THE BAA OBSERVERS' WORKSHOPS

Cambridge — *2003 February 15*
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A fascinating insight into observing and analysing the orbital dance of distant binary stars.

Observing eclipsing variables: *a beginner's guide*

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by Tony Markham

The *General Catalogue of Variable Stars* (GCVS)[1] lists many different classes of variable star. Some of these are well known and contain many members; others are more obscure and contain only a few examples. However, it is also possible to split variable stars into just two basic categories: the intrinsic variables – stars like Mira variables, Cepheid variables, novae and supernovae – in which the stars themselves are varying in brightness, and the extrinsic variables, in which the individual stars themselves do not actually vary, and prominent among these are the eclipsing variables.

Types of eclipsing variable

Algol type

The most famous eclipsing variable is probably Algol (Beta Persei). For most of the time, Algol is the second brightest star in the constellation of Perseus – only Alpha Persei is brighter. However, sometimes it becomes much fainter.

It is not clear when the brightness variations of Algol were first recog-nised. Offic-ially the credit goes to Geminiano Montanari in 1667, but it is likely that the variations were known earlier to Arab astronomers and possibly also to the Chinese. However, early reports merely noted that Algol sometimes faded, and it was not until 1782 that it was realised that these fades were not occurring randomly. In that year, the English astronomer John Goodricke recognised that the fades occurred at regular intervals, and he found this interval to be approximately 2 days and 21 hours.

Not only did Goodricke recognise this pattern, he also put forward the correct explanation. Goodricke suggested that Algol is not merely a single star whose brightness is varying. Instead, there must also be a darker object which is in orbit around it. The orbital plane must be edge on as seen from the Earth so that every 2d 21h, the darker object will obscure most of the light from the bright star. Goodricke had no way of knowing what the 'darker object' was, but we now know that it is another star. Indeed, it is not actually 'dark' – it is comparable in brightness with our Sun, but is much less luminous than the brighter star in the Algol system. The two stars are approximately 6 million miles apart and so, on the scale of our solar system, their orbits would easily fit inside the orbit of Mercury.

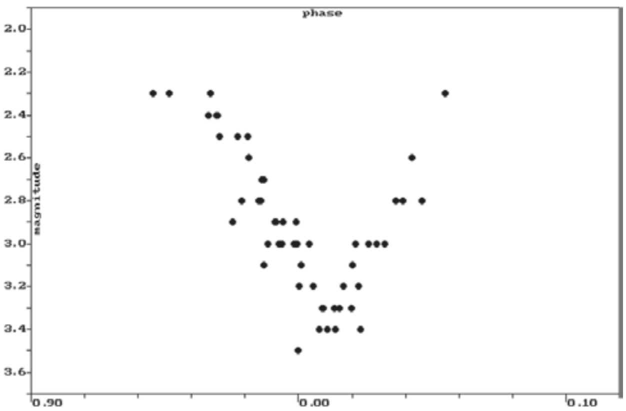

Figure 1. The eclipse of Algol in 1999, using GCVS elements.

Figure 1 shows the primary eclipse of Algol, in which the brighter star is eclipsed by the fainter star. This light curve combines observations of several eclipses from 1999 made by members of the Society for Popular Astronomy Variable Star Section (SPA VSS). The vertical axis shows the magnitude (i.e. the brightness) and the horizontal axis shows the phase – the phase is the fraction of the orbit that has been completed.

As we move from left to right in the light curve, the brightness of Algol fades as the brighter star is progressively covered and then rises again as it emerges from eclipse. This is all over in about 10 hours, and for the remaining 2d 11h of the orbit we see no significant brightness changes.

Beta Lyrae type

Not all eclipsing variables behave like Algol. Only two years after recognising the pattern in the variations of Algol, Goodricke discovered another eclipsing binary – β Lyrae – in which the period of variation is approximately 13 days.

Figure 2 shows the variations of β Lyrae over a whole 13-day orbital cycle. This light curve combines all observations made during 1998 by members of the SPA VSS. There is some scatter, as is usually the case when combining the visual estimates of several different observers, but the main features of the light curve can be seen.

We can see the primary eclipse, near phase 0.25, in which the brighter star is eclipsed by the fainter star. We can also see a secondary eclipse, near phase 0.75, in which the fainter star is eclipsed by the brighter star. In the case of Algol, the secondary eclipse is so shallow that we cannot easily detect it visually. The most important difference is that whereas in the case of Algol, there is a long interval between eclipses when there is no signifi-

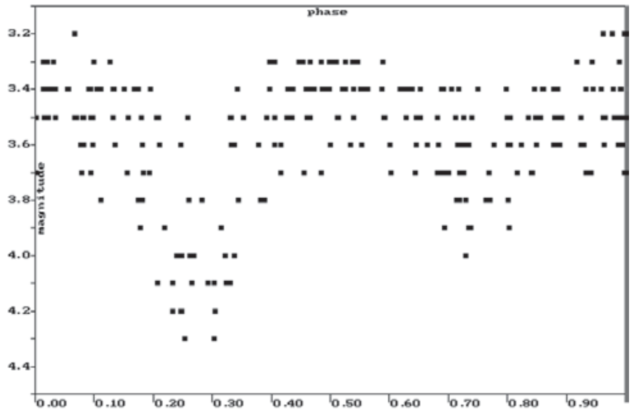

Figure 2. Light curve of β Lyrae over a 13-day orbital period in 1998.

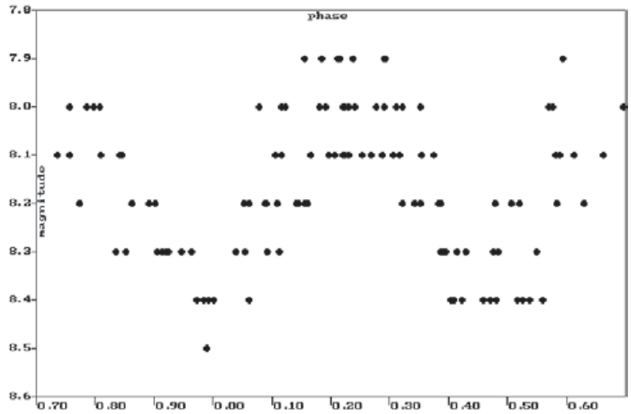

Figure 3. Light curve of W UMa in 1996–1999, from observations by the author.

cant change in brightness, this is not the case for β Lyrae – the brightness is changing all the time.

Like Algol, the β Lyrae system consists of two stars of unequal brightness which periodically eclipse each other. The orbital period is longer because the stars are further – over 20 million miles – apart.

However, whereas in systems like Algol, the two stars are more or less spherical, in the case of β Lyrae, the two stars have distorted each other gravitationally and become more egg-shaped. When we see such egg-shaped objects side on (as is the case midway between eclipses) we are seeing light from a bigger surface area than when we see them end on (just before and after the eclipses). Seeing a bigger surface area means that we see more light from the stars. Thus, even after the eclipse ends we see β Lyrae still continuing to brighten, and it becomes brightest midway between eclipses.

W Ursae Majoris type

Although Algol type and β Lyrae type eclipsing binaries are the most well known, they probably are not the most common type of eclipsing binary. The most common type are probably the W Ursae Majoris type eclipsing variables.

Figure 3 combines observations of eclipses of the variable W Ursae Majoris, made by the author over a number of years. These systems consist of two stars more or less in contact with each other. Typically, the two stars are comparable in brightness with our Sun and so less luminous than the stars in Algol or β Lyrae, and so not visible over such large distances in the galaxy. Indeed the brightest examples are only about 8th magnitude.

In most cases, the two stars are similar to each other and consequently the primary and secondary eclipses tend to be of similar depth – differing by only about 0.1 mag in the case of W Ursae Majoris itself. For the same reason, they have short orbital periods, in the case of W UMa, about 8 hours.

Most significantly, because the two stars are in contact with each other, there is no gap between eclipses – as soon as the primary eclipse ends, the secondary eclipse starts immediately; as soon as the secondary eclipse ends, the primary eclipse starts, and so on. Hence you never need to look up predicted times of eclipses for a W UMa type variable, as it will always be in eclipse.

Partial and total eclipses

As has been described, there are three main types of eclipsing variables, whose differently shaped light curves provide information about the stars which make up these systems. We can also extract further information by looking at the shapes of the primary eclipses.

Figure 4 shows the primary eclipse of the Algol type variable RZ Cassiopeiae. Figure 5 shows the primary eclipse of U Cephei, another Algol type variable. As can be seen , the shapes of the two light curves are different. The light curve of RZ Cas is fairly 'V'-shaped whereas that of U Cep is more flat-bottomed.

The light curve of U Cep is flat-bottomed because we are seeing a total eclipse. The initial fade occurs as more and more of the brighter star is eclipsed. However, once the brighter star is totally eclipsed, the fading stops and the magnitude of the system remains constant for about two hours while the brighter star is hidden. Finally the brighter star starts to emerge from eclipse and the brightness increases again.

In the case of RZ Cas, we only see a partial eclipse. The magnitude drops as more and more of the brighter star is eclipsed and the system is faintest when the partial eclipse reaches its maximum extent. Immediately after this, however, the brightness starts to increase again and consequently the eclipse is not flat-bottomed. In summary, partial eclipses are

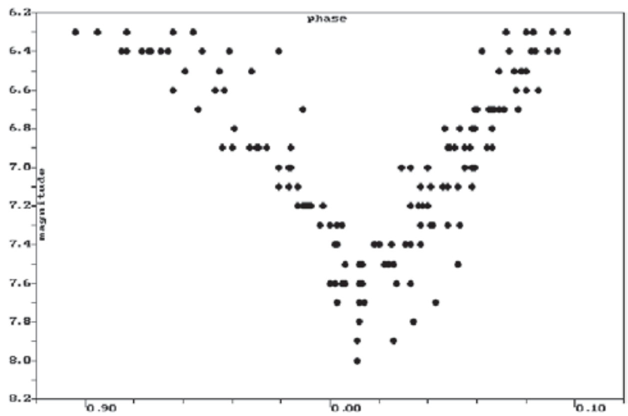

Figure 4. A primary eclipse of RZ Cassiopeiae in 1993. Note the sharp V-shape of the light curve.

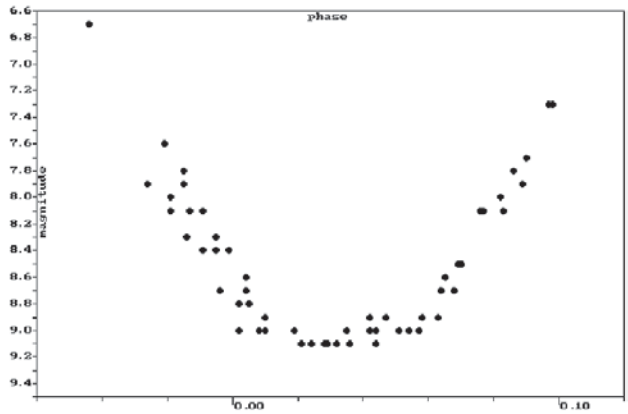

Figure 5. The U-shaped eclipse of U Cephei in 1996 (GCVS elements).

'V'-shaped whereas total eclipses are flat-bottomed.

Comparing observations with predictions

The light curves shown so far have had the magnitude shown on the vertical axis and the phase on the horizontal axis. We now need to consider where these phase values are coming from. After all, when you make an observation, you record the time of the observation and don't readily know the value of the phase.

The phase in these light curves was calculated using the information in the *General Catalogue of Variable Stars*.[1] In addition to listing the position and magnitude ranges of eclipsing variables, the GCVS also gives two other pieces of information: the time of a previous primary eclipse, and the orbital period.

Rather than use calendar dates and hours and minutes when specifying the date and time of the earlier eclipse, the GCVS uses Julian dates, as this makes the calculations easier. Although it might be assumed that the Julian date system is related in some way to Julius Caesar, this is not the case. The system was invented in the 1580s by Joseph Scalinger. It is not the number of days since Julius Caesar and it is not even named after him; it was actually named after the father of Joseph Scalinger, who happened to be named Julius. The start date of the Julian date system was also long before the time of Julius Caesar, being 1st January 4713 BC (Julian calendar).

For U Cep, the GCVS lists the following elements:

Julian date of a previous eclipse = 2444541.6031
Orbital period = 2.4930475 days

Thus 2444541.6031 days after the Julian date system started, there was a primary eclipse of U Cephei. If you convert this to a date and time (in the Gregorian calendar), you find that this eclipse occurred on Sunday 1980 October 28 at approximately twenty five past two in the morning.

Hence there was a primary eclipse of U Cep at that time and the GCVS tells us that the next primary eclipse was due 2.4930475 days later, another was due 2.4930475 days later and so on. If you add 2.4930475 days often enough, you will eventually reach the current year and find out when eclipses are due in the coming months.

However, we can also run this process in reverse and, for an observation made at a given date and time, calculate the predicted phase – i.e. the fraction of the orbit that should have been completed. This is a bit harder than predicting times of eclipses, but with the advent of PCs and spreadsheets it has become a lot easier than it used to be. How accurate are these predictions?

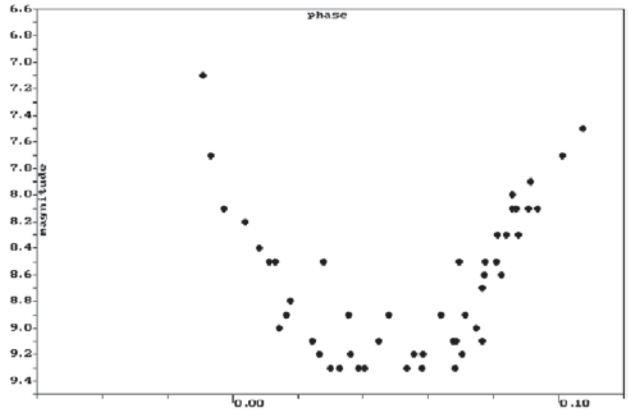

Figure 6. Eclipse of U Cep in 1999 (GCVS elements).

Figure 5 shows observations of U Cep made during 1996. The light curve in Figure 6 combines observations made during primary eclipses of U Cep in 1999. In these light curves the phases were calculated using the elements in the GCVS.

If the eclipses were occurring on schedule, then primary eclipse would be centred on phase 0. As can be seen, neither eclipse is centred on phase 0 – both are shifted to the right relative to phase 0 and so occurred later than predicted. The eclipse in the 1996 light curve is actually centred at around phase 0.035. Given that the orbital period of U Cep is approximately 2.5 days, this corresponds to the eclipse occurring more than an hour later than predicted.

In the 1999 light curve, the eclipse is shifted slightly further to the right, and is centred at about phase 0.045, indicating that the discrepancy between observations and predictions had increased by about 20 minutes.

Figure 7 shows combined observations of β Lyrae made during 1992, 1995, 1999 and 2002. As can be seen, the primary eclipse in 1992 was centred near phase 0.95. This could be interpreted as indicating that it was either 12 days later than predicted or 1 day early (it was actually many orbits plus 12 days late). In 1995, the primary eclipse was centered near phase 0.15. Given that the orbital period of β Lyrae is approximately 13 days, this corresponds to a shift of nearly 3 days in the discrepancy since 1992. By 1999, the discrepancy had increased further with primary eclipse now being centred near phase 0.35 and by 2002 the primary eclipse was centred at around phase 0.50. Hence there is essentially no correlation between the observed and the GCVS-predicted times of eclipses for β Lyrae.

Other variables show smaller discrepancies. Figure 4 shows that the primary

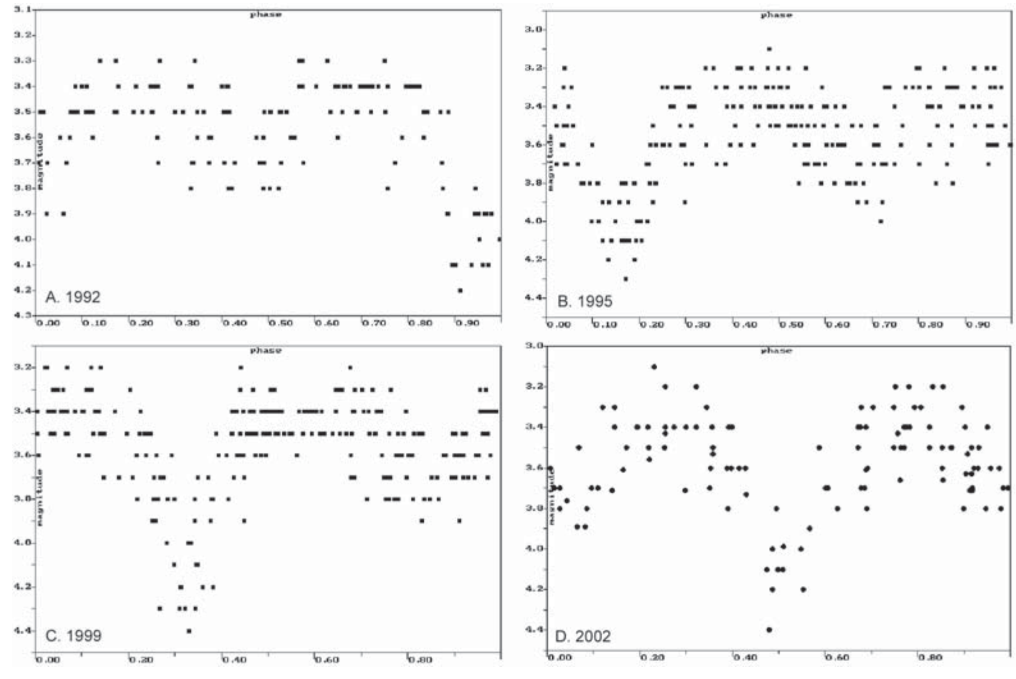

Figure 7. Observations of β Lyrae in 1992, 1995, 1999 and 2002 (GCVS elements).

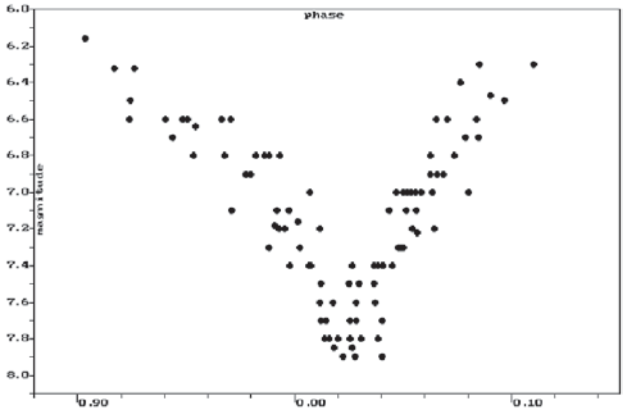

Figure 8. Lightcurve of RZ Cas in 1999 (GCVS elements).

eclipse of RZ Cas in 1993 was centred at about phase 0.015, indicating that eclipses were occurring about 20–25 minutes later than predicted. By 1999, Figure 8 shows that the discrepancy had increased, with primary eclipse being centred at around phase 0.030 – about 40–45 minutes later than predicted.

By combining observations made over many years, we can see how the discrepancies between observations and predictions are evolving over time. Figure 9 shows the evolution in the discrepancy for RZ Cas since the mid 1980s. The vertical axis shows the difference between the predicted time of primary eclipse and the observed time. Note that this is measured in days (rather than the phase difference, although for RZ Cas, the values are rather similar since the orbital period of 29 hours is fairly close to a day).

As can be seen, the discrepancy was quite small in the mid 1980s, but it has increased over the years.

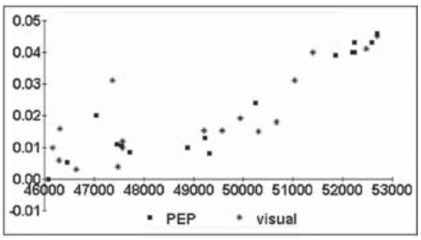

Figure 9. O–C (Observed–Calculated) diagram for RZ Cas since the mid-1980s, showing the evolution of the discrepancy with time.

Causes of the discrepancies

Why don't eclipses occur at the predicted times? There are two main possibilities. The first is that the eclipses do indeed occur at regular intervals, but the information in the GCVS is not accurate. As described earlier, the GCVS data include two pieces of information – the time of a previous eclipse and the orbital period.

Suppose that the quoted period is correct, but the Julian date listed for the earlier eclipse is incorrect. This could happen if, for example, there was scatter in the light curve due to variable sky conditions, and as a result, the reported time was incorrect by 15 minutes. In such a case, the later eclipses will always be late by 15 minutes, and the difference between the observed and predicted times will be constant.

Alternatively, suppose that the time listed for the previous eclipse is accurate, but the quoted orbital period is not. If the listed orbital period is short by 1 minute, then the next eclipse will be 1 minute late, the next 2 minutes late, the next 3 minutes late and so on, and the difference between observed and predicted time will increase at a fixed rate.

Hence the discrepancies between observations and predictions for some eclipsing variables may be due to the limited accuracy of the data in the GCVS. The more interesting possibility however, from a scientific point of view, is that the orbital period may be changing.

There are several reasons why this may occur. There may be transfer of mass between the two stars. Many of these systems are physically quite close together in space and in some cases one of the stars may have evolved into a giant star with a tenuous outer atmosphere. Some of this outer atmosphere may be lost into space and this 'lost' gas may subsequently be pulled on to the surface of the other star. As a result, the relative masses of the two stars will change, as will their separation in space, and consequently we see a change in the orbital period.

The other possibility is that there may be another star in the system. Although we think of eclipsing variables as binary systems, there will sometimes be a third star in the system whose orbital period may last for decades, or even centuries. Although not directly involved in the eclipses, this third star will gravitationally perturb the orbits of the first two stars as it orbits around them, causing eclipses to occur early at some times and late at others.

Making improved predictions

As we have seen, the GCVS elements aren't always that useful when it comes to predicting future eclipses. One problem can be the age of these elements. For example, we have already seen that the elements for U Cephei are relative to an eclipse that occurred in October 1980. The situation is worse for β Lyrae, for which the elements listed in the GCVS are:

Julian date of earlier eclipse	= 2408247.950
Orbital period	= 12.913834 days

The above Julian date actually occurred in June 1881!

Fortunately more up-to-date elements, which are based on more recent observations, do exist. One useful set of elements is the SAC elements published by Krakow University in Poland. Here are the SAC 65 elements[2] for β Lyrae:

Julian date of earlier eclipse	= 2449352.80
Orbital period	= 12.93804 days

These elements are relative to a 1993 eclipse and have a longer orbital period than do the GCVS elements – indeed if we convert the difference between the GCVS and SAC 65 elements into minutes we find that the SAC 65 orbital period is nearly 35 minutes longer than the GCVS value. Given that approx 29 orbits of β Lyrae take place every year, the discrepancies soon add up and so it is not surprising that they become so large.

It so happened that the discrepancy between the observed and the GCVS predicted times of eclipses for β Lyrae was roughly equal to a whole number of orbits in 1993, so we can compare the results of the GCVS and SAC 65 elements to see how they were faring by the late 1990s.

Figures 2 and 10 show light curves of β Lyrae from 1998. The phases in the first light curve were calculated using the GCVS elements; those in the second were calculated using the SAC 65 elements. If the eclipses were occurring on schedule,

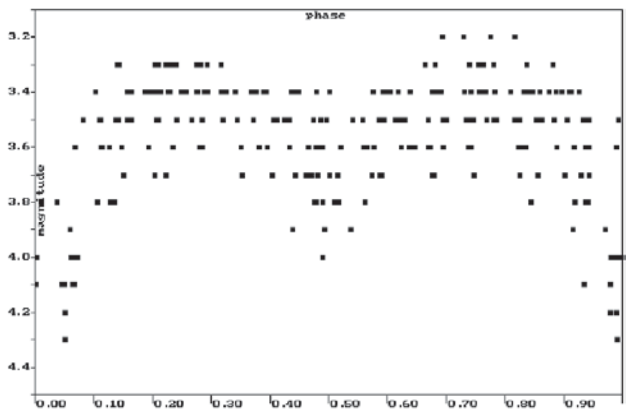

Figure 10. Light curve of β Lyrae for 1998 (SAC 65 elements.)

then primary eclipse should be centred on predicted phase 0. In the GCVS-based light curve β Lyrae clearly was not in primary eclipse at predicted phase 0 – it was near maximum brightness. In fact primary eclipse did not occur until three days later.

The SAC 65 elements perform much better, with β Lyrae being close to mid-primary eclipse at predicted phase 0; there was only a small discrepancy. Mid-eclipse occurred slightly after predicted phase 0, but this is because the orbital period of β Lyrae is still increasing – indeed the SAC 74 elements[3] list the orbital period as about 12.940 days, a further increase of about 3 minutes.

Hence the conclusion is that predicted phases calculated using the GCVS elements are useful if we want to monitor long term trends, but when it comes to making predictions for future eclipses, it is better to use the latest SAC elements.

Not all eclipsing variables show period changes as dramatic as that for β Lyrae. Here are the GCVS elements and the SAC 74 elements for RZ Cas:

GCVS

Julian date of earlier eclipse = 2443200.3063

Orbital period = 1.195247 days

SAC 74

Julian date of earlier eclipse = 2448960.2122

Orbital period = 1.1952572 days

The GCVS elements are relative to an eclipse that occurred in 1977. As can be seen the GCVS and SAC 74 orbital periods only differ at the fifth decimal place and the difference only corresponds to approximately 0.8 seconds. It might seem that this is too small to make any difference. However, given that the orbital period is only about 29 hours, there will be approximately 300 primary eclipses of RZ Cas every year and 300 multiplied by 0.8 seconds adds up to a discrepancy of 4 minutes after one year. Again this is still quite small, but after 10 years it amounts to 40 minutes, and so on, so it is still worthwhile using the latest elements.

Observing predicted eclipses

Having to look up the SAC elements and then calculate the eclipse times yourself would be quite time-consuming, so to make life easier, predictions for RZ Cas, Algol and Lambda Tauri are included in the BAA *Handbook*. Predictions for further eclipsing binaries are included in VSS *Circulars* and on the VSS web pages.[4] In these latter locations, space is at less of a premium so as well as giving the mid-times of eclipses, we also give the times between which they are observable from the UK, taking into account daylight and low altitude.

Magnitude estimates of eclipsing variables are made in the same way as for other variable stars. However, because the brightness variations take place over shorter timescales, observations are made more frequently. Observing visually, making estimates every 20–30 minutes around the predicted times of eclipses is sufficient for most eclipsing variables. For longer period variables such as β Lyrae, you only need estimate the brightness once on every clear night. Visual estimates should be recorded to the nearest tenth of a magnitude, with the time to the nearest minute. Charts showing the location of eclipsing variables and suitable comparison stars can be downloaded from the BAA VSS web pages.

Eclipsing variables are certainly worth observing. They are not totally predictable, and by timing when eclipses actually occur, we can see how they are evolving – and as we have seen, even the naked eye and binocular objects are doing interesting things. You can often observe a whole eclipse in a single night and you don't need expensive equipment in order to make a useful contribution.

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References

1 Khopolov P. N. *et al.*, *General Catalogue of Variable Stars* 4th edition (1985)
2 *Supplemento ad Annuario Cracoviense* (SAC) 65 (1994)
3 *Supplemento ad Annuario Cracoviense* (SAC) 74 (2003)
4 BAA VSS web pages: http://www.britastro.org/vss