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D. Koester, S. Moehler

The Mass of the sdB Primary of the Binary HS 2333+3927

U. Heber, H. Drechsel, and C. Karl

Dr. Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstraße 7, D-96049 Bamberg, Germany

R. Østensen, S. Folkes

Isaac Newton Group of Telescopes, E-37800 Santa Cruz de La Palma, Canary Islands, Spain

R. Napiwotzki

Department of Physics & Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK

M. Altmann

Departamento de Astronomia, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Chile

O. Cordes

Sternwarte der Universität, Auf dem Hügel 71, D53121 Bonn, Germany

J.-E. Solheim

Institute of Theoretical Astrophysics University of Oslo, p.box 1029, N-0315 Blindern-Oslo, Norway

B. Voss, D. Koester

Institut für Theoretische Physik und Astrophysik, Universität Kiel, 24098 Kiel, Germany

Abstract. Short period sdB binaries with cool companions are crucial to understand pre-CV evolution, because they will evolve into cataclysmic variables, when the sdB will have left the extended horizontal branch. Recently we discovered the sixth such system, HS 2333+3927, consisting of an sdB star and an M dwarf (period: 0.172 d) with a very strong reflection effect, but no eclipses. The reflection is stronger than in any of the other similar systems which renders a quantitative spectral analysis very difficult because the Balmer line profiles may be disturbed by the reflected light. A spectroscopic analysis results in $T_{\rm eff}$ $= 36\,500$ K, $\log g = 5.70$, and $\log(n_{\rm He}/n_{\rm H}) = -2.15$. Mass-radius relations were derived from the results of the analysis of light and radial-velocity curves. Comparison with the mass-radius relation derived from the surface gravity of the sdB star favours a rather low mass of 0.38 $M_\odot$ for the primary. The mass of the companion is 0.29 $M_\odot$. HS 2333+3927 is the only known sdB+dM system with a period above the CV period gap.

1. Introduction

SdB binaries are important to clarify the evolutionary origin of sdB stars because the analysis of light and radial velocity curves can constrain their dimensions and masses. However, only five suitable systems are known up to now.

There is general consensus that the sdB stars can be identified with models for Extreme Horizontal Branch (EHB) stars (Heber 1986). Like all HB stars they are core helium burning objects. However, their internal structure differs from typical HB stars, because their hydrogen envelope is very thin (<1% by mass) and therefore inert. As a consequence EHB stars evolve directly to the white dwarf cooling sequence, thus avoiding a second red giant phase. How they evolve to the EHB configuration is controversial. The problem is how the mass loss mechanism of the progenitor manages to remove all but a tiny fraction of the hydrogen envelope at *precisely* the same time as the He core has attained the mass ($\sim$0.5 $M_\odot$) required for the He flash.

Considerable evidence is accumulating that a significant fraction of the sdB stars reside in close binaries (Maxted et al. 2001; Napiwotzki et al., 2004, see also Karl et al, these proceedings). Therefore mass transfer should have played an important role in the evolution of such binary systems. Detailed investigations of sdB binaries, in particular eclipsing systems, are crucial to determine their masses. However, only three such eclipsing binaries, HW Vir, PG 1336-013, and HS 0705+6700 (see Drechsel et al. 2001) and two non-eclipsing ones are known up to now, which consist of an sdB star and an M dwarf companion revealed by reprocessed light from the primary (reflection effect). Recently, Heber et al. (2004) discovered another related system, HS 2333+3927, which is, however, not eclipsing, but otherwise possesses very similar system parameters and configuration.

2. Observations

The first hint for light variations emerged when HS 2333+3927 was monitored at the Nordic Optical Telescope on October 19, 1999 in order to search for pulsations. The light curve of HS 2333+3927 (see Fig. 1) was measured from CCD photometry in the B, V, and R bands at four telescopes (JKT 1.0m, Calar Alto 1.23 m, IAC 0.8 m Hoher List 1.06 m) in 15 nights between July 2 and November 11, 2002.

The radial velocity curve (see Fig. 2) was measured during an observing run at the Calar Alto Observatory with the TWIN spectrograph at the 3.5m telescope. A total of 18 spectra were taken from 11 to 18 August 2002 covering the wavelength ranges from 3900 Å to 5000 Å at a resolution of 1.3 Å in the blue part of the spectrum, and from 6000 Å to 7000 Å at a resolution of 1.2 Å in the red part.

HS 2333+3927 was also observed at the Calar Alto Observatory with the CAFOS spectrograph at the 2.2m telescope in order to derive atmospheric parameters by Balmer line fitting. A total of 13 low resolution spectra were taken on August 31, 2003 covering the wavelength range from 3300 Å to 6000 Å at a spectral resolution of 4.5 Å. This allowed to measure the entire Balmer series (except Hα) up to the Balmer jump.

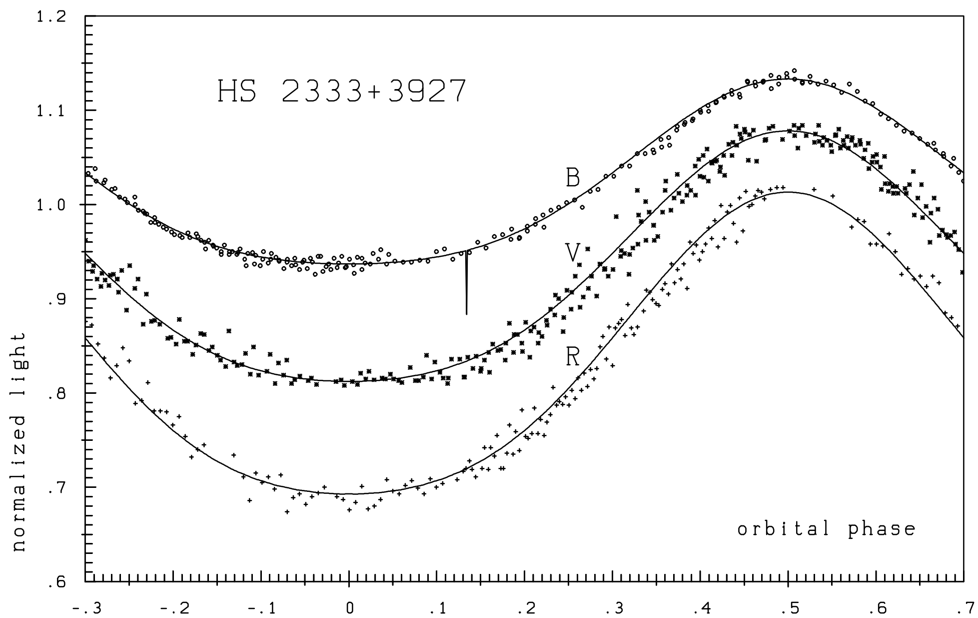

Figure 1. *BVR* light curves of HS 2333+3927 (Heber et al. 2004).

3. Analysis of Light and Radial Velocity Curves

The numerical solution of the light curves was performed with the Wilson-Devinney (1971) based light curve program MORO (Drechsel et al. 1995). The best fit to the B, V, R light curves is shown in Fig. 1. A strong reflection effect is visible ($\Delta B = 0.21$, $\Delta V = 0.28$, $\Delta R = 0.33$ mag), but no eclipses are apparent. We determined the period to be P=0.1718023 d.

The spectrum of HS 2333+3927 is single-lined and the radial velocity curve is sinusoidal (Fig. 2) indicating that the orbits are circular. The semi-amplitude is $K_1 = 89.6$ km/s and the mass function follows as $f(m) = 0.0128\,\mathrm{M}_\odot$.

The light curve analysis provided us with an estimate of the system's inclination. For any assumed primary mass we can calculate the secondary mass from the mass function. In addition the orbital radius a_1 of the primary can be calculated. The separation a of the components can then be calculated from the mass ratio q. The light curve allows us to determine the ratio of the radii in units of the separation. Hence we can determine the radii of both components for any given sdB mass, i.e we can derive mass-radius relations for both components.

4. Spectroscopic Analysis

The Balmer and helium lines in the blue spectra can be used to determine the atmospheric parameters by performing a quantitative spectral analysis. Because the medium resolution TWIN spectra cover only few of the Balmer lines, we used the CAFOS spectra which cover the Balmer series to its limit. Since the high Balmer lines are probably least affected by reprocessed light from the secondary, much emphasis was put in the fit procedure to reproduce these lines well. Since

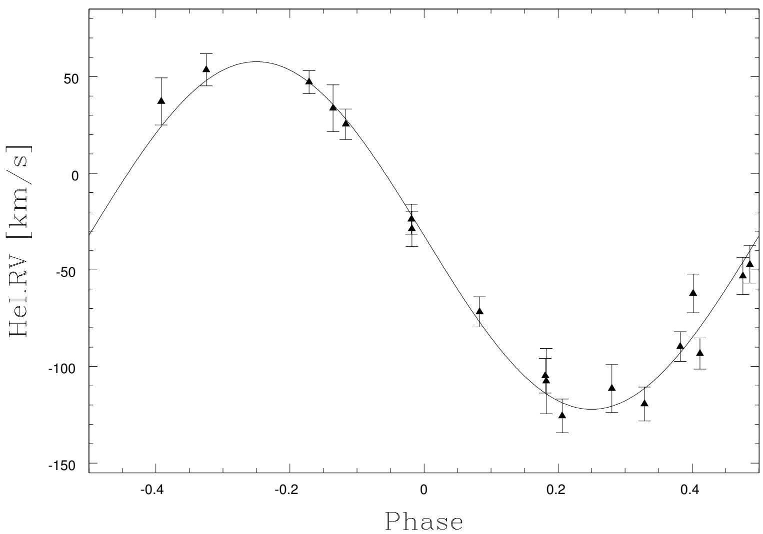

Figure 2. Radial velocity curve of HS 2333+3927 (Heber et al. 2004).

the spectrum displays helium lines from two stages of ionization, we made also use of the ionization equilibrium of helium to determine $T_{\rm eff}$.

The atmospheric parameters determined from spectra taken near lower conjunction should be least affected by reprocessed light from the secondary and, therefore, the atmospheric parameters derived from them should be the closest approximation to the true atmospheric parameters of the sdB star.

Based on the above considerations we derived $T_{\rm eff} = 36\,500 \pm 1000$ K, $\log g = 5.70 \pm 0.1$ and $\log(n_{\rm He}/n_{\rm H}) = -2.15 \pm 0.15$ for the atmospheric parameters of HS 2333+3927.

5. Masses and Radii

The mass-radius relations derived from the analysis of the light and radial velocity curves can be compared to independently determined relations. For the sdB star such a relation follows from the gravity (Newton's law). For the cool companion a theoretical mass-radius relation for M-dwarfs may be appropriate. In principle the masses and radii of the sdB star and the M dwarf, respectively, could be determined by requesting these mass-radius relations to be consistent.

Fig. 3a compares the mass-radius relation of the sdB derived from the light and radial velocity curves to that derived from gravity. The gravity of $\log g = 5.7$ is too low to match the M-R-relation from light and radial velocity curve for reasonable masses. The intersection of both M-R-relations in Fig. 3a would give a sdB mass of 0.2 $M_\odot$, clearly too low for a core helium burning star. Evolutionary scenarios by Han et al. (2003) suggest that the most likely mass is $\approx$0.47 $M_\odot$, but possible masses range from 0.38 to 0.8 $M_\odot$. As can be seen from Fig. 3a the sdB gravity should be $\log g \approx 5.86$ if the sdB star is of canonical mass. This is significantly higher than derived from a quantitative spectral analysis of the Balmer lines: $\log g = 5.7 \pm 0.1$. However, if we adopt the lowest mass core

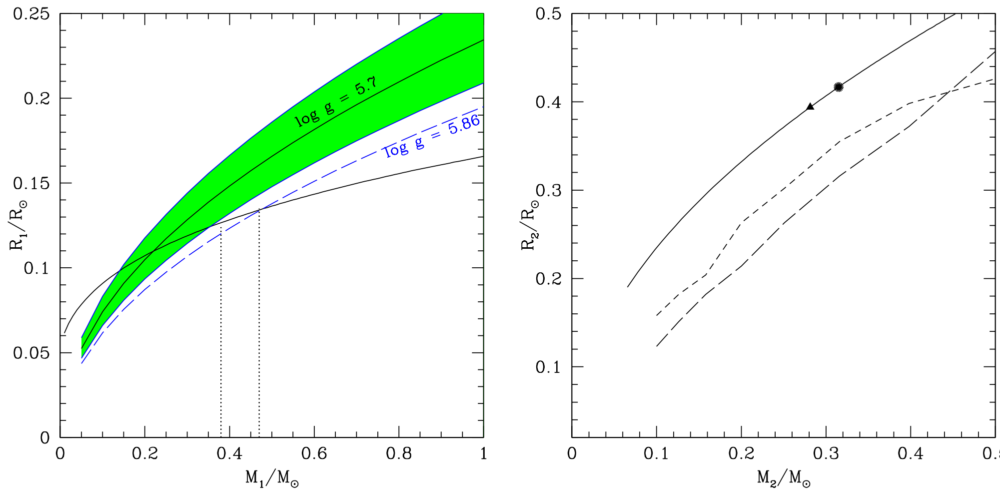

Figure 3. a) left: Comparison of the sdB mass-radius relation from the analysis of light and radial velocity curves (solid line) to those derived from different gravities. The spectroscopic $\log g$ estimate is 5.7±0.1. Dotted lines mark the most probable (0.47 $M_\odot$) and the lowest mass (0.38 $M_\odot$) according to the evolutionary models of Han et al. (2003). Note that the gravity would need to be as high as 5.86 (dashed line) if the star were of canonical mass (0.47 $M_\odot$).
b) right: Comparison of the companion's mass-radius relation derived from the analysis of light and radial velocity curves (solid line) to relations for M-type dwarfs (short-dashed: observed relation from Clemens et al. 1998; long-dashed: theoretical predictions from Baraffe & Chabrier, 1996). Filled circle: sdB has canonical mass (0.47 $M_\odot$); triangle: sdB has lowest possible mass.

helium burning star that can form in the Han et al. scenario, consistency could be achieved if we adopt the largest gravity allowed by the spectroscopic analysis (see Fig. 3a).

The mass-radius relation for the companion star is compared to observations and model predictions for M-type main sequence stars in Fig. 3b. The empirical relation for the unseen companion of HS 2333+3927 lies above those for normal M-stars. However, it is possible that the M-star is over-luminous due to the strong irradiation of its surface by the nearby hot star and hence has a larger radius than a normal M dwarf of the same mass.

6. Discussion

6.1. Results

From the analysis presented above we conclude that a model for a low mass (≈0.38 $M_\odot$) core helium burning sdB star and a 0.29 $M_\odot$ M-dwarf fits the observations best. However, the results have to be taken with a grain of salt. The spectral analysis of the Balmer lines, is plagued by reflected light, as is evident from the line profile variations observed in Hα, but less obvious in other Balmer lines. An improved measurement of the gravity, therefore, is urgently needed.

Another important observational constraint would be a precise measurement of the projected rotational velocity. The rotation of the sdB star in HS 2333+3927 is very likely tidally locked to the orbital motion. Drechsel et al. (2001) showed this to be true for HS 0705+6700. Determining the projected rotation velocity would therefore allow an independent estimate of the inclination of HS 2333+3927.

The spectral lines of the Lyman series are sensitive gravity indicators and plenty of metal lines can be used to measure $v \sin i$. These measurements will allow us to constrain mass and radius much better

6.2. SdB Stars and pre-CV Evolution

Short period sdB binaries with main sequence companions, like HS 2333+3927, are important not only to understand the formation and evolution of sdB stars. When the sdB star will have left the EHB, it will evolve into a cataclysmic variable. Therefore, these objects are also crucial to understand pre-CV evolution. Schenker (these proceedings) has suggested that cataclysmic variables with short periods, i.e. below the CV period gap evolve from sdB + dM binaries. While four other known systems have periods between 1.7 h to 2.8 h, i.e. below the CV period gap, the period (4.13 h) of HS 2333+3927 is a bit above the CV period gap. Its orbital separation is so small that the secondary is appreciably distorted. The shrinkage of the binary orbit by gravitational wave radiation will initiate mass transfer turning the system into a cataclysmic variable. It is likely that the HS 2333+3927 system will then still have a period larger than the CV period gap. Hence sdB + dM binaries form an evolutionary channel to the population of longer period cataclysmic variables as well as to the short-period population.

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