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Research Note

A theoretical study of tidal interaction of the eclipsing binary HV 2274 in the Large Magellanic Cloud

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Abstract. About three years ago we did predict, only on the base of theoretical evolutionary models and of the measured apsidal motion rate, the radii and masses for the components of the extragalactic eclipsing binary HV 2274 in the Large Magellanic Cloud. At that time the radial velocity curves were not available and the need of more complete observations to compare with the evolution theory was emphasized. Recently, through ground-based photometry, spectroscopy and spectrophotometry on board the Hubble Space Telescope the absolute dimensions of that system were obtained. In this research note we perform a more complete comparison between observations and theoretical predictions since the light and radial velocity curves are now available. The theoretical radii and apsidal motion rate inferred from models computed for the precise observed masses were found to be in good agreement with observational data. The importance of the case of HV 2274 lies mainly in the fact that this system is the first extragalactic binary system where it has been possible to investigate its surface astrophysical parameters as well as the tidal interactions using the techniques of apsidal motion.

Key words: stars: binaries: close – stars: binaries: eclipsing – stars: evolution – stars: individual: HV 2274 – galaxies: individual: LMC

1. Introduction

CCD photometry is of prime importance to investigate extragalactic eclipsing binaries, particularly in the Magellanic Clouds. Systematic observations, as the photometric monitoring that is being carried out, gave out some binary systems which could be used to test more accurately evolutionary models in an environment chemically different from the solar one (Tobin 1994 and references given therein). This class of observation, although important, is incomplete since spectroscopic measurements are also needed in order to obtain absolute dimensions. However, even without the respective spectroscopic data, the photometric observations may be useful under certain conditions. A very favorable case is the detached system HV 2274 (Watson et al. 1992). Reliable light curves were obtained indicating that both components were similar, and in addition, the period of apsidal motion U was determined (about 123 years). Using the mentioned binary as prototype, we have introduced a method to infer the masses and radii of eclipsing binaries when some fundamental astrophysical parameters are not available but apsidal motion is detected and measured. Specifically we have applied it to HV 2274. Considering that the components are similar from the shape of the light curve and using the observed apsidal motion period as a constraint, the masses of the components were restricted to be between 10 and 12 $M_\odot$ (Claret 1996). As the radial velocity curves were not yet available, it was emphasized the need to obtain such data to compare the *observed* masses, radii and apsidal motion rate directly with theoretical models.

Recently Guinan et al. 1998, using the spectroscopic instruments installed on board the Hubble Space Telescope determined the masses and radii of HV 2274 with sufficient accuracy (around 5% in mass). Therefore, the set of data - light and radial velocity curves - is complete. Within this range of uncertainties, we are now able to compare the absolute dimensions with theoretical models and apply the additional test to stellar evolution, say, the apsidal motion of HV 2274. Some aspects of the dynamical evolution of the system are also discussed.

2. The masses, radii and the theoretical models

2.1. Non rotating models

The astrophysical data to be used in the comparison with stellar models are summarized in Table 1. They are essentially derived from Table 1 of Guinan et al. 1998. The quoted errors in the effective temperatures (180 K) are internal and model-dependent. In our opinion, this error bar is unrealistically small and it was assumed here that the mean errors in the effective temperatures are of the order of 500-1000 K, compatible with other temperature determinations of stars in this mass range.

The metal content of the LMC is accepted to be between 0.004 and 0.01 and we selected Z=0.007 as representative (Maeder et al. 1999). The corresponding theoretical HR diagram for (X, Z)=(0.734, 0.007) is shown in Fig. 1. The non rotating models were computed using the stellar evolution code by Claret

Table 1. Astrophysical parameters of HV 2274 (in solar units)

	Primary	Secondary
Mass	12.1±0.4	11.4±0.4
Radius	9.84±0.24	9.03±0.20
log g	3.54±0.03	3.58±0.03
log T_{eff}	4.362	4.364
Period	e	$\dot{\omega}$
5.726006±0.000012	0.136±0.012	0.0459 deg/cycle

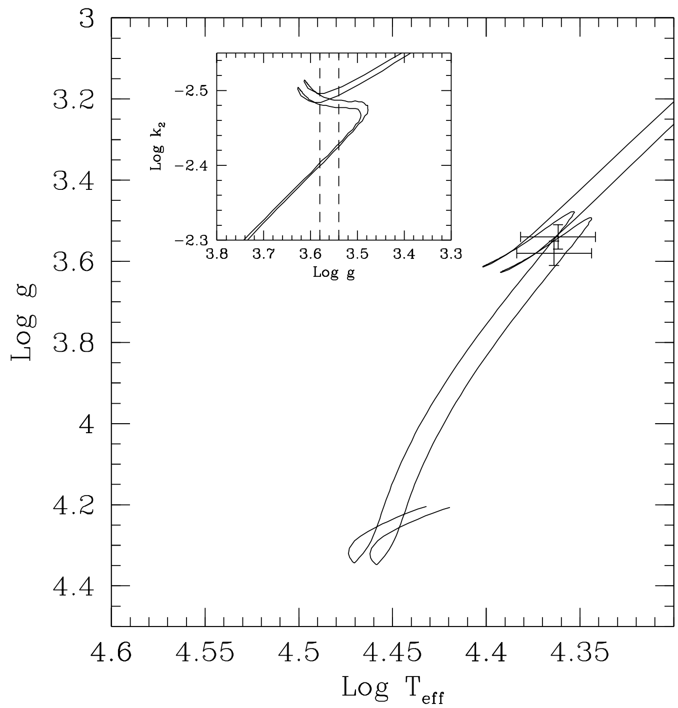

Fig. 1. Theoretical HR diagram for HV 2274. The upper left corner shows the theoretical models in the plane log k_2 versus log g. The vertical dashed lines indicate the position of the observed surface gravities for the two components. X=0.734, Z=0.007. Non rotating models.

1995 for the precise observed masses. The variables which characterize the convective energy transport are the mixing-length parameter α=1.52 and the overshooting amount $\alpha_{\rm ov}$=0.20. Both stars (mainly the primary) are placed in a difficult region, coinciding approximately, with the end of the hydrogen burning stage, as already pointed out by Claret 1996. The derived ages are 17.4 and 18.8 Myears, respectively. For models computed with smaller metallicities this effect is more pronounced (Fig. 2). The probability of finding stars in this zone is small if compared with stars located on the middle of the Main-Sequence, for example. In principle, it seems that an increase of convective core overshooting could place both stars in a more favorable zone of the HR diagram. However, this is not supported by observations, at least at the present time.

One way to try to elucidate the situation would be to use evolved eclipsing binaries in the mass range of HV 2274 for which the effects of overshooting are more conspicuous. However, some eclipsing binaries that would be good candidates for discriminating the amount of core overshooting are not observed with sufficient accuracy (errors in masses and radii about 10%). We have performed some tests that indicate that, if one takes into account a larger $\alpha_{\rm ov}$, for example 0.40, the agreement theory-observation begins to fall due to the increasing of the theoretical effective temperatures. Whether there is a need for a larger convective core overshooting and/or whether it depends on the stellar mass is currently an open question and it is beyond the scope of this research note. For models using Schwarzschild's criterion the situation is still worse since both stars are located in a fast evolutionary phase.

2.2. Models with rotation

Stellar rotation affects the internal structure of stars causing distortions and changes in the effective temperature and luminosity (Tassoul 1978). It is expected that theoretical apsidal motion constants also change with rotation. A good indicator of the influence of rotation on stars is λ=$2v^2/(3gR)$, where v is the rotational velocity, g the local gravity and R the stellar radius. For break up velocities, λ takes the value 0.30. The average value for HV 2274 is 0.04, indicating that the effects of rotation may be important. Thus it is fair to introduce this important mechanism in the stellar evolutionary codes in order to make a more detailed comparison. The quasi-spherical approximation, with some modifications, was implemented in our stellar evolution code to take into account the effect of rotation on the internal structure of the stars and, in particular, on the apsidal motion constant (Claret 1999). The rotating models were computed for the same input physics as for the previous ones. Initial angular velocities were selected assuming that the current velocities correspond to the pseudo-synchronization. The results are presented in Fig. 3. The inferred ages are 17.4 and 18.9 Myears. There is no significant effect other than that the theoretical k_2 are a little bit smaller than in the previous case. The overall agreement can be considered equally good given the levels of observational uncertainties.

The rotating models were computed with some simplifications:

– it was assumed rigid body rotation and therefore, the redistribution of angular momentum is highly effective.
– the diffusion equation, which must be solved simultaneously with the equation of angular velocity, was ignored.

These simplifications may limit our conclusions since the differential rotation and the induced diffusion of the chemical elements change the evolution of a rotating star. Especially important is the diffusion. Some recent investigations (Zahn 1992a, Talon et al. 1997) indicate that models with induced diffusion present similar properties as the models with moderate core overshooting. Taking into account these comments, it is of special interest to investigate the effects of such phenomena in order to clarify what is the real role of rotation and core overshooting and their interaction.

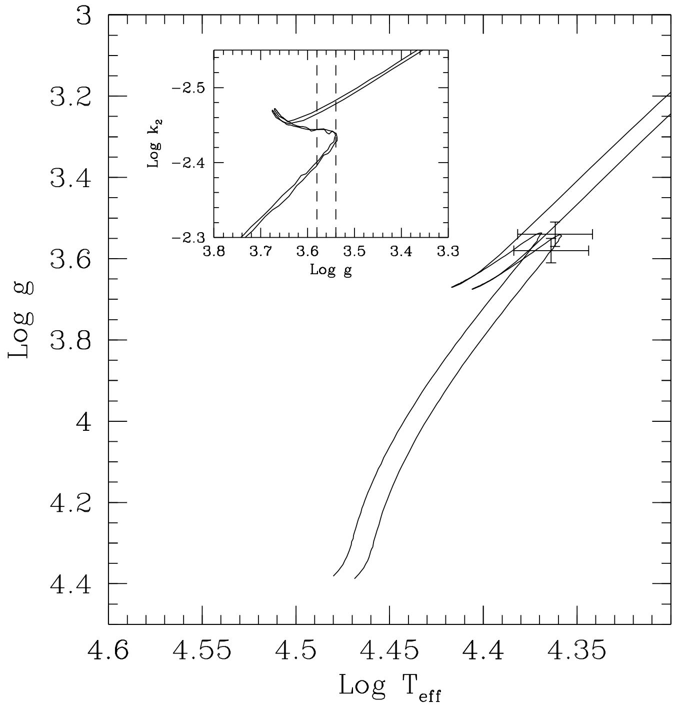

Fig. 2. The same label as in Fig. 1 but for X=0.744, Z=0.004

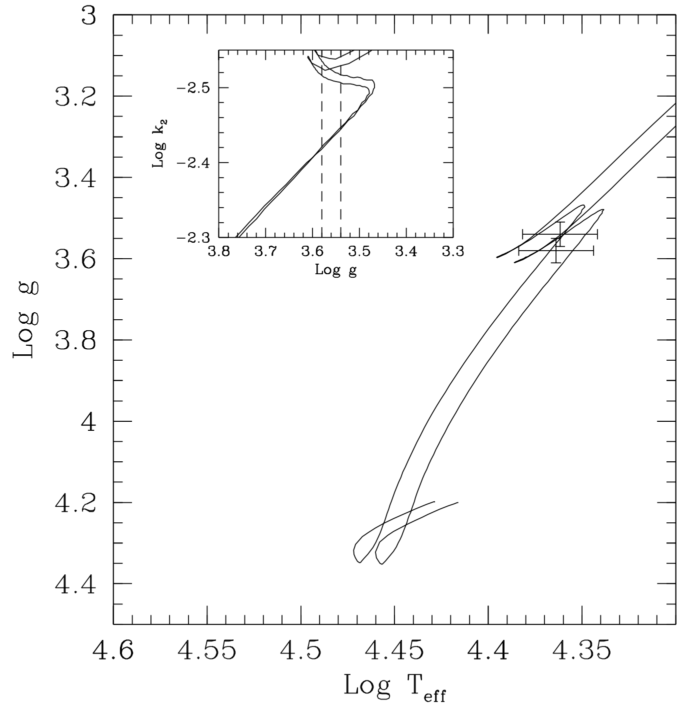

Fig. 3. The same label as in Fig. 1 but for rotating models

3. The apsidal motion test

In order to analyze the apsidal motion, the equations given in Claret & Giménez 1993 were used. For completeness, we reproduce them here. The period of apsidal motion U is related with the internal structure of the stars k_{2i} as

$$\frac{P}{U} = c_{21}k_{21} + c_{22}k_{22} \tag{1}$$

$$c_{2i} = \left[\left(\frac{\omega_i}{\omega_K}\right)^2\left(1+\frac{m_{3-i}}{m_i}\right)f(e) + \frac{15m_{3-i}}{m_i}\frac{(8+12e^2+e^4)f(e)^{2.5}}{8}\right]\left(\frac{R_i}{A}\right)^5 \tag{2}$$

where

$$f(e) = (1-e^2)^{-2} \tag{3}$$

e is the eccentricity, ω_i is the angular velocity of the component i, ω_K is the keplerian angular velocity, m_i, R_i, A are the mass and radius of the component i and the semi major axis respectively, in solar units. The mean value of the internal structure constant to be compared with that derived from theoretical models is given by:

$$\overline{k}_{2obs} = \frac{1}{360\,(c_{21}+c_{22})}\dot{\omega}_{obs} \tag{4}$$

if the apsidal motion rate is given in degrees/cycle.

Rotational velocities are needed to derive both theoretical and observed apsidal motion rates. We assume that both components are synchronized at the periastron since the observational values are not yet available. The observed apsidal motion, after the relativistic correction (Levi-Civita 1937), is log$\overline{k_{2obs}}$ = -2.46±0.05. The relativistic correction contributes only with 3% to the total. Using the individual contribution of each star we finally obtain log$\overline{k_{2the}}$=-2.43±0.07, which is in good agreement with the observations. Similar results were also obtained using models computed with the same code but with slightly different metallicities.

With respect to dynamical evolution, this is a matter of strong discussion now-a-days. Three mechanisms were invoked to explain the synchronization and circularization levels of close binary systems:

- hydrodynamical currents
- turbulent dissipation
- radiative damping

In the first mechanism, described by Tassoul (1987, 1988), the hydrodynamical currents due to the tidal and rotational distortions tend to synchronize and circularize the orbit. The respective time scales depend on a free parameter N which is the ratio between the eddy and radiative viscosities. On the other hand, Zahn (1989, 1992b) revised the last two mechanisms. The turbulent dissipation was identified as the responsible for the braking in late-type stars while the radiative damping acts on hotter ones. By inspecting the times scales and making some numerical experiments, we can deduce that the Tassoul formalism is much more effective than the mechanisms described by Zahn. Independently of the mechanism used, the differential equations which govern the orbital parameters must be integrated since an analysis based on only time scales may yield a wrong interpretation (see Claret & Cunha 1997, Sect. 5).

Let us apply these concepts to the case of HV 2274. In order to do that, we first integrate the tidal evolution equations

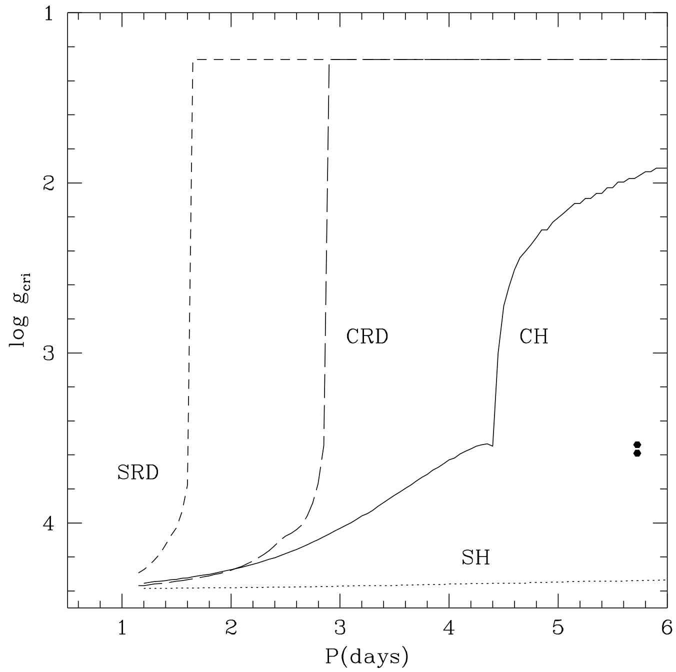

Fig. 4. Critical log g for circularization and synchronization. The labels SRD and CRD indicate the curves for synchronization and circularization using radiative damping while SH and CH denotes the hydrodynamical mechanism. The observational data are represented by hexagons. For sake of clarity, only the calculations for the primary are represented.

for the hydrodynamical formalism using the equations given in Claret et al. 1995 for that purpose. A convenient way to show the results is presented in Fig. 4. The diagnostic diagram period versus $logg_{cri}$ shows that both components of HV 2274 are synchronized since the observational points are out of the critical curve. This theory also predicts that the system is still eccentric, which is confirmed by observations.

However, if one uses the radiative damping, which is appropriate to stars in the effective temperatures range of HV 2274, the situation is different. The resulting $logg_{cri}$ for circularization indicates that it is also compatible with the observed eccentricity of HV 2274 but the critical values for synchronization are very different from those obtained using the hydrodynamical mechanism. Following the radiative damping mechanism, both components of HV 2274 are not yet synchronized. The contradiction is then obvious although not surprising. The formalism by Tassoul has been subject to severe criticism. In 1992, Rieutord pointed out some reservations concerning it. He argued that currents driven by the Ekman pumping are not efficient to reduce the time scales and if the fluid is an incompressible one, the time scale is of the order of the viscous time. Such a paper was refuted in a paper by Tassoul & Tassoul 1997. The situation is far from being clear. Given these remarks, one should be careful concerning tidal evolution theory. Besides the integration, one should investigate the three cases, and it is not "recommendable" to take one of them as definitive (Claret et al. 1995; Claret & Cunha 1997).

Anyway, the assumption of pseudo-synchronism has no large influence on the comparison with observations concerning apsidal motion given that the rotational contribution is only 17% of the total apsidal motion rate. Finally, we would like to emphasize a point: the importance of investigating an eclipsing binary born in a different chemical environment. In fact, it was shown that extragalactic eclipsing binaries should not be investigated only under the evolutionary point of view - comparison with the absolute dimensions - but also from the tidal interactions perspective.

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