

# Eclipsing Binaries in Open Clusters

John Southworth ([jkt@astro.keele.ac.uk](mailto:jkt@astro.keele.ac.uk)) and Jens Viggo Clausen ([jvc@astro.ku.dk](mailto:jvc@astro.ku.dk))

*Niels Bohr Institute, Copenhagen University, Denmark.*

**Abstract.** The study of detached eclipsing binaries in open clusters can provide stringent tests of theoretical stellar evolutionary models, which must simultaneously fit the masses, radii, and luminosities of the eclipsing stars and the radiative properties of every other star in the cluster. We review recent progress in such studies and discuss two unusually interesting objects currently under analysis. GV Carinae is an A0 m + A8 m binary in the Southern open cluster NGC 3532; its eclipse depths have changed by 0.1 mag between 1990 and 2001, suggesting that its orbit is being perturbed by a relatively close third body. DW Carinae is a high-mass unevolved B1 V + B1 V binary in the very young open cluster Collinder 228, and displays double-peaked emission in the centre of the H $\alpha$  line which is characteristic of Be stars. We conclude by pointing out that the great promise of eclipsing binaries in open clusters can only be satisfied when both the binaries and their parent clusters are well-observed, a situation which is less common than we would like.

**Keywords:** stars: fundamental parameters – stars: binaries: eclipsing – stars: binaries: spectroscopic – open clusters and associations: general

## 1. Eclipsing binaries in open clusters

Detached eclipsing binary stars (dEBs) are of fundamental importance to stellar physics because they are, apart from the few closest objects to the Earth, the only stars for which we can accurately measure basic quantities such as mass, radius and surface gravity (Andersen, 1991). The realism and reliability of the current generation of theoretical stellar evolutionary models ranks as one of the great achievements of modern astrophysics, but this success would have been much more difficult without the ability to check the effects of particular physics against the accurate physical properties of stars in dEBs.

Given good photometric and spectroscopic data, it is possible to derive masses and radii of stars in a dEB to accuracies better than 1% and surface gravities to within 0.01 dex (Southworth et al., 2005b). However, the predictions of theoretical models can usually match even properties as accurate as this, both because of their sophistication and because there are several important unconstrained parameters, e.g., metal and helium abundance and age. More constraints are needed to investigate the success or otherwise of a number of physical parameters which are only very simplistically treated in theoretical models, e.g.,

convective core overshooting, mass loss, mixing length and rotational effects. For example, small changes in the mixing length can change the derived ages of the oldest globular clusters, which constrain the age of the Universe, by 10% (Chaboyer, 1995).

An answer to this problem is to study dEBs which are members of stellar clusters (Southworth et al., 2004a; Thompson et al., 2001). Because the dEB and the other cluster members have the same age and chemical composition, theoretical models must be able to simultaneously match the masses, radii and luminosities of the two stars in the dEB and the radiative parameters of every other cluster member, for one age and chemical composition. This allows much more detailed tests to be made of the success or otherwise of different physical ingredients in models. Alternatively, if the cluster is poorly studied, a comparison of the properties of the dEB with model predictions allows the cluster metal abundance and age to be derived.

Detached eclipsing binaries are also excellent distance indicators (Clausen, 2004), through a variety of methods such as using bolometric corrections or surface brightness calibrations (see Southworth et al., 2005a for a detailed analysis). dEBs in clusters therefore give an accurate distance to the cluster without the problems and theoretical dependence which affect the main sequence fitting method.

An unique advantage of studying dEBs in clusters is that it can be possible to place four or more stars with the same age and chemical composition onto one mass–radius or  $T_{\text{eff}}\text{--}\log g$  plot, if several dEBs are members of one cluster (Southworth et al., 2004a; 2004c). Some Galactic open clusters are known to contain four or more dEBs, e.g., NGC 7086 (Robb et al., these proceedings).

## 2. GV Carinae in NGC 3532

GV Car ( $m_V = 8.9$ ,  $P = 4.29$  d) is a member of the nearby open cluster NGC 3532 and contains two metallic-lined A stars. It displays apsidal motion with a period of  $U \approx 300$  yr.

Complete Strömgren *uvby* light curves, with 775 observations in each passband, were obtained at the Strömgren Automated Telescope (ESO La Silla) in 1987–1991, with additional data from 2002–2004 (Fig. 1). These light curves have been analysed using the EBOP code (Popper & Etzel, 1981; Etzel, 1975) and the Monte Carlo error analysis algorithm implemented in JKTEBOP (Southworth et al., 2004b; 2004c).

Spectroscopic observations of GV Car were obtained in 2001–2004 using the FEROS échelle spectrograph at the 1.5 m and 2.2 m telescopes at ESO La Silla. Radial velocities have been derived by cross-correlating

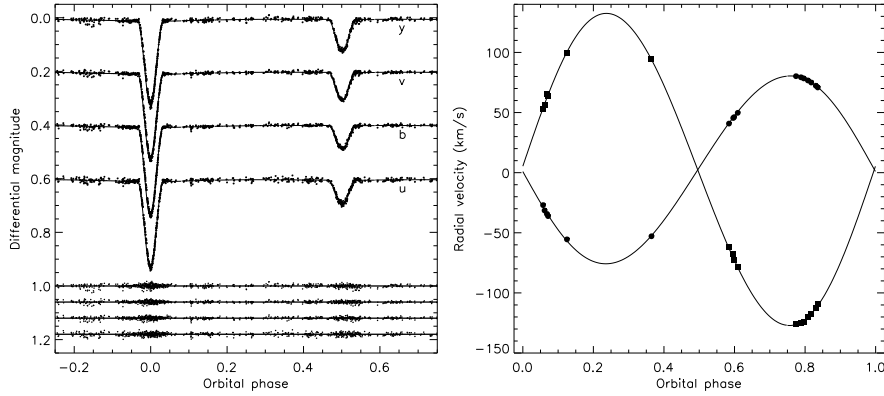


Figure 1. The observed light curves (left) and radial velocity curves (right) of GV Car with the best-fitting models shown using solid lines.

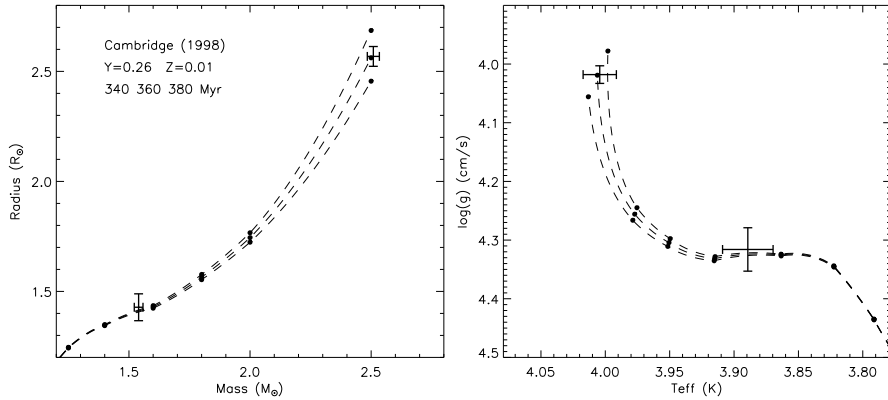
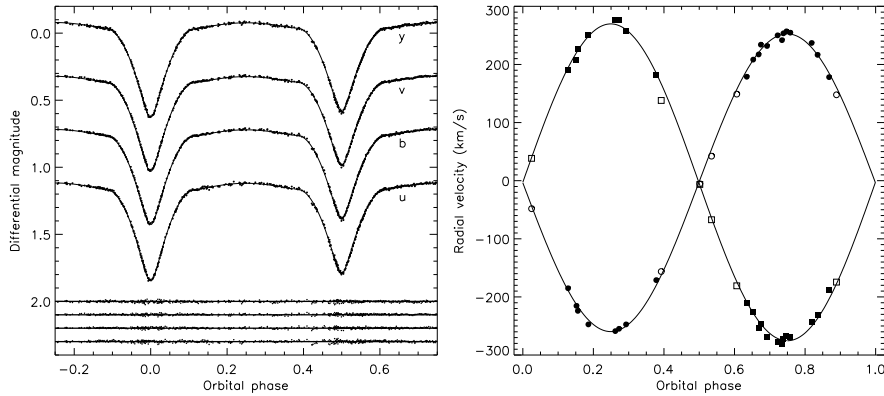


Figure 2. Mass-radius and  $T_{\text{eff}}-\log g$  comparison plots between the properties of the components of GV Car and the predictions of the Cambridge theoretical models.

spectra of GV Car from the 4360–4520 Å échelle order against a spectrum of GV Car taken at the midpoint of a secondary eclipse. They have been fitted with an eccentric orbit using SBOP (written by P. B. Etzel), which is shown in Fig. 1.

The spectra have been modelled using the UCLSYN synthesis code (see Southworth et al., 2004a for references), giving  $T_{\text{effA}} = 10\,100 \pm 300$  K and  $T_{\text{effB}} = 7750 \pm 350$  K, consistent with the  $uvby\beta$  colours of the system and the flux ratios found in the light curve analysis.

The masses and radii of GV Car are  $M_A = 2.51 \pm 0.03 M_\odot$ ,  $M_B = 1.54 \pm 0.02 M_\odot$ ,  $R_A = 2.57 \pm 0.05 R_\odot$  and  $R_B = 1.43 \pm 0.06 R_\odot$ . These are well fitted by the Cambridge theoretical models (Pols et al., 1998) for an age of  $360 \pm 20$  Myr and a metal abundance of  $Z = 0.01$  (Fig. 2). This age is in good agreement with, and more precise than, main-sequence-



*Figure 3.* Observed light curves (left) and radial velocity curves (right) of DW Car with best-fitting models shown using solid lines. Radial velocity observations for the primary and secondary stars are indicated using circles and squares, respectively, and rejected observations are shown using open symbols.

fitting estimates (González & Lapasset, 2002). Our value for the metal abundance is the first published estimate for NGC 3532.

But we do not yet understand GV Car fully; whilst its eclipses were 0.33 and 0.12 mag deep in 1987, they had shallowed to 0.22 and 0.08 mag in depth in 2004. This change can be explained by either an increase in third light (implying a companion which is itself variable) or a decrease of about  $3^\circ$  in orbital inclination (which suggests a perturbed orbit). The latter explanation seems more likely, but because there is no other evidence of a third star in the system it must have a low mass or be a compact object. Further observations will be required to fully understand this interesting system.

### 3. DW Carinae in Collinder 228

DW Car ( $m_V = 9.7$ ,  $P = 1.33$  d) is a high-mass dEB in the young open cluster Cr 228. Strömgren *uvby* light curves, 518 points in each pass-band, were obtained as with GV Car and modelled using the 2003 version of the Wilson-Devinney code (Wilson & Devinney, 1971) (Fig. 3).

The radial velocity analysis of DW Car is difficult because the spectra have very few features. Apart from the hydrogen lines, which do not give reliable velocities (Andersen, 1975), there are only four He I spectral lines of reasonable strength. These lines have been analysed individually using cross-correlation, the TODCOR algorithm (Zucker & Mazeh, 1994), Gaussian fitting and spectral disentangling (Simon & Sturm, 1994). Good results have been obtained for disentangling and Gaussian fitting, whilst cross-correlation is significantly affected by line

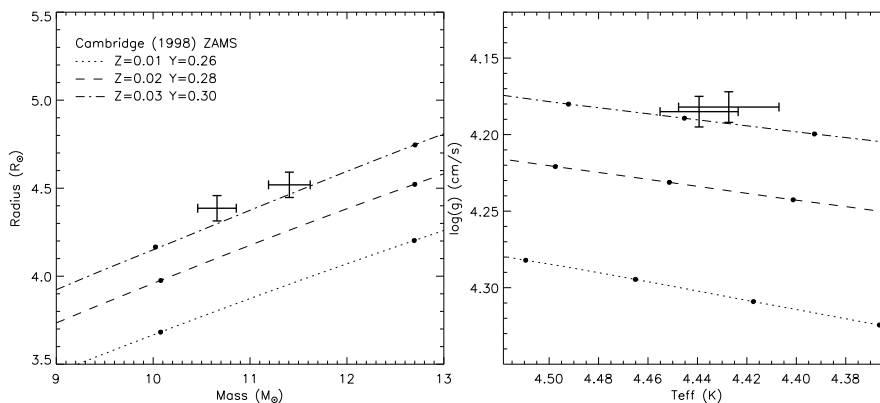


Figure 4. Mass-radius and  $T_{\text{eff}}-\log g$  comparison plots between the properties of the components of DW Car and the predictions of the Cambridge theoretical models.

blending. Circular orbits were fitted using SBOP, and the orbit from fitting the HeI  $\lambda 4471$  line with a double Gaussian is shown in Fig. 3.

The resulting masses and radii of DW Car are  $M_A = 11.4 \pm 0.2 M_{\odot}$ ,  $M_B = 10.7 \pm 0.2 M_{\odot}$ ,  $R_A = 4.52 \pm 0.07 R_{\odot}$  and  $R_B = 4.39 \pm 0.07 R_{\odot}$ . Strömgren index calibrations and the flux ratio from the light curves give  $T_{\text{eff}A} = 27\,500 \pm 1000$  K and  $T_{\text{eff}B} = 26\,750 \pm 1250$  K. These parameters are acceptably fitted by the predictions of the Cambridge models using the  $Z = 0.03$  ZAMS, but no conclusions can be drawn from this until definitive values for the radii are obtained.

DW Car shows a double-peaked emission line at  $H\alpha$  with a sharp central absorption characteristic of a Be star. The line profile does not change with the orbital motion so must come from circumbinary rather than circumstellar matter, as expected given the closeness of the stars to each other. DW Car is a very young system and the rotational velocities are ‘only’ about  $170 \text{ km s}^{-1}$ . These two facts are very unusual for the Be phenomenon, which is thought to increase slightly with age and only be present in stars which are rotating at above 70–80% of their critical velocities (Porter & Rivinius, 2003).

#### 4. Where next?

The study of dEBs in open clusters has been shown to be an excellent way to determine the parameters of clusters by comparison with theoretical stellar models (Southworth et al., 2004b), but the goal of simultaneously fitting models to both the cluster and the two stars in the dEB remains elusive. The main problems are that definitive ob-

servations of both the cluster and the dEB requires extensive telescope time and that the clusters are often too sparsely populated to be useful.

Clusters containing several dEBs are excellent targets for study, because accurate fundamental parameters can be found for four or more stars with the same age, chemical composition and distance, and using the same photometric CCD observations. Several Galactic open clusters, in both the Northern and Southern hemispheres, are known to contain at least four high-mass dEBs, and full studies of these should provide excellent tests of theoretical models.

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