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Letter to the Editor

Mass and radius of the white dwarf in the binary V471 Tau from ORFEUS and HIPPARCOS observations

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Abstract. We present a model atmosphere analysis of the white dwarf component in the K2V/DA eclipsing binary system V471 Tau, based upon FUV spectra obtained by the ORFEUS satellite. This system is regarded as the prototype of a post-common envelope WD + MS binary and, hence, is of considerable importance for our understanding of close binary evolution.

From a line profile fit to the FUV hydrogen Lyman series we obtain $T_{\rm eff}$=35 125 K and log g =8.21. The HIPPARCOS trigonometric parallax measurement (21.37 ± 1.62 mas) confirms the Hyades membership of V471 Tau and we can derive the white dwarf radius. Together with its astrometric mass, which is known from analyses of the orbital parameters and which is compatible with our spectroscopic surface gravity determination, we can compare this individual WD to the theoretical mass-radius relation.

Key words: stars: individual: V471 Tau – stars: fundamental parameters – stars: atmospheres – binaries: eclipsing – white dwarfs – ultraviolet: stars

1. Introduction

V471 Tau is among the best studied eclipsing binary systems. It comprises a K2 main sequence star and a hot white dwarf. System parameters suggest that the detached stars form a post-common envelope WD + MS binary (see e.g. de Kool & Ritter 1993, and references therein). Hence it is an object which is important for our understanding of close binary evolution.

Based on its proper motion it is commonly anticipated that V471 Tau is a member of the Hyades cluster which, however, was at variance with several parallax measurements. Consequently, V471 Tau was excluded from population studies of the Hyades (Eggen & Iben 1988, Weidemann et al. 1992). The question as to the Hyades membership of V471 Tau is not only important for these studies, but also for the analysis of the binary system in itself, as it is desirable to know its distance. Recently published ground-based as well as HIPPARCOS parallaxes have now confirmed the cluster membership of V471 Tau. The HIPPARCOS result (21.37 ± 1.62 mas, Provencal et al. 1996) agrees with the recently published ground-based value (21.0 ± 1.5 mas, Van Altena et al. 1995).

The V471 Tau binary system is important for white dwarf research because it allows to study in great detail the characteristics of an individual WD. In particular we are interested in the WD mass and radius in order to compare with the theoretically predicted mass-radius relation for white dwarfs. Only very few mass determinations exist which are precise enough to test this relation, and the most reliable ones were derived from white dwarfs in binaries (see e.g. Schmidt 1996). Radius estimates from spectroscopically determined $T_{\rm eff}$ are usually hampered by poorly known distances, although the situation has been improved considerably by recent HIPPARCOS results for 20 WDs (Vauclair et al. 1997). Hence white dwarfs in binaries play an important role as the distance may be found from a luminosity estimate for the companion. Unfortunately, in most such cases the late type companion dominates at optical wavelengths so that the WD is not accessible for spectroscopic analyses. Measurements in the ultraviolet, where the WD radiation dominates, are necessary for further investigations.

In the case of V471 Tau Guinan & Sion (1984) used IUE low resolution spectra to derive $T_{\rm eff}$=35 000±3 000 K (and log g ≈8) from a fit to the Lyα profile, which is marginally in agreement with estimates from light curve studies of the system ($T_{\rm eff}$=31 000±2 000 K, Cester & Pucillo 1976; $T_{\rm eff}$=32 000 K, Young & Nelson 1972). In this paper we present a new and more precise spectroscopic temperature and gravity determination which is based on the hydrogen Lyman line series covered by ORFEUS, combined with pure hydrogen line-blanketed model atmospheres.

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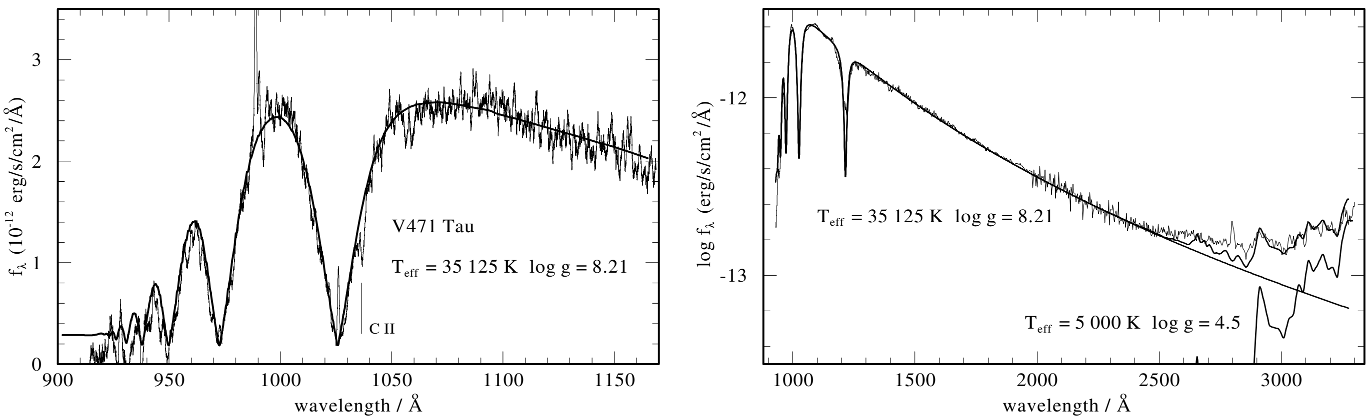

Fig. 1. Left: Minimum χ^2 fit to the ORFEUS spectrum of the hot white dwarf in V471 Tau. The flux below 912Å is blocked by interstellar hydrogen. A geocoronal emission line is seen at O I 989Å as well as an interstellar C II 1036Å absorption line. The spectra are smoothed with a 0.5Å boxcar. Right: Combined ORFEUS and IUE spectra. The main sequence companion is responsible for the red flux upturn at $\lambda > 2500$ Å. Overplotted are our final DA model and a Kurucz model for a K2V star, as well as the sum of both. The ORFEUS and our synthetic spectrum are convolved with a Gaussian (7 Å FWHM) in order to match the IUE resolution

2. FUV Observations

V471 Tau was observed for 953 s in September 1993 with the Berkeley spectrometer at the ORFEUS (Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer) telescope. ORFEUS was mounted on the free flying Astro-SPAS platform which was deployed from and later recovered by the space shuttle DISCOVERY. ORFEUS is a 1 m normal incidence telescope. The Berkeley instrument covered the 390–1170Å wavelength range with a resolution of 3000. Interstellar absorption, however, restricts the useful range in our case to wavelengths redward from the Lyman absorption edge at 912Å. Details on instruments are presented in Grewing et al. (1991) and Hurwitz & Bowyer (1991). Data reduction techniques are described in Hurwitz & Bowyer (1995). The S/N of the spectrum is not good enough to identify unambiguously any interstellar lines, with the exception of C II 1036.3Å, which is among the strongest lines identified in an ORFEUS spectrum of the hot DA G191-B2B (Hurwitz & Bowyer 1995). Geocoronal emission is evident in the Lyβ and Lyγ cores and at O I 989Å.

3. Analysis

A grid of pure hydrogen NLTE line-blanketed model atmospheres ranging from $T_{\rm eff}$=30 000–40 000 K in 250 K steps and log g =7.7–8.7 in steps of 0.05 dex was calculated with our ALI code (see Werner 1996 and references therein for modeling details). It was verified that NLTE effects are completely unimportant over the entire wavelength range comprising the Lyman series. Profiles for these lines were computed using the tables calculated by Lemke (1997), based upon the VCS theory (Vidal et al. 1973).

Effective temperature and surface gravity were determined by fitting the model spectrum to the flux calibrated spectrum of V471 Tau performing a χ^2 test (see e.g. Bevington & Robinson 1992). The fit excludes the innermost line cores which show geocoronal emission components and the result is $T_{\rm eff}$=35 125±1275 K and log g =8.21±0.23 (see Fig. 1). The error ranges correspond to the formal 1 σ errors (Fig. 2), however, one has to be aware of systematic errors, which are hard to assess. Flux calibration of the observation is expected to be better than 10% (Raymond et al. 1995). Systematic errors induced by the models are probably small, because a) the broadening theory for the Lyman lines can be regarded as very good, b) no photospheric convection occurs, avoiding well known uncertainties in theoretical treatment, and c) the assumption of a pure hydrogen composition is justified here, although this point deserves closer elucidation.

V471 Tau was observed by EXOSAT and the discovered 555 s period of the EUV emission (which stems from the WD) was suspected and later confirmed by the Whole Earth Telescope (Clemens et al. 1992) and ROSAT observations (Barstow et al. 1992) to be due to a “spotted” atmosphere resulting from accretion of a wind from the cool companion, hence reflecting the rotation of the WD. Recent EUV light curves and phase resolved EUV spectroscopy revealed details of the spot geometry and chemistry (Dupuis et al. 1997). Accordingly, it is suggested that the spots cover roughly 50% of the surface with 10^{-3}–10^{-4} of the solar abundances of He+CNO (by number). In order to look whether additional EUV opacity affects the model flux in the range of the Lyman lines, we re-computed our final model but now including 10^{-4} of He. As a consequence, the model flux redward of the Lyman edge is virtually unchanged. This result is in contrast to the case of the very hot DAs ($T_{\rm eff} \gtrsim$50 000 K), where the addition of even traces of He and heavier elements strongly enhances the visible and UV fluxes, affects the spectral lines and, hence, the results of spectroscopic analyses (see e.g. Vennes et al. 1996). The reason for this behavior is that in the “cooler” DAs (in contrast to the “hot” ones) the bulk of the radiation is emitted redward of the Lyman edge, so that additional flux blocking in the EUV cannot influence the atmospheric structure.

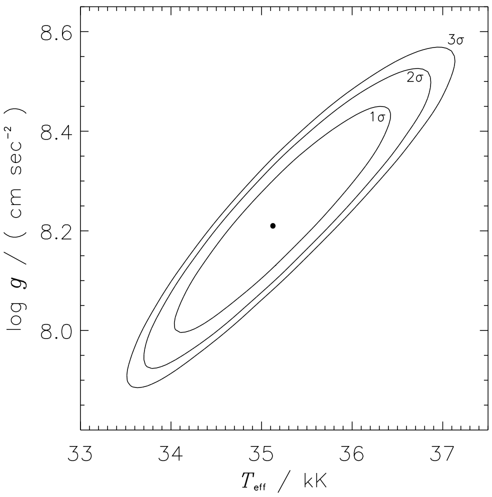

Fig. 2. Contours of constant χ^2 from the fitting procedure

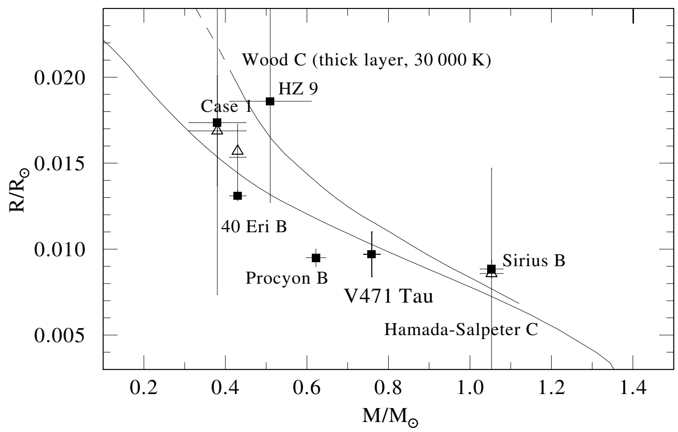

Fig. 3. Mass and radius of the DA in the binary V471 Tau. The astrometric mass is combined with the radius determined from the comparison of the observed FUV flux with models. Also shown are other binary DA white dwarfs with masses and radii derived in a similar manner (from Schmidt 1996). For Procyon B the latest result by Provencal et al. (1997) is shown. Curves display the Hamada & Salpeter (1961) zero temperature relation and the evolutionary models of Wood (1994)

Interstellar absorption by hydrogen is small and does not affect the higher Lyman lines. From EXOSAT data Jensen et al. (1986) and from the EUVE spectrum Dupuis et al. (1997) derived n_H = 4.5 and $1.5 \cdot 10^{18}$ cm^{-2}, respectively.

UV spectra taken from the IUE final archive are useful to study the cool component. We have retrieved and co-added 36 SWP spectra and 6 LWP spectra and the result is shown in Fig. 1 (right panel). Note the continuous run of the spectra at the transition points of the ORFEUS/SWP and SWP/LWP wavelengths (1150Å and 1980Å, respectively). They perfectly fit our DA model except for the longest wavelengths where the contribution of the cool star becomes evident. The overall flux can be fitted reasonably by co-adding a Kurucz model for a K2V star (solar metallicity, $T_{\rm eff}$=5000 K, $\log g$=4.5) after proper scaling of the model flux. The flux scaling factor can be used to calculate (via Eq. 1) the radius of the K2V star, which results in 0.83 $R_\odot$, consistent with its spectral type.

4. Discussion

Our analysis of the Lyman lines covered by the ORFEUS spectrum results in a new temperature determination for the WD in V471 Tau: $T_{\rm eff}$=35 125±1275 K which, regarding the error ranges, is in agreement with the earlier result from Guinan & Sion (1984) mentioned above and with a combined IUE Lyα/EXOSAT EUV analysis by Vennes (1992) who arrived at $T_{\rm eff}$=34 000 K and $\log g$=8.40, although the latter parameters are located outside of our 3σ error ellipse. We are confident that our result is of superior reliability because of the better quality of observations. We can now proceed and use our model flux and observed absolute flux in order to calculate the WD radius R from

$$f(\lambda) = \pi \left(\frac{R}{d}\right)^2 F(\lambda) \qquad (1)$$

where $f(\lambda)$ denotes the energy flux at Earth and $F(\lambda)$ is the (astrophysical) energy flux at the stellar surface. Reading f(1100Å)= $2.5 \cdot 10^{-12}$ from Fig. 1 and taking the respective flux from our model atmosphere F(1100Å)= $3.7 \cdot 10^{10}$ (units: erg/cm^2/s/Å) and adopting the distance d = 46.8±3.8 pc results in the radius $R = 0.0097 \pm 0.0013\,R_\odot$, where the error range regards the 3σ error of the spectral fit and the relative error in the distance, which are both of similar order. This value agrees with the astrometric result which yields R between 0.009 and 0.01 $R_\odot$ (Cester & Pucillo 1976, Ibanoglu 1978).

We could now go on and determine the WD mass M from our gravity determination via

$$g = GM/R^2 \qquad (2)$$

where G is the gravitational constant. However, our error in $\log g$ results in a large uncertainty for the mass (factor 1.7). Instead, the mass determination from the astrometric analysis (Bois et al. 1988) is most probably more exact. From their derived mass function we find the mean value $M = 0.759 \pm 0.02\,M_\odot$, assuming a K2 dwarf mass of 0.8 $M_\odot$. The error margin given here reflects the uncertainty in the mass function and the inclination angle. We can in turn infer $\log g$ from the above equation using $R = 0.0097\,R_\odot$ and $M = 0.759\,M_\odot$. This gives $\log g$=8.35, which is compatible with our spectroscopic result.

In a recent examination Schmidt (1996) summarized the pre-HIPPARCOS situation of the empirical mass-radius relation using spectroscopic determinations of $T_{\rm eff}$ and $\log g$ and best values of parallaxes and gravitational redshifts. The data show a large scatter due to observational errors, which means that the theoretical mass-radius relation cannot be confirmed. Only a handful of DA white dwarfs in binaries allows the derivation of parameters precise enough to show the expected correlation. Although the situation has improved considerably by HIPPARCOS parallax measurements of 20 white dwarfs (Vauclair et al. 1997), it is still of considerable interest to analyze individual objects with highest possible accuracy. Fig. 3 shows the position of V471 Tau in the M-R diagram, together with other binary DA white dwarfs. Also shown are the theoretical zero temperature relation of Hamada & Salpeter (1961) and the evolutionary models of Wood (1994) for a carbon white dwarf with a thick hydrogen layer and $T_{\rm eff}$=30 000 K. According to the formal errors V471 Tau is in agreement with the theoretical Hamada-Salpeter M-R relation but not with Wood's models, however, the discrepancy appears to be rather small. A more deviating result has been obtained recently by Provencal et al. (1997) in the case of Procyon B. From HST UV photometry they derive a radius which is even smaller than the two values found by previous analyses (Schmidt 1996). Provencal et al. suggest that Procyon B has a heavier core than carbon and call into question the assumption of carbon core composition commonly used for white dwarf stars. The deviation of V471 Tau from the Wood M-R relation is much less spectacular and we do not want to make a similar suggestion here.

Finally, the observed 555 s period and the radius determined above imply a rotational speed of v=76 km/s for the WD. This value is markedly higher than the upper limits of the projected rotational velocity $v \sin i$ derived from high resolution Hα spectroscopy for six other (isolated) Hyades white dwarfs by Heber et al. (1997), which ranges between 21 and 35 km/s. As a matter of fact the present mass of the V471 Tau white dwarf is well within the mass range of the six other WDs (0.66–0.80 $M_\odot$), but it is worthwhile to note that the initial mass of the isolated Hyades WDs is in the mass range between 2.5 and 3 $M_\odot$ (Weidemann et al. 1992), whereas in contrast the V471 Tau primary has evolved from a 5 $M_\odot$ main sequence star (Eggen & Iben 1988). However, the rotation of V471 Tau is not detectable in our spectra because of insufficient resolution. In addition interstellar absorption and incomplete removal of geocoronal emission masks rotational broadening of the innermost Lyman line cores.

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