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The mass, temperature and distance of the white dwarf in V471 Tauri

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ABSTRACT

We present an analysis of far-UV observations of V471 Tauri made during the first *ORFEUS* mission. Combining this spectrum with archival data from *IUE* allows a first unambiguous measurement of the effective temperature and surface gravity of the white dwarf by matching the observed Lyman line profiles to the predictions of stellar model atmosphere calculations ($T_{\rm eff} = 32\,400\ +270/-800$ K and $\log g = 8.16\ +0.18/-0.24$). However, a mass estimate of the white dwarf based on the Bois et al. mass function provides a more precise value for $\log g$ (8.27 ± 0.07). Using the accurate *Hipparcos* parallax for the system, from which we obtain a distance of 47 ± 4 pc, we are able to obtain an independent measurement of the white dwarf radius and, therefore, its mass. Comparison with the theoretical mass–radius relation of Wood, for a star at this temperature, confirms that these evolutionary calculations are a good representation of the white dwarf structure. This lends confidence to spectroscopic mass determinations and estimates of the age of the galactic disc, inferred from the white dwarf luminosity function and cooling ages, based on these models. The white dwarf, now confirmed by the *Hipparcos* parallax to be a member of the Hyades cluster, is clearly the hottest and possibly the most massive and youngest white dwarf in that cluster. Finally, weak absorption features in the *ORFEUS* data hint at the possible presence of nitrogen and iron in the photosphere of the white dwarf.

Key words: stars: abundances – stars: atmospheres – stars: individual: V471 Tau – white dwarfs – ultraviolet: stars – X-rays: stars.

1 INTRODUCTION

The eclipsing binary system V471 Tauri (BD+16°516) is one of the most interesting and well-studied astronomical objects. Comprising a hot DA white dwarf and a K2V detached companion (Nelson & Young 1970), V471 Tau appears to a be a member of the Hyades cluster, based on distance and proper motion considerations (Young & Capps 1971). The orbital period of the system is 0.52 d, while eclipse of the white dwarf, which is total, lasts about 50 min with ingress and egress of only 68 s (Warner, Robinson & Nather 1971).

Van Buren, Charles & Mason (1980) were the first to identify V471 Tau as a source of X-ray emission but at the time they and others (e.g. Young et al. 1983) believed this to originate from the active K star component. However, both optical (Young & Nelson 1972) and *International Ultraviolet Explorer (IUE)* (Guinan & Sion 1984) observations of the white dwarf, which yielded effective temperatures of 32 000 and 35 000 K respectively, indicated that the white dwarf could make a significant contribution to the X-ray flux. In fact, at the very lowest energies, below 0.3 keV and in the EUV, the white dwarf is now known to dominate the emission (e.g. Jensen et al. 1986; Barstow et al. 1992). Only above ≈0.3 keV is the K dwarf the major component.

A central problem in understanding the nature of the V471 Tau system has been the origin of the 555-s X-ray pulsations discovered by *EXOSAT* observations (Jensen et al. 1986) and subsequently also observed at optical wavelengths, but with much lower amplitude, by Robinson, Clemens & Hine (1988) (9.7×10^{-4} cf. ≈0.2: see Jensen et al.). Two alternative explanations were proposed. Either the pulsations could arise from accretion of the wind on to magnetic polar regions of the white dwarf, which must then be rotating with a period of ≈555 s, or the white dwarf might be a non-radial pulsator. In the latter case, the star would have to lie in a new instability strip, since its temperature is well outside the range of known pulsating white dwarfs. An intensive multisite campaign of optical observations discovered a new 562-s periodicity in the optical light curve of the binary, which is believed to arise from reprocessed radiation (Clemens et al. 1992). From the phase difference between the directly observed pulses and the reprocessed radiation, Clemens et al. (1992) predicted that the optical pulsations were not in phase with the X-rays, suggesting that the best model for the white dwarf is a magnetic accretor with poles that are dark at X-ray wavelengths and bright in the visible band. The optical pulsation ephemeris of Clemens et al. (1992) was very precise, allowing their phase to be recovered to within a fraction of a cycle for the *ROSAT* All-Sky Survey X-ray and EUV observations. Consequently, Barstow et al. (1992) were able to confirm that the X-ray and optical light variations were indeed out of phase and the rotation/accretion model was the correct one. Most recently, this interpretation has been supported by detailed studies using a combination of photometric and spectroscopic data from the *Extreme Ultraviolet Explorer* (*EUVE*) (Cully et al. 1996; Dupuis et al. 1997).

The technique of determining the effective temperature and surface gravity for a white dwarf by fitting the observed Balmer line profiles to the predictions of synthetic spectra is now well established (e.g. Holberg et al. 1985; Bergeron, Saffer & Liebert 1992). Using evolutionary models, such as those of Wood (1992, 1995), which define the mass–radius relation as a function of stellar temperature, it is then possible to estimate the mass of the white dwarf. Observations of white dwarfs in binary systems potentially represent a direct test of these evolutionary models, since the white dwarf mass can, in principle, be determined independently from the orbital and physical elements of the system. In practice, however, few such systems have been studied in sufficient detail to make such comparisons. An extensive radial velocity study of V471 Tau has obtained a mass function of 0.174 ± 0.002 (Bois, Lanning & Mochnacki 1988), corresponding to a white dwarf mass in the range 0.74 to 0.77 $\mathrm{M}_\odot$, assuming a mass of 0.8 $\mathrm{M}_\odot$ for the K2V component and an inclination of between 80° and 90°.

One particular problem in evaluating the validity of the theoretical mass–radius relation is in determining $T_{\rm eff}$ and log g for V471 Tau. At optical wavelengths the glare of the K2V primary swamps the signature of the white dwarf component, preventing an analysis of the Balmer lines. EUV spectroscopy might provide a suitable alternative (see Cully et al. 1996; Dupuis et al. 1997) but these results are sensitive to the assumed composition of the white dwarf photosphere (Dupuis et al. 1995). Furthermore, while $T_{\rm eff}$ might be measured, the shape and flux level of EUV spectra are comparatively insensitive to the value of the surface gravity (Dupuis et al. 1995). Far-UV observations with *IUE* and the *Hubble Space Telescope* (*HST*) cover the Lyman α line at 1216 Å, the profile of which can provide constraints on both $T_{\rm eff}$ and log g. However, the information obtained may be ambiguous since a particular profile shape cannot necessarily be assigned to unique values of $T_{\rm eff}$ and log g. For example, early *IUE*-based studies of HZ43 assigned an erroneously high value of 57 500 K for $T_{\rm eff}$ and 8.5 for log g (Holberg, Wesemael & Basile 1986), while a Balmer line analysis obtains log $g = 7.7 \pm 0.2$ (Napiwotzki et al. 1993). Similarly, we might anticipate that $T_{\rm eff}$ and log g estimates for V471 Tau based solely on the UV, and adopted in a number of later analyses, are also overestimated.

The $\approx$1150-Å lower limit to the wavelength range accessible to either *IUE* or *HST* precludes using any of the higher lines in the Lyman series shortward of 1200 Å to estimate effective temperature and surface gravity. However, both the *Hopkins Ultraviolet Telescope* (*HUT*) and the *Orbital Free Flying Extreme UV/Ultraviolet Spectrometer* (*ORFEUS*) operate in this wavelength range, including the Lyman series limit at 912 Å. Data from both these Space Shuttle experiments offer the opportunity of using the H Lyman series to determine $T_{\rm eff}$ in the absence of the Balmer lines. In the case of binaries like V471 Tau with bright optical companions, Lyman series observations are particularly important and may be the only way of establishing accurate estimates of $T_{\rm eff}$ and log g values of the white dwarf components.

The technique of Lyman line analyses is not as well established as is the use of Balmer lines. Extensive studies of large samples of DA white dwarfs with optical data have been used to establish the temperature scale and study the mass distribution of the isolated population (e.g. Bergeron, Saffer & Liebert 1992; Liebert & Bergeron 1995; Finley, Koester & Basri 1997; Marsh et al. 1997; Vennes et al. 1997). In contrast, few measurements have been published based on Lyman line data. Furthermore, while the Lyman and Balmer line measurements for G191−B2B are in good agreement, those for REJ 0457−281 (=MCT 0455−2812) are not (Vennes et al. 1996; Barstow et al. 1997). A reliable distance measurement can give an important additional constraint on stellar radius and, therefore, mass, independently of spectroscopic limits. The availability of *Hipparcos* data provides such a measurement.

We present here new measurements of $T_{\rm eff}$ and log g from an analysis of the Lyman series lines detected in an *ORFEUS* spectrum of V471 Tau, together with the Lyman α line from a co-added *IUE* spectrum constructed from the reprocessed (NEWSIPS) archive. Combining these data with the accurate distance derived from the *Hipparcos* parallax allows us to confirm that the binary resides in the Hyades and that the white dwarf component has a mass and a radius consistent with the predictions of Wood's (1995) evolutionary models.

2 FAR-ULTRAVIOLET SPECTROSCOPY

High-resolution EUV and far-UV spectra of several hot white dwarfs were obtained with the *ORFEUS* mission during the 1993 September flight of the Space Shuttle *Discovery*. An important paper reporting the discovery of sulphur and phosphorus in the stars G191−B2B and MCT 0455−2812 (=REJ 0457−281) has already been published along with effective temperature and surface gravity determinations using Lyman line profiles (Lyman β to ϵ: Vennes et al. 1996). These spectra, together with an observation of V471 Tauri, are now available in the public domain. A detailed description of the Berkeley spectrometer is given by Hurwitz & Bowyer (1991), while the observation procedures and instrument calibration are found in Hurwitz & Bowyer (1995). The spectral resolution achieved during this first *ORFEUS* flight was $\lambda/\Delta\lambda \approx 3000$, corresponding to a velocity $\approx 100\ \mathrm{km\ s^{-1}}$, with an intrinsic uncertainty of $\pm 100\ \mathrm{km\ s^{-1}}$ in the wavelength scale arising from the unknown position of each target within the telescope aperture.

A single 953-s exposure of V471 Tauri was obtained on 1993 September 18. The *ORFEUS* spectra suffer from contamination by a scattered light component, which is a combination of flux from the second spectral order and direct scatter from the grating (Hurwitz, private communication). When added to the stellar spectrum, the apparent level of the continuum flux is higher than the true one. Measurements of $T_{\rm eff}$ and log g from the line profiles, whether Balmer or Lyman, require an accurate continuum. Hence, the scattered light component must be accounted for in any analysis to avoid obtaining erroneously high temperatures from apparently weaker lines. Shortward of the Lyman limit, the stellar spectrum makes no contribution to the net flux, as a result of absorption by interstellar neutral hydrogen. Hence, the value of the scattered light component was estimated from the observed flux in the 850–900 Å range. In our own analysis of the archival data of G191−B2B and REJ 0457−281 the corresponding scattered light components are estimated to be 3.5 and 2.0 photon $\mathrm{cm^{-2}\ s^{-1}\ Å^{-1}}$ respectively, corresponding to about 4 per cent of the far-UV flux of each star. In the case of the fainter V471 Tau, we find a similar relative level of scattered light, amounting to 0.0011 photon $\mathrm{cm^{-2}\ s^{-1}\ Å^{-1}}$.

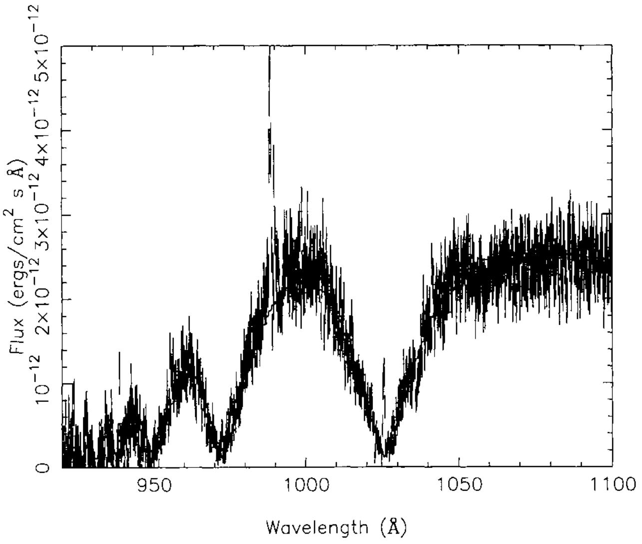

Figure 1. The *ORFEUS* far-UV spectrum of V471 Tauri (error bars), showing the characteristic broad absorption features of the H Lyman series. The solid curve shows the pure-H model which gives the best match to the data, corresponding to $T_{\rm eff}$ = 32 400 K and log g = 8.16.

Fig. 1 shows the *ORFEUS* far-UV spectrum of V471 Tauri, spanning the wavelength range 912–1100 Å, and clearly reveals the signature of the hot DA white dwarf, which is dominated by the K2V companion at optical wavelengths. The V471 Tau DA star is intrinsically fainter (2.5×10^{-12} erg cm^{-2} s^{-1}) than either G191–B2B or REJ 0457–281 (3×10^{-11} and 4×10^{-12} erg cm^{-2} s^{-1} respectively). Coupling this with a much shorter exposure time, ≈20 per cent of the other two stars, the signal-to-noise ratio (S/N) of this spectrum is considerably poorer than those of the two brighter objects. Consequently, it has been necessary to combine the raw data points, sampled with 0.019-Å wavelength spacing, into 0.2-Å bins. This achieves a typical S/N of 10:1 for each point in the displayed spectrum while avoiding significant degradation of the useful spectral resolution (FWHM=0.32 Å). With this S/N, weak absorption features such as the photospheric (Si, P and S) and interstellar (C, N, O) lines found by Vennes et al. (1996) cannot, in general, be detected in the V471 Tau spectrum. Nevertheless, in addition to the Lyman series lines of hydrogen, a number of features can be seen.

Apart from the Lyman lines, the most prominent feature seen in the V471 Tau spectrum is a strong emission line near 988.6 Å. This was also noted in the spectrum of REJ 0457–281 by Vennes et al. (1996) and arises from diffuse O I airglow/geocoronal emission in the range 988–990 Å (Gladstone, Bowyer & Hurwitz 1995). A second 'line' at slightly longer wavelength is also a result of the O I emission, taking on the appearance of a doublet because an absorption feature, tentatively identified as N III by Vennes et al., is superimposed on the broad geocoronal line.

Lyman β and γ emission cores are also seen in the broad photospheric absorption. A similar Lyman β feature noted by Vennes et al. in REJ 0457–281 is attributed to geocoronal emission which is probably also true for the V471 Tau data. However, in this case we cannot completely rule out the possibility that some of the emission might arise from the K2 companion.

Several weak absorption features can also be seen in the V471 Tau spectrum. That in the wing of the Lyman β profile coincides with interstellar C II 1036.337 Å and, like Vennes et al., we use this to correct the wavelength scale of the spectrum which is intrinsically uncertain to ±110 km s^{-1}. A clear absorption feature is located just longward of the O I geocoronal line, centred on a wavelength of 992.115 Å. Intriguingly, this lies very close to the He II 992.373 Å line. However, there is no evidence for a second He II feature at 1084.954 Å, which would be expected if this identification were correct, nor has any detection of photospheric He II been reported in previous observations of V471 Tau. An alternative identification may be with a multiplet of Fe III, but no Fe has been seen in the spectrum of V471 Tau. Supporting evidence for this interpretation may lie in the broad pair of features centred on 1055.74 and 1058.48 Å respectively. While no obvious identification can be found for these, several Fe lines, mainly Fe III, are located at these wavelengths. Table 1 lists the observed wavelengths of the absorption features seen in the *ORFEUS* spectrum together with the wavelengths of the potential identifications.

We have constructed a co-added *IUE* spectrum of V471 Tau based on spectra obtained from the final mission archive after reprocessing using the NEWSIPS software. This software (Nichols et al. 1994) offers significant improvements over the prior IUESIPS processing of the data. Most important of these are increased S/N, a temporally corrected flux scale, an internally derived flux uncertainty, and an improved absolute flux scale. These combine to produce a very superior data product which invites a new more rigorous analysis of the data. Fig. 2 shows our co-added *IUE* spectrum of the V471 Tau white dwarf. This spectrum was produced by co-adding of a selection of 10 well-exposed large- and small-aperture NEWSIPS spectra (given in Table 2). The co-addition procedure is similar to that described in Holberg et al. (1986) but now includes a flux uncertainty from a statistical combination of the NEWSIPS sigma vectors. Careful attention was paid to geocoronal contamination of the core of the Lyman α line by masking out obvious regions of geocoronal signal during the co-addition process.

Table 1. Observed lines in V471 Tauri and possible identifications.

$\lambda_{\rm obs}$ (Å)	Poss. species	$\lambda_{\rm lab}$ (Å)	EW(m Å)	Comment
988.1-990.9	O I	988.7-990.2	1202	Airglow
989.377	O I /N III	988.7-990.2/989.779	1144	mainly local OI
992.115	N III /He II	991.577/992.373	223	probably photospheric N III
1036.51	C II	1036.337	473	mainly ISM
1055.48-1057.04 (1056.07)	Fe III		206	uncertain identification
1057.83-1060.37 (1059.00)	?	–	347	unidentified

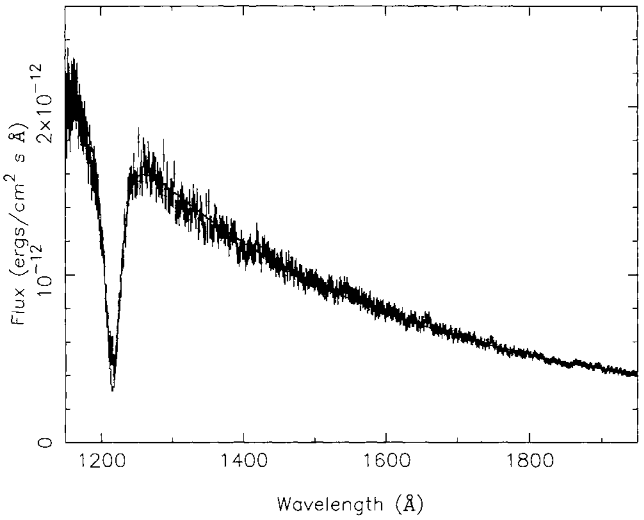

Figure 2. The *IUE* far-UV spectrum of V471 Tauri (error bars), showing the characteristic broad Lyman α line. The solid curve shows the pure-H model which gives the best match to the data, corresponding to $T_{\rm eff}$ = 32 400 K and log g = 8.16.

2.1 Determination of $T_{\rm eff}$ and log g from Lyman line profiles

A visual inspection of the *ORFEUS* V471 Tau spectrum in Fig. 1 shows that only three of the Lyman lines (β, γ, δ) have sufficient S/N for the measurement of $T_{\rm eff}$ and log g. While the Lyman β and γ lines can be used at the nominal 0.2-Å sampling, it was necessary to increase the binning of the Lyman δ region by a factor of 5 to 0.1 Å. In contrast, the *IUE* Lyman α line has higher S/N than the *ORFEUS* lines and, hence, does not require rebinning. Although the intrinsic resolution of the *IUE* spectrum is greater ($\approx$6 Å) than that of *ORFEUS* ($\approx$0.32 Å), at the temperature and gravity of V471 Tau, the widths of the Lyman lines are considerably broader than the spectral resolution of either instrument, allowing the data to be sensibly combined.

To determine $T_{\rm eff}$ and log g from the V471 Tau Lyman lines, we use the same spectral analysis technique we originally developed for Balmer line work (e.g. see Marsh et al. 1997), dealing with all the lines simultaneously but applying an independent normalization constant to the *ORFEUS* and *IUE* data sets to minimize the effect of any systematic differences in the absolute flux calibration. As before, we use the homogeneous H+He models of Koester (1991; see also Finley et al. 1997). We assume the helium abundance is negligible, setting it to zero, an assumption justified by limits determined from both earlier studies of V471 Tau (Barstow et al. 1993; Cully et al. 1996; Dupuis et al. 1997) and our analysis of the *ORFEUS* spectrum (see Section 6.2). Figs 1 and 2 show the four Lyman lines compared with the synthetic spectrum, generated from the pure-H model atmosphere which gives the best match to the data. We obtain $T_{\rm eff} = 32\,400(+270/-800)$ K and log g = 8.16(+0.18/ − 0.24) from this analysis.

The value of $T_{\rm eff}$ obtained from the combined *ORFEUS* and *IUE* spectra is slightly lower than the 35 000- to 34 000-K estimates of earlier studies (e.g. Bois et al. 1988; Guinan & Sion 1984; Kidder 1991). However, these were based on cruder data and had correspondingly large uncertainties of several thousand degrees, overlapping with ours. A more relevant comparison can be made with an analysis based on the long-wavelength EUV continuum (> 350 Å) observed with the *EUVE*. Dupuis et al. (1995) have demonstrated that the flux level of the EUV continuum seen in the *EUVE* long-wavelength spectrometer channel is very sensitive to the stellar effective temperature, although not to the surface gravity. However, $T_{\rm eff}$ values obtained by this method also depend strongly on the assumed composition. For example, in the very hot DA stars included in the work of Dupuis et al. (Feige 24, G191−B2B and REJ 0457−281), models that incorporate appropriate levels of heavy elements (C, N, O and Fe etc.) yield effective temperatures several thousand degrees lower than models composed purely of hydrogen. These three stars are all known, from far-UV and EUV observations, to contain significant quantitites of heavy elements (e.g. Vennes et al. 1992; Lanz et al. 1996; Barstow et al. 1997) and it is important to account for these in any EUV study. In contrast, while the photosphere of the white dwarf in V471 Tau may contain some heavy element contamination, the EUV photometry shows that the atmosphere clearly does not display large departures from a pure-H composition (Barstow et al. 1993). Cully et al. (1996) have used the *EUVE* long-wavelength spectrum (from 340 to 600 Å) to measure $T_{\rm eff}$ for the white dwarf, fixing the surface gravity at an assumed value of log g = 8.5. Our value of $T_{\rm eff}$ is completely consistent with theirs (33 100 ± 500 K) with a similar range of uncertainty. Where the new Lyman line data make the most significant contribution is in providing a first unambiguous spectroscopic determination of the surface gravity.

3 SPECTROSCOPIC AND ASTROMETRIC MASS AND DISTANCE ESTIMATES

The process of estimating, first the mass and radius and subsequently other fundamental parameters such as the luminosity or age

Table 2. Log of *IUE* observations used for the co-added NEWSIPS spectrum.

Image	Aperture	Exposure (sec)	Date	Counts/Background	Observer
SWP 09782	L	719.5	1980 Aug. 14	172/21	Guinan
SWP 09782	S	1199.6	1980 Aug. 14	168/21	Guinan
SWP 09783	L	719.5	1980 Aug. 14	176/21	Guinan
SWP 09783	S	1199.6	1980 Aug. 14	153/21	Guinan
SWP 09786	L	719.5	1980 Aug. 14	177/21	Guinan
SWP 09786	S	1319.6	1980 Aug. 14	177/21	Guinan
SWP 09789	L	719.5	1980 Aug. 14	192/26	Guinan
SWP 09789	S	1319.6	1980 Aug. 14	193/26	Guinan
SWP 25304	L	719.5	1985 Feb. 23	186/22	Guinan
SWP 25304	S	1439.6	1985 Feb. 23	201/22	Guinan

of a white dwarf, frequently involves adopting a theoretical mass–radius relationship. In the past, this choice was most often zero-temperature (fully degenerate) mass–radius relationships such as those of Hamada & Salpeter (1961). Currently, more realistic models are used, such as those of Wood (1992), which follow the thermal evolution of white dwarfs as they cool and which also account for several different possible configurations of hydrogen and/or helium in the outer layers (Wood 1995). It is most common to assume a carbon core. In general, thermal effects are most pronounced in hot ($T_{\mathrm{eff}} > 30\,000$ K) and low-mass ($M_* < 0.55\,\mathrm{M}_\odot$) white dwarfs. At lower temperatures and higher mass, evolutionary models closely resemble zero-temperature models.

This approach has been used by a number of authors to determine masses for large samples of isolated white dwarfs (e.g. Bergeron et al. 1992; Marsh et al. 1997; Vennes et al. 1997; Finley et al. 1997). Taking the values of T_{eff} and log g (and their associated errors) measured for V471 Tau, together with a value for the V magnitude, allows us to estimate the mass of the white dwarf. V471 Tauri is too hot for a zero-temperature relation (e.g. Hamada & Salpeter 1961) to be appropriate. Therefore, we use the carbon core + helium envelope evolutionary models of Wood (1992), modified to include an outer H layer of $10^{-4}\,\mathrm{M}_\odot$ appropriate for a DA star (Wood 1995). A value of 13.635 ± 0.02 was assumed for the V magnitude, estimated from the co-added *IUE* NEWSIPS spectra. Interpolating the Wood models, we obtain a respective *spectroscopic* mass and radius of $0.61 + 0.14/-0.1\,\mathrm{M}_\odot$ and $0.014 \pm 0.003\,\mathrm{R}_\odot$.

Since V471 Tau is an eclipsing spectroscopic binary, an *astrometric* estimate of the white dwarf mass also exists from the accurate orbital elements determined by Bois et al. (1988). These measurements, based on their 1983 November data, give a value of $0.174 \pm 0.002\,\mathrm{M}_\odot$ for the mass function $[m^3 \sin^3 i/(M+m)^2]$. A mass estimate for the white dwarf secondary then depends on knowledge of the primary mass and orbital inclination. Since the eclipse of the white dwarf is total, the inclination of the system must be greater than $\approx 80°$. Taking this limit as the value of i, with a mass of $0.8\,\mathrm{M}_\odot$ for the K2V star, gives a white dwarf mass of 0.765 ± 0.005. If the inclination is actually 90° the white dwarf would be slightly less massive at $0.745 \pm 0.005\,\mathrm{M}_\odot$. The major uncertainty lies in the spectral type and, therefore, the mass of the K dwarf. For example, for a nominal K2 mass of $0.8\,\mathrm{M}_\odot$, a change in spectral type of ± 1 gives a difference in mass of $\approx \pm 0.04\,\mathrm{M}_\odot$. This corresponds to an error of approximately 0.007 in the mass function, when convolved with the observational error.

Provided the theoretical mass–radius relation used in this analysis is valid, an estimate of the distance to the system can be obtained for comparison with other independent measurements such as those derived from the parallax. The details of this calculation are documented by Fleming et al. (1996) in their determination of the white dwarf X-ray luminosity function, since their work required information about the distance to each star. Briefly, the bolometric luminosity is calculated from T_{eff} and R_* by the Stefan–Boltzmann law and converted into absolute bolometric magnitude. After applying an appropriate bolometric correction, derived from the synthetic spectral models, the apparent bolometric magnitude is determined from m_V. The distance is then estimated from the distance modulus using the standard relation ($M_b - m_b = 5 - 5 \log d$). This 'photometric' distance estimate is dominated by the uncertainty in the radius, which is itself much more sensitive to the error range in log g than T_{eff}, and lies in the range 44.5 to 68.4 pc.

An independent estimate of the distance to the V471 Tau system from an accurate parallax measurement would provide an important additional test of the theoretical mass–radius relation by fixing the stellar radius. Published parallaxes, however, give conflicting distances. For example, Borgman & Lippincott (1983) obtain a distance of 100 pc, implying that the V471 system is not a member of the Hyades. Bois et al. (1988) estimate $d = 43 \pm 6$ pc from the zero-temperature Hamada–Salpeter relation and an assumed white dwarf mass of $0.75\,\mathrm{M}_\odot$. They interpret the difference with Borgman & Lippincott in terms of a discrepant parallax originating from a third body, although the Bois et al. estimate suffers from the same limitations as ours. The van Altena, Truen-Liang Lee & Hoffleit (1995) catalogue of stellar parallaxes gives a value of 0.0138 ± 0.0023, corresponding to a distance of $72.5 + 14.5/-10.4$ for V471 Tau. This result is consistent with ours and has a similarly large (± 20 per cent) uncertainty.

4 THE *HIPPARCOS* PARALLAX AS A TEST OF THE MASS–RADIUS RELATION

Assuming a mass–radius relationship for a white dwarf involves making a choice regarding the composition of the outers layers of the star besides placing confidence in a detailed theoretical model of the internal structure of the white dwarf under study. Attempts to compare directly independently determined white dwarf masses and radii with theoretical mass–radius relationships have not been very satisfying. First, the number of stars for which it is possible to make reliable empirical estimates of masses or radii is small. Only a few stars have dynamically measured astrometric masses of useful precision. For others, there is the possibility of using precise parallaxes, surface gravities and gravitational redshifts to estimate masses and radii. As pointed out by Schmidt (1996), even when observations of sufficient precision exist, two circumstances conspire to frustrate direct observational tests of mass–radius relationships. The first effect is the nature of joint observational uncertainties in the mass–radius plane to be nearly orthogonal to the theoretical mass–radius relationships. The second is the well-known tendency of white dwarf masses to be narrowly distributed near $0.6\,\mathrm{M}_\odot$. This limits the opportunity to compare observations over a significant range of masses.

The *Hipparcos* mission (ESA 1997) has offered the prospect of achieving significantly higher accuracy for parallax measurements than is possible with ground-based techniques. In response to the 1992 call for '*Hipparcos* Research Programme' proposals (within the mission consortia), for use of early release data, we have received parallax measurements for a sample of EUV-selected white dwarfs which are found in the *Hipparcos* input catalogue. This catalogue has a limiting magnitude of $V \approx 12.4$ and is complete up to $V = 7.3$–9.0. The median accuracy of the parallax determinations is ≈ 1 mas but the actual accuracy for individual stars is correlated with their magnitudes. As white dwarfs are intrinsically faint, with visual magnitudes typically greater than the input catalogue limit, the majority of these stars are binary systems where the white dwarf has a visually more luminous companion. V471 Tauri is one object in the EUV-selected list with an observed parallax of 21.37 ± 1.62 mas, corresponding to a distance of $47 + 4/-3.5$ pc. This measurement is consistent with the estimate of Bois et al. (1988) and our photometric calculation, based on the evolutionary mass–radius models. This distance also conclusively places V471 Tau within the Hyades cluster which has estimated distances of 45.7 ± 2.1 pc (Upgren et al. 1990) and 47.2 ± 1.5 pc (Schwann 1990) from parallax and convergent point methods, respectively. In principle, on the assumption that V471 Tau is a Hyad, its distance could be used to refine the distance estimate for the cluster. However, the depth of the cluster is likely to be several times the uncertainty in the *Hipparcos* measurement and, therefore, it is not appropriate to take a value measured for a single star as a definitive result. Nevertheless, this does highlight the interesting prospect of gathering a truly three-dimensional picture of the Hyades through *Hipparcos* measurements of many cluster members.

For V471 Tau, we have two pieces of information that can be used to provide independent estimates of the stellar radius – the high-precision *Hipparcos* parallax measurement and the surface gravity. A third potential piece of information, a gravitational redshift measurement, is not yet available. From the parallax, one can use the spectroscopically determined effective temperature and absolute flux, most often the V magnitude, to calculate stellar radius using the fundamental equation

$$F_\lambda = 4\pi(R_{\hat\pi}^2/D^2)H_\lambda(T_{\rm eff}, \log g), \tag{1}$$

which relates the observed monochromatic flux (F_λ) to the Eddington flux (H_λ) at the stellar surface through the stellar solid angle (R^2/D^2). Here R is the stellar radius and D is the distance given by the parallax $\hat\pi$. The Eddington flux can be specified with considerable confidence and accuracy using emergent fluxes calculated from model atmospheres. We use the results of Bergeron, Wesemael & Beauchamp (1995) to estimate Eddington fluxes, primarily as a function of temperature and, much less sensitively, as function of surface gravity. The resulting estimate of $R_{\hat\pi}$ and uncertainty $\Delta R_{\hat\pi}$ are independent of stellar mass and depend directly on the parallax and effective temperature. The stellar surface gravity

$$g = GM/R_g^2 \tag{2}$$

provides a second estimate of stellar radius as a function of mass.

These two independent estimates of radius can be combined to yield a best-fitting radius (and mass) as well as the corresponding uncertainties in the mass–radius plane. This is done by minimizing the χ^2 variable,

$$\chi^2 = [(R - R_{\hat\pi})/\Delta R_{\hat\pi}]^2 + [(R - R_g)/\Delta R_g]^2. \tag{3}$$

In the above equation the Δ quantities correspond to the uncertainties in the radius propagated from the observational uncertainties in the parallax (from $T_{\rm eff}$ and V) and surface gravity, using standard relations.

In Fig. 3 we show the best-fitting mass for the white dwarf in V471 Tauri and the associated 1σ and 2σ uncertainty contours. Also shown is the theoretical mass–radius relationship for $T_{\rm eff} = 32\,400$ K taken from the Wood (1995) models. Three curves are just discernible, representing the value and $\pm 1\sigma$ uncertainties of $T_{\rm eff}$. The chi-squared contours and mass–radius relation are consistent with each other for a radius of $\approx$0.010–0.012 $R_\odot$ and mass of 0.73–0.83 $R_\odot$.

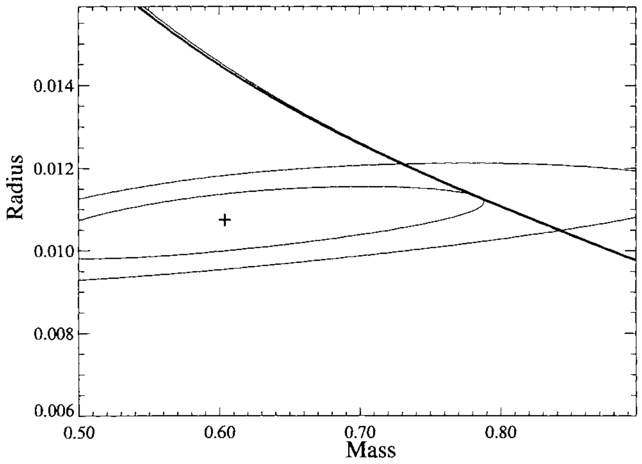

Figure 3. The best-fitting mass and radius for V471 Tau (marked by the cross) together with the associated 1σ and 2σ uncertainty contours. These are compared with curves corresponding to the predicted mass–radius relation derived from the Wood (1995) models and the *ORFEUS* measurement of $T_{\rm eff}$.

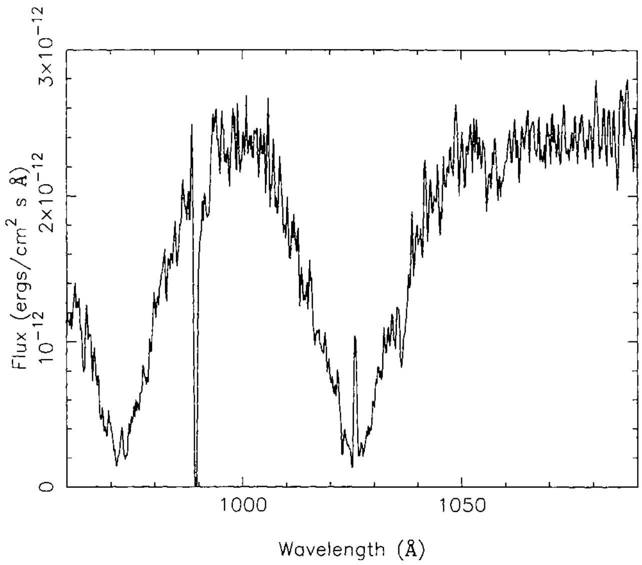

Figure 4. The *ORFEUS* far-UV spectrum of V471 Tauri, after subtraction of the O I geocoronal component. The data have been smoothed with a 0.14-Å Gaussian, corresponding to the rms resolution of the instrument, to show the weak lines more clearly.

5 HEAVY ELEMENTS IN THE ATMOSPHERE OF THE V471 TAURI WHITE DWARF

We have noted the presence of several possible features in the *ORFEUS* spectrum of V471 Tau that might be associated with helium or heavier elements in the photosphere. At a temperature of 32 400 K, the expected composition of a DA white dwarf would, from both observational (Barstow et al. 1993; Marsh et al. 1997) and theoretical evidence (Chayer, Fontaine & Wesemael 1995a; Chayer et al. 1995b), be close to that of a pure-H atmosphere. However, it is believed that the V471 Tau white dwarf is accreting material from its companion. Furthermore, both EUV photometry and spectroscopy indicate that heavy elements may be present in the white dwarf photosphere. Using a grid of non-LTE models, computed using the TLUSTY code of Hubeny (1988), modified and improved by Hubeny & Lanz (1995), we have compared the predicted line strengths for a range of heavy elements that might be expected.

The strength of the geocoronal line makes it difficult to estimate the equivalent width of the superimposed absorption feature and determine its wavelength. To solve this problem we have used the $T_{\rm eff} = 32\,400$ K, $\log g = 8.16$ spectral model, which best represents the Lyman lines, to determine the level of the white dwarf continuum. Subtracting this synthetic spectrum from the *ORFEUS* data leaves a residual emission component due to the geocoronal O I, which can then be represented by a simple

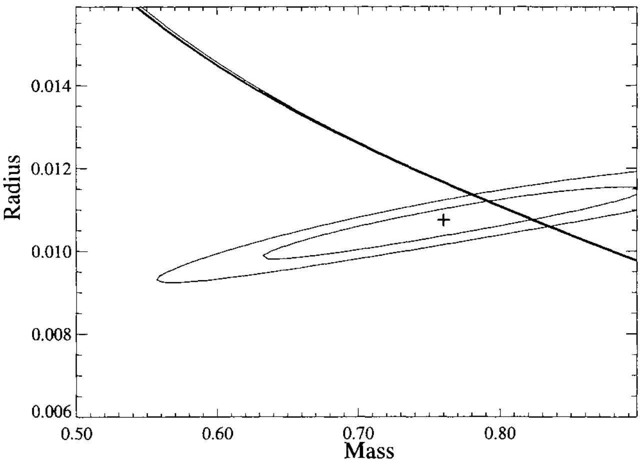

Figure 5. The best-fitting mass and radius for V471 Tau together with the associated 1σ and 2σ uncertainty contours when the mass estimate taken from the Bois et al. (1988) study is included as an additional constraint. These are compared with curves corresponding to the predicted mass–radius relation derived from the Wood (1995) models and the *ORFEUS* measurement of $T_{\rm eff}$.

Gaussian, ignoring the presence of the possible N III absorption. Subtracting the Gaussian model from the *ORFEUS* spectrum appears to remove all the geocoronal contamination leaving a narrow saturated absorption feature at a wavelength of 989.860 Å (Fig. 4). The equivalent width of the line is 1.144 Å. The possible He II absorption, at a measured wavelength of 992.115 Å, is also more clearly seen after subtraction of the geocoronal component.

Possibly, the most intriguing absorption feature in the *ORFEUS* spectrum is that coincident with He II at 992.373 Å, particularly as the *EUVE* data hint at the possible presence of absorption near the He II Lyman series during rotational phases 0.9–1.0 of the white dwarf (Dupuis et al. 1997). If the 992.373-Å line were photospheric, an abundance approaching 10^{-1} (by number) is required to match the observed 'line' strength. However, the absence of the 1084.95-Å line only places an upper limit of 10^{-2} on the possible abundance of He II, rather higher than the 10^{-4}–10^{-3} that can be accommodated by the EUV data.

The predicted He II wavelength of 992.373 Å is not exactly coincident with that observed (992.115 Å). In addition, there are a pair of N III lines at 991.54/991.58 Å which lie close to the absorption feature. Hence, these lines provide an alternative identification. Attributing the observed absorption to photospheric N III requires an abundance of 10^{-6}. At this level, N II lines in the range 1084.56 to 1085.70 Å are predicted to have a combined strength below the noise level of the *ORFEUS* data.

There are a large number of lines from elements heavier than He that might also contribute to the 992.115-Å line. Tests with all potentially abundant elements through to Fe and Ni show that none can account for the strength of the observed line without producing lines that would be far stronger than can be hidden in the noise of the *ORFEUS* spectrum. Fe could account for the shortward of the two broad features at 1055.74 but we are unable to identify any species, or combination of species, with combinations of lines that could give rise to the 1058.48-Å feature.

6 DISCUSSION

6.1 Mass and radius of the white dwarf

Most of the work reported on the mass distribution of white dwarfs has depended on evolutionary models that define the mass–radius relation as a function of stellar temperature (see Introduction; e.g. Wood 1992, 1995). However, observational tests of this work have proved elusive. The accurate parallax provided by *Hipparcos* effectively allows a direct determination of the stellar radius (see equation 1), yielding a value of 0.011 $R_\odot$. Using the observed value of log $g = 8.16$, the white dwarf mass (0.6 $M_\odot$) can then be obtained from equation (2). These estimates correspond to the best-fitting value plotted in Fig. 3 with the ellipses showing the range of uncertainty associated with the observations. The predicted mass–radius relation, derived from the Wood (1995) models, for the value of $T_{\rm eff}$ (32 400 K) derived from the *ORFEUS*/*IUE* observations is consistent with the measurement.

The formal error on the *Hipparcos* distance measurement is only ≈10 per cent. Hence the dominant uncertainty in the analysis is that associated with the measurement of surface gravity, which is of the order of 50 per cent, a factor of 5 greater. Clearly, the observations could provide a more stringent test of the theoretical mass–radius relation if the surface gravity were better determined. Additional information is available in the form of the mass function for the system, derived by Bois et al. (1988) from spectroscopic radial velocity studies of the K star component (see Section 3). Taking into account the possible range in i and in the K dwarf mass gives a conservative estimate for the white dwarf mass of about $0.76 \pm 0.02\,M_\odot$. For a radius of $0.0107 \pm 0.0009\,R_\odot$, based on the *Hipparcos* parallax, this corresponds to a log surface gravity

Table 3. Masses of Hyades white dwarfs from Reid (1996) and Bergeron, Liebert & Fulbright (1995, BLF).

Star		Reid Mass $M_\odot$	BLF Mass $M_\odot$	BLF log g	$T_{\rm eff}$ (K)	Age (Myr)
WD0352+096	HZ4	0.743 ± 0.039	0.678 ± 0.035	8.16	14770	340
WD0406+169	EG29	0.810 ± 0.036	0.776 ± 0.036	8.30	15190	400
WD0421+162	EG36	0.696 ± 0.017	0.652 ± 0.033	8.09	19570	96
WD0425+168	VR16	0.691 ± 0.011	0.673 ± 0.033	8.11	24420	30
WD0431+125	EG39	0.671 ± 0.015	0.623 ± 0.032	8.04	21340	46
WD0437+138		0.748 ± 0.037				
WD0438+108	EG42	0.662 ± 0.039	0.652 ± 0.032	8.07	27390	15
Mean		0.716 ± 0.046	0.677 ± 0.048	8.13		
Weighted mean		0.695 ± 0.073	0.673 ± 0.013			
V471 Tau[1]				8.16	32 400	10

[1] This work.

of log g = 8.27 ± 0.07, which lies well within the range allowed by the Lyman line analysis. Fig. 5 shows the effect of including the additional constraint on the mass as a third parameter in the χ^2 analysis of Section 4. The agreement between the empirical mass–radius relation and that derived from the evolutionary calculations of Wood (1995) is improved when compared with Fig. 3.

The mass of the white dwarf in V471 Tauri is more tightly constrained by the work of Bois et al. (1988) than by the surface gravity measurement obtained by the Lyman line analysis, as can be seen from the change in size of the error contours between Figs 3 and 5. The best-fitting value for the mass changes from 0.60 to 0.76 $M_\odot$. Nevertheless, this serves to demonstrate that the use of the Lyman line series to determine $T_{\rm eff}$ and log g, as an alternative to using Balmer lines, does give sensible results.

Since the *Hipparcos* parallax clearly places V471 Tauri in the Hyades, it is interesting to compare the mass and age of its white dwarf component with similar estimates for the other Hyades white dwarfs (Table 3). In comparison with both the gravitational redshift measurements of Reid (1996) and the Balmer line analysis of Bergeron, Liebert & Fulbright (1995) the V471 Tauri white dwarf mass is at the high-mass extreme of the range found for the Hyades white dwarfs; in fact it may be the most massive of the Hyades white dwarfs. It may also be one of the youngest, since the Wood (1995) models yield a cooling age as short as 10 million years. This is in contrast to the estimated age of 700 million years (Weidemann et al. 1992) for the cluster as a whole. This presents a subtle dilemma. Massive white dwarfs are presumed to be descended from more massive progenators which evolved off the main sequence at an early date. Massive degenerates, which also cool more slowly then less massive stars, are expected to be among the oldest such stars in a cluster like the Hyades. For example, the relatively massive cool stars WD 0352+096 and WD 0406+169 in Table 3 are also the oldest Hyades white dwarfs at 340 to 400 million years, respectively. Thus, the white dwarf in V471 Tau appears to be at odds with this scenario. Although the white dwarf is presently accreting material from the K2V star, the estimated accretion rate (Dupuis et al. 1997) is nearly seven orders of magnitude too low to account for the excess mass. It may well be that the explanation for its peculiar combination of high temperature and mass is due the prior phase common envelope evolution of the V471 Tau system or higher temperature of the white dwarf. However, the net effect of common envelope evolution would appear to shorten, not lengthen, the total time between leaving the main sequence and reaching a particular cooling age as a white dwarf. A possible solution to the problem could be a late burst of star formation in the Hyades, with V471 Tau then evolving from these younger stars, as proposed by Eggen & Iben (1988).

6.2 Heavy elements in the atmosphere of the DA white dwarf

The *ORFEUS* spectrum of V471 Tau reveals some tantalizing evidence for the presence of heavy elements in the white dwarf photosphere, with the detection of several absorption features (see Table 1). However, it is difficult to unambiguously associate these with plausible identifications. For example, the 992.115-Å line is near both an He II feature and several lines of N III. The 1055.74-Å line matches an Fe III complex although other nearby lines are not detected. A photospheric abundance of 3×10^{-5} gives the best match to the observed line but overpredicts the strength of those not seen. A lower abundance of 1×10^{-5} gives better agreement but the 1055.74-Å Fe III line strength in the synthetic spectrum is a little weaker than that observed.

An unreasonably large abundance of photospheric helium is required to explain the observed line strength at 992.115 Å. For example, while a solar abundance of He gives a good match to that feature, the 1084.954-Å line is predicted to be much stronger, yet it is not observed. Furthermore, the best match to the EUV spectrum has a helium component ranging from 10^{-4} to 10^{-3} times the solar abundance, depending on rotational phase (Dupuis et al. 1997). An He/H fractional abundance of 10^{-1} would completely suppress the EUV flux shortward of the He II Lyman series edge at 228 Å, a result which is definitely not seen by *EUVE*.

In their observations of G191−B2B and REJ 0457−281, Vennes et al. (1996) attributed the N III 989.799-Å and C II 1036.337-Å lines to absorption in the ISM, although this was a somewhat tenatative conclusion in the case of N III. For such hot, $T_{\rm eff}\approx 60\,000$ K, stars this is a reasonable proposition, since any photospheric carbon present in the star is predicted to be ionized above the level of C II . In V471 Tauri, where the effective temperature is some 25 000–30 000 K lower than in these other stars, the C II and N III can plausibly be photospheric. If the C II were assumed to be entirely photospheric then the estimated C abundance would be $\approx 4\times10^{-5}$, about 1/10 the abundance found in the Sun. However, with this abundance a further C II line at 1065.95 Å should be visible and its absence imposes an upper limit of 4×10^{-6} on the possible level of carbon in the white dwarf photosphere. The predicted 1036.337-Å line strength is then much weaker than observed, implying that most of the material is genuinely interstellar.

Identifying the observed 992.115 line as N III gives a more consistent result than assuming that it is attributable to He. Including an abundance of 10^{-6} matches the strength of the feature and the predicted strength of the number of N II lines in the 1084–1085.70 Å region lies within the noise level of the *ORFEUS* data. However, the observed 989.377-Å feature is much stronger than expected, the predicted equivalent width of N III being a few mÅ compared to a measured value of 1.144 Å. Since, this strong absorption feature is coincident with the geocoronal O I line a possible alternative explanation is that it arises from neutral oxygen in the local environment.

Although the observed 992.115-Å feature can be explained by photospheric nitrogen if not by helium, we should also consider alternative ideas such as the possibility that circumstellar He II or N III may play a role. This is particularly relevant when we remember that material from the K dwarf wind is believed to be accreted by the white dwarf. The He II 992.373-Å line is a transition arising from a low ($n=2$) energy level to an excited ($n=5$) state and could be a plausible circumstellar line. However, the absence of the longer wavelength 1084.954-Å He II component ($n=2$ to 7) remains a problem with this interpretation.

In summary, we seem to be able to explain 992.115- and 1055.74-Å lines as photospheric N III and Fe III, respectively, but the C II 1036.337-Å feature is mostly interstellar. Since circumstellar gas may be present in the system we cannot completely rule out alternative contributions to the oberved features from this source. Unfortunately, the spectral resolution of the *ORFEUS* data is insufficient to distinguish the two components with radial velocity information. With a typical resolution equivalent to a redshift of $\approx$100 km s^{-1}, the *ORFEUS* data cannot distinguish between interstellar and photospheric components, which are typically only a few tens of km s^{-1} different in white dwarfs studied with higher dispersion. A further complication is that, since V471 Tau is believed to be accreting from its companion on to the magnetic polar regions of the white dwarf, any photospheric material is not necessarily uniformly distributed on the stellar surface. In fact, it seems more reasonable to suppose that any heavy elements present will be concentrated near the accretion region. Dupuis et al. (1997) model the EUV light curve and phase-resolved spectrum of the white dwarf with two spots covering about 20 and 30 per cent of the total stellar surface area with compositions of 10^{-3} and 10^{-4} times the solar abundance of He, C, N and O respectively. These compositions are clearly at variance with the amounts of C and N required by our analysis if the absorption lines are entirely photospheric, suggesting that the interstellar contribution is significant, if not dominant, in these lines.

7 CONCLUSIONS

We have made the first accurate measurements of $T_{\rm eff}$ (32 400 K) and log g (8.16) for the white dwarf in the V471 Tauri binary system, by modelling the shapes and strengths of the Lyman lines present in the far-UV *ORFEUS* and *IUE* spectra. However, the surface gravity is more tightly constrained by an estimate of the mass of the white dwarf obtained from the mass function for the system, determined by spectroscopic radial velocity observations of the K companion (see Bois et al. 1988). Nevertheless, this represents an important demonstration of the usefulness of Lyman line observations in measuring the physical parameters of a white dwarf in a system where the Balmer lines, which are usually used for this work, are not accessible due to contaminating light from the companion star. This technique may be the only possible method of determining the white dwarf mass in binary systems where dynamical information is not available due to large separation or low inclination.

Considerable discussion has centred on whether or not V471 Tauri is a member of the Hyades. The *Hipparcos* parallax (21.37 ± 1.62 mas) places the star at the distance of the cluster, supporting this point of view. Having an accurate distance measurement and knowing $T_{\rm eff}$, log g and the V magnitude allows the stellar radius to be calculated, independently of any assumed white dwarf mass–radius relation. Since the mass is also constrained by log g and the measurements of Bois et al. (1988), we are able to obtain an empirical measurement of the mass–radius relation at a single temperature and gravity that is in excellent agreement with the finite temperature evolutionary calculations of Wood (1995). This provides new experimental evidence that such advanced theoretical models are representative of real white dwarfs and can be used, with confidence, to study the white dwarf population. This is an important result when considering the reliability of the spectroscopic mass determinations that rely on these models and estimates of the age of the galaxy, based on predicted cooling rates, which in turn depend on the assumed stellar radii and masses.

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