sort of a very low-resolution spectroscopy.

Figure 11. Telescope (left) and CCD camera (right) at the Paul E. Hickes Observatory on the Juniata College campus.

Figure 12. Juniata College students Caitlin Everhart (left) and Lauren Taylor (right) with the 31-inch telescope at Lowell Observatory in Flagstaff, Arizona.
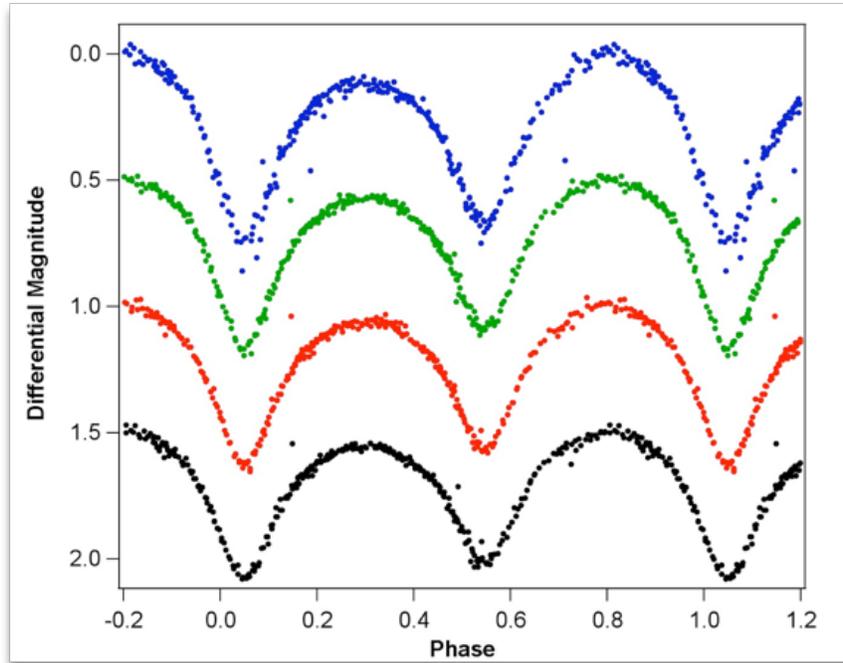
Figure 13. Light curves acquired through blue, green, red and infrared filters (top-bottom) of the eclipsing binary star system V1038 Herculis.
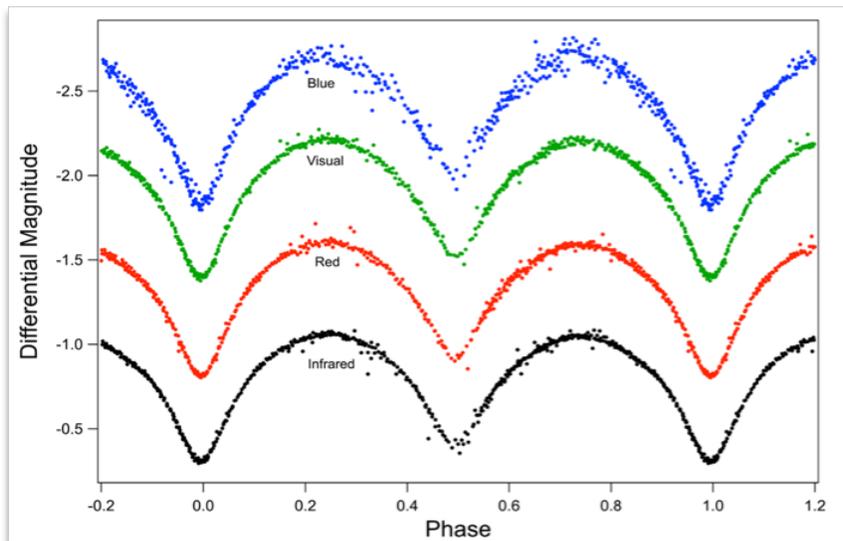
Figure 14. Light curves acquired through blue, green, red and infrared filters (top-bottom) of the eclipsing binary star system SWLacertae.

Here are some examples of data we have gotten (Figure 13). These are eclipsing binary light curves that show the O'Connell effect. You should notice that the two maxima (the two shoulders) are different.

We decided to investigate a star named SWLacertae, and when we measured its light curve, it didn't really show that much of an O'Connell effect (Figure 14). However, we knew that in the past it had

exhibited a very large O'Connell effect. Our measurements from this summer showed roughly equal maxima, but we knew from the literature that there were times when it was much different. What we thought we would do is go back through the past fifty or so years, and extract all that information from the literature and add ours to it, and put together a history of the O'Connell effect for this star, since it has been so well studied over time.

What I have here is a graph of the difference between the two maxima (Figure 15). On the vertical axis is delta-m, the measure of the O'Connell effect. Our measurement was around zero in 2010, but over time you can see it has zigzagged to rather big deviations from that. Clearly this star is going through some kind of process that no one understands very well.
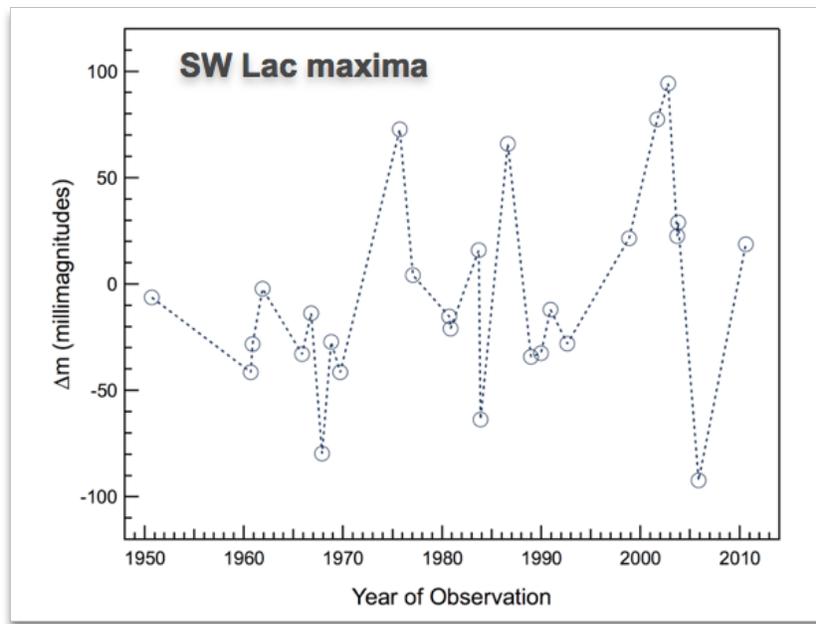
Figure 15. Changes in the difference between the primary and secondary maxima – the O'Connell effect – of the eclipsing binary star system SW Lacertae between 1950 and 2010.

The dramatic change in the O'Connell effect shows that some asymmetry-causing effect is coming and going. We also found through the literature that the difference between the primary and secondary minima also changed, and that was kind of interesting — there is not a lot of mention of that in the literature. Lots of people know about the O'Connell effect, but they always associate it with the maxima. We can also plot the difference in the minima, and they are jumping all over the place, too (Figure 16).

The problem in what we are seeing is that the difference between the maxima — i.e., the O'Connell effect — is changing all the time, but it doesn't answer the question of whether there is any pattern to this. If you are looking for a physical reason, you want to try first to derive or extract some sort
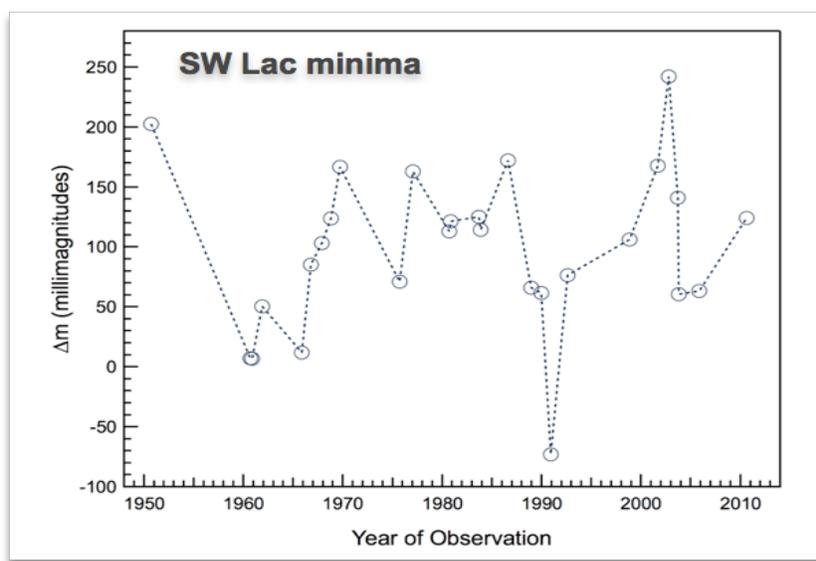
Figure 16. Changes in the difference between the primary and secondary *minima* of the eclipsing binary star system SW Lacertae between 1950 and 2010.

of pattern that you can assign to a cause. What we see is random and irregular. Perhaps the star system is going through a cycle that is very rapid, and we are just randomly sampling here and there at widely spaced intervals, in which case we are never going to see the pattern. What we need is something that will provide us with constant data over a very long time — light curves every day, for example — for years and years, that we can examine without any guesswork. To the rescue, almost like it was made for us, came the Kepler space mission. The Kepler space mission spent three years studying a part of the sky in the constellation Cygnus, looking for extrasolar planets, especially Earth-like extrasolar planets. In the process, it studied hundreds of thousands of stars and found over two thousand eclipsing binaries among those stars. Those eclipsing binaries were very well sampled.

So here is what we did. (I always say we, when it's really the students who do all the work and deserve the credit.) We took a light curve generated by Kepler for a single eclipsing binary star system over the span of three years and sliced it up into every single cycle — every revolution. Then we stitched the individual light curves together into a movie (Video 1). The blue x's are the data, and the red line is a model fit to the data. What I want you to watch are the two maxima. As the movie runs, you can watch those two shoulders change. They seem to be doing it pretty regularly. Notice that the minima are also changing.
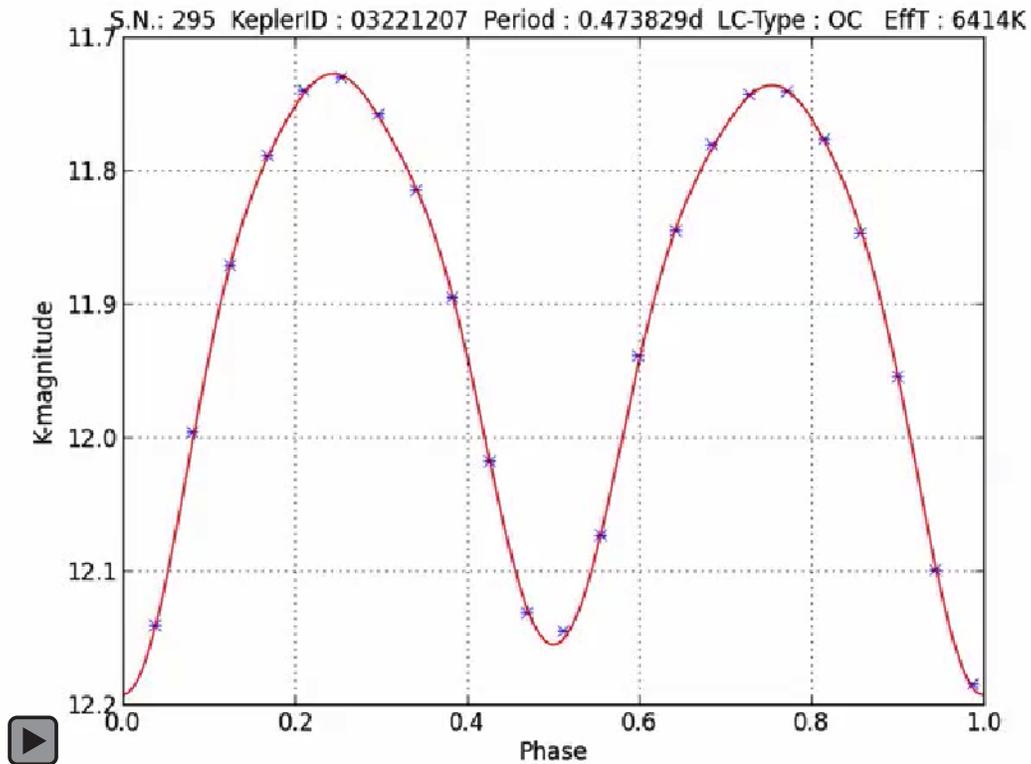
Video 1. Changes in the light curve of an eclipsing binary star system over three years. Move the mouse over the image to see the video controls. This video will play in Adobe Acrobat and in some web browsers.

We next plotted the difference between the maxima, delta-m (Figure 17). Each dot in the upper picture here represents the delta-m value for a single cycle. The red ones are for the maxima and the blue ones are for the minima. What we're looking for is change that has some sort of pattern to it that we can grab onto and work with. This example shows practically no change. The variation is very small, and it is just about noise in the data. Nothing really exciting is going on.
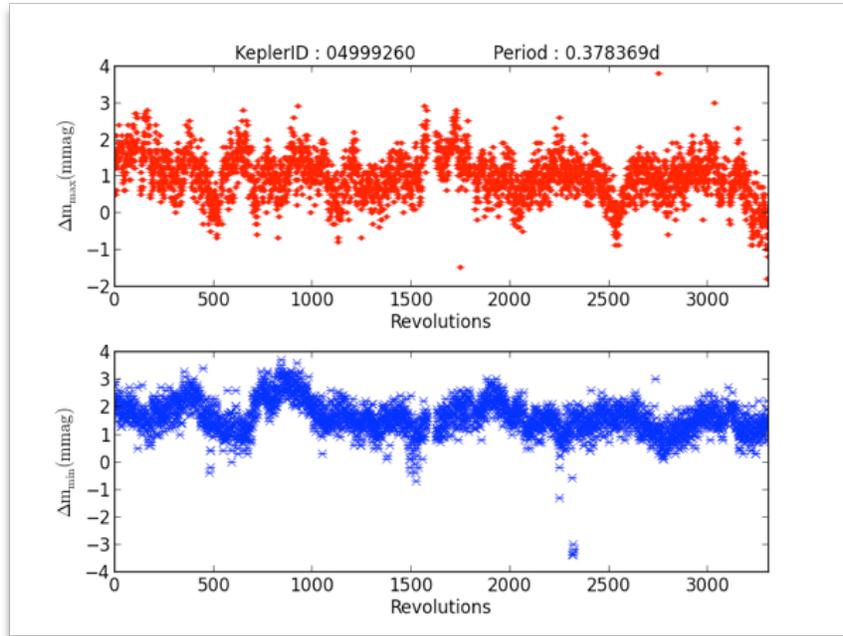
Figure 17. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) of the eclipsing binary star system *KID 4999260* as measured by the Kepler Space Telescope.
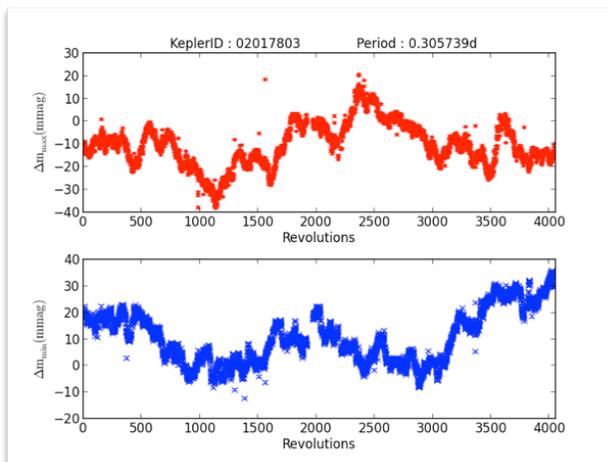
Figure 18. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) of the eclipsing binary star system *KID 2017803* as measured by the Kepler Space Telescope.
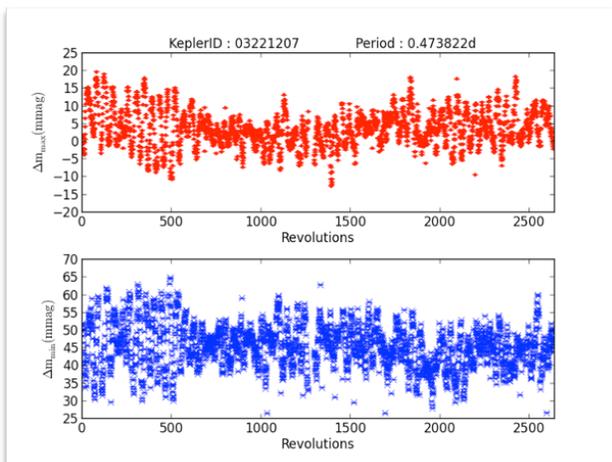
Figure 19. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) of the eclipsing binary star system *KID 3221207* as measured by the Kepler Space Telescope.

Next is an example of one that is changing over time, but in a pretty irregular way (Figure 18). Both the maxima and the minima are changing their relative depths or heights, but in a way that doesn't really grab my attention. Something is definitely going on, but it's a pretty random process whatever it is. Next is one that over almost three thousand cycles, over almost a thousand days, is varying, and we can

see some up and down cycles there (Figure 19). The amplitude is changing in time, but the period of the variation looks pretty constant.

But what really grabbed our attention was this one here (Figure 20). This shows the maxima changing regularly, in a way that you can't see in data taken over random intervals over a sixty-year time span. But you can see it with over three thousand data points over three years. And it is really even better to me that while it seems nice and regular at first, the variation in the maxima goes away for a while as if something changed, like a star spot disappeared or something like that.
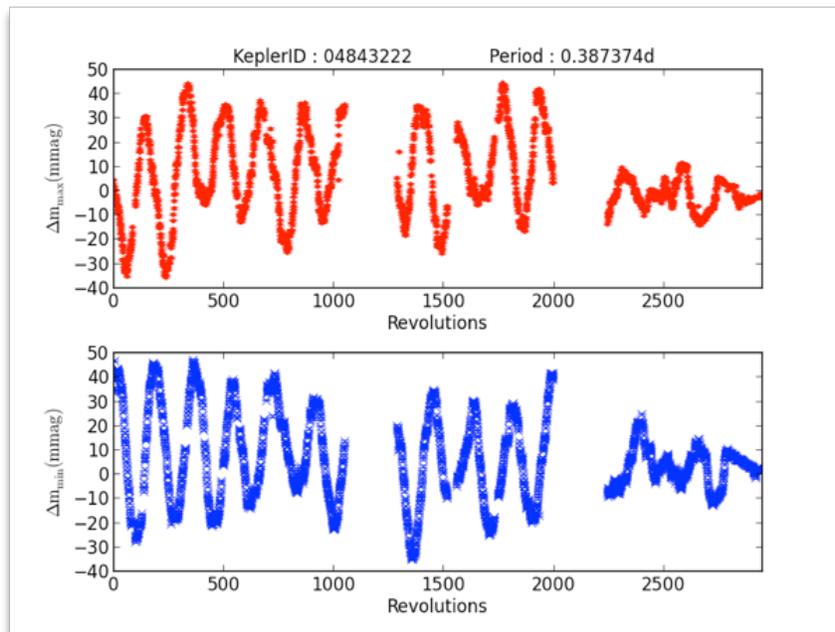
Figure 20. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) of the eclipsing binary star system *KID 4843222* as measured by the Kepler Space Telescope.

By the way, I want to credit the students again for all the hard work on this. It has meant downloading reams of data from the Kepler space mission repository, writing computer code to interpret it, then chopping it up into pieces, and finally analyzing it and fitting it with various fitting programs. It is a lot of work and the end result is impressive. What we're hopefully seeing here is evidence of some process that is causing the O'Connell effect. We're seeing it in motion, in action.

The last step is to use a program called Binary Maker that allows you to create models of binary stars (Figure 21). None of this is actual data — this is just a model. You tell it the parameters of the star in the upper left box and it shows you a picture of the star in the upper right box, a light curve in the lower left box, and a radial velocity curve in the lower right box. The students created a binary star with a star spot on it and let the star spot move around the star (Figure 22). There's no reason why star spots have to be fixed on the star. It starts up top, it disappears around the back of the star, and then it reappears around
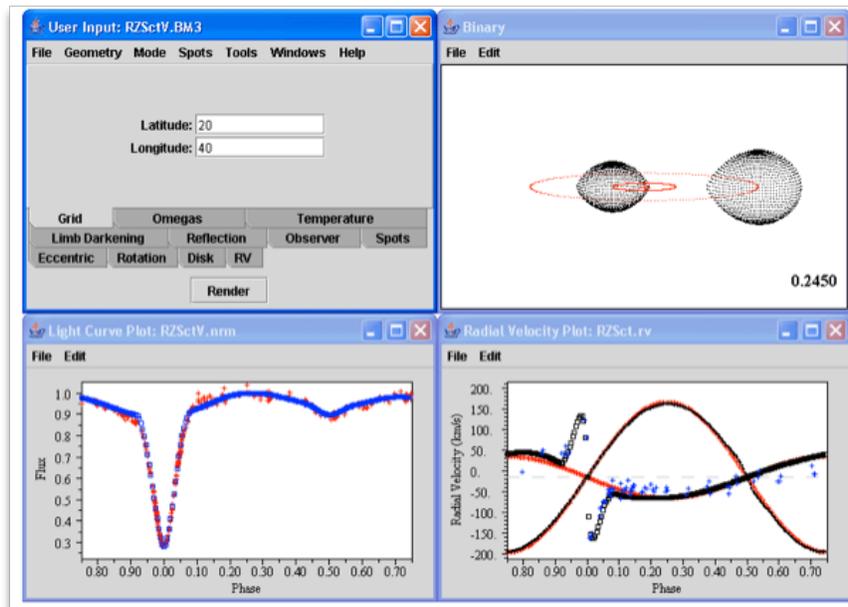
Figure 21. A screenshot of the eclipsing binary star modeling software, Binary Maker 3. Top left: input parameters; top right: binary system model; bottom left: model fit (blue) to light curve data (red); bottom right: model fit (red and black) to radial velocity curve data (blue).
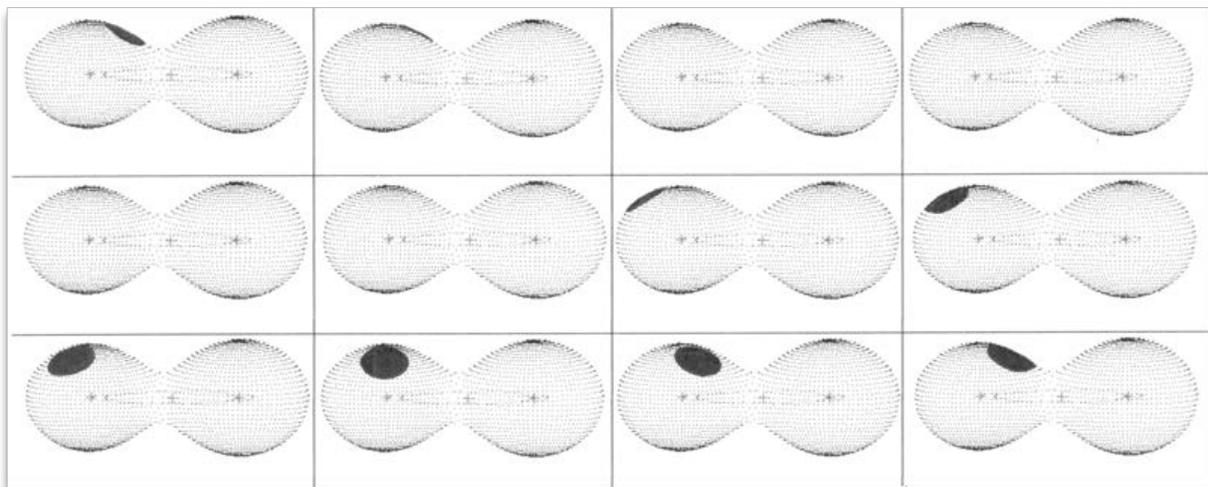
Figure 22. A model of a contact eclipsing binary system generated using Binary Maker 3. A star spot was placed on one star at a latitude of 50 degrees and allowed to migrate in latitude around the star.

the front of the star and returns back to its original position. Model light curves were generated using this model, one for each revolution of the binary system, and the O'Connell effect was measured and plotted for each one.

What we get from the model is a variation in the difference between the maxima and a variation in the difference between the minima. In other words, we see the O'Connell effect in our model (Figure

23). Interestingly, the peak of the difference in the maxima is offset in time a little bit from the peak difference in the minima. When one reaches a maximum, the other is not quite there. If we compare the identical graph for the real star we measured using Kepler data, it looks very much the same to my eyes (Figure 24). We get a variation around zero for the difference in the maxima, and the peak of the difference in the minima is offset in time a little bit from it. I even fooled myself into thinking that the little dip in the third blue peak in Figure 24 is just like a dip in the graph from the model data. I know that it is only one dip so you really can't say that, but I like to think so. And so I think we are on track to say, at least for some stars, that migrating star spots might be a cause of the O'Connell effect, leading to a changing O'Connell effect over time. There's more to be done with this, lots more stars to study in the database, but this is a very good start.
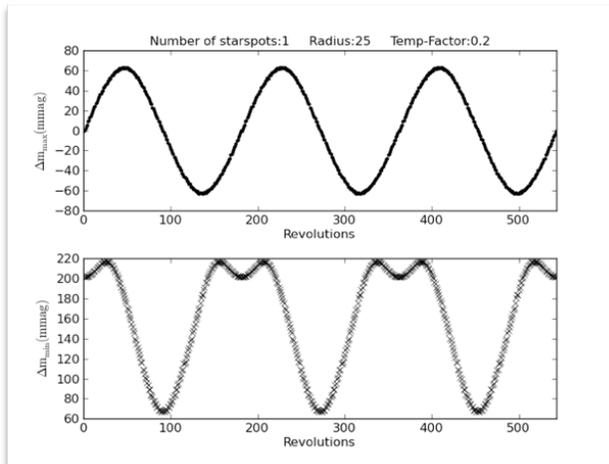
Figure 23. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) for the model eclipsing binary system with a migrating star spot shown in Figure 22.
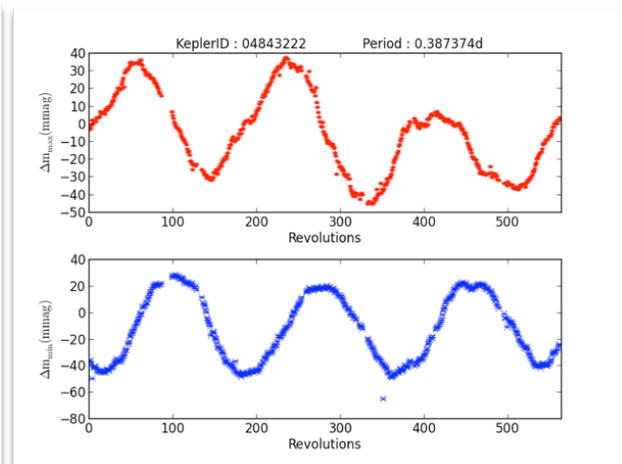
Figure 24. Variations in the difference between the primary and secondary maxima (top) and minima (bottom) of the eclipsing binary star system *KID 4843222* over 500 revolutions.

In conclusion, I hope you now have some understanding of why eclipsing binary stars are important to stellar astrophysicists. And there is still a future ahead of understanding stars by studying eclipsing binary stars, hopefully for decades to come.