New $V I_C$ photometry of the sdOB binary AA Dor and an improved photometric model

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ABSTRACT
New $V I_C$ CCD photometry, obtained with integration times of 20s, of the sdOB+degenerate-dwarf eclipsing binary system AA Dor has provided new complete light curves with an rms scatter about a mean curve of $\pm 0.004 \text{mag}$. These data are analysed with an improved LIGHT2 light curve synthesis code to yield more accurate determinations of the radii of both stars, the orbital inclination, and the flux ratio between the two components. These radii are only a little different from the values derived 25 years ago from less complete data, but the uncertainties on these values are improved by a factor of two. The apparent discrepancy remains between the surface gravity of the sdOB primary star obtained from the light-curve solution with the published spectroscopic orbit and that obtained from NLTE analysis of high-resolution spectra of the sdOB star.

The substantial reflection effect in the system is adequately represented by the LIGHT2 code with a bolometric albedo of unity in light curves extending from 0.35 $\mu \text{m}$ to 2.2 $\mu \text{m}$. However, there are differences at individual wavelengths in the derived albedo, which may indicate redistribution of flux from shorter wavelengths into the $V$ and $I_C$ passbands.

Key words: stars: binary,eclipsing; stars: binary,close; reflection effect; stars: astrophysical parameters; stars: individual (AA Dor).

1 INTRODUCTION
The blue star LB 3459 (HD269696; $V \simeq 11.1 \text{m}$, $RA = 05^h 31^m 40^s.3$, $Dec = -69^\circ 53' 02''.2$ (2000)), and situated at high galactic latitude ($b = -32^\circ.18$), was discovered to be variable in brightness by Kilkenny, Hilditch & Penfold (1978). Observations with the University of Cape Town high-speed photometer revealed the light curve of an eclipsing binary (designated AA Doradus) with an orbital period of 0.261 day and a primary eclipse of depth 0.4 mag in the $V$-band. Spectroscopic and further photometric observations followed over many years, and the present understanding of the properties of this remarkable binary system is summarized in Hilditch, Harries & Hill (1996) (hereafter HHH), and in Rauch (2000) where references to previous publications on this system may be found.

HHH obtained échelle spectra of AA Dor from the Anglo-Australian Telescope and determined a velocity semi-amplitude for the sdOB primary star of 40.8 $\pm 0.7 \text{km s}^{-1}$. Many attempts to detect spectral signatures of the secondary component from these data failed, and HHH were forced to adopt a representative mass of 0.5 $M_\odot$ for the sdO star in order to calculate the mass of the secondary star from the derived mass function and the earlier light-curve analyses, and establish the absolute sizes of the stars in this system. The sdOB star seemed to be an unremarkable member of that class of evolved stars, whilst the unseen secondary component at $0.09 M_\odot$ seemed to be a degenerate red dwarf of surface temperature $\simeq 2000 \text{K}$. The derived surface gravity of the primary star was found to be $\log g = 5.53 \pm 0.03$ which was in some disagreement with an earlier NLTE analysis by Kudritski et al. (1982), where a value of $5.3 \pm 0.2$ was derived. HHH recommended that a new determination of $\log g$ from spectral line profiles would help to resolve this issue and permit a direct determination of the mass of the sdOB star and therefore also the secondary component.

The more recent work by Rauch (2000) addressed this issue directly by detailed NLTE analysis of high resolution optical and ultraviolet spectra. Rauch obtained an effective temperature for the primary component of 42000 $\pm 1000 \text{K}$, in agreement with Kudritski et al., and a value of $\log g =$
5.21 ± 0.10 which clearly exacerbated the problem. He also derived a mass for the sdO star of 0.330± 0.006 from comparison of the location of the primary in the $T_{eff}$ vs log g plane with evolution tracks for post-RGB stars. The consequent mass for the secondary component was 0.066 ± 0.001 $M_\odot$ which places it firmly in the brown dwarf category.

With the discrepancy about the surface gravity still unresolved, we decided to secure new complete light curves of AA Dor in the V and I bands in order to re-determine the radii of both stars relative to the semi-major axis of the relative orbit. Most recently, Rauch & Werner (2003) have published a new spectroscopic study of AA Dor based upon many 180s-exposure UVES spectrograms obtained with the ESO Very Large Telescope.

2 PHOTOMETRIC OBSERVATIONS

Because the primary eclipse of AA Dor has a total duration of only 26 minutes and a depth of 0.4 mag, it is clear that photometry has to be secured with excellent time resolution in order to ensure that the detailed shape of the eclipse curve is established without compromise. Accordingly, the University of Capetown CCD camera, mounted on the 1.0-m telescope at the South African Astronomical Observatory, was used to secure these data. This camera operates in frame-transfer mode, so that there is essentially no time lost between exposures. Integration times of 15- or 20-s were used for the V observations, and 20-s for the $I_C$ observations, ensuring that the eclipse curves were well sampled. To be certain of this time resolution, all the observations on a single night were obtained in one filter only, rather than alternating between the V and $I_C$ passbands. The field of view of the UCT CCD camera on the 1-m telescope is only about 1.8 × 1.2 arcminutes so that, despite AA Dor being a foreground object to the Large Magellanic Cloud, the field is remarkably free of useful comparison stars. One comparison star is ≲1 m fainter than AA Dor at maximum, and the rest are all at least 2m fainter.

Observations of the AA Dor field were obtained on 4 consecutive nights, two nights with incomplete light curves, and two nights with complete light curves, one in each of the V and $I_C$ passbands that are in routine use at the SAAO. The data were reduced with an SAAO version of DoPhot, slightly modified to reduce data “on-line” so that an almost immediate assessment of photometric quality can be made. Differential magnitudes were derived relative to the brightest comparison star using standard SAAO software. The constancy of this star was established by comparing it with the fainter stars in the field.

Infrared JHK photometry was obtained using the MkIII photometer (Glass 1973), with the f/50 chopping secondary, on the 1.88-m reflector of the SAAO. Observations were made during two allocations of time: 1984 January 17–23 and 1984 January 27–30. For each filter, observations were obtained in modules of two 10-s integrations. Beamswitching occurred twice in each module, which was repeated as necessary in order to achieve the desired accuracy. On a given night, a single filter was selected and AA Dor monitored for an entire orbital period. The star HD37027 was selected as a comparison star since it was an early-type star close to AA Dor and which Cousins (1987) subsequently published as a secondary UBV standard star.

Infrared standard stars were selected from the SAAO list, which Carter (1993,1995) later published, and observed in so far as was practicable at approximately the same airmass as AA Dor. These enabled differentially- corrected infrared magnitudes to be placed on the standard system. The intention was to detect a signature of the cool secondary component in the infrared light curves, specifically by examining whether the depth of the secondary eclipse would be found to dip below the occultation of the reflection effect by the primary, that is, below the level recorded immediately outside the primary eclipse, and thereby yield some measurement of the infrared flux from the secondary star. The data were of poorer quality than had been hoped, and they failed to show a clear signature of the flux from the secondary star beyond the known reflection effect; they are included graphically as a further test of reflection-effect modelling, considered in section 3.3.

3 ANALYSIS OF THE LIGHT CURVES

3.1 The $V_I$ data

The most recent orbital ephemeris for AA Dor has been determined by Kilkenny et al. (2000) from times of primary eclipse minima observed from 1977 to 1999. This linear ephemeris has a reference time of primary minimum of $HJD_{2443196.34868}$ ± 0.00002, and an orbital period of 0.261539731 ± 0.000000002 d, and has been used to convert the heliocentric Julian Dates into orbital phases. To improve photometric accuracy, the individual observations were added in orbital-phase bins of $\Delta \phi = 0.0020$ and then differential magnitudes formed between the variable and the comparison star. Most bins had 2-3 observations yielding a typical Poisson uncertainty of ±0.004 m in V and ±0.003 m in $I_C$.

The two complete light curves are plotted in Figure 1 with a total of 500 binned observations defining the V curve from 1157 individual observations obtained on JD2451880, and in Figure 2 with a total of 500 binned observations defining the $I_C$ curve from 1287 individual observations obtained on JD2451879. On each of these nights complete light curves were secured and the small region of orbital-phase overlap with data obtained at the beginning and end of each night showed no differences. The overall V curve shows some minor irregularities from a symmetric curve, but the $I_C$ curve is entirely symmetric.

3.2 Geometric parameters

The two stellar radii, expressed in terms of the semi-major axis of the relative orbit, and the orbital inclination are determined very well from the annular primary eclipse curve alone, as noted in HHH. We have used the LIGHT2 light-curve-synthesis code (Hill 1979, Hill & Rucinski 1993) to analyse the complete V and $I_C$ curves separately, and the results are given in Table 1. We adopted standard values of linear limb darkening for both stars, together with standard values of the gravity darkening exponent. A mass ratio of 0.20 (secondary/primary) was adopted from Rauch
Figure 1. The complete V band light curve of AA Dor defined by 500 binned observations (crosses with Poisson uncertainties of ±0.004 mag). The solid line shows the LIGHT2 model fit to these data, whilst the dotted line is the theoretical curve with the albedo fixed at unity. The observed-calculated (O − C) values are also plotted displaced by +0.45 m from zero.

Figure 2. The complete I_C band light curve of AA Dor defined by 500 binned observations (crosses with Poisson uncertainties of ±0.003 mag). The solid line shows the LIGHT2 model fit to these data, whilst the dotted line is the theoretical curve with the albedo fixed at unity. The observed-calculated (O − C) values are also plotted displaced by +0.50 m from zero.

The effective temperature of the sdO star was taken to be 42000 K also from Rauch’s (2000) NLTE spectral analysis, and that of the cool secondary star to be a nominal 2000 K. Solutions of the I_C-band curve with different fixed values of the secondary temperature (T_{sec}) showed that the χ^2 value increases by a factor 2 over the range 2000 K < T_{sec} < 6000 K. The reason for this lack of dependence on the secondary temperature is simply that the flux ratio (primary/secondary) is 10^3 in the I_C band and 10^5 in the V band immediately after egress from the primary eclipse, when we see only the averted unheated hemisphere of the secondary. At the maximum of the reflection effect this ratio has reduced to 13 in I_C and 19 in V, which suggests that it should be possible to detect the heated face of the secondary in near-infrared spectra obtained at the appropriate orbital phases.

It is clear from the results in Table 1 that the solutions for the mean, or volume, radii and the inclination from the V and I_C curves are in excellent agreement, and that the I_C solution is slightly more precise. The average values have been adopted in all subsequent analyses as fixed parameters, and we should note that they are little different from those found in earlier studies from less complete and less accurate data, but they are more precisely determined.

The excellent agreement between these V and I_C-band observations and the model light curves are shown in detail through the primary and secondary eclipse curves in Figure 3, Figure 4, Figure 5, and Figure 6. V and I_C curves defined by the individual observations were also solved, and the same values for the geometrical parameters were determined as in Table 1 but with larger uncertainties. Combining the observations into these phase-binned values has not systematically affected the derivation of the relative stellar radii.

| passband | r_{pri} | r_{sec} | incl | rms |
|----------|--------|--------|------|-----|
| V        | 0.1413 | 0.0759 | 89.60 | ± 0.0053 |
|          | ±0.0008 | ±0.0006 | ±0.56 |
| I_C      | 0.1425 | 0.0769 | 88.82 | ±0.0039 |
|          | ±0.0007 | ±0.0005 | ±0.20 |
| average  | 0.1419 | 0.0764 | 89.21 | ±0.0005 |
|          | ±0.0003 | ±0.30 |

Figure 3. The V band primary eclipse light curve of AA Dor (crosses with Poisson uncertainties of ±0.004 mag). The solid line is the LIGHT2 model fit to these data solving for the geometrical parameters and the albedo of the secondary star. The dotted line is a theoretical curve calculated from the average geometrical parameters and adopting an albedo of unity for the secondary. The observed-calculated (O − C) values are also plotted displaced by +0.45 m from zero.

Table 1. Geometric parameters
3.3 Reflection effect

The manner in which the reflection effect is modelled does not significantly affect the solution for the geometrical parameters in AA Dor, which is why that part of the analysis has been separated. In HHH, it was explained that the LIGHT2 code had difficulty in fitting the observed reflection effect, and recourse was made to rather extreme measures to fit the data, by changing the limb-darkening coefficient of the heated secondary star to negative (limb-brightening) values. Whilst such drastic action did provide a solution, it was clearly not satisfactory.

With these new complete light curves, it was necessary to resolve this issue, particularly in view of the fact that users of the Wilson-Devinney (WD) code (Wilson & Devinney 1971, Wilson 1979, 1990) on eclipsing binaries with similar large-amplitude reflection effects did not experience such major difficulties (e.g. Wood et al. 1993, Zola 2000), although it did seem necessary for Wood et al. to adopt some unusually low values for the limb-darkening coefficients. A detailed reexamination of the code by GH finally revealed a one-line error in the reflection calculation subroutine, a missing factor π coupled with an incorrect expression involving the angle to the surface normal of emergent intensity. Making this correction increased the calculated amplitude of the reflection effect up to that calculated by the WD code.

This revised code was tested against a set of light curves kindly provided by Professor R.E.Wilson (private communication). These monochromatic light curves were generated with the current version of the wd code using nominal values of the two radii, the orbital inclination, and the temperatures of the two stars in AA Dor, and setting the bolometric albedo of the secondary star to be unity. The monochromatic wavelengths were set to the mean wavelengths of the Strömgren-Crawford uvby filters, the V and IC filters, and the infrared JHK passbands. Since it is already long-established that the wd and LIGHT2 codes agree in all geometrical respects, (cf., for example, Bell et al. 1991), these uvby and VIC light curves were solved individually by the revised LIGHT2 code for the albedo of the secondary component. Two descriptions of the reflection effect were used, one adopting that in the wd code of complete absorption and re-radiation of the incoming flux from the primary star by the secondary star (i.e. heating), and the other that provided by Sobieski(1965) where some of the incoming flux may be scattered by free electrons in the atmosphere of the secondary and the remainder goes into direct heating. The direct heating approach yielded a mean albedo from the 9 light curves of 0.97 ± 0.06, whilst the Sobieski approach yielded a mean albedo of 0.90 ± 0.06.
Table 2. Values of heating albedo for the secondary component

| passband | heating – only | Sobieski |
|----------|----------------|----------|
| u        | 0.46           | 0.49     |
| ±0.12    | ±0.16          | ±0.12    |
| v        | 0.45           | 0.48     |
| ±0.06    | ±0.06          | ±0.06    |
| b        | 0.39           | 0.42     |
| ±0.05    | ±0.06          | ±0.05    |
| y        | 0.55           | 0.63     |
| ±0.07    | ±0.10          | ±0.07    |
| V        | 1.43           | 1.70     |
| ±0.05    | ±0.06          | ±0.05    |
| IC       | 2.02           | 2.40     |
| ±0.04    | ±0.05          | ±0.04    |

albedo of 1.16 ± 0.07. This direct comparison between the WD and the LIGHT2 code shows a satisfactory agreement in the representation of the reflection effect.

The V and IC light curves were analysed with the LIGHT2 code, adopting black-body fluxes convolved with the standard filter response curves, and solving for the two radii, the orbital inclination, and the albedo (αsec) of the secondary component. Because of the large range in temperature across the heated hemisphere of the secondary component (2,000 – 20,000 K), we used the option in LIGHT2 to use a limb-darkening coefficient appropriate to the local temperature of each code pixel on the secondary surface rather than a mean value. Both modes of calculating the reflection effect were used, and these provided identical values of the geometrical parameters. These values are reported in Table 1 as already noted. The values for αsec are given in Table 2 for the two wavelengths and both modes of calculating the reflection effect. The root-mean-square (rms) scatter of the binned observations about the fitted light curves (noted in Table 1) are only 0.001 m larger than the Poisson uncertainties on these binned data, demonstrating that the fits are very good.

The uoby light curves of AA Dor published by Kilkenny, Penfold & Hilditch (1979) (Figure 7) were also analysed with the LIGHT2 code solving only for the albedo of the secondary component in both the heating-only mode and in the Sobieski mode, and adopting as fixed values the average geometrical parameters given in Table 1 from the V and IC light curve solutions. These results, together with those determined from the V and IC curve solutions are listed in Table 2.

Irrespective of the mode of reflection calculation used, there are significant departures from an idealised αsec = 1.0 model. In Figures 3-7, these solution curves are plotted as solid lines, there being no difference between the two modes. Also plotted in these figures are theoretical light curves for a binary with the average geometrical parameters and αsec = 1.0. The uoby light curves give an average value of αsec = 0.50 ± 0.05 for the Sobieski mode and αsec = 0.46 ± 0.04 for the heating-only mode. The αsec = 1.0 light curves systematically do have reflection effects with larger amplitudes than the observations, but those differences amount only to 0.01 – 0.02 m, and the observational uncertainties are of the same order per observation. For the better-defined V and IC curves, the observations present a reflection effect of higher amplitude than the αsec = 1.0 curves and these systematic differences are clearly evident, particularly in Figure 5 and Figure 6. Since these single epoch V and IC light curves were obtained 22 years after the uoby data, we cannot rule out the possibility of some intrinsic variability in the system that conspires to simulate an enhanced reflection effect in two wavelengths and a suppressed effect at shorter wavelengths. Alternatively, perhaps this is observational evidence for some redistribution of flux from the near-UV and blue regions into the visual and near-IR regions by means of substantial line blocking/blanketing. Note that this intrinsically very cool secondary star has an unperturbed Teff = 2000 K, and a temperature at the substellar point directly underneath the sdOB primary star of some 20,000 K. It would be interesting to know what type of overall spectrum would be calculated for such an illnminated hemisphere. (cf., e.g., Barman, Hauschildt & Allard, 2002). In our analysis, the black-body fluxes are a reasonable representation of the broad-band sdOB spectrum. But the spectrum of the heated hemisphere of the secondary component is likely dominated by emission lines and our black-body representation is clearly a limitation. It might also be expected that circulation currents would exist on the facing hemisphere of the irradiated secondary star (Podsiadlowski 1991), and that the limb-darkening values would be reduced compared to normal. Reducing the limb-darkening values increases the calculated amplitude of the reflection effect for a given value of the albedo, as already demonstrated by Wood et al., and by HHHH.

In Figure 8 the infrared JHK band data are plotted, together with theoretical curves calculated from the average geometrical parameters and with αsec = 1.0. Despite the obvious large uncertainties in these data, such theoretical light curves are consistent with these data and do not suggest any large-scale departure from a model with a bolometric albedo of unity for the secondary star.

We note again that Wood et al. experienced some difficulties in fitting their multi-colour observations of HW Vir with the WD code in the sense that they had to adopt low
values of the limb-darkening coefficients in order to increase the theoretical amplitude of the reflection effect up to that observed. In a study of the system PG1336-018, Zola (2000) modified the wd code to assign limb-darkening coefficients appropriate to the local temperatures of each of the stellar surface pixels in the code, and obtained an albedo value in the range 0.45 – 0.95 dependent on other parameters for the system. Thus there is evidence that in these binary systems displaying extreme reflection effects the accepted standard light-curve-synthesis codes experience some difficulties in matching the observations.

4 ASTROPHYSICAL PARAMETERS

The results of several observational programmes investigating the fraction of hot subdwarf stars that are found in binary systems have been published in recent years. Specifically, Maxted, Heber, Marsh & North (2001) and many references therein, have demonstrated that the observed fraction of extreme horizontal branch stars that are members of binary systems with orbital periods less than 10 days is \( \approx 70\% \). Two recent papers by Han et al. (2002) and Han, Podsiadlowski, Maxted & Marsh (2003) have discussed the various evolution channels that can explain the observed properties of sdB,sdOB, and sdO stars in binary systems, concluding that the different channels can explain why some hot subdwarfs are found in short-period binaries, others in binaries with much larger orbits, and some are now merged single objects. The first common-envelope-ejection (CEE) channel is the evolution path where the initially more massive star experiences dynamical mass transfer on its first ascent of the red-giant branch, leading to the formation of a common-envelope followed by a spiral-in phase with the binary system attaining a short orbital period \((P < 10\, \text{d})\) and being composed of a hot subdwarf and a main-sequence companion. The distribution of masses of the hot subdwarf stars in this evolution channel is expected to lie in the range \(0.33 – 0.47 \, M_\odot\), with a main peak at around \(0.46 \, M_\odot\) and a much smaller peak around \(0.33 \, M_\odot\). These binary population synthesis models do succeed in explaining the observed distributions of properties of sdB,sdOB,sdO star binaries. Specifically with regard to AA Dor, the first CEE models seem to provide a sensible explanation for its observed properties.

Since the spectrum of the secondary star in AA Dor has not yet been observed, so that we do not know its orbital velocity curve, we have to assume a mass for the sdOB star, and then calculate all the absolute astrophysical parameters from the derived values of relative radii, orbital inclination, and the velocity semi-amplitude of the primary component. HHH derived a value of \(K_{\text{pri}} = 40.8 \pm 0.7 \, \text{km s}^{-1}\) whilst Rauch & Werner (2003) determined a value of \(K_{\text{pri}} = 39.19 \pm 0.05 \, \text{km s}^{-1}\). Adopting an expected range of subdwarf mass of 0.33 – 0.47 \(M_\odot\), with both values of \(K_{\text{pri}}\), and the geometric parameters from Table 1 we obtain the ranges of possible values of masses, radii, surface gravities, and synchronous rotational velocities given in Table 3.

The corresponding range of mass ratio is 0.168 – 0.200 and has no effect upon the derived relative radii, orbital inclination etc from the light curve analyses. These ranges result from the assumed range of primary star mass, and are larger than the range of uncertainties that would result from propagation of the formal uncertainties of the derived quantities. They may be compared with the values determined by Rauch (2000) and Rauch & Werner (2003) from their analyses of spectra of AA Dor.

Rauch (2000) derived a mass for the sdOB star of \(0.330 \pm 0.006 \, M_\odot\) from comparison of their derived effective temperature \((T_{\text{eff}} = 42000 \pm 1000 \, \text{K})\), and surface gravity \((\log g = 5.21 \pm 0.10)\) with theoretical models for the evolution of subdwarf stars of different masses plotted in the \(T_{\text{eff}} \text{ vs } \log g\) plane. This value of surface gravity disagrees with that determined from the velocity curve of the primary component and the above light curve analysis. We note that Rauch & Werner (2003) state: “Since the analysis of Rauch (2000) was hampered by the relatively long exposure times \((1\, \text{h} \text{ and } 2-3\, \text{h}, \text{respectively})\) and hence, a relatively large orbital velocity coverage (the observed line profiles were broadened by the star’s rotation as well as by smearing due to orbital motion within the observations), it has been speculated that \(\log g\) from Rauch (2000) is somewhat too low.”

The new data reported in Rauch & Werner (2003) (hereafter RW) have exposure times of just 180s and remove this problem. From NLTE model atmospheres, RW fitted theoretical line profiles for the He II \(\lambda 4686\) absorption line and derived \(T_{\text{eff}} = 44000 \, \text{K}, \log g = 5.4,\) without published uncertainties, and \(V_{\text{rot}} = 43 \pm 5 \, \text{km s}^{-1}\). They note, however, that this determination of \(T_{\text{eff}}\) is not as definitive as that determined by Rauch (2000) from the ionization equilibria of many species, whilst the value of \(\log g = 5.21\) was determined from the broad Balmer lines of hydrogen. Later, RW note that: “Unfortunately, significant effects of changes in

| parameter  | primary mass \(M_\odot\) | secondary mass \(M_\odot\) |
|------------|----------------|-----------------|
| mass  \(M_\odot\) | 0.33 – 0.47 | 0.064 – 0.082 |
| radius \(R_\odot\) | 0.179 – 0.200 | 0.097 – 0.108 |
| \(\log g\) (cgs) | 5.45 – 5.51 | 5.27 – 5.29 |
| \(V_{\text{rot}}\) \(\text{km s}^{-1}\) | 34.7 – 38.6 | 18.7 – 20.8 |

**Figure 8.** The JHK light curves of AA Dor (crosses) obtained by AELG. The solid lines show the theoretical curves calculated from the average geometrical parameters for an albedo of unity.
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which differ only a little from those determined earlier, but they are defined more precisely. These results together with the published orbital parameters from IIIH and RW provide new determinations of the astrophysical parameters with an adopted range of primary star mass. These results are compatible with the theoretical evolution models for binary systems containing hot subdwarf stars published by Han et al. (2002, 2003).

An error in the reflection effect subroutine within the LIGHT2 code has been corrected with the result that it agrees with the accepted standard wd code. Analysis of the observed reflection effect demonstrates significant departures within some passbands from an idealised albedo of unity for the heated hemisphere of the secondary star, but the overall bolometric value is most likely close to unity. It is suggested that further theoretical work should be done on modelling the reflection effect in these types of binaries containing stars with very different effective temperatures.

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5 SUMMARY

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