The stellar detective – *Tom Richards*

tomprettyhill@gmail.com

Reading the clues in light curves of eclipsing binaries

Part I – finding star sizes

Capturing a light curve of stellar eclipses, transits, or occultations - by stars or planets - can often be done in a single night with electronic imaging. Although sophisticated software is available to help you derive astrophysical information from the light curve, a thoughtful contemplation of it can yield a very great deal of information about the system. This series of articles, based on my presentation to NACAA XXVII, Sydney, Easter 2016, will show how.

Introduction – how do you model an eclipsing binary?

The age of computers and two-dimensional photovoltaic detectors has opened up the study of fast-changing and low-amplitude variables. Today amateurs with very limited equipment (even just a DSLR camera) can make magnitude measurements minute by minute throughout the night, with near to millimagnitude precision. This has revolutionized the study of eclipsing binaries, as well as other types of variables that could not be studied with any precision visually or photographically – either because they changed too quickly or because they changed so little. Even photoelectric photometers, though accurate, could not match the speed which CMOS or CCD cameras could take measurable images. No wonder many amateurs are turning to this fruitful area of variable star research.

In the course of one night, an observer may collect up to 1000 images of a variable, then measure its brightness on all those images the next day in the course of minutes. (Most astronomical camera control and imaging software applications will do this.) The result is a light curve which, for eclipsing binaries, may cover an entire eclipse, or even an entire orbital cycle. Sometimes, for longer period eclipsers, it may be necessary to stitch together the work of several nights to get the entire orbital cycle. Figure 1 is an example, combining measurements from several observers. The orbital period *P* of that system, CU Hya, is 0.719 days.

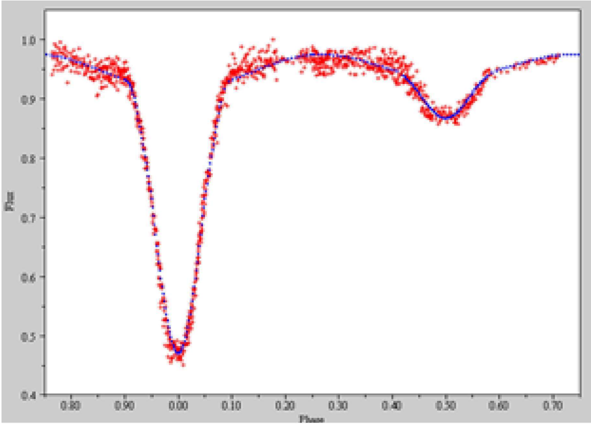

Figure 1. Light curve of CU Hya, derived from CCD observations by several observers. (Richards et al, 2013)

But before even obtaining a full light curve, you can still measure *P* by capturing two or more minima and using software that will find the times of minima in your eclipse curves. So now, armed just with (a) a complete light curve and (b) knowledge of the orbital period, what can you deduce about the eclipsing binary you are studying? The answer is, a surprising amount (and you don't really even need (b).

The light curves of eclipsing binaries are, to a first approximation, determined just by the star shapes and sizes, and their orbit – plus of course the angle of your line of sight to the system. Interpreting a light curve is, to that extent, an intuitively geometrical matter accessible by common-sense reasoning. Forget Euclid and trigonometry. Highly mathematical algorithms do exist for doing a proper modelling job on a light curve, telling you in detail about the star shapes, relative sizes and masses, temperatures, spot cover-age, and much more. Allied with spectra, especially to measure orbital radial velocity, these programs will also calculate the absolute sizes of the stars and the orbital parameters, as well as delivering their spectral classifications. But in these articles we will eschew such sophisticated aids and play Sherlock Holmes, just deducing what we can from what we see. Plus a bit of simple arithmetic here and there.

This is what makes eclipsing binaries such fun – you can find out so much about the stars just from reasoning about the light curves, because the cause of the light curve is mainly geometrical. With other types of variables, such as pulsators, this is not so. The cause of their variation lies deep inside them, accessible only to sophisticated astrophysical theorizing – left to the experts.

So let's make a start with our amateur detective work, and see what we can deduce about the sizes of stars in an eclipsing system.

Star sizes from total eclipses

Once you have a full light curve, it is not hard to estimate the relative sizes of the two stars. Figure 2 illustrates how to use the durations of entry and exit from a total transit (A) or equally, a total occultation (B). The illustration shows a smaller, brighter star and a larger, dimmer star in a system with inclination to the line of sight $i = 90°$ (orbital plane is edge-on). The time to go from position 1 to 2, ingress, given by the left descent of the eclipse, equals the diameter of the smaller star relative to the length of the orbit – as the light curve below the star diagrams reveals. *Assumptions:* the orbit is circular (which it most often is, especially for stars close together); and the direction of the smaller star's movement is across the line of sight, with no line-of-sight component (safe enough if the stars are far apart). (Quick check – if the smaller star were appreciably advancing towards us during ingress, would the time taken for ingress be longer or shorter than to move through its own diameter?)

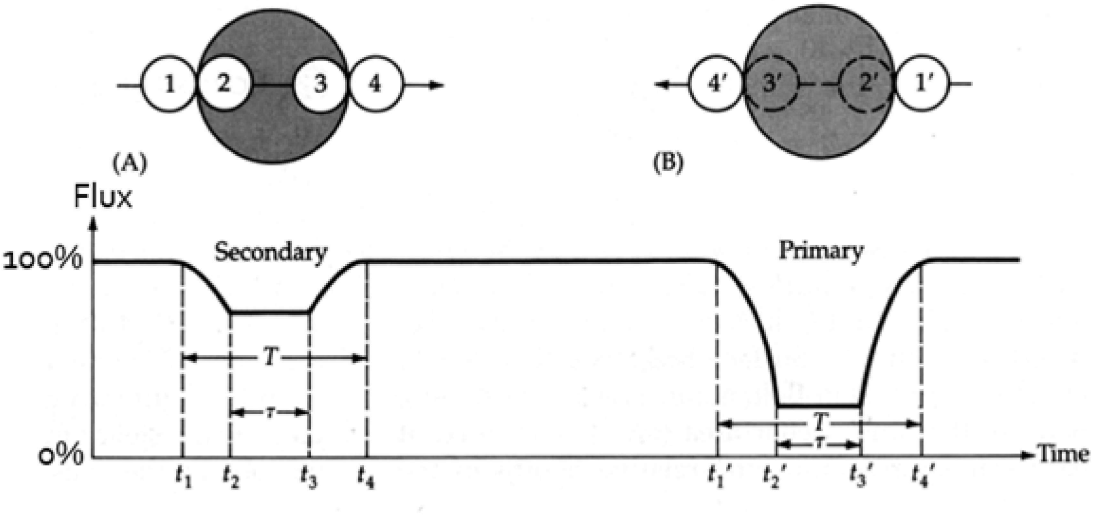

Figure 2. An edge-on (I = 90°) total transit in (A), and total occultation in (B), showing how ingress and egress shapes the light curve ascents and descents

The same sort of deduction shows that the time (relative to P) to move from position 1 to position 3 gives the diameter of the larger star, again relative to the length of the orbit. Note in Figure 2 (B), the geometry of the stars in the primary eclipse is identical to that in the secondary – reversing the stars front to back makes no difference. This symmetry is true independently of I, so ascents and descents in the light curve are *always* of the same duration. Lurking behind that claim is another *assumption*: the stars are radially symmetrical in their brightness distribution across their disks. Starspots for example could distort an ascent or descent curve, widening the shoulder.

For the same geometrical reason, the two totalities must be of the same duration.

Not edge-on?

Plainly, the chance of your light curve representing a binary with $I = 90°$ is very small, even for total eclipses. So what happens in more realistic situations? Figure 3 shows an ingress edge-on (*I* = 90°) and another at a lesser inclination. In the second case, by the time the smaller star has moved through its own diameter, it is still far from second contact (point of first contact is arrowed). So for the ingress time to be the same as the *I* =90° case, it would have to be a much smaller star. Deduction: assuming *I* = 90° the calculated diameter of the smaller star is an upper bound of its actual size (relative to size of orbit of course). (Quick check: We used the *I* = 90° simplification to calculate the relative diameter of the larger star too. Is that an upper or a lower bound on its size?)

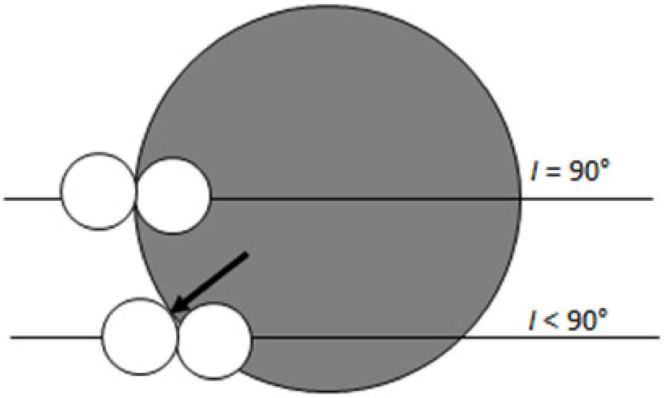

Figure 3. The effect of inclination on time of ingress.

What's the clue for totality?

So now, knowing *P* and just thinking about the geometry of total transits and occultations, you have been able to put limits on the sizes of the stars relative to the orbital length. But how do you know the transits (hence the occultations) were total? Well, looking at the primary eclipse curve in Figure 2, why does it have a flat bottom? It can only be because the smaller star has disappeared completely for that time – a total occultation. If it remained visible during the occultation, never completely hidden, there would be a continuous change in the amount of light it delivers to us. Since the front-to-back orbital geometry is symmetrical, the flat bottom of the secondary eclipse shows the smaller star is transiting across the uniformly bright disk of the larger star; so again there is no change in total brightness. Then how come we have cases like Figure 4, where only the secondary eclipse has a flat bottom?

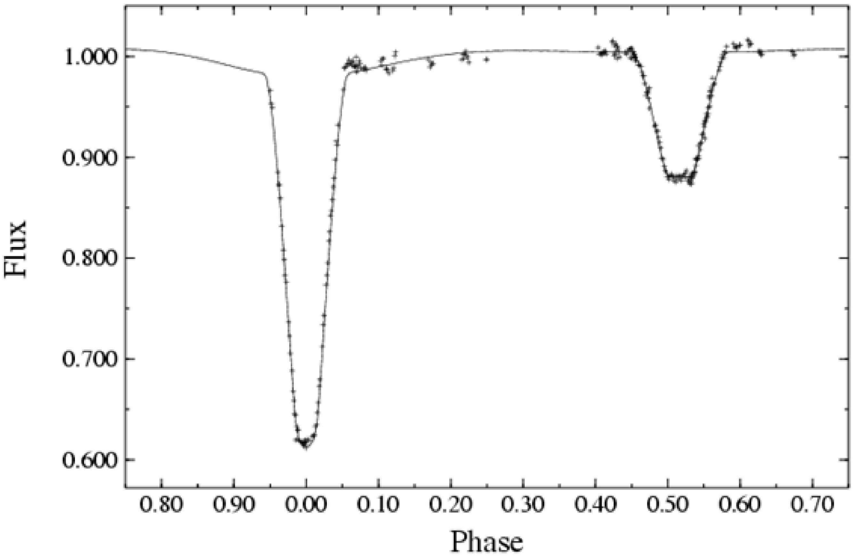

Figure 4. Light curve of IQ Peg. From CALEB (Bradstreet 2004).

From symmetry, we know that a total occultation (in the secondary eclipse) *must* be matched by a total transit (primary eclipse) of equal duration. So the total transit *must* be across a non-uniformly bright star. You have detected limb darkening!

Next instalment

Understanding eclipse depths.

References

Bradstreet, D., 2004. Catalog and Atlas of Eclipsing Binaries. http://ebola.eastern.edu. Accessed 1 March 2016.

Richards, T., et al, 2013. "CU Hydrae – a neglected bright eclipsing binary star". J Br Astron Assoc, 123, 3.

Old friends and new mysteries – *Tom Richards*

tomprettyhill@gmail.com

SEB CCD targets for August to October 2016

Well, judging by the minima records coming into the SEB Dropbox, some enviable people are getting clear skies this winter. Terry Bohlsen, Simon Lowther, and Robert Jenkins and especially Neil Butterworth have brought the total for the year up to 39. Mark Blackford is keeping a lot of analyses in his Pending tray until he gets his house shift to his dark-sky retirement property more under control. I sympathize. My contributions were definitely not from the winter of my discontent – the last observable night I had was May 2nd with YY Aps. Neil has discovered an apparent primary/secondary minima reversal for V883 Sco compared to GCVS data. There are two possible reasons for switching minima – the stars did it or the original observer did. Mistakes happen. (Definitely not by Neil!) Anyway it needs following up, if only because the partial light curve Neil has looks to me very like an EA, not the listed EB/KE.

For this three-month period I have chosen target systems of magnitude 10-12 in the RA band of 21-02 hours inclusive and south of -30° declination. Brighter targets are better handled by DSLR equipment.

Some EA friends

We begin with some EAs (detached, semi-detached) that the SEB group has worked on already, but need more data. Using data from the former VSS EA/SPADES project, Streamer *et al* (2015) provided revised light elements of 25 southern EAs. These systems need more minima measurements as confirmation, so they are all good and useful targets. Two of these (RU Gru and CT Phe) are within our RA band.

Star	RA 2000.0	Dec 2000.0	Vmag	VSS E0	VSS P	Please observe	Note
Gru RU	22 27 0.55	-37 11 8.2	11.01	2455805.1032(5)	1.8932001(18)	Secondary eclipses	Tiny sec. ecl. Model in CALEB needs confirming.
Phe CT	01 25 46.35	-39 56 0.6	11.422	2456195.0750(5)	1.2608260(25)	Primary eclipses	ASAS3 LC suggests period change. Tiny secondary eclipse.

Some known unknowns

Next, I went looking for some systems about which very little is known, and what is said to be known by the GCVS might be very wrong (Samus et al, 2007-15). It lists them all as E, which means it's unknown what type of eclipser they are (EA EB or EW). Some even have the colon of uncertainty, so doubly dubious. An interesting bunch, worth some papers in this Newsletter if we can pin down anything interesting. (A literature search might throw up some more information.) Why is AF Gru said to be an