Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **412,** 487–491 (2011) doi:10.1111/j.1365-2966.2010.17919.x

The orbital periods of AA Dor and NY Vir

D. Kilkenny[★]

Department of Physics, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa

Accepted 2010 October 26. Received 2010 September 30; in original form 2010 August 25

ABSTRACT

New timings of eclipses made between 2000 and 2010 are presented for two binary systems with hot subdwarf primary stars. In the case of AA Dor, an sdOB star with a very cool secondary, the period is found to be constant at a level of about 10^{-14} d per orbit. In the case of NY Vir, a rapidly pulsating sdBV$_r$ with a cool companion, the period is discovered to be decreasing at a rate of -11.2×10^{-13} d per orbit.

Key words: binaries: eclipsing – stars: individual: AA Dor – stars: individual: NY Vir.

1 INTRODUCTION

Close binary stars are particularly useful for the determination of fundamental stellar parameters. Double-lined spectroscopic binaries enable the mass ratio of the binary components to be determined and, if the inclination of the binary orbit can be measured or reasonably constrained (as in the case of an eclipsing system), then the absolute masses can be found. In addition, the light curve of an eclipsing system allows relative stellar radii to be found and even the absolute radii if the system is a double-lined binary.

This is no less true for hot subdwarf stars in binary systems but in the case of these evolved stars, binarity presents a number of other interesting considerations:

(i) the evolutionary history of the hot subdwarfs (or ‘extended horizontal-branch’ stars) is not well understood. In particular, it is not clear how almost all of the hydrogen can be lost from the star at the same time that the helium core starts helium burning at around 0.5 M$_\odot$, although more than 30 yr ago Mengel, Norris & Gross (1976) showed that significant mass-loss can occur in close binaries.

(ii) Binary subdwarf B (sdB) stars have orbital periods down to slightly less than a tenth of a day, with the components being separated by $\sim$1 R$_\odot$. In these cases, the system must have undergone a ‘common envelope’ phase with the possibility of extensive mass-loss from the system or mass transfer between the components. Such systems provide an excellent opportunity to study the products of common envelope evolutionary processes.

(iii) Recent studies have shown that a substantial fraction (perhaps 70 per cent) of field sdB stars are radial velocity variables and are binary – typically with a cool M star or white dwarf companion (Maxted et al. 2001; Morales-Rueda et al. 2003). Additionally, studies of optical and infrared (2MASS) colours of stars have indicated that F- to K-type companions to sdB stars can easily be detected (Stark & Wade 2003; Reed & Stiening 2004) in something like 20–50 per cent of cases (with some completeness uncertainties).

(iv) Theoretical work by Han et al. (2002, 2003) has indicated at least three evolutionary sequences by which binary stars can produce hot subdwarfs.

(v) The evolution subsequent to the horizontal branch of sdB stars in binaries is of considerable interest; Maxted, Marsh & North (2000) have shown that KPD 1930+2752 is probably a SN Ia progenitor system and Schenker (2005) has suggested that cataclysmic variables below the ‘period gap’ might all be the product of post-sdB binary evolution.

The above notes are intended to be a very brief background to the subdwarf binaries; for a substantial and detailed description of hot subdwarfs, see the recent review by Heber (2009). This paper presents eclipse timings and resulting ephemerides for two close binaries with hot subdwarf primary stars.

2 OBSERVATIONS

Some of the earlier observations reported here were made with the St Andrews photometer (StAP) on the 1-m telescope at the Sutherland site of the South African Astronomical Observatory (SAAO), but the bulk of the data were obtained with the UCTCCD photometer on the 1-m or 1.9-m telescopes at the same site. The StAP was a GaAs photomultiplier system (now decommisioned) and the UCTCCD – obviously a CCD system – is described briefly by O’Donoghue, Koen & Kilkenny (1996). The instruments employed, filters and integration times (t), are listed in Tables 1 and 2 for each eclipse measured. Colour equations were not used in the data reduction; each set of observations was corrected only for sky background and mean atmospheric extinction, since the aim of the observations was simply to establish an accurate mid-point of each eclipse. In the case of the CCD observations, differential corrections for transparency variations were made whenever suitably bright ‘comparison’ stars were present in the field (with the 1.9-m telescope, the field of the UCTCCD is so small that suitable local comparison stars are not always present). A few of the reduced light curves showed small time-dependent ‘drifts’ – probably due to slight sky transparency/extinction variations or small differential extinction effects

---

[★]E-mail: dkilkenny@uwc.ac.za

Table 1. New eclipse timings for AA Dor. Numbers in parentheses are the errors in the last digit of the eclipse timing (BJD).

Year	Eclipse number	BJD (244 0000+)	Phot	Filter	t (s)
2000	33192	11877.37617 (3)	UCT	V	15
	33196	11878.42235 (1)	UCT	I	20
	33200	11879.46850 (3)	UCT	I	20
	33204	11880.51463 (1)	UCT	V	20
2002	34897	12323.30142 (1)	StAP	B	20
	34901	12324.34759 (2)	StAP	B	20
2005	39057	13411.30675 (1)	UCT	B	20
	39076	13416.27599 (2)	UCT	B	20
2006	40422	13768.30846 (1)	UCT	B	20
2007	42786	14386.58836 (1)	UCT	–	12
	42797	14389.46530 (2)	UCT	–	15
2009	44666	14878.28309 (1)	UCT	–	10
2010	46119	15258.30031 (1)	UCT	–	12

Table 2. New eclipse timings for NY Vir. Numbers in parentheses are the errors in the last digit of the eclipse timing (BJD).

Year	Eclipse number	BJD (245 0000+)	Phot	Filter	t (s)
2001	17760	2017.40603 (3)	StAP	–	20
	17761	2017.50707 (6)	StAP	–	20
	17762	2017.60808 (4)	StAP	–	20
	17781	2019.52742 (5)	StAP	–	20
2004	29212	3174.24093 (7)	UCT	*BG38*	10
	29321	3185.25163 (4)	UCT	*BG38*	10
2005	31571	3412.53767 (4)	UCT	–	10
	33053	3562.24327 (3)	UCT	B	15
2010	50921	5367.19638 (5)	UCT	–	20
	50922	5367.29733 (3)	UCT	–	20
	50931	5368.20648 (6)	UCT	–	20
	50941	5369.21663 (5)	UCT	–	20

in the corrected data. In these light curves a linear trend (always very small) was removed from the eclipse to produce equal brightness just before ingress and just after egress. Eclipse minima were measured by the bisected chords method – essentially measuring the mid-points of a number of chords joining eclipse ingress and egress curves and running parallel to the time axis in a magnitude/time plot. These mid-points always lie very close to a line perpendicular to the time axis, indicating eclipse symmetry, and such a fit has been demanded in every case.

3 AA Dor (=LB 3459)

AA Dor is a star in the foreground of the Large Magellanic Cloud and is also referred to in the literature as LB 3459, HD 269696 and CPD−69°389, amongst others. It was discovered to be a short-period eclipsing binary by Kilkenny, Hilditch & Penfold (1978) with a primary of type sdOB (weak He I lines and He II 4686 are present in the spectrum).

Early analyses derived component masses and radii of $M_1 = 0.5\,\mathrm{M}_{\odot}$, $M_2 = 0.07\,\mathrm{M}_{\odot}$, $R_1 = 0.2\,\mathrm{R}_{\odot}$ and $R_2 = 0.1\,\mathrm{R}_{\odot}$, with a component separation of $1.4\,\mathrm{R}_{\odot}$. $T_{\mathrm{eff}} = 40\,000$ K and $\log g = 5.3 \pm 0.2$ were derived for the primary, together with a very low helium abundance of 0.3 per cent by number (see Kilkenny, Penfold & Hilditch 1979; Kilkenny, Hill & Penfold 1981; Kudritzki et al. 1982, for example).

More recently, a number of analyses have appeared, using data from ground-based and satellite sources. To mention a few: Hilditch, Harries & Hill (1996) analysed echelle spectrograms to obtain more accurate results (but similar to those above) as well as a secondary temperature of $T_2 = 2000$ K; Rauch and his collaborators have carried out a number of analyses using ground-based and *FUSE* results, arguing for $T_{\mathrm{eff}} = 42\,000$ K and generally a somewhat lower mass for the primary ($M_1 = 0.33\,\mathrm{M}_{\odot}$) which in turn implies a brown dwarf mass for the secondary (Rauch 2000, 2004; Rauch & Werner 2003; Fleig et al. 2008, for example).

Most recently, Vučković et al. (2008) have detected emission and absorption lines from the irradiated surface of the secondary star, resulting in velocity amplitudes, $K_1 = 39\,\mathrm{km\,s^{-1}}$ for the primary and a lower limit of $K_2 = 230\,\mathrm{km\,s^{-1}}$ for the secondary. These values imply $M_1 = 0.45\,\mathrm{M}_{\odot}$ and $M_2 = 0.076\,\mathrm{M}_{\odot}$, putting the secondary just above the substellar mass limit. Rucinski (2010) has argued for lower primary and secondary masses ($M_1 = 0.25\,\mathrm{M}_{\odot}$; $M_2 = 0.054\,\mathrm{M}_{\odot}$) indicating a brown dwarf status for the secondary, although Müller, Geier & Heber (2010) favour higher masses ($M_1 = 0.51\,\mathrm{M}_{\odot}$; $M_2 = 0.085\,\mathrm{M}_{\odot}$) but a lower temperature for the primary.

Thus, after more than 30 yr, some of the parameters of the system are still in dispute, though it seems the secondary must be close to the red dwarf/brown dwarf boundary (and probably just on the stellar side).

The most recent ephemeris for the primary eclipses of AA Dor is that given by Kilkenny et al. (2000) which included eclipses measured between 1977 and 1999. In Table 1 are listed another 13 primary eclipse timings obtained between 2000 and 2010. Previously, such timings from SAAO have been reported in Heliocentric Julian Date (HJD) based on Coordinated Universal Time (UTC). The difference between the heliocentric and barycentric corrections (the latter allowing for the movement of the Sun caused principally by Jupiter and to a lesser extent by Saturn) varies by a maximum of between about +4 and –4 s for a star in the plane of the ecliptic. AA Dor which is close to the ecliptic pole is unaffected by this difference at the level of precision of our timings. However, HJD calculated from UTC and Barycentric Julian Date (BJD) calculated from Terrestrial Time (TT) differ by the intrusion of 'leap seconds' which are a correction to 'civil' time – UTC – which is highly undesirable when seeking changes in, for example, astronomical (O−C) diagrams. This is exacerbated by the irregular nature of the addition of leap seconds to UTC. For example, between 1972 and 1998, leap seconds were added at a rate of roughly one per year; between 1999 and 2009, only two leap seconds were added. (An excellent review of the various systems we impose on the measurement of time is given by Eastman, Siverd & Gaudi 2010; fig. 3 of that paper illustrates the leap second issue very well.) Given the above, the new results presented here are in BJD (TT) and appropriate correction has been made to published timings used herein to ensure – as far as possible – that the ephemerides determined are based on homogeneous timings. Note that the input to SAAO data acquisition instruments is generally to the nearest second, so that it is not possible in principle to achieve a better precision than 0.5 s per eclipse measurement.

A linear least-squares solution (based on Bevington 1969) for all the SAAO measurements (1977–2010) gives

$$T_0 = 244\,3196.349\,25\ (2)\ \mathrm{d},$$

$$P = 0.261\,539\,7362\ (8)\ \mathrm{d}$$

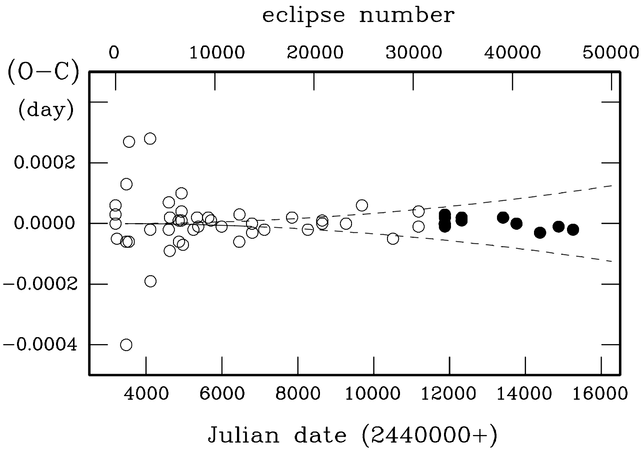

Figure 1. (O−C) diagram for AA Dor. Filled circles are the Table 1 eclipses and open circles are eclipses from earlier SAAO observations. The broken lines illustrate the effect of a period increase (upper) or decrease (lower) of 10^{-13} d per orbit.

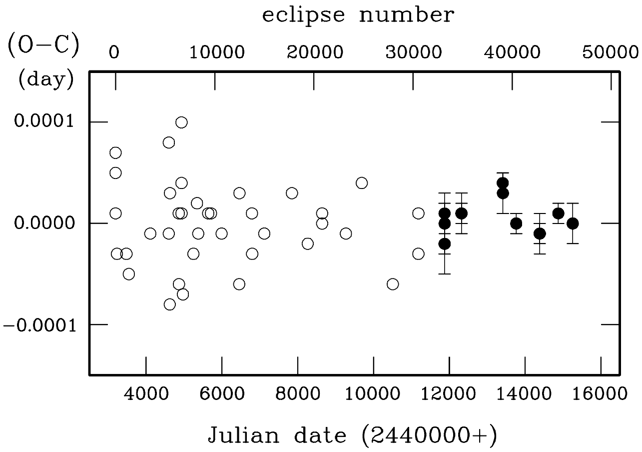

Figure 2. (O−C) diagram for AA Dor without the five largest residuals in Fig. 1. Filled circles are the Table 1 eclipses, open circles are eclipses from earlier SAAO observations and error bars are from the measurements listed in Table 1. The ordinate scale is expanded relative to Fig. 1.

for an ephemeris of the form $T_{\min} = T_0 + nP$ and where the numbers in parentheses are the formal errors from the least-squares solution in the last digit of each number.

Fig. 1 shows the (O−C) diagram for this solution and it is apparent that a linear ephemeris is sufficient. Measures of the accuracy of each eclipse mid-point are listed in parentheses in Table 1, based on the standard deviation of a series of bisected chords. Perhaps a better measure of the real error is given by the scatter in different eclipse measurements – the scatter seen in, for example, Figs 1 and 2. In Fig. 1, the broken lines indicate the effect of a period increase or decrease of 10^{-13} d per orbit; it is clear that any change cannot be substantially bigger than about 10^{-14} d per orbit.

A few of the earliest eclipses were measured with less accuracy – largely because the sampling was less frequent. If we rather arbitrarily omit the five eclipse timings with residuals greater than 0.0001 d, we obtain a linear fit to the measurements of

$$T_0 = 244\,3196.349\,240\ (8)\,\mathrm{d},$$

$$P = 0.261\,539\,7363\ (4)\,\mathrm{d},$$

which is not significantly different from the solution including *all* eclipse measures. The residuals from this fit are shown in Fig. 2 with an expanded ordinate scale.

A fit to all the eclipses including a quadratic term

$$T_{\min} = T_0 + nP + n^2 k_1$$

yields a formal result:

$$k_1 = (-2.3 \pm 7.8) \times 10^{-14} \qquad (\text{where } 2k_1 = \mathrm{d}P/\mathrm{d}n),$$

and omitting, as before, the five largest residuals yields

$$k_1 = (-3.2 \pm 3.3) \times 10^{-14},$$

in effect, no significant change in the orbital period. Interestingly, if the period change rate can be measured to the level of 10^{-15} d per orbit or smaller, then a relativistic effect – the decay of the orbit due to gravitational radiation energy losses – should become detectable. This writer is unlikely to find any such effect, as its detection is almost certainly decades away.

4 NY Vir (=PG 1336−018)

PG 1336−018, a sdB star discovered by the Palomar–Green survey (Green, Schmidt & Liebert 1986) was found to be an extraordinary variable; it is a short-period eclipsing system (period ∼0.1 d) with an sdB primary which is also a rapid pulsator (Kilkenny et al. 1998). These authors also found relative radii $r_1 = 0.19$ and $r_2 = 0.205$, and component effective temperatures $T_1 = 33\,000$ K and $T_2 \sim 3000$ K (implying a spectral type ∼M5).

A multisite (WET) campaign (Kilkenny et al. 2003b) identified 28 pulsation frequencies in the star and showed that the amplitudes of at least the strongest frequencies were varying on time-scales of days. Attempts were made to identify pulsation modes by using the eclipse observations only – in eclipse, some modes should change amplitude and some modes previously unobservable (due to cancellation effects) could appear – but the data proved too little for this to be viable. An attempt was also made to determine the size of the binary orbit by measuring phase shifts in the pulsation frequencies, but it was only possible to put an upper limit of 1 s on the light travel time across the orbit – a result already indicated by the binary orbit solution in the discovery paper (Kilkenny et al. 1998).

Recent work on this system has used evolutionary models to set limits around 0.38–0.48 $\mathrm{M}_\odot$ for the mass of the primary (Hu et al. 2007; Vučković et al. 2007),

Eclipse timings for NY Vir are less accurate than for AA Dor because of the pulsations. These cannot be removed simply because – as noted above – some modes will change appearance during eclipse. The eclipse timings have therefore been made including the effects of pulsation which are sometimes negligible – and sometimes not (see, for example, fig. 10 in Kilkenny et al. 2003b). However, errors introduced will be of the order of 0.000 05 d and essentially random – unless there is commensurability between the pulsation and orbital frequencies (unlikely because of the variable appearance of the pulsations from eclipse to eclipse).

An ephemeris for NY Vir was given by Kilkenny et al. (2000) from the first four seasons of observation (1996–99); this appeared to be linear, with no period change ‘as high as $\mathrm{d}P/\mathrm{d}n = \pm 2 \times 10^{-12}$’. However, an eclipse measured in early 2010 differed from the ephemeris prediction by about 2 min which caused unseemly haste in locating unreduced observations from earlier years as well as in obtaining new measurements. Table 2 gives a list of the 12 eclipses observed between 2001 and 2010 together with an error measure, and Fig. 3 shows linear and quadratic fits to these and

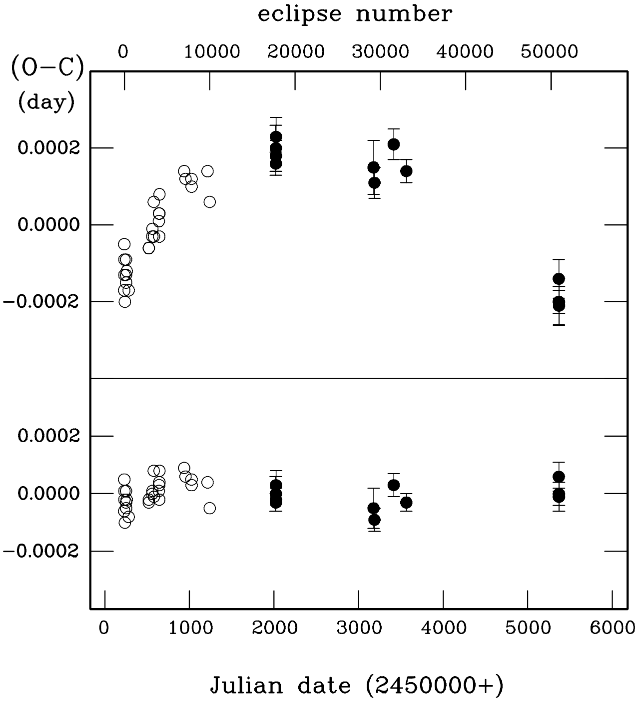

Figure 3. (O−C) diagram for NY Vir. The upper panel illustrates a linear fit to the eclipse timings and the lower panel a quadratic fit with the same cycle numbers. Filled circles are the Table 1 eclipses, open circles are eclipses from earlier SAAO observations and error bars are from the measurements listed in Table 2.

earlier eclipse timings using the same eclipse numbers in each case. [Errors in the later eclipse numbers are unlikely because the earlier data (Kilkenny et al. 2000) show the ephemeris to be very close to linear, and extrapolation is then minimal.]

The quadratic fit to the NY Vir data (1996–2010) gives

$T_0 = 245\,0223.362\,09\ (1)\,\mathrm{d}$,

$P = 0.101\,015\,999\ (2)\,\mathrm{d}$,

$k_1 = (-5.7 \pm 0.4) \times 10^{-13}$,

where the quadratic term is clearly significant, both in the formal least-squares errors and the residuals illustrated in Fig. 3. The k_1 term is equivalent to a period decrease of $\mathrm{d}P/\mathrm{d}n = -\,11.2 \times 10^{-13}$ d per orbit.

5 CONCLUSIONS

The eclipsing sdOB system, AA Dor, has been shown to have an orbital period which is stable at a level of perhaps 10^{-14} d per orbit – only an order of magnitude greater than the level at which orbital decay from gravitational radiation energy losses should become detectable.

The extraordinary eclipsing sdBV$_r$ system NY Vir has been discovered to have a period decrease rate equivalent to -11.2×10^{-13} d per orbit. The cause of the latter is, as yet, unknown – and might remain so for some time. The system HW Vir, which is very similar to NY Vir (except that the sdB primary is not a pulsator), also exhibits an orbital period change. After many years of observation, this appeared to exhibit a sinusoidal variation which was interpreted by Kilkenny, van Wyk & Marang (2003a) to be due to a third body in the system – possibly a brown dwarf. Several years later, however, and with more data, Lee et al. (2009) find a more complex (O−C) structure which they interpret as a secular quadratic term (ascribed to angular momentum loss) plus two cyclic terms. The secular term derived by Lee et al. (2009) for HW Vir implies a period decrease of $-8.3 \times 10^{-9}\,\mathrm{d\,yr^{-1}}$, more than twice that observed (so far) in NY Vir, but leaving the period change in NY Vir still explicable in terms of the magnetic wind braking mechanism proposed by Lee et al. (2009). However, those authors also find cyclic terms in the HW Vir (O−C) diagram with periods of 15.8 and 9.1 yr and amplitudes of 77 and 23 s, respectively, which they interpret as light travel time effects caused by reflex motions in the binary due to substellar companions with masses of about 19 and nine times the mass of Jupiter. Additionally, Qian et al. (2009) find that the rather similar eclipsing sdB system, HS 0705+6700, exhibits a (apparently) purely cyclic term in the (O−C) diagram with a period of just over 7 yr and an amplitude of 92.4 s which they explain as a brown dwarf tertiary companion to the close binary. From this small sample, it is thus clear that interpreting effects in (O−C) diagrams for these systems is by no means simple and that substantial baselines in time might well be required to get even close to the correct solution. The prototype of these systems, HW Vir, is ample demonstration of this; it was initially interpreted as having a simple cyclic term (Kilkenny et al. 2003b); the most recent published work (Lee et al. 2009), using data gathered over a 24-yr baseline, indicates greater complexity – and it is quite likely that the HW Vir system is still not completely solved. It remains to be seen what causes the period change detected in NY Vir.

ACKNOWLEDGMENTS

I am very grateful to Jason Eastman (Ohio State University) and Steve Potter (SAAO) for extremely useful discussions on time and the complexity of its measurement, and to Jason Eastman for his generous software efforts (see, for example http://astroutils.astronomy.ohio-state.edu/time/). I am also grateful to an anonymous referee for helpful comments on the first version of this paper and for spotting a typographical error which might have caused mild embarrassment.

Thanks are due to the SAAO for allocations of telescope time over many years. This paper is based upon work supported financially by the National Research Foundation (NRF) of South Africa.

REFERENCES

Bevington P. R., 1969, Data Reduction and Error Analysis for the Physical Sciences. McGraw Hill, New York, p. 140
Eastman J., Siverd R., Gaudi B. S., 2010, PASP, 122, 935
Fleig J., Rauch T., Werner K., Kruk J. W., 2008, A&A, 429, 565
Green R. F., Schmidt M., Liebert J., 1986, ApJS, 61, 305
Han Z., Podsiadlowski P., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449
Han Z., Podsiadlowski P., Maxted P. F. L., Marsh T. R., 2003, MNRAS, 341, 669
Heber U., 2009, ARA&A, 47, 211
Hilditch R. W., Harries T. J., Hill G., 1996, MNRAS, 279, 1380
Hu H., Nelemans G., Østensen R., Aerts C., Vučković M., Groot P. J., 2007, A&A, 473, 569
Kilkenny D., Hilditch R. W., Penfold J. E., 1978, MNRAS, 183, 523
Kilkenny D., Penfold J. E., Hilditch R. W., 1979, MNRAS, 187, 1
Kilkenny D., Hill P. W., Penfold J. E., 1981, MNRAS, 194, 429
Kilkenny D., O'Donoghue D., Koen C., Lynas-Gray A. E., van Wyk F., 1998, MNRAS, 296, 329
Kilkenny D., Keuris S., Marang F., Roberts G., van Wyk F., Ogłoza W., 2000, Obser., 120, 48
Kilkenny D., van Wyk F., Marang F., 2003a, Obser., 123, 31

Kilkenny D. et al., 2003b, MNRAS, 345, 834
Kudritzki R. P., Simon K. P., Lynas-Gray A. E., Kilkenny D., Hill P. W., 1982, A&A, 106, 254
Lee J. W., Kim S.-L., Kim C.-H., Koch R. H., Lee C.-U., Kim H.-I., Park J.-H., 2009, AJ, 137, 3181
O'Donoghue D., Koen C., Kilkenny D., 1996, MNRAS, 278, 1075
Maxted P. F. L., Marsh T. R., North R. C., 2000, MNRAS, 317, L41
Maxted P. F. L., Heber U., Marsh T. R., North R. C., 2001, MNRAS, 326, 1391
Mengel J. G., Norris J., Gross P. G., 1976, ApJ, 204, 488
Morales-Rueda L., Maxted P. F. L., Marsh T. R., North R. C., Heber U., 2003, MNRAS, 338, 752
Müller S., Geier S., Heber U., 2010, Ap&SS, 329, 101
Qian S.-B. et al., 2009, ApJ, 695, L163
Rauch T., 2000, A&A, 356, 665
Rauch T., 2004, ApSS, 291, 275
Rauch T., Werner K., 2003, A&A, 400, 271
Reed M. D., Stiening R., 2004, PASP, 116, 506
Rucinski S. M., 2010, MNRAS, 395, 2299
Schenker K., 2005, in Koester D., Moehler S., eds, ASP Conf. Ser. Vol. 334 14th European Workshop on White Dwarfs, Astron. Soc. Pac., San Francisco, p. 351
Stark M. A., Wade R. A., 2003, AJ, 126, 1455
Vučković M., Aerts C., Østensen R., Nelemans G., Hu H., Jeffery C. S., Dhillon V. S., Marsh T. R., 2007, A&A, 471, 605
Vučković M., Østensen R., Bloemen S., Decoster I., Aerts C., 2008, in Heber, U., Jeffery S., Napiwotzki R., eds, ASP Conf. Ser. Vol. 392, Hot Subdwarfs and Related Objects. Astron. Soc. Pac., San Francisco, p. 199

This paper has been typeset from a TEX/LATEX file prepared by the author.