Southern Close Binaries Programme of the VSS

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Abstract

We review the programme of studies of southern close eclipsing binary systems that has been underway in recent years, involving observations at the Mt John University Observatory and elsewhere in the region. We include brief descriptions of equipment used, before presenting summary results on four typical examples (U Oph, V831 Cen, R CMa and η Mus) drawn from the programme. We show that absolute stellar parameters thus obtained are of high enough quality to compare favourably with any other recent data in this field. Thus, for U Oph, we derived a new value for the third star's mass, and an age consistent with the system's origin in Gould's Belt. We announced the chemical peculiarity of the third star accompanying V831 Cen. Our new parameters for R CMa solve the longstanding 'overluminosity' issue, although the close pair must have lost considerable angular momentum. For η Mus, we discovered another member of the system that removes the problem of the (otherwise) anomalous radial velocity of η Mus B. Such new findings encourage interest in further pursuit of the programme.

1. Introduction

The 'eclipse method' of stellar astronomy means using the light and colour curves of close eclipsing binary stars (EBs), coupled with spectroscopic information on their radial velocities, to determine absolute parameters of stars, such as their masses, radii and luminosities. Distances can also be deduced and results compared or combined with direct astrometry in some cases. A programme devoted to such purposes has been running in recent years, involving various institutes and facilities in New Zealand and abroad. The southern binaries programme (SBP) is aimed particularly towards relatively under-observed, or newly discovered, southern binaries. A more distant purpose is to have clearer information on the relationship of stellar properties to their galactic environment.

In this article we summarize some examples of close binaries that have been studied in this programme, referring particularly to examples shown in posters displayed at RASNZ Annual Conferences.

As well as stellar absolute luminosities, masses, radii and temperatures, *distances* (alternatively, parallaxes Π) can also be derived from data on normal EBs. Knowing the visual magnitude *V*, as well as the radius *R*, which is obtained from measurements of the eclipses, the eclipse method uses the relationship

$$\log \Pi = 7.450 - \log R - 0.2V - 2F'_V \quad ,$$

where the visual flux F'_V, the luminous power per square m emitted by a star, can be derived from its effective temperature T_e, that in turn can be found from the observed colour (e.g. the blue minus visual magnitude difference, $B - V$). Semeniuk (2000) pointed out that parallaxes obtained by this method could have an accuracy, in principle, surpassing that of the HIPPARCOS survey (ESA, 1997), if care was taken about the choice of binaries and adopted flux-colour relation. Only one star in about 1000 is an EB, but the fact that eclipses can be observed as far as stars can be individually monitored gives the method wide significance.

In the last decade or two, the eclipse method has been used to greater distances within our own Galaxy and even outward to the nearest neighbouring galaxies – the LMC & SMC and beyond. Nowadays, analysable light curves are available for EBs within the Local Group of galaxies. Spectrometry has been applied to candidate objects in the nearer galaxies using ground-based large telescopes. Improved or more specialised filter systems have also been introduced.

But there are also numerous close binaries nearer to home: relatively bright systems that have tended to be somewhat overlooked, probably because of their southerly positions. Such stars are well-positioned as targets for the particular facilities available in New Zealand, notably the HERCULES high dispersion spectrograph at Mt John University Observatory (MJUO), and also their accessibility for photometry from smaller local facilities. We will present a few details of four close binary systems that have been studied in this way in our 'Southern Binaries Programme' over the last few years. But before that we will include a few words on the tools and techniques used in this programme.

2. Instruments and observations

2.1 Photometry

One reason for the unstudied nature of many of the stars in the SBP is that it was only after the detailed analysis of the photometric data systematically produced by the HIPPARCOS satellite in the early nineties that their variability was discovered, and its nature deduced. The importance of the HIPPARCOS database for the SBP is therefore difficult to overstate. Although the HIPPARCOS light curves are only in one spectral range (close to the standard V (visual) magnitude) and typically contain only around 100-200 data points, nevertheless they represent a uniform and high quality resource. Analysis of the relevant HIPPARCOS light curves has been an almost mandatory initial step in the SBP's approach.

Another interesting new development has involved the use of digital single lens reflex (DSLR) cameras of commercial design. One important point in the study of eclipsing binary stars concerns checking on their predicted times of minimum light. This kind of checking can be nowadays conveniently carried out with a DSLR camera and to a relatively very high accuracy (Blackford & Schrader, 2011). The Variable Stars South (VSS) section of the Royal Astronomical Society of New Zealand (RASNZ) has espoused the SBP as one of its official activities[1]. Data used so far were gathered

[1] Southern Binaries DSLR (SBDSLR) Project at http://www.variablestarssouth.org/

using an unmodified Canon 450D (Digital Rebel XSi) and Nikkor 180mm lens operated at f4. Instrumental magnitudes were then obtained from differential aperture photometry, using several comparison stars. The procedure includes corrections for atmospheric extinction and transformations from the camera's own three-colour Bayer filters to the standard Johnson BVR system. Results hitherto have included eclipse minima and sometimes complete light curves of a surprising accuracy; that is to say, binned magnitude measures using a home-based DSLR technique over the last year or so compare favourably with front-line light curves from large observatories of the eighties and (early) nineties.

2.2 Spectroscopy

New spectroscopic data for the SBP have been generally taken with the High Efficiency and Resolution Canterbury University Large Échelle Spectrograph (HERCULES) of the Department of Physics and Astronomy, University of Canterbury (Hearnshaw et al, 2002). This spectrograph is used with the 1-m McLellan telescope at the Mt John University Observatory (MJUO), (for further details see also Skuljan et al., 2004). A 100 μm optical fibre has generally been used to convey light from the Cassegrain focus to Hercules, and that enables a resolution of approximately 40000, in keeping with the moderate seeing conditions typically obtained. Exposure times have to be long enough to yield a reasonable signal-to-noise (S/N) ratio (~100) in the useful spectral region between ~470 and ~670 nm, yet short enough to avoid smearing of spectral features due to changes in radial velocity during the exposure time. This will depend on the period of the particular binary being studied, so the program could go, in principal, to fainter stars at longer orbital period.

Early in the SBP the spectra were recorded with a Spectral Instruments SITe series (1024x1024 pixels) camera. That camera covered only part of the whole spectral range, but in mid-2006 it was replaced by an SI600s type camera. This camera has a larger number of smaller pixels, covering the whole field effectively in a 4096x4096 array. Initial data acquisition and reduction have been performed with the on-site HERCULES Reduction Software Package (HRSP) (Skuljan & Wright, 2007); however, the change of camera during the programme required the use of different versions of HRSP, up to the present time when version 5 is in use. This version is portable and robust: it will run via Cygwin on an MS Windows platform.

A two-dimensional wavelength calibration capability, using the numerous Th/Ar reference lines produced by a comparison lamp, is a key element in HRSP. But the static, highly controlled arrangement of HERCULES means that the wavelength calibration changes little from exposure to exposure (inter-exposure shifts may amount to tens of m/s). This value can be significantly improved by averaging over the full width of the échelle, taking into account many orders. In principle, an accuracy in the range of cm/s could be achieved on a bright target. A deeper investigation would go far beyond the scope of this paper. But these observations confirm that HERCULES is indeed a world-class instrument.

Reference information on the Th/Ar spectrum is readily available from the internet (http://www.noao.edu/kpno/specatlas/thar/), and the calibrations for both cameras can be checked using these data (see Figure 1). Generally, individual spectral orders can be well fitted by fifth-order polynomials, and third-order polynomials satisfactorily match coefficient variations across the orders. Besides HRSP, the user-friendly freeware ImageJ[2] includes options to facilitate checks on these procedures.

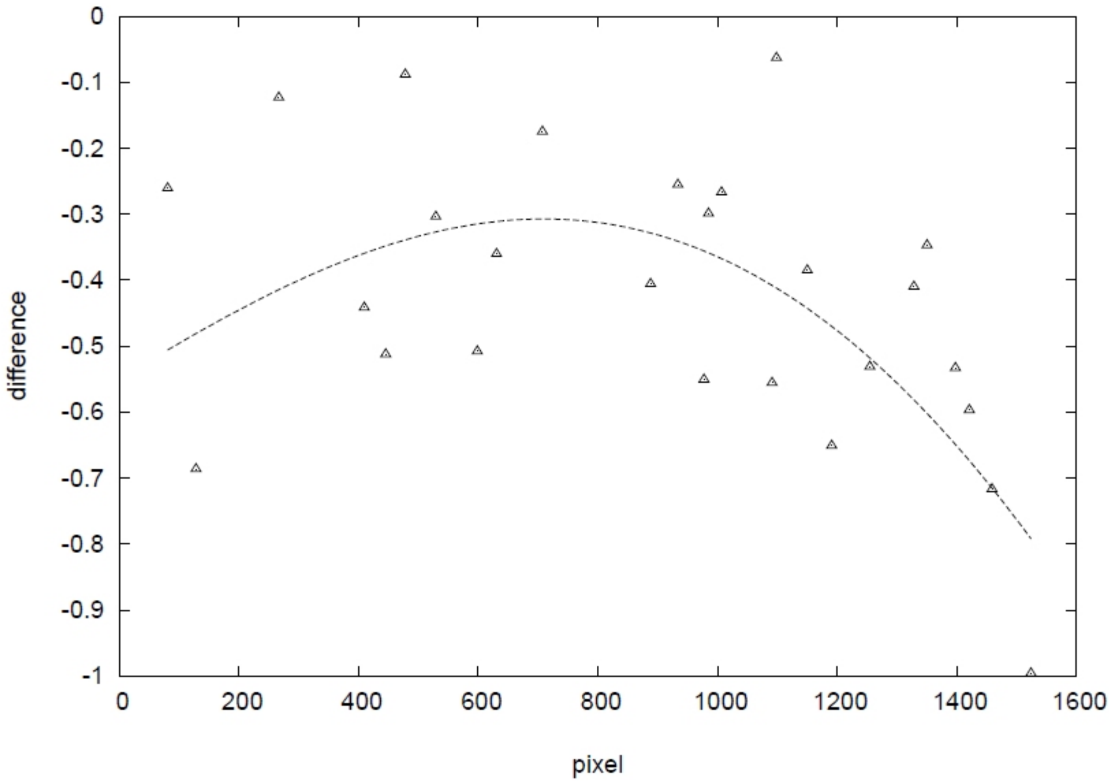

Figure 1. Fourth order polynomial fitting to the difference from a linear relation of 27 Th/Ar reference lines for échelle order 110. The abscissae are in pixels (1 pix ≈ 0.03 Å), while the ordinates show the differences in pixels between lines located using ImageJ and a simple linear pixel-versus-wavelength relation.

HRSP allows processed data to be stored simultaneously as 'FITS' files. This is convenient for further analysis using the IRAF software package[3], which we have used in deriving radial velocities (RVs). There are usually less than a dozen measurable lines for these early-type, rapidly rotating stars, but prominent among these are the helium lines at 6678, 5875, 5047 and 4713 Å. H_α and H_β are also present in the usable range, but the hydrogen lines are notoriously complex and require careful attention for the determination of reliable RVs.

3. Four close binaries of the Southern Binaries Programme

3.1   U Oph

A full report on U Oph was given by Budding and co-workers in 2009. This eclipsing binary has been a standard example for evaluation of the absolute parameters of early-type stars. It is relatively bright (V = 5.903; B – V = 0.021), and near the equator, so it

[2] The public-domain software ImageJ is available for download at http://rsbweb.nih.gov/ij/.
[3] IRAF is distributed by the National Optical Astronomy Observatories operated by the Association of Universities for Research in Astronomy Inc. (AURA), under cooperative agreement with the National Science Foundation.

was observed and studied over a long time. Gould (of Gould's Belt fame) was the first to note its regular variability in 1879, but a low light-level was apparently observed by the famous astronomer-mathematician F.W. Bessel in 1823 (JD 2386717.38). That observation, in principle, allows a very accurate determination of the mean period, using a baseline of the last couple of centuries (P = 1.67734543 d). But a number of studies have reported small shifts of the minima from a complete regularity: an effect that has been attributed either to orbital eccentricity or a light travel time effect (LITE).

Koch & Koegler, in 1977, suggested a cyclic variation on the order of twenty years for these displacements that might come from a general rotation of an elliptic orbit (apsidal motion) with around that period. Kämper (1986) confirmed that a small eccentricity (e = 0.003) together with a 20 year period of apsidal motion could explain the shifts of times of minima (ToMs), and this has been reaffirmed by a number of later investigations, including our own.

The galactic position, distance, and early spectral type of both stars (B5), when taken together, suggest the system may be associated with the Gould's Belt giant star-formation region. Multiple stars like U Oph thus turn out to be useful providers of information on the origins of stars in the solar neighbourhood. The main close binary (ADS 10428A) has a faint (V = 12.14) visual companion (BD +1 3408B = ADS 10428B) about 20 arcsec to the north. There is also a ROSAT X-ray source near to the system, but it is not sure if this can be associated with the close binary, the faint companion, or perhaps some other object close by. Our study found, when modelling the eclipsing binary system, that there is extra light in the system that most probably comes from an unresolved companion, closer in than ADS 10428B. (We will find this kind of situation repeated in other objects of the programme.)

Although U Oph has been observed numerous times spectroscopically, the overall picture remains a bit unclear. It has been disputed that U Oph really has an eccentric orbit. Photometrically similar effects can be associated with the LITE, mentioned before. The known effects of circumbinary gaseous matter in distorting a radial velocity curve have been used to explain away the apparent eccentricity of the radial velocity curve. There is also an accumulation of interstellar matter in the line of sight to the star which tends to complicate analysis, particularly of the stellar colours. In turn, this renders a precise evaluation of the distance, using the formula given in Section 1, difficult. This may connect with discussions of polarimetric anomalies of the light from U Oph that have also been reported. These effects were related to stellar winds that show short-lived eruptive episodes. Anomalous absorption effects in the line of sight are consistent with a relatively recent star-formation region.

Kämper, in addition to the previously mentioned apsidal period, also demonstrated the presence of a LITE, with a period of a little less than 40 years. This was also confirmed in more recent investigations. Kämper estimated the age of the system to be about 30 million years, which was essentially confirmed by our own study, although uncertainties on the absolute parameters, relating to the previously mentioned complications, allow for significant differences in age estimates.

Our photometric and spectroscopic results are shown in Figures 2 and 3.

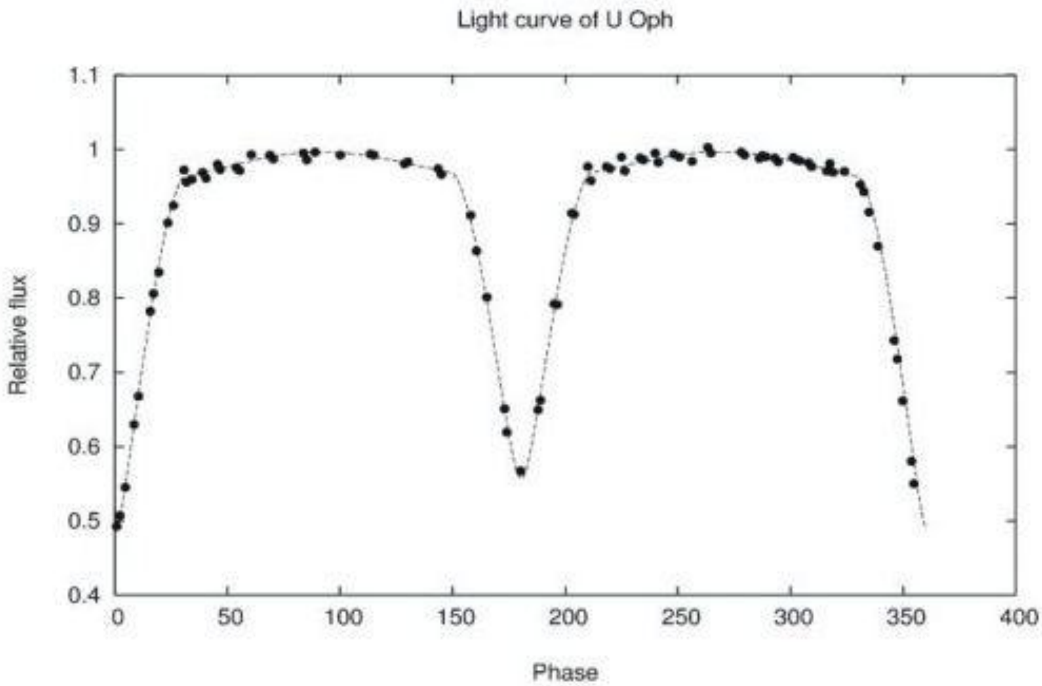

Figure 2. V-band light-curve of U Oph. The phase is recorded in orbital degrees.

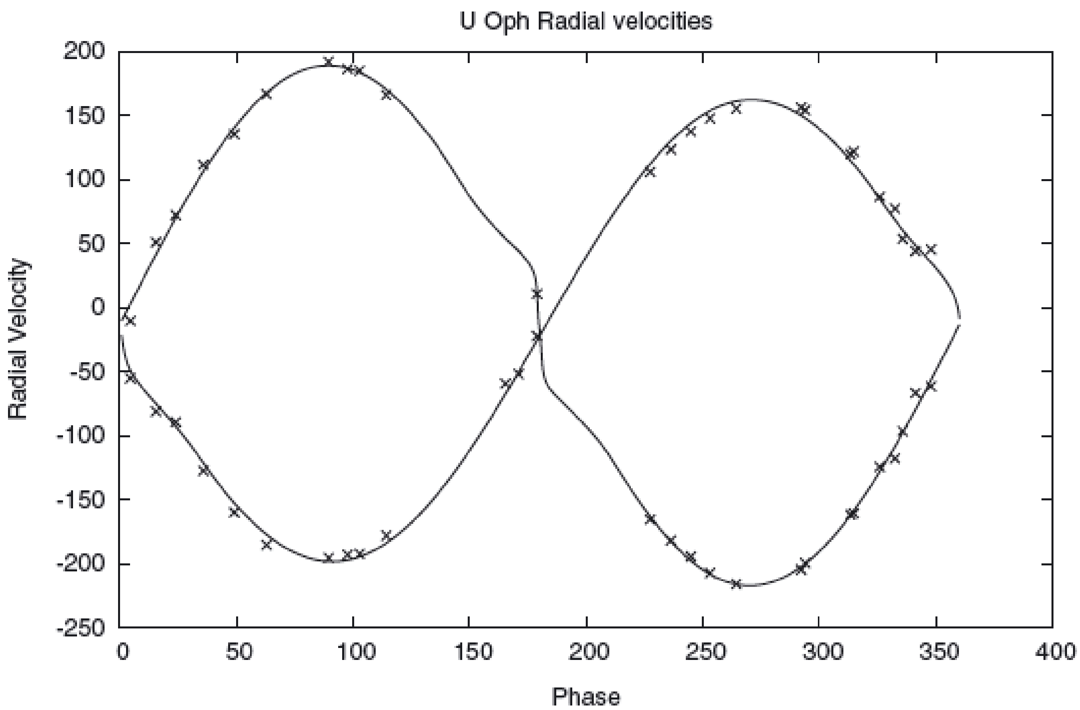

Figure 3. RV-curve of U Oph. The phase is recorded in orbital degrees. The measured RVs are plotted against a fitting function taking into account both proximity and eclipse effects. Note the Rossiter-effect for the secondary component around the time of secondary eclipse (near 180º). This effect is far less pronounced for the less eclipsed primary (near 0º).

From these data and their analysis we found the following absolute parameters (in solar units): primary mass = 5.13, secondary mass = 4.56 (+/– 2%); primary radius = 3.41, secondary radius = 3.08 (+/– 1%) for the early-type eclipsing binary that dominates the system. We have combined ToMs with other data for the triple system that makes up the primary of the wide visual binary, utilizing also astrometric data from the HIPPARCOS satellite. We found the mass of the third star to be 0.83 solar masses. We derived an age of the system of around 30-40 My, using the (internet-available) stellar evolution models of the Padova Group[4]. This age and other details are consistent with an origin of the U Oph system in Gould's Belt.

3.2 V831 Cen

The bright (V ~ 4.5 mag) star known as V831 Cen is young multiple star that includes an early-type near-contact binary as well as at least two other studied companions. At least one more fainter likely member of the system at a greater separation has been noted in previous literature. From its position on the sky, estimated distance and proper motions, V831 Cen is thought to be a member of the Lower Centaurus Crux concentration of the Sco-Cen young star (OB) Association, within the giant formation complex of Gould's Belt. This is another example of a fascinating object that, because of its sky location in the far south, is perhaps not as well known as it otherwise would be. The near contact binary is the main component of a very close visual pair (needing a good telescope and excellent seeing to separate), whose component magnitudes were estimated at 5.3 and 6.0 by Geoff Douglass, whilst working at the US Naval Observatory at Black Birch (cf. Worley and Douglass, 1996). A full review of the system was given by Budding et al (2010)

The HIPPARCOS (ESA, 1997) light curve has the form of a low amplitude quasi-sinusoidal variation, looking like that of a contact binary with appreciable third light present, or perhaps at low inclination. Officially, the variable was thus categorized as of the 'ellipsoidal' type. Given the shallowness of the minima and the smooth pattern of variation, difficulties in finding a unique photometric model could be expected: a point that can be discerned from early accounts. Suitable inspection of the main available evidence will allow reasonable inferences enabling a preliminary model to be constructed, however. Thus, the blue colour (B – V ~ –0.08) of the main component is consistent with the generally assigned B8V spectral type. This would correspond to an effective temperature of around 12000 K, using easily available data on Main Sequence and comparable stars.

A trial model for the close binary would then consist of two similar stars with total mass close to 7 solar masses. The short period (about 0.64252 d) together with Kepler's third law and these masses, leads to a separation of about 6.0 solar radii. A typical Main Sequence pair of such (about equal) masses would have undistorted mean radii of about 2.4 solar radii, suggesting an over-contact configuration. It is known that a close binary whose average radii expressed as a fraction of the separation of the two mass centres area sum up to about 0.75 of that separation will tend to merge into each other. This arises basically from the mutual tidal interaction. Given the youth of this particular binary, however, its components may well have mean radii less than typical, and indeed that point, which bears on the age and structure of the stars, was a prompt for the more detailed study of the present programme.

[4] The modelling tools are accessible at http://stev.oapd.inaf.it/ (Osservatorio Astronomico di Padova).

The new high-resolution spectroscopy of V831 Cen from the HERCULES spectrograph of MJUO enabled radial velocity curve fittings to confirm the central binary to be close to contact. The masses were found to be M_1 = 4.08 +\– 0.07; M_2 = 3.35 +\– 0.06; the mean radii were R_1 = 2.38 +\– 0.03; R_2 = 2.25 +\– 0.03; all in solar units. Surface temperatures were found as T_1 = 13000+\–300 K, T_2 = 11800+\– 300 K. The distance, from the 'eclipse method', turned out to be 110 +\– 10 parsec, and the age, from the Padova stellar evolution models, came out as about 20 +\– 5 million years.

Detailed examination of the HERCULES spectrograms indicated that the close third component (V831 Cen B) is a chemically peculiar (Ap-type) star (see Figure 4). We also analysed the orbit of that star about the close binary using historic astrometric measurements. This led to an estimate of the third star's mass to be about 2.5 solar masses. Astrometric information was also available for the known fourth star, identified as the fainter component of the wide "binary" I424 (i.e. the lower mass companion of the central triple; also known as V831 Cen C). We estimated V831 C to have a mass of about 1.5 solar masses and to be in an eccentric orbit with a period of about 2000 years. The present separation of the wide pair is a little less than 2 arcsec, but it was only ~0.5 arcsec at its closest approach, about 1000 years ago, according to our model.

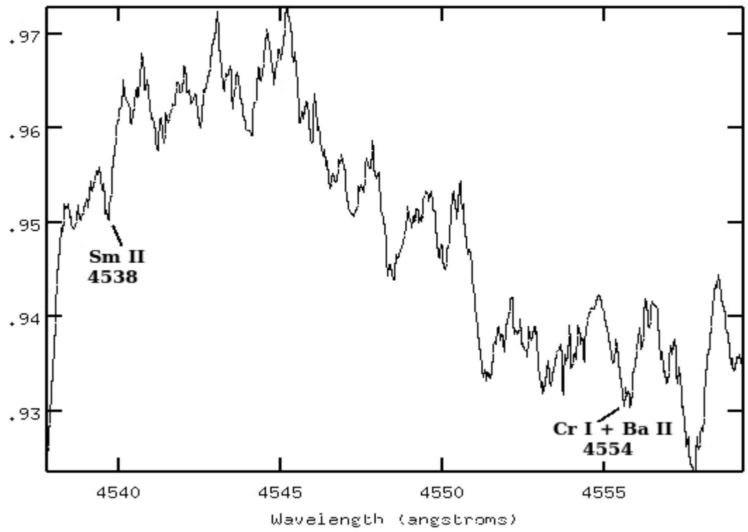

Figure 4. The spectrum of V831 Cen reveals the lines of a third component, containing peculiar lines of chromium (Cr I), europium (Eu I), gadolinium (Gd II), manganese (Mn I), samarium (Sm II) and possibly neodymium (Nd II), suggesting a Bp- or Ap-type star. The graph shows some of the unexpected features in the list of identified lines, the samarium feature and also the chromium and barium blend. The (approximate rest) wavelengths on the diagram labels refer to the normal air wavelengths. HERCULES is calibrated to vacuum wavelengths, resulting in a ~2 Å shift in the scale.

This hierarchically structured stellar configuration has come into being over the last few tens of millions of years in the wake of the ongoing star formation in the Sco-Cen OB2 association, within the galactic scale structure of Gould's Belt. Our study has improved knowledge of some properties of the massive close binary at the centre of the system. In fact, though, V831 Cen still offers more interesting challenges about its physical details; concerning the properties of the Ap component, for example, or else further details on the lower mass stars that are further out from the central close binary. It will surely repay continued observations and analysis.

3.3 R CMa

The relatively bright (6th mag) eclipsing binary system R Canis Majoris has been a repeated topic of study for many stellar astronomers over the years. Its configuration resembles that of the prototype Algol (β Persei), in that one of the stars pushes up against its 'Roche lobe' limit of stability, while the other component appears like a normal Main Sequence star. In the case of R CMa, however, the period is quite shorter than typical (about 1.13 d), and the overall mass of the system (less than 2 solar masses, at most) is also small. Of particular interest is the combination of low period and low secondary mass, which points to a considerable loss of angular momentum from the binary somewhere in its history.

R CMa was one of the stars studied by Brad Wood – one of the main original supporters of MJUO. Wood remarked on the "puzzling" nature of the system in the review of it he gave in his PhD thesis (1946). Several of the early (visual) observers cited by Wood had noted what they thought were photometric irregularities, although those do not seem to have turned out as large as might have been expected in the photoelectric era. A radial velocity (RV) curve was published by Jordan from the Allegheny Observatory in 1916. Although Jordan's observing conditions were not good (100 min exposures) for this southerly star (dec -16 deg), and his RV curve suggest significant eccentricity, his mean RV and its amplitude were surprisingly close to recently adopted values (within 1 km/sec or so). Although later RV curves ruled out orbital eccentricity, the main RV parameters have not changed much.

Wood and other early observers considered real the apparent sudden change of period that occurred around 1915, though that now looks likely to be a rapidly changing part of some more long-term (about a century) cycle. The period obtained from the HIPPARCOS satellite (1.13596 d) is certainly longer than those considered by Wood.

In 1985, J. Tomkin published RV data in which, for the first time, lines from the secondary were identified. If we know both RV amplitudes, then we can work out how far the secondary travels around the primary in the known orbital period; in other words, we can determine the absolute size of this orbit, or the separation of the two stars. Again, combining this separation with the period, and using Kepler's Law, we can work out the stars' masses. This calculation resulted in masses that were less than 1.5 solar masses, however: unexpectedly low masses that had also been indirectly inferred by earlier investigators. This point raises the problem of overluminosity for the stars: not just the secondary, which can be interpreted as part of the general Algol evolution theory, but also the primary, which would be much too bright for its supposed Main-Sequence-like character (cf. Wilson & van Hamme, 2009). A number of Algols were identified to be like this in Kopal's (1959) book on close binary systems. Kopal's 'R CMa type' binaries later became the subject of much controversy. Although true that the stellar parameters cited by Kopal were quite wide of the mark in some cases, the underlying point that there exists a group of Algols with the low mass-ratio and low period combination has turned out to be valid and worthy of further study.

In 2010 a study was produced by Glazunova and co-workers, using data from the 82-inch reflector of the Macdonald Observatory, that revised the stellar masses. Their ~60% increase in derived masses was a good motivator for a new compilation of RV data and analysis, since Glazunova et al. did not actually measure more than one pair of RVs directly. This formed a reason in our plan to revisit the binary using the HERCULES spectrograph at Mt John.

Photometric light curves also come into the size derivations, but there has been more uniformity about those. Almost all studies have shown that the secondary star does indeed essentially fill its Roche lobe (see Figure 5), so that the system is of Algol type in that sense. This inference was made by Ed Budding, Gordon and Richard Hudson, Kim-Young Chen and Brad Wood in 1994 from light curves obtained with the then recently introduced automated photometric telescope (APT) of Carter Observatory. The rather large scatter in such light curves tended to make feasible the early discussions of photometric irregularities, possibly related to gaseous material transferred between the stars, which is a known feature of Algol binaries.

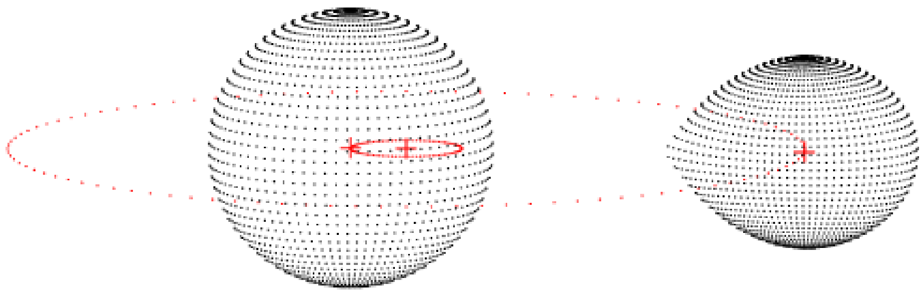

Figure 5. The R CMa system at phase 0.24. The secondary component on the right is shown to fill its Roche lobe. Model produced using Binary Maker 3 (Bradstreet & Steelman, 2002) [5].

In 2002, Ribas et al. introduced the important idea of bringing photometric (Figure 6) and *astrometric* data into a combined analysis. Although generally regarded as separate branches of double star research, these subjects can be seen as different aspects of the same one, and, as with spectroscopy and photometry, make for a more insightful overall picture when combined. This relates to the century-long cycle of period change mentioned before, and in turn this led to the inference of the likely presence of a third body, quite less than the main binary system in mass, but still appreciable enough to cause a light travel time effect in the timing of the minima. A third body had been argued for by Radhakrishnan et al in 1984, and this point may be behind many of the puzzles raised by Wood (revisited by Chen, Budding and Wood, 1992).

[5] Binary Maker 3 is commercial software available from www.binarymaker.com.

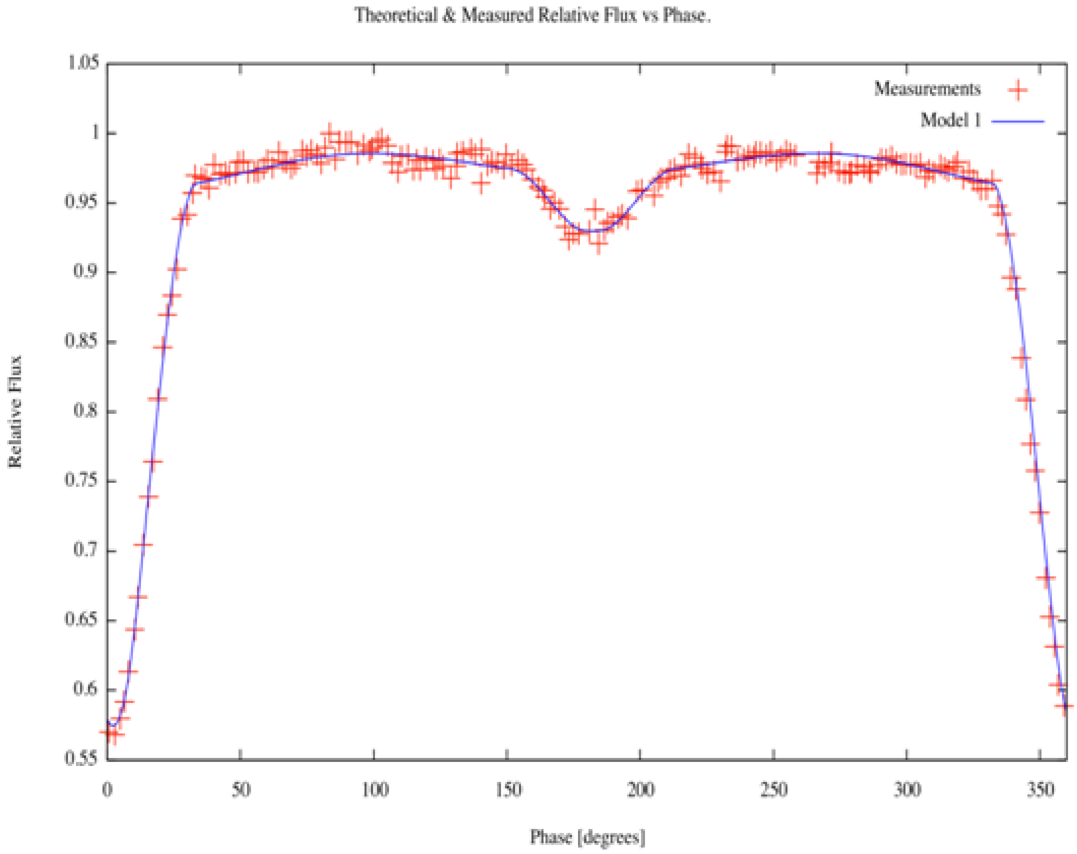

Figure 6. Curve-fitting applied to Sato's (1971) V-band lightcurve using the information limit optimization technique (ILOT) approach (Banks & Budding, 1990).

The new work on R CMa at Mt John was reported by Budding and Butland (2011), which includes also more of the detailed background. The main results from 36 HERCULES spectrograms and re-investigation of literature photometry were M_1 = 1.67 +/– 0.08, M_2 = 0.22 +/– 0.07; R_1 = 1.78 +/– 0.03, R_2 = 1.22 +/– 0.03; L_1 = 8.2 +/– 0.2, L_2 = 0.49+/– 0.01 (all in solar units); and photometric parallax 22 +/–1 (mas). The combination of low period and low mass ratio was inferred to be related to the role of the third body in a secular process of angular momentum transfer. A re-analysis of the astrometric data resulted in M_3 = 0.8 +/– 0.1; R_3 = 0.83+/–0.07; and L_3 = 0.4 +\– 0.1 (solar units).

3.4 η Mus

Like V831 Cen, η Mus is also a multiple star containing a bright (V ~ 4.8 mag), young B8V type eclipsing binary, referred to as η Mus A. This is about one arcminute from the 7.3 mag visual companion η Mus B and within 3 arcsec of the ~10th mag (in infra-red) η Mus C. η Mus-B has been known to be a chemically peculiar (Ap-type) star for 40 years. Two years ago Butland & Budding announced the discovery of an additional object η Mus D, still closer in. This latter component cannot be resolved optically; its presence has been determined by indirect dynamical effects. Again like U Oph and V831 Cen, the combination of properties of the star make it a likely member of the Sco-Cen association within the Gould's Belt megastructure. Such stars, particularly if also eclipsing binary systems are of special interest to star formation studies and understanding how multiple stars behave.

Detailed photometric studies of η Mus (A) have been made for at least 60 years and around 30 years ago a definite variability was reported. However, it was only during the HIPPARCOS survey of the early nineties that the regular succession of eclipses in a period of about 2.4 days were discovered. The star had been known as a likely spectroscopic binary already in the southern binaries programme of the Lick Observatory in the 1920s, but an alias of the true period of the binary had been used to phase the data, with the result that the estimated stellar configuration was quite different to how it later turned out.

The wide (AB) binary was estimated to have a period of about 200,000 years in Tokovinin's (1997) catalogue and masses of the three components of the AB system were given there. But this arrangement was challenged in the study of Bakış et al (2007), based on the first set of high dispersion spectrograms taken with the HERCULES spectrograph at Mt John as part of the PhD programme of Volkan Bakış. That another star might complicate the picture was certainly a factor after Hubrig and his collaborators located η Mus C in 2001. This was during a programme, using the large aperture ADONIS facility of the European Southern Observatory at La Silla, to check the source of occasional flaring X-ray emission, which is identified with the known behaviour of pre-Main Sequence stars of low mass.

Most of the absolute parameters for η Mus in the present programme turned out not that much different from those published by Bakış et al in 2007. There are, however, several ways in which the newer data from Mt John have taken further our understanding of η Mus in the last few years, in particular, that the wide AB system is indeed gravitationally bound. This point was not so clear, because the motion of η Mus D changes the apparent average velocity of the close massive binary at the centre of the hierarchy. In addition, our newer work has included a complete listing of over 450 lines – many due to the rare-earth elements – in the spectrum of the Ap star η Mus B. Not least, new photometry coming from the additional contributions of the VSS DSLR group have given new times of minima that support the dynamical model first evidenced from the HERCULES spectra. This new source of photometry is also allowing high quality new (3-colour) light curves to be added to the documentation of this interesting object. Another point concerns the age of η Mus. The HERCULES spectra indicate that the secondary rotates with a higher speed than the secondary, yet both stars are of almost exactly the same mass and bound in a close system that normal theory asserts must synchronize the rotations within less than a million years.

We would normally expect young stars of such closely similar masses (the radial velocity curves have the same amplitude to within measuring accuracy) to have also very similar radii, or at least the primary to be somewhat larger than the secondary. Close study of recent evolutionary models has, however, revealed the possibility of a phase during the few millions of years before a proto-star becomes established on the "Zero-Age" Main Sequence during which it can experience bursts of expansion in its outer layers – the so-called 'deuterium burning' episodes (see Figure 7). If this is the case for η Mus, then we could be reasonably confident that the close binary is only a few million years beyond it stage of Hayashi collapse, and therefore, indeed, a relatively very young system.

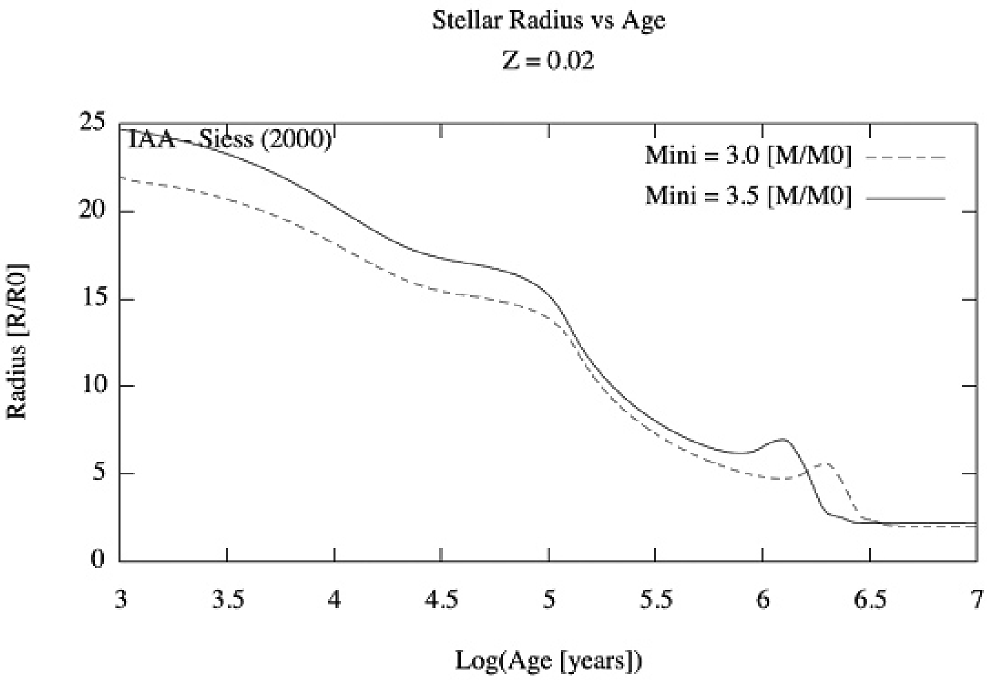

Figure 7. Stellar evolutionary curves of radii derived from interpolated Siess (2000) data for a substantially pre-main-sequence period. Note in particular the radius expansion just prior to the stars reaching the main sequence.

4. Conclusion

The Southern Binaries Programme aims to make use of modern, high-quality instruments applied to relatively understudied regions of the sky that have great significance to general problems of stellar cosmogony. Topics receiving special attention in recent international meetings are addressed. We also apply relevant special experience and software development to deal with new data reduction and analysis. We have delivered definite new results of significance to current astrophysical research, especially in the area of observations and their interpretation.

A key element concerns high-accuracy radial velocity measurements. This is a relatively underdeveloped area for binaries south of declination about –20 degrees. Taking advantage of this research opportunity falls naturally within the framework of our programme.

A primary aim is to combine photometry and spectroscopy to derive reliable absolute parameters of stars. As well as stellar absolute luminosities, masses, radii and temperatures, it is also possible to derive distances (parallaxes). We have shown that parallaxes obtained by the eclipse method can have an accuracy at least comparable to that of HIPPARCOS, if sufficient care is taken. The fact that, in principle, eclipses can be studied as far as stars can be individually monitored gives this approach a cosmic significance. Comparable procedures have been applied, by other groups using larger facilities, to close binaries discovered in neighbouring galaxies. But our own recent work has concentrated, in particular, on one of the most significant star-forming environments, namely the southern sky's Sco-Cen OB Association.

The Sco-Cen complex is an important laboratory for stellar astrophysics. Close binary or multiple systems, especially if eclipses are present, represent a small but highly significant subgroup within this population, whereby hard evidence on stellar masses, luminosities, composition and other inferred properties can be quantified. The interesting discussion on the dependence of stellar properties on their galactic environment can thus be followed and commented on. It is also scientifically important that such evidence as we discuss continues to be gathered, carefully checked and, where possible, counterchecked by alternative groups, methods and technologies. The four case-studies reviewed in Section 3 offer various responses, new interpretations and challenges to existing literature on these, and similar, stars. But our own findings and claims should then invite still more detailed observations and continued future research.

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