*Baltic Astronomy, vol. 9, 197–204, 2000.*

# REFLECTION EFFECT IN PG 1336-018

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Received September 11, 1999

**Abstract.** The Wilson-Devinney model has been modified to account for significant temperature rise in the hemisphere of a cool star, illuminated by a sdB companion. The new approach, where the limb darkening coefficients are calculated on-line from the local temperature, has been applied to the light curve of PG 1336-018.

**Key words:** stars: binaries, oscillations, individual: PG 1336-018

## 1. INTRODUCTION

PG 1336-018 belongs to the new class of variable stars – called EC 14026, after the prototype EC 14026-2647 (Kilkenny et al. 1997a). The class has been discovered during the Edinburgh-Cape blue object survey (Kilkenny et al. 1997b). The EC 14026 stars are short period pulsators (2–3 min), pulsating with at least two periods. They are sdB stars with temperatures about 35 000K. Since the first four EC 14026 pulsators have cool (F or G) companions it was suspected that this was typical of this group of stars. However, recently new members of the class were found with no detectable companions (O'Donoghue et al. 1998).

PG 1336-018 has been measured by Wesemael et al. (1992) with the Strömgren filters. The data showed very large deviations in the $y$ filter and similarity to another eclipsing system: HW Vir (Wood, Zhang & Robinson 1993). New photometric observations of PG 1336-018 have been obtained with the University of Cape Town

CCD photometer on the 1 m telescope at the Sutherland Observatory (Kilkenny et al. 1998). On the night of May 19/20 a white light run has been obtained. It shows rapid oscillations, eclipses, occurring with a period close to 0.1 d and very pronounced reflection effect indicating the existence of a cool companion. Kilkenny et al. (1998) concluded that the sdB component must be the source of observed low amplitude variability. More, although shorter runs (but covering the whole orbital period) were obtained by these authors in the broad band $V$ and $R$ filters. They also found a period of 0.1010174 days. The frequency analysis revealed two periods of the low amplitude oscillations: $P_1$=184.0 and $P_2$=141.3 seconds. It was found that amplitudes of these frequencies were variable, in case of $P_2$ even below detection limit for some runs.

Spectroscopic data for PG 1336-018 were acquired in the 1996 season (Kilkenny et al. 1998) on the 1.9 m telescope at SAAO. The radial velocity curve for the sdB star has been determined, yielding the semi-amplitude ($K_1$) to be about 78 km/s (mass function $f(m)$=0.005, $a \sin i$=0.156$R_{\odot}$). Fitting the Balmer line profiles to the summed spectrograms resulted in the following parameters for the sdB component: its effective temperature $T_1$ = 33 000 K and $\log g$ = 5.7, in good agreement with the temperature derived from the fits to the IUE spectra.

Kilkenny et al. (1998) used the $UVR$ light curves of PG 1336-018 to get a good fit using the Wilson-Devinney model. They did not attempt to derive the best solution but with some parameters fixed (mass ratio $q$=0.3, the sdB component temperature $T_1$ = 33 000 K and the cool component temperature $T_2$ = 3 000 K), they varied others, using the Binary Maker code and tried to achieve the best fit by trial and error.

The main conclusions from the light curve analysis are as follows:

(1) inclination and fractional radii are well constrained by the shape of observed light curves ($i = 81°$, $r_1$=0.19, $r_2$=0.205),

(2) to obtain a reasonably good fit, it was necessary to force the limb darkening coefficient of the cool component to be zero for $U$ and $V$ filters,

(3) albedo of the cool star must be set to 1 or even greater than 1 for the R filter.

Preliminary results from light curve modeling obtained by Kilkenny et al. show striking similarities between PG 1336-018 and HW Vir, although the former system is much more interesting, since some properties of the sdB component can be independently derived by methods of asteroseismology.

The main aims of this paper is to derive the best fit to the observed light curve, using the light curve synthesis technique, along with the Monte Carlo method as the search procedure.

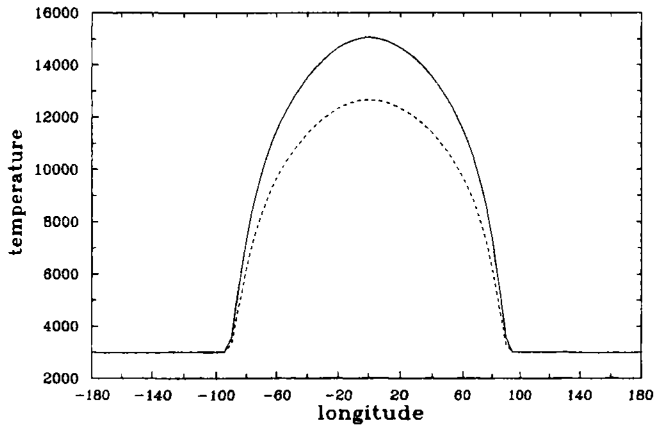


**Fig. 1.** Temperature distribution along the equator of the cool component.

## 2. LIGHT CURVE MODELING

The Wilson-Devinney (Wilson 1974, 1979, 1993) model (W-D) has been used to obtain the best fit and parameters of the eclipsing system PG 1336-018. However, instead of the original differential correction procedure, I applied the Monte Carlo search method (Price 1976). This method works despite correlations among parameters. It also does not require starting values for searched parameters, the search is done within given ranges. This method has worked successfully with the W-D code in the ST Ind case (Zoła et al. 1997). I used the NF run taken in SAAO on May 19/20, 1996, kindly sent to me by Dave Kilkenny. Instead of using all single points I have averaged them to 150 normal ones so they cover a full orbital cycle, uniformly along the light curve. Equal weights for each normal point have been assigned. Phases were calculated by the ephemeris given by Kilkenny et al. Finally, magnitudes have been transformed into flux units, normalized to 1.0 at the phase 0.25, and the effective wavelength of the R647 photomultiplier tube has been assumed to be similar to the $B$ filter one..

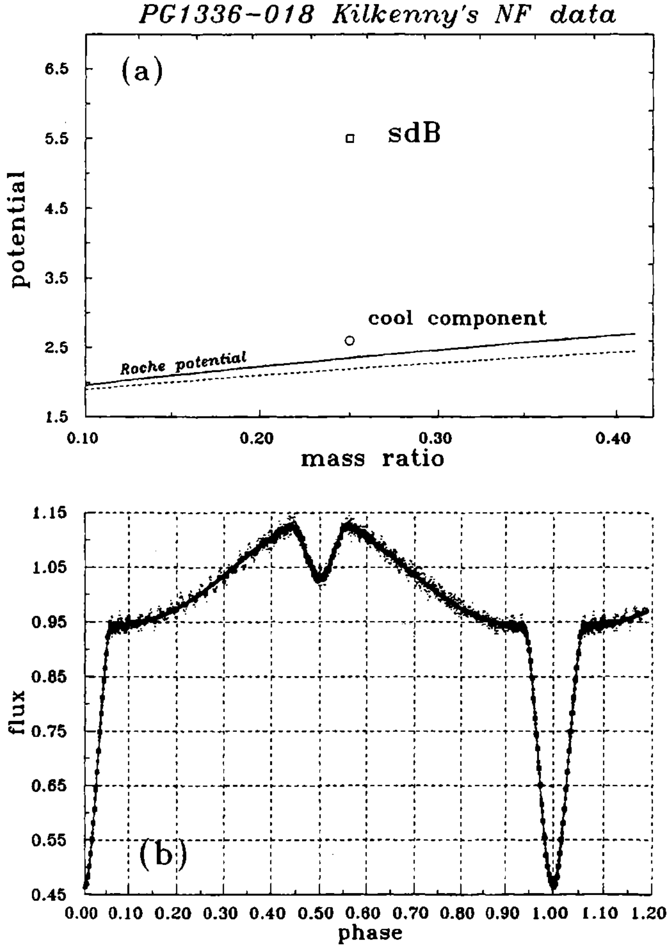


**Fig. 2.** Cross-section of the search array (a) and comparison between synthetic and observed light curves (b).

First, I have checked how much radiation from the sdB component can rise the temperature of the illuminated hemisphere of the cool star. This is shown in Fig. 1, where the temperature distribution is shown along the equator of the cool component. The continuous line represents the distribution for the albedo of the cool star set to 1.0, while the dashed one, is for albedo set at 0.50. This

Figure has been constructed for a system with the mass ratio $q$=0.3, temperatures of the components $T_1$ = 33 000 K and $T_2$ = 3 000 K. Potentials were set to $\Omega_1$=5.5, $\Omega_2$=3.8 (detached configuration) for the sdB star and the cool component, respectively. As one can see, maximum temperature on the equator can rise more than five times if albedo is 1, or four times if albedo is 0.50. Second, influence of the gravity darkening coefficient has been considered. It turned out, that light curves computed for $g_2$=0.32 and $g_2$=1.00 are almost indistinguishable. I would conclude that albedo should be closer to 1.0 than to 0.50, when one attempts to model light curves of the systems like PG 1336-018 or HW Vir. Resulting light curve practically does not depend on the gravity darkening coefficient unless the cool star is very distorted. Finally, the main problem would be the limb darkening coefficient for a star that is cool on one hemisphere and hot on the other.

The limb darkening coefficient depends on two parameters: the temperature of a star and on the wavelength at which the star is observed. The W-D code has been modified in the following way. The limb darkening coefficient is determined for the cool component temperature and a given wavelength. This value is used for the hemisphere not irradiated by the hot component. On the other hemisphere, the local temperature, that could be much higher due to radiation from the sdB star, is being computed for every element, and a new limb darkening coefficient determined from the Al Naimy (1978) tables.

## 3. RESULTS

Three models have been checked:

(1) model I: temperature of the sdB star was fixed at 33 000 K, while other parameters were searched within the following ranges: inclination between 75 and 85 degrees, the mass ratio between 0.1 and 0.8, the temperature of the secondary star between 1500 K and 4200 K, potentials of the components between 1.5 and 45;

(2) model II: temperature of the secondary star was set to 3000 K and the primary star temperature was searched between 25 000 K and 42 000K, other parameter ranges were taken as in model I;

(3) model III: the sdB star mass was assumed to be $0.5 M_\odot$, then the mass ratio $q$ has been calculated from the mass function ($q$ = 0.25), both temperatures have been treated as free parameters.

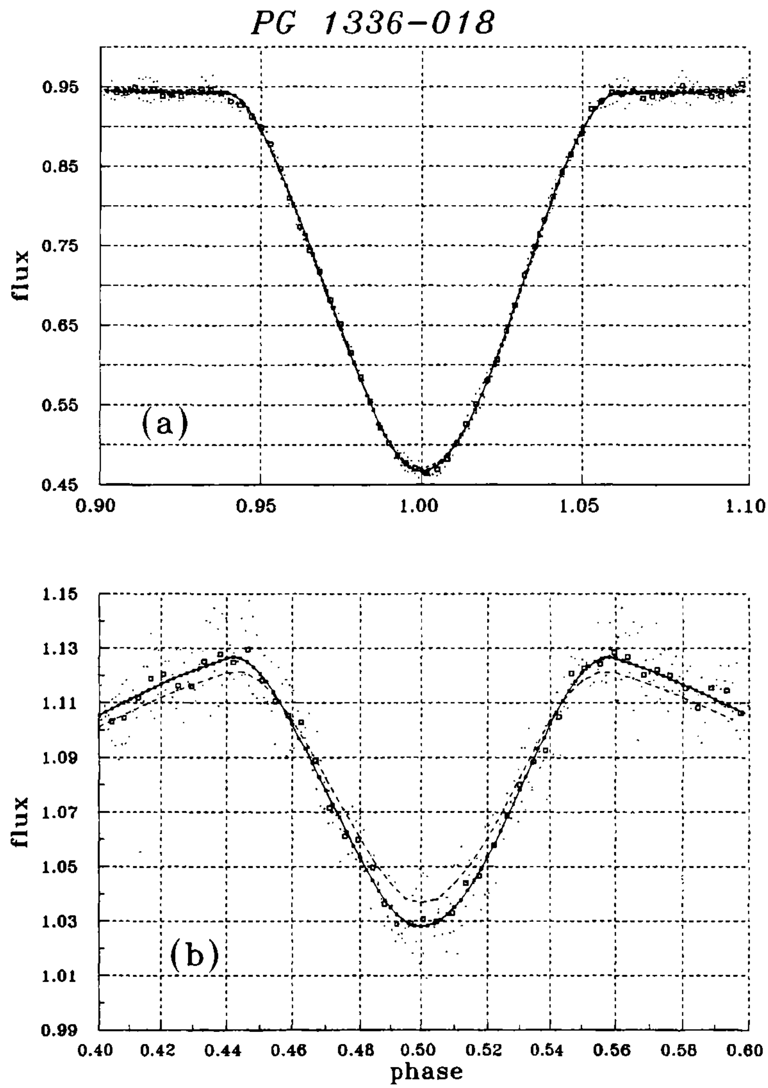


**Fig. 3.** Comparison between theoretical and observed light curves in the (a) primary and (b) secondary minimum.

Results are presented in Table 1 and shown in Figures 2 and 3. Fig. 2a displays the cross-section of the search array for model III in the $\Omega$-$q$ plane, at the end of the search. Fig. 2b shows comparison between the data and theoretical light curves. In Fig. 3 we present details of the fit in the primary and the secondary minima. The light curve of model III is plotted as continuous line. Dots represent single observations while squares the normal points. The best fit that has been obtained using the original W-D code (without modifications concerning the limb darkening coefficient), is plotted as the dashed line. The masses and radii of the components, corresponding to the three models are presented in Table 1.

**Table 1.** Absolute parameters of PG 1336-018.

| | $q$ | $M_1$ | $M_2$ | $R_1$ | $R_2$ | $A$ |
|---|---|---|---|---|---|---|
| Model I | 0.197 | 0.95 | 0.20 | 0.18 | 0.20 | 0.95 |
| Model II | 0.534 | 0.08 | 0.04 | 0.09 | 0.09 | 0.45 |
| Model III | 0.250 | 0.52 | 0.13 | 0.15 | 0.16 | 0.79 |

All three models of PG 1336-018, presented in this paper, were derived for albedo $A_2$=1.0 and $g_2$=1.0. The best solution (model II) was obtained for the mass ratio about 0.5. However, if the $K_1$ value published by Kilkenny et al. (1998) is not wrong by a large factor, this solution would imply too small masses of the components.

Much more reliable results would be obtained if such modeling was done for multicolor observations from infrared to ultraviolet (Strömgren $u$ preferred).

ACKNOWLEDGMENTS. The Monte Carlo computations were done at ACK 'Cyfronet' in Cracow under grant No. KBN/UJ/015/95 which I gratefully acknowledge. The author thanks Dave Kilkenny for sending his observations.

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