Hubble Space Telescope Spectroscopy of V471 Tauri: Oversized K Star, Paradoxical White Dwarf

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ABSTRACT

1Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555.
We have used the Goddard High Resolution Spectrograph onboard the *Hubble Space Telescope* to obtain Lyman-α spectra of the hot white-dwarf (WD) component of the short-period eclipsing DA+dK2 pre-cataclysmic binary V471 Tauri, a member of the Hyades star cluster.

Radial velocities of the WD were determined from eight post-COSTAR spectra, obtained near the two quadratures of the orbit. When combined with ground-based measurements of the dK velocities, eclipse timings, and a determination of the dK star’s rotational velocity, the data constrain the orbital inclination to be \( i = 77^\circ \), and yield dynamical masses for the components of \( M_{\text{WD}} = 0.84 \) and \( M_{\text{dK}} = 0.93 \, M_\odot \). Model-atmosphere fitting of the Lyα profile provides the effective temperature (34,500 K) and surface gravity (\( \log g = 8.3 \)) of the WD.

The radius of the dK component is about 18% larger than that of a normal Hyades dwarf of the same mass. This expansion is attributed to the large degree of coverage of the stellar surface by starspots, which is indicated both by radiomeric measurements and ground-based Doppler imaging; in response, the star has expanded in order to maintain the luminosity of a 0.93 \( M_\odot \) dwarf.

The radius of the WD, determined from a radiometric analysis and from eclipse ingress timings, is 0.0107 \( R_\odot \). The position of the star in the mass-radius plane is in full accord with theoretical predictions for a degenerate carbon-oxygen WD with a surface temperature equal to that observed. The position of the WD in the H-R diagram is also fully consistent with that expected for a WD with our dynamically measured mass. Both comparisons with theory are probably the most stringent yet made for any WD. The theoretical cooling age of the WD is \( 10^7 \) yr.

The high effective temperature and high mass of the WD present an evolutionary paradox. The WD is the most massive one known in the Hyades, but also the hottest and youngest, in direct conflict with expectation. We examine possible resolutions of the paradox, including the possibility of a nova outburst in the recent past, but conclude that the most likely explanation is that the WD is indeed very young, and is descended from a blue straggler. A plausible scenario is that the progenitor system was a triple, with a close inner pair of main-sequence stars whose masses were both similar to that of the present cluster turnoff. These stars became an Algol-type binary, which merged after several hundred million years to produce a single blue straggler of about twice the turnoff mass. When this star evolved to the AGB phase, it underwent a common-envelope interaction with a distant dK companion, which spiralled down to its present separation, and ejected the envelope. We estimate that the common-envelope efficiency parameter, \( \alpha_{\text{CE}} \), was of order 0.3–1.0, in good agreement with recent hydrodynamical simulations.
1. Introduction

V471 Tauri (BD +16° 516) is a remarkable binary system belonging to the Hyades star cluster. It is an eclipsing binary with an orbital period of only 12.5 hr, whose components are a hot DA white dwarf (WD) and a dK2 main-sequence (MS) star. Following discovery of the eclipses by Nelson & Young (1970), Vauclair (1972) pointed out that V471 Tau’s current system mass is much lower than the mass that the progenitor system must have had. It was also realized during the early 1970’s that the system’s current orbital separation is much smaller than the radius of the red giant that had to have existed in the binary in order to form the WD.

These puzzles would be resolved if the progenitor binary had an initial orbital separation large enough for the original primary star to attain red-giant dimensions before encountering its MS companion. Only then did extensive loss of mass and orbital angular momentum lead to extreme contraction of the orbit. In a classic paper, Paczyński (1976) proposed a scenario in which the expanding giant primary engulfs its companion in a “common envelope” (CE). Friction then leads to a rapid spiraling-down of the orbit, during which coalescence of the red giant’s core and the MS companion may be avoided if the CE can be spun up to the critical rotation velocity and ejected from the system. Planetary nebulae with extremely close binary nuclei (Bond & Livio 1990; Bond 2000, and references therein) provide the most direct evidence that CE interactions and envelope ejections do occur in nature. As discussed by Paczyński (1976), V471 Tau is most probably directly descended from a system of this type, and will evolve eventually into a cataclysmic variable (CV); thus V471 Tau is often considered to be the prototypical “pre-cataclysmic” binary (e.g., Bond 1985).

A critical parameter that determines the outcome of a CE interaction is the efficiency with which orbital energy is converted into ejection of matter from the system. This efficiency, denoted $\alpha_{\text{CE}}$, is defined (see Iben & Livio 1993) by

$$\alpha_{\text{CE}} = \frac{\Delta E_{\text{bind}}}{\Delta E_{\text{orb}}},$$

where $\Delta E_{\text{bind}}$ is the binding energy of the ejected material and $\Delta E_{\text{orb}}$ is the change in the orbital energy of the binary between the beginning and end of the spiraling-in process.

If $\alpha_{\text{CE}}$ is high, $\sim 1$, then envelope ejection occurs early in the interaction, and most of the
binaries emerging from CEs will still have relatively long orbital periods (typically 10–100 days; cf. Yungelson, Tutukov, & Livio 1993). If, however, $\alpha_{\text{CE}}$ is much lower than unity, then short-period CE descendants along with mergers will be much more common, making it easier to produce close-binary planetary nuclei, V471 Tau-like detached WD/red-dwarf binaries, CVs, and eventually Type Ia supernovae. Knowledge of the typical values of $\alpha_{\text{CE}}$ is therefore crucial in understanding the evolution of populations of binary systems.

V471 Tau is one of two known post-CE, pre-CV systems in the Hyades cluster (the other being HZ 9). V471 Tau’s cluster membership is confirmed by Hipparcos proper-motion and parallax measurements (pro96,per98,deBruijne01. The high surface temperature of the WD, $T_{\text{eff}} \simeq 35,000$ K, implies a very short cooling age of $\sim 10^7$ yr (see §7.3). Thus, it ought to be possible to assume the original mass of the WD progenitor to have been equal to the cluster’s current MS turnoff mass; by measuring the masses of both components of the current system, we would then have all of the information needed to determine $\alpha_{\text{CE}}$ entirely empirically.

Since the V471 Tau system eclipses, we simply require the radial-velocity curves (along with, for highest accuracy, the inclination of the orbit with respect to the line of sight) in order to measure purely dynamical masses of both components. However, it has not proven possible to measure reliable radial velocities of the WD component from the ground (gil83, e.g.), since its optical light is badly swamped by that of the K2 component. Thus, the primary goal of this project was to measure radial velocities of the WD in the ultraviolet, where the K2 star contributes negligibly to the flux.

Additionally, UV spectroscopic observations of V471 Tau would allow investigation of other astrophysical questions. The WD mass-radius relation is still relatively poorly constrained by observation, with Sirius B and Procyon B being virtually the only WDs with very accurately measured dynamical masses. V471 Tau, a bright, detached eclipsing binary, offers an excellent opportunity to add to this short list.

Also of interest is the finding by Jensen et al. (1986) of a periodic 9.25-min modulation in the soft X-ray flux of V471 Tau, subsequently found also in the optical band by Robinson, Clemens, & Hine (1988). Clemens et al. (1992) showed that the X-ray and optical modulations are 180$^\circ$ out of phase, and argued that they arise because of magnetic accretion from the K dwarf’s wind onto the pole(s) of the WD. In this picture, the WD’s rotation period is 9.25 min, and metallic opacity darkens the pole(s) of the WD in soft X-rays while brightening them through flux redistribution in the optical (see Dupuis et al. 1997). Time-resolved UV spectroscopy offers the possibility of testing this model by detecting absorption lines of accreted metals.
With the above motivations, we obtained observations of V471 Tau with the Goddard High-Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST). This paper deals with the measurement and interpretation of the radial-velocity variations of the WD, and use of the GHRS spectra to determine the temperature and gravity of the WD. In addition, we have used the same set of observations to detect a Zeeman-split photospheric Si\textsc{iii} absorption line whose strength is modulated on the rotation period of the WD, strongly confirming the magnetic accretion picture; we have described these results separately (Sion et al. 1998). Moreover, we serendipitously detected two episodes of transient metallic absorption-line features—caused by clumpy material in the stellar wind from the K dwarf passing across the line of sight to the WD—and have likewise described this phenomenon elsewhere (Bond et al. 2001).

2. \textit{HST} Observations

Our \textit{HST} observations consisted of twelve GHRS G160M spectra, centered at Lyman-\(\alpha\) (1216 Å). The aim of the program was to obtain spectra at orbital phases 0.25 and 0.75, for optimum determination of the velocity amplitude of the WD’s spectroscopic orbit. In spite of the demanding spacecraft scheduling requirements, all but two of our observations were successfully obtained at mid-exposure times within \(\pm 0.065\) of the desired phase; however, due to a misinterpretation of the scheduling software, our first two observations were actually made one spacecraft Earth occultation interval later than desired. Four of our spectra were obtained in 1993 with the pre-repair GHRS, and the remaining eight with the COSTAR-corrected GHRS in 1994–1995. The latter group of spectra had, of course, significantly higher signal-to-noise, and form the bulk of the useful data for our analysis.

Each of the spectra had a dispersion of 0.07 Å diode\(^{-1}\) and covered an interval of 36 Å, which spans only the central 50\% of the Stark-broadened Ly\(\alpha\) absorption profile. Half of the spectra were taken centered on the rest wavelength of Ly\(\alpha\), and half were shifted by 1 Å in order to lessen the effects of fixed-pattern features in the detector. Each observation was 29.0 (pre-COSTAR) or 36.3 min (post-COSTAR) long, and was broken up into 16 equal-length subexposures in order to look for spectroscopic variations on the 9.25-min rotational period of the WD. (Rotational variations were indeed found, as discussed separately by Sion et al. 1998.)

The spectra were processed and calibrated using the standard STSDAS/GHRS pipeline software. The best available calibration files and appropriate versions (for the pre- and post-COSTAR observations) of CALHRS were used. Spectra of the Pt–Ne calibration lamp (WAVECAL observations) were taken prior to, or immediately following, each observation.
so that we could obtain the best possible wavelength scales. The output spectra were all shifted during the processing to heliocentric velocities.

Table 1 lists details of the twelve spectra used in our study. In order to determine orbital phases, we noted that the times of primary eclipses tabulated by İbanoğlu et al. (1994) and Guinan & Ribas (2001) indicate that the orbital period was nearly constant throughout the mid-1990’s. The following ephemeris, which fits the nine published eclipse timings from 1992.0 through 1999.2 with a maximum error of 13 s,

\[
T_0 = t_{\text{mid-eclipse}} = \text{HJD } 2,440,610.05693 + 0.52118373 E, \quad (2)
\]

was used to calculate the phases listed in Table 1.

Also given in Table 1 are the measured radial velocities, which will be discussed below.

Figure 1 displays plots of all of the spectra obtained in our study, in order of orbital phase. The lower S/N ratios of the four pre-COSTAR observations are obvious. The spectra show a number of features, which are explained in Figure 2; this figure plots a coadded spectrum made by summing the eight post-COSTAR observations, without any velocity shifts. Most obvious are the WD’s broad and deep Lyα absorption wings. Three sharp interstellar N I absorption lines (1199.55, 1200.22, and 1200.71 Å) lie near the short-wavelength end of the spectrum. The complicated structure in the core of Lyα consists of a broad chromospheric Lyα emission line from the K dwarf, into which cuts a strong interstellar Lyα absorption core. The emission profiles are highly variable in structure and strength, indicating varying levels of chromospheric activity and its distribution across the stellar surface. An additional weak interstellar deuterium (D I 1215.35 Å) absorption is present on the blue side. Finally, there is a weak geocoronal Lyα emission feature in the center of the strong interstellar absorption core. On two occasions a transient absorption line of Si III 1206.51 Å appeared suddenly in the spectra, which we attribute to coronal mass ejections from the K dwarf passing in front of the WD; these are described separately (Bond et al. 2001).

Referring back to Figure 1, one can clearly see the orbital motion of the WD Lyα wings (blue-shifted in the top six spectra, red-shifted in the bottom six), the out-of-phase motion of the K dwarf’s chromospheric emission core, and the stationary interstellar and geocoronal features. The bottom spectrum, at orbital phase 0.815, shows a strong transient Si III 1206 Å absorption feature, as mentioned above.
3. Spectroscopic Measurements

3.1. Radial Velocities

Radial velocities of the WD were determined through a cross-correlation technique. We initially cross-correlated the 12 individual spectra with a reasonable model spectrum, which we calculated for $T_{\text{eff}} = 35,000$ K, $\log g = 8.2$ using the TLUSTY/SYNSPEC software package (Hubeny 1988; Hubeny & Lanz 1995). Using the Levenberg-Marquardt least-squares algorithm (Press et al. 1992), we determined the velocity shift and flux scale factor that best fit the model spectrum to each observation (the flux scaling factor being necessary both to convert from model fluxes to observed fluxes, and because slightly different centerings of the star in the GHRS aperture for the different observations led to small changes in the total flux). We then used the resulting initial velocity estimates to shift each individual spectrum to zero velocity, and summed all of the spectra to obtain a grand “zero-velocity” spectrum with a much higher S/N ratio than any of the individual spectra. After smoothing the grand spectrum using a 16-point running average, we fitted it again to each individual spectrum to obtain improved velocity estimates. The process was then iterated a second time in order to derive the final velocity measurements (convergence having been achieved with the second iteration).

At each stage of the above process we were careful to mask out the central portions of each spectrum, which contained the features from the K star and interstellar medium described above, along with the region around the interstellar N I triplet and the transient Si III line. Because of suspected differences in the absolute flux calibrations between the pre- and post-COSTAR data (see below), we actually created two different grand spectra: one each for the pre- and post-COSTAR data. We then cross-correlated the 4 individual pre-COSTAR spectra with the pre-COSTAR grand spectrum, and the 8 post-COSTAR spectra with the post-COSTAR grand spectrum, to get the final velocities. Table 1 lists the resulting velocities for all 12 spectra. The listed errors are 1σ, calculated from the least-squares fit, and are of course larger for the lower-S/N pre-COSTAR spectra. The zero points of the velocity scales are discussed in detail below (§4).

3.2. Effective Temperature and Gravity of the White Dwarf

The final post-COSTAR coadded spectrum, based on a total of nearly 5 hours of GHRS exposure time, gives us the opportunity to make a precise new spectroscopic determination of $T_{\text{eff}}$ and $\log g$ for the WD component. We constructed a grid of pure-hydrogen TLUSTY models covering the range $7.5 < \log g < 8.7$ (in steps of 0.1 dex) and $30,000$ K $< T_{\text{eff}} < 40,000$ K
(in steps of 500 K), and then cross-correlated the resulting synthetic spectra (created using SYNSPEC) with the grand coadded spectrum. We initially constructed both LTE and non-LTE models, but the primary difference between them is a sharper, deeper Ly$\alpha$ absorption core in the NLTE models. Since this core is obliterated in our spectra by the K-dwarf and interstellar features anyway, the LTE and NLTE models fitted the final spectrum equally well. The best fit is obtained for $T_{\text{eff}} = 34,500 \pm 1,000$ K and $\log g = 8.3 \pm 0.3$—very close to the “reasonable” model used initially to estimate the velocities. Figure 3 shows the excellence of the fit.

Our results are in good agreement with previous determinations. In an early study of the Ly$\alpha$ profile from $IUE$ spectra, Guinan & Sion (1984) found $T_{\text{eff}} = 35,000 \pm 3,000$ K and $\log g \simeq 8$. Cully et al. (1996) used the EUV flux distribution to derive $T_{\text{eff}} = 33,100 \pm 500$ K (for an assumed $\log g = 8.5$), while from the same $EUVE$ data Dupuis et al. (1997) found 32,000 K. Barstow et al. (1997) and Werner & Rauch (1997) have used $ORFEUS$ spectra of the Lyman series to derive the effective temperature and gravity. Barstow et al. obtain $T_{\text{eff}} = 32,400^{+270}_{-800}$ K and $\log g = 8.16^{+0.18}_{-0.24}$, while Werner & Rauch find 35,125 $\pm 1,275$ K and 8.21 $\pm 0.23$, the primary difference in the analyses being the inclusion of the $IUE$ Ly$\alpha$ profile in the analysis by Barstow et al.

We will return to the temperature and gravity of the WD in §7, in order to discuss the star’s radius and cooling age, and to constrain the evolutionary history of the binary.

4. The Double-Lined Spectroscopic Orbit

We performed a least-squares fit of the final WD velocities to a sine curve of the form

$$V(t) = \gamma - K_{\text{WD}} \sin \left[ \frac{2\pi(t - T_0)}{P_{\text{orb}}} \right],$$

where the systemic velocity, $\gamma$, and the WD’s radial-velocity semi-amplitude, $K_{\text{WD}}$, are the fitting parameters, and the time of mid-eclipse, $T_0$, and the orbital period, $P_{\text{orb}}$, are known (our equation [2]). (The orbital eccentricity is assumed to be zero, in agreement both with observation [Bois, Lanning, & Mochnacki 1988] and theoretical expectation.) We fitted the pre- and post-COSTAR data separately.

In our initial fits, we found that, although the the pre- and post-COSTAR data yielded the same $K_{\text{WD}}$ to within the errors, the systemic $\gamma$ velocities were significantly different, with the pre-COSTAR value being more negative by about 60 km s$^{-1}$. We believe we have traced this problem to the fact that the absolute GHRS instrumental sensitivity falls off sharply across the Ly$\alpha$ line; this means that the reduction of the instrumental spectra to absolute
fluxes involves multiplication by a function that has a very steep slope with respect to wavelength. Detailed examination of the GHRS detector sensitivity as a function of wavelength, kindly provided by S. Hulbert (2000, private communication) of the GHRS team at the Space Telescope Science Institute (STScI), showed moreover that the pre- and post-COSTAR calibration curves adopted in the reduction pipeline differ significantly from each other. It is thus perhaps not surprising that our analysis of a very broad spectral feature would yield different velocity systems for the two sets of spectra. (This effect would be expected to be much smaller on sharp features, such as the three interstellar N I lines. We investigated their behavior by first measuring velocities in the individual 29- and 36-min spectra; this confirmed self-consistent velocities, within the errors, among the individual pre- and post-COSTAR spectra. We then, as described above, prepared grand summed spectra for the 4 pre-COSTAR and 8 post-COSTAR spectra. This revealed a small systematic shift between the two sets of spectra, in the same sense as that obtained from Lyα, but much smaller. For the pre-COSTAR grand spectrum, the mean N I velocities for the 1199.55, 1200.44, and 1200.71 Å lines were $+15.2 \pm 4.0$, $+19.5 \pm 5.4$, and $+21.0 \pm 7.8 \text{ km s}^{-1}$, respectively, while for the higher-quality post-COSTAR spectra the velocities were $+23.7 \pm 1.8$, $+23.0 \pm 2.3$, and $+23.5 \pm 3.3 \text{ km s}^{-1}$. The weighted mean difference between the pre- and post-COSTAR velocities was thus only about 6 km s$^{-1}$.)

In view of these differences, we decided, in the remainder of the analysis, to use only the eight post-COSTAR spectra. Moreover, although all of the 8 velocities should be on the same system, we feel that the absolute velocity zeropoint for Lyα is not trustworthy because of the steep sensitivity function.

Our final result for the WD velocity semi-amplitude is $K_{WD} = 163.6 \pm 3.5 \text{ km s}^{-1}$. For the dK star’s semi-amplitude, we adopt $K_{dK} = 148.46 \pm 0.56 \text{ km s}^{-1}$ from the ground-based spectroscopic orbit of Bois et al. (1988, their Table V; we took the mean of the two circular orbits presented in their table, weighted by number of observations),

In Figure 4 we plot the ground-based velocity observations of the K dwarf, taken from Bois, Lanning, & Mochnacki (1988), our 8 post-COSTAR WD velocities, and the best-fitting sine functions. For simplicity, we have plotted the WD velocity curve with a $\gamma$ velocity assumed to be the same as that of the K dwarf. (Note that, unfortunately, the above discussion implies that we are unable to make an independent measurement of the gravitational redshift of the WD based on our Lyα observations.)
5. Component Masses

The component masses and velocity semi-amplitudes are related through Kepler’s third law, which can be written as

\[ M_{(WD,dK)} \sin^3 i = 1.0385 \times 10^{-7} (K_{WD} + K_{dK})^2 K_{(dK,WD)} P_{\text{orb}}, \tag{4} \]

where the respective masses of the two stars, \( M_{(WD,dK)} \), are in \( M_\odot \), the respective velocity semi-amplitudes, \( K_{(dK,WD)} \), are in km s\(^{-1}\), and the orbital period, \( P_{\text{orb}} \), is in days.

In order to proceed, we need to determine, or place limits on, the inclination, \( i \), of the plane of the binary orbit to the line of sight.

5.1. Constraining the Orbital Inclination

It will be useful in the following discussion to consider the location of the K dwarf in the mass-radius plane, which is shown in Figure 5. We immediately have a lower limit on \( M_{dK} \) by setting \( i = 90^\circ \) in equation (4) and adopting the values of \( K_{WD} = 163.6 \pm 3.5 \text{ km s}^{-1} \) and \( K_{dK} = 148.46 \pm 0.56 \text{ km s}^{-1} \) from §4, and \( P_{\text{orb}} = 0.52118373 \text{ day} \). This gives \( M_{dK} \geq 0.86 \pm 0.04 M_\odot \). The region excluded in this manner is shown in Figure 5 as the vertical shaded area on the right-hand side whose edge is labelled at the top with \( 90^\circ \). Also shown as vertical ticks along the top edge are the values of \( M_{dK} \) corresponding to \( i = 65^\circ, 70^\circ, 75^\circ, \) and \( 80^\circ \).

We can further limit the permitted region in Figure 5 by assuming that the K dwarf has a radius no smaller than that of a Hyades zero-age main-sequence (ZAMS) star of the same mass. (Since the star is constrained to rotate synchronously with the short-period orbit [see below], is magnetically active, covered with starspots, and has relatively recently emerged from a CE event, one cannot be sure that it is not larger than a ZAMS star, but there seems to be no plausible way for it to be smaller\(^2\).) Perryman et al. (1998, their Table 10) have presented tables of computed values of the Hyades ZAMS masses, luminosities, and effective temperatures, which agree well with observations. The ZAMS radii may of course be calculated from these tables. The following formula fits the Perryman et al. Hyades ZAMS mass-radius relation to 0.6% accuracy or better over the interval \( 0.8 \leq M/M_\odot \leq 1.2 \):

\[ R/R_\odot = 0.7126 - 0.6277(M/M_\odot) + 0.7826(M/M_\odot)^2. \tag{5} \]

\(^2\)Exceptions to this statement can occur under conditions of high mass loss or mass accretion—e.g., Sarna, Marks, & Smith 1995 and references therein.
This relation, and the excluded triangular region below it, are shown by the dark shaded area on the lower left-hand side of Figure 5.

The K star’s radius is limited at the upper end by the fact that the binary is detached, i.e., the K star does not fill its Roche lobe. This limit is, however, off the top of Figure 5, at $R_{dK} \approx 1.3 R_\odot$ (see §5.2 below).

Further constraints on the radius of the K dwarf come from radiometric considerations. İbanoğlu et al. (1994), on the basis of their heroic multi-decade photometric monitoring program on V471 Tau, report that the mean brightness (outside eclipse) of the system increased almost monotonically by 0.21 mag over the interval from 1970 to late 1992, without an appreciable change in $B - V$ color. This indicates strongly that a significant, and time-variable, fraction of the K star’s surface is covered by dark spots, as is indeed confirmed directly by the spectroscopic Doppler imaging of Ramseyer, Hatzes, & Jablonski (1995). Hence a straightforward radiometric analysis will yield only a lower limit to the physical radius of the star. The highest limit will be obtained by taking the brightest $V$ magnitude that has ever been observed, this corresponding to the smallest spot covering fraction of the area of the visible hemisphere, $f_{\text{spot}}$. (In our simplified approach, $f_{\text{spot}}$ refers to the equivalent fractional area of the hemisphere that would be covered if the starspots were completely black.)

The brightest mean $V$ and $B$ magnitudes tabulated by İbanoğlu et al. are 9.39 and 10.26, respectively (at epoch 1992.88), with errors of about $\pm 0.03$ mag. V471 Tau exhibits a photometric wave on its orbital period, which arises from the patchy distribution of starspots across its surface. In late 1992 the peak-to-peak amplitude of the rotational light curve was $\sim 0.1$ mag (Tunca et al. 1993), so we adopt $V_{\text{max}} = 9.34$ and $B_{\text{max}} = 10.21$ as the very brightest magnitudes that it has reached. The WD has $V = 13.64$ according to Barstow et al. (1997), who extrapolated IUE spectra out to visual wavelengths; the result agrees well with the $V = 13.6$ quoted by Warner, Robinson, & Nather (1971) from direct measurements of the eclipse depth in the $V$ band. The color of the WD is $B - V = -0.24$ (from the model atmospheres of Bergeron et al. 1995). The WD therefore contributes 2% of the system light at $V$ and 6% at $B$, leading to corrected values of $V_{\text{max}} = 9.36$, $B_{\text{max}} = 10.27$, and $(B - V)_{\text{max}} = 0.91 \pm 0.04$. (At our level of approximation, we are neglecting the facts, discussed by Ramseyer et al. 1995 in more detail, that a $\sim 3\%$ ellipsoidal orbital variation arises from tidal distortion, and that there is a small amount $[\sim 100 \text{ K}]$ of heating of the dK star on its sub-WD hemisphere.) Note that this color is in quite good agreement with the value of $B - V = 0.92$ actually measured during primary eclipse (thus isolating the K dwarf) by Young & Nelson (1972), but that the K star had brightened appreciably in 1992 from the $V = 9.71$ that Young & Nelson measured during primary eclipse in the early 1970’s.
The direct trigonometric parallax of V471 Tau from the Hipparcos mission is 21.37 ± 1.62 mas. More recently, however, de Bruijne et al. (2001) have used Hipparcos-Tycho proper motions to determine a more accurate secular parallax of 21.00 ± 0.40 mas (corresponding to \( d = 47.6 \pm 0.9 \) pc), based on the constraint that the star shares the space motion of the Hyades cluster. This distance then implies a brightest absolute magnitude \( M_{V,\text{max}} = 5.97 \pm 0.06 \) for the dK component.³

Using the photometric model library of Lejeune, Cuisinier, & Buser (1997), and assuming \([\text{Fe/H}] = 0.1\) and no interstellar reddening, we find that a color of \( B - V = 0.91 \pm 0.04 \) implies that the K dwarf has an effective temperature of \( T_{\text{eff}} = 5040 \pm 100 \) K. (More precisely, this is the temperature of the unspotted portion of the stellar surface.) The corresponding bolometric correction is \( BC(V) = -0.28 \pm 0.02 \), yielding \( M_{\text{bol, max}} = 5.69 \pm 0.06 \) and (adopting \( M_{\text{bol, \odot}} = 4.746 \) from Lejeune et al. 1997), we derive \( L_{\text{dK, max}}/L_{\odot} = 0.42 \pm 0.02 \). The radius of the K star is then

\[
R_{\text{dK}}/R_{\odot} = (0.84 \pm 0.04)(1 - f_{\text{spot}})^{-1/2}. \tag{6}
\]

Doppler maps of the K star by Ramseyer et al. (1995) suggest that \( f_{\text{spot}} \approx 0.2 \) in late 1992; since this estimate is based only on our visual inspection of their published maps, and the starspots that they have detected may not be completely black, the uncertainty in \( f_{\text{spot}} \) is probably of order a factor of two. The derived values of \( R_{\text{dK}}/R_{\odot} \) for \( f_{\text{spot}} = 0.1, 0.2, 0.3, \) and 0.4 are shown as four horizontal dot-dash lines in Figure 5, labelled with the corresponding values of \( f_{\text{spot}} \). We believe that it is likely that the star’s radius lies between the top and bottom lines.

The next constraint on \( R_{\text{dK}} \) is a geometrical one that comes from the duration of primary eclipse. It can be shown (e.g., Young & Nelson 1972, their eq. [1]) that the radius of the K star is related, to good approximation, to the orbital phase, \( \phi \), at which the eclipse ends by

\[
R_{\text{dK}} = a (\sin^2 i \sin^2 \phi + \cos^2 i)^{1/2}, \tag{7}
\]

where \( a \) is the semi-major axis of the orbit. We define \( \phi = (0.5 \Delta t_{\text{ecl}}/P_{\text{orb}}) \times 360^\circ \), where \( \Delta t_{\text{ecl}} \) is the duration of the eclipse measured from mid-ingress to mid-egress. The duration is given by \( \Delta t_{\text{ecl}} = \Delta t_{12} + \Delta t_{23} \), where (in the notation of Warner et al. 1971) \( \Delta t_{12} \) is the time

³Perryman et al. (1998) use \( B - V = 0.83 \) to place V471 Tau (which they catalog as HIP 17962) about 0.2 mag below the Hyades ZAMS. This however is the color of the system outside eclipse, which, as noted, includes some contamination from the WD component. Our values place the star on the Hyades MS in the \( M_V, B - V \) diagram, although this is somewhat fortuitous given the star’s large amount of spot coverage (see §6 below).
interval between first and second contacts (i.e., the duration of eclipse ingress) and $\Delta t_{23}$ is that between second and third contacts (i.e., the duration of totality). Based on the high-speed photometry of Warner et al., we adopt $\Delta t_{12} = 68.3 \pm 2.0$ s and $\Delta t_{23} = 2822.6 \pm 2.0$ s, so that $\Delta t_{ecl} = 2890.9 \pm 2.8$ s and $\phi = 11^\circ 56 \pm 0^\circ 01$.

The separation of the stars is given by

$$a \sin i = 1.3751 \times 10^4 (K_{WD} + K_{dK}) P_{\text{orb}} \text{ km},$$

where the velocity semi-amplitudes are in km s$^{-1}$ and $P_{\text{orb}}$ is in days. Substituting our measurements of $K_{WD}$ and $K_{dK}$ into equation (8), and then substituting $a$ and $\phi$ into equation (7), we obtain a relation between $R_{dK}$ and $\sin i$, which is plotted in Figure 5 as the curve labelled “$\Delta t_{ecl} = 2891$ s,” along with the 1$\sigma$ error limits on either side. Regions of the plot outside the allowed limits are lightly shaded.

Yet another constraint on the K dwarf’s radius can be derived from its observed rotational velocity, under the assumption that it rotates synchronously with the orbital period (i.e., $P_{\text{rot, dK}} = P_{\text{orb}}$). This assumption is strongly supported by the fact that photometric variations of the system arising from starspots on the dK component occur almost precisely on the orbital period (e.g., İbanoğlu 1978; Skillman & Patterson 1988 and references therein). On the further assumption that the rotational axis is perpendicular to the orbital plane, the projected rotational velocity is given by

$$v_{\text{rot, dK}} \sin i = \frac{2\pi R_{dK}}{P_{\text{orb}}} \sin i.$$  \hspace{1cm} (9)

The rotational velocity of the K dwarf has been measured to be $v_{\text{rot, dK}} \sin i = 91 \pm 4$ km s$^{-1}$ by Ramseyer et al. (1995). The family of points satisfying equation (9) is plotted in Figure 5 as the curve labelled “$v \sin i = 91$ km/s,” again with the associated 1$\sigma$ error limits plotted on either side. Again we have shaded the excluded regions of the plot outside the allowed limits.

Figure 5 now shows that the mass and radius of the K star have been fairly tightly constrained to the small unshaded parallelogram-shaped box, based on our measurement of the WD’s velocity amplitude combined with purely geometrical measurements. The orbital inclination corresponding to the intersection of the two relations is

$$\sin i = 0.976 \pm 0.020,$$ \hspace{1cm} (10)

or $i = 77.4^{+7.5}_{-4.5}$ degrees. Note also that the radiometric radius determination discussed above would be in good agreement with these constraints, if the hemispheric spot-covering fraction in late 1992 during the brightest phase of the rotational light curve was $f_{\text{spot}} \approx 0.2$–0.3. The physical radius of the K star corresponding to the intersection of the two relations is $R_{dK} = 0.96 \pm 0.04 R_{\odot}$. 


5.2. The Stellar Masses and Orbital Parameters

We now have all of the ingredients required to calculate the masses directly from the orbital parameters. According to equations (4) and (10), combined with the measurements of $K_{\text{WD}}$ and $K_{\text{dK}}$, the WD and K-dwarf masses are:

$$M_{\text{WD}} = 0.84 \pm 0.05 \, M_\odot,$$
$$M_{\text{dK}} = 0.93 \pm 0.07 \, M_\odot.$$

Most previous authors have followed Young & Nelson (1972) in adopting masses near 0.7–0.8 $M_\odot$ for both components of V471 Tau. Until now, it was necessary to assume that the dK star had a normal ZAMS mass and radius appropriate to its spectral type, since the velocity amplitude of the WD component was unknown, and then to derive other parameters of the system from the single-lined spectroscopic orbit of the K component. Now that the velocity curves for both stars are available (along with the crucial measurements of the eclipse timings and the K star’s rotational velocity), we can derive the system parameters without recourse to assumptions about the K star—and indeed we have found that assumption of a normal ZAMS mass and radius for the K star would be incorrect.

Other orbital parameters also follow from our measurements. The orbital separation of the two stars (from equation [8]) is $a = 3.30 \pm 0.08 \, R_\odot = 3.43 \pm 0.08 \, R_{\text{dK}}$. The Roche-lobe radii (from equation [18], given below in §8) of the two stars are $R_{L,\text{WD}} = 1.22 \pm 0.10 \, R_\odot$ and $R_{L,\text{dK}} = 1.28 \pm 0.09 \, R_\odot$. The K star fills its Roche lobe by only $R_{\text{dK}}/R_{L,\text{dK}} = 73\% \pm 6\%$, so it is well inside its lobe.

We will now discuss some of the physical properties of each component star in more detail.

6. The Oversized K Star

Figure 5 illustrates that the dK star in V471 Tau is about 18% oversized for its mass, relative to normal Hyades ZAMS stars. This conclusion has already been suggested by previous authors (e.g., Ramseyer et al. 1995), but is strengthened by our new analysis.

What about the location of the K dwarf in the mass-luminosity plane? A normal Hyades ZAMS star of 0.93 $M_\odot$ would have $L/L_\odot = 0.40$ (Perryman et al. 1998, their Table 10). To estimate the actual luminosity of the dK star in V471 Tau, it is appropriate to use the mean system brightness (thus averaging over the entire surface of the spotted star). In late 1992, the mean brightness was $V = 9.41$ (İbanoğlu et al. 1994, corrected for the WD contribution;
Using the bolometric correction and solar $M_{\text{bol}}$ from §5.1 and the known distance, we find $L/L_\odot = 0.40$ for the dK star, in perfect agreement with the expected luminosity for the star’s mass. This can be compared with the fact that, for the mass of $\approx 0.7–0.8\ M_\odot$ assumed in earlier literature, a Hyades ZAMS star would have $L/L_\odot \leq 0.20$, according to Perryman et al. (Our result, however, applies strictly only to the 1992 epoch, and we would have gotten a somewhat different result at earlier epochs when the star was somewhat fainter.)

We conclude that the K star has a luminosity that is approximately appropriate for its measured mass, but a radius that is larger than that of a ZAMS star of the same mass. We will discuss two possible reasons for the unusually large radius of the K star: (a) the star is still out of thermal equilibrium because of its recent immersion in a CE; or (b) the star is so covered by starspots that convective energy transport is inhibited, causing the radius to increase. (Irradiation of the dK star by the WD companion appears to be a minor effect, which we will not consider further; the K star intercepts about 2% of the luminosity of the WD, or only about 1% of its own luminosity. Tidal heating is also negligible, given the synchronous rotation and circular orbit.)

The response of MS stars to CE events has been studied theoretically by Hjellming & Taam (1991). Although the star does go out of thermal equilibrium while it is immersed in the CE, it is expected to revert very quickly to its original configuration once the envelope has been ejected. This reversion occurs on the thermal timescale of the accreted material, which is $\approx 10^3–10^4\ yr$ according to Hjellming & Taam. Since V471 Tau emerged from its CE about $10^7\ yr$ ago (see §7.3 below), it should have relaxed back to its ZAMS radius long ago. Thus the CE interaction seems not to be the cause for the current oversized radius.

The second hypothesis appears to have more merit. As discussed above, the surface of the active dK star is partially covered by starspots, which blocked $\approx 25\%$ of the surface area of the star in the early 1990’s. The response of MS stars to starspot covering has been considered by Spruit (1982) and modelled theoretically by Spruit & Weiss (1986), who show that the response depends on the timescale with which the spot covering fraction varies. If the covering fraction were to increase, say, on a timescale short compared to the thermal timescale of the stellar envelope\(^4\), the blocked luminosity would simply go into increasing the energy content of the envelope, and the stellar radius and the surface temperature outside the spots would remain essentially unchanged. The photometric behavior of V471 Tau over the past few decades, described above, agrees with this prediction—there is a change in overall

\(^4\text{Sometimes loosely called the “Kelvin-Helmholtz timescale of the envelope,” this is }\approx 10^5\ \text{yr for the Sun (Spruit 1982).}\)
brightness with little or no change in color. However, if the star is permanently covered with spots, over timescales long compared to the thermal timescale, Spruit & Weiss argue that both the surface temperature and radius will increase relative to their values for a spot-free star. This is because, as described by Spruit & Weiss (1986), the luminosity produced by the core is affected only slightly (for stars of \( \approx 1 M_\odot \), which have only shallow convective layers) and must continue, time-averaged, to escape from the star.

Our observation is thus in rough qualitative agreement with the theoretical expectation. However, quantitatively, Spruit & Weiss predict that, for stars of \( \approx 0.9 - 1.0 M_\odot \), the stellar radius and surface temperature will both increase by nearly the same factors of about 4% each (for a spot covering fraction of 25%), whereas we actually find an increase of \( \approx 18% \) in radius and a small decrease in the surface temperature. (Part of the difference may be that Spruit & Weiss calculate \( T_s \), the “surface temperature” of the spot-free regions of the photosphere, while the temperature that we infer from the observed \( B-V \) color is actually an average of the hotter spotless regions and the cooler, but not completely dark, spot umbrae and penumbrae.)

We can estimate what the time-averaged effective spot covering fraction, \( f \), has to be in order for V471 Tau to maintain the luminosity of a 0.93 \( M_\odot \) ZAMS star, as follows:

\[
R_{ZAMS}^2 T_{\text{eff},ZAMS}^4 = (1 - f) R_{dK}^2 T_{\text{surf},dK}^4,
\]

where \( T_{\text{surf},dK} \) is the temperature of the unspotted portion of the surface, and \( f \) is averaged over the entire surface of the star, whereas in §5.1 we defined \( f_{\text{spot}} \) to be the minimum coverage fraction for the visible hemisphere seen during the 12.5-hr rotation period. From Perryman et al. (1998) we have \( R_{ZAMS} = 0.806 R_\odot \) and \( T_{\text{eff},ZAMS} = 5105 \) K, and for the V471 Tau K star, we found \( R_{dK} = 0.96 R_\odot \) and \( T_{\text{surf},dK} = 5040 \) K, from which we deduce \( f \approx 0.26 \), in quite good agreement with the observations. It thus appears that, on average, the spot covering fraction has been close to its current value for at least the past \( \approx 10^5 \) yr.

Note also that Mullan & MacDonald (2001) have presented evidence that magnetically active, but single, M dwarfs have significantly larger radii than inactive dM stars of the same effective temperature. This may well be another manifestation of the phenomenon seen in V471 Tau. The cool component in the pre-cataclysmic binary BE UMa was found by Ferguson et al. (1999) to be larger by about a factor of 2 than a MS star of the same mass; however, since BE UMa is surrounded by a faint planetary nebula, it must have emerged from its CE very recently, and the large radius may be due to the cool star still being out of thermal equilibrium.
7. The Paradoxical White Dwarf

We now turn to the other component of the V471 Tau binary, the 0.84 $M_{\odot}$ WD. We will first show that it is by all appearances a normal, hot white dwarf—which in fact provides the most stringent test yet of the theoretical mass-radius relation for WDs—and then show that this normality actually raises a serious paradox involving the evolution of the binary system.

7.1. Radius of the White Dwarf

We have two methods available to determine the radius of the WD: indirectly from radiometry, and directly from eclipse ingress timings.

The radiometric method is based on knowledge of the effective temperature and distance of the star, combined with a measurement of its absolute flux. Determinations of $R_{\text{WD}}$ have been made by Barstow et al. (1997) and Werner & Rauch (1997), based on the Hipparcos trigonometric parallax of $21.37 \pm 1.62$ mas, effective temperatures of $T_{\text{eff}} = 32,400^{+270}_{-800}$ and $35,125 \pm 1,275$ K, respectively (see §3.2), and absolute fluxes from ORFEUS and IUE. The resulting radii reported by these authors were $0.0107 \pm 0.0009 R_{\odot}$ and $0.0097 \pm 0.0013 R_{\odot}$, respectively, the primary source of the difference being the different adopted $T_{\text{eff}}$ values.

We have recalculated the radius as follows: first we adopt our new temperature determination (from §3.2) of $T_{\text{eff}} = 34,500 \pm 1,000$ K (which is close to the mean of the two determinations above), and second we use the new, slightly smaller and more precise secular parallax of de Bruijne et al. (2001), $21.00 \pm 0.40$ mas. Applying these two adjustments to the Werner & Rauch calculation yields $R_{\text{WD}} = 0.0102 \pm 0.0011 R_{\odot}$, with the remaining error coming mostly from the $\sim 10\%$ uncertainty of the ORFEUS absolute flux measured at 1100 Å. A nearly identical result is obtained if the Barstow et al. radius is similarly adjusted to the new temperature and distance.

The direct geometric method for determining the radius is based on the duration of eclipse ingress (or egress), which we denoted $\Delta t_{12}$ in §5.1. Following the discussion in §5.1, we adopt $\Delta t_{12} = 68.3 \pm 2.0$ s from Warner et al. (1971). (Other authors, e.g. İbanoğlu 1978 and references therein; Beavers, Oesper, & Pierce 1979; and Guinan & Ribas 2001, have given somewhat different values for $\Delta t_{12}$, ranging from 55 to 76 s, but the data of Warner et al., based on high-speed photon-counting photometry with a 2-m class telescope, appear to have the highest quality for this purpose.)

The geometry of the eclipses in V471 Tau has been discussed by Warner et al. (1971)
and Young & Nelson (1972). The large difference in stellar radii, $R_{dK} \gg R_{WD}$, means that the eclipse of the WD star by the limb of the dK companion can be treated as the passage of a straight edge over the WD. It can then be shown that the latitude on the dK star at which the WD eclipses occur as seen from Earth, $\beta$, is related to the eclipse timings by

$$\cos \beta = \left( \frac{R_{WD}}{R_{dK}} \frac{\Delta t_{ecl}}{\Delta t_{12}} \right)^{1/2}$$

(12)

(see Warner et al. 1971, their eq. [5], and Young & Nelson 1972, their eq. [2]).

The relative velocity of the two stars across the line of sight at mid-eclipse is $V_{dK} + V_{WD} = (K_{dK} + K_{WD})/\sin i$, and the length of the WD’s path behind the dK star is approximately $2R_{dK} \cos \beta$. The eclipse duration is thus given to good approximation by

$$\Delta t_{ecl} = 2R_{dK} \cos \beta \sin i / (K_{WD} + K_{dK})$$

(13)

By eliminating $\cos \beta$ from equations (12) and (13) and rearranging, we find

$$R_{WD} = \frac{\Delta t_{12} \Delta t_{ecl} (K_{WD} + K_{dK})^2}{4R_{dK} \sin^2 i}$$

(14)

Inserting the measured values, we obtain $R_{WD} = 0.0109 \pm 0.0007 R_\odot$. The agreement with the radiometric radius is remarkably good, especially considering that the observational determination of $\Delta t_{12}$ is both technically challenging and somewhat dependent upon the limb-darkening law of the WD, as discussed in detail by Warner et al.

7.2. Location in the Mass-Radius Plane and Core Composition

Figure 6 shows the location of the WD component of V471 Tau in the mass-radius plane. We use our dynamical mass of $M_{WD} = 0.84 \pm 0.05 M_\odot$ and a radius $R_{WD} = 0.0107 \pm 0.0007 R_\odot$, which is the weighted mean of the radiometric and geometric radii discussed in the previous subsection.

For comparison with theory we plot mass-radius relations in Figure 6 from calculations of Wood (1995, and 1999 private communication) for carbon and oxygen WDs with a surface hydrogen-layer mass of $10^{-4} M_\odot$. We show Wood’s relations both for zero-temperature WDs and for WDs with an effective temperature of 35,000 K, very close to that measured for the V471 Tau WD. In addition, we plot the zero-temperature relations for WDs composed of Mg and Fe, from Hamada & Salpeter (1961).
The figure shows that Mg and Fe core compositions are excluded. However the agreement with C and O compositions is excellent, and indeed, at about the 1σ level, we even confirm that the CO models with a 35,000 K surface temperature provide a better fit than the zero-temperature models.

Our observations provide perhaps the most stringent test and confirmation yet made of the theoretical relation; it is rivaled in accuracy only by two or three WDs with dynamical masses from visual-binary orbits and radiometric radii based on trigonometric parallaxes (see Provencal et al. 1998).

We conclude that the WD in V471 Tau matches the theoretical structure of a normal CO WD with the star’s measured mass, radius, and surface temperature.

7.3. Location in the H-R Diagram and Cooling Age

We can also plot the position of the WD component in the theoretical H-R diagram, log $T_{\text{eff}}$ vs. log $L/L_{\odot}$. The effective temperature and radius have been derived above, and the luminosity is given by $L_{\text{WD}} = (R_{\text{WD}}/R_{\odot})^2 (T_{\text{eff, WD}}/T_{\text{eff, \odot}})^4 L_{\odot} = 0.146 \pm 0.016 L_{\odot}$. The resulting position of the WD is shown in Figure 7. We also show the cooling tracks of Wood (1995, and 1999 private communication), along with the cooling ages, as functions of WD mass from 0.6 to 1.0 $M_{\odot}$. As noted in the previous subsection, these tracks are for CO white dwarfs with a surface hydrogen-layer mass of $10^{-4} M_{\odot}$.

The figure shows that the position of the WD is in excellent agreement with that expected from its dynamically measured mass of 0.84 $M_{\odot}$. It should be noted that the $T_{\text{eff}}$ was determined purely spectroscopically, and that one of the two accordant methods used to determine the radius was based only on spectroscopic and photometric methods. Thus the information used to plot its position in Figure 7 is essentially independent of the star’s distance, and independent of its mass. The fact that the WD lies almost exactly on the theoretical position expected for its dynamically measured mass is therefore a remarkable and gratifying confirmation of WD theory. Indeed, if we were to read off the mass from Figure 7, we would find $0.83 \pm 0.06 M_{\odot}$, in quite astonishing agreement with the dynamical measurement.

As just noted, the luminosity of the WD can be calculated without any recourse to distance measurements, if we use only the radius of $0.0109 \pm 0.0007 R_{\odot}$ that we determined from the eclipse ingress timings. Hence we can combine the resulting luminosity with a brightness measurement to determine a distance. The calculated luminosity based only on the ingress-determined radius would be $0.151 \pm 0.026 L_{\odot}$. The corresponding bolometric
correction, from Bergeron et al. (1995), is $BC(V) = -3.30$, so the calculated absolute magnitude of the WD is $M_V = +10.10$. Adopting the observed $V$ magnitude of 13.6 (Warner et al. 1971), we find a distance modulus $m - M = 3.50 \pm 0.20$, corresponding to a distance of $50.1 \pm 4.8$ pc and a parallax of $20.0 \pm 1.8$ mas. This agrees very well with the measured secular parallax of $21.00 \pm 0.40$ mas.

The cooling age of the WD is seen from Figure 7 to be very close to $10^7$ yr.

For convenience we summarize all of the measured and inferred parameters of the V471 Tau system in Table 2.

7.4. Dynamical Validation of the Spectroscopic Gravity

The dynamical mass and radiometric/geometric radius imply a WD surface gravity of $\log g = 8.31 \pm 0.06$, in excellent agreement with the value of $8.3 \pm 0.3$ that we derived from fitting model-atmosphere spectra to the Ly$\alpha$ line, as discussed in §3.2. This is an extremely reassuring validation of the method of spectroscopic determination of surface gravity via model-atmosphere line-profile fitting.

7.5. The Paradox of the Temperature and Mass

The WD in V471 Tau is too hot for its mass. This is clearly indicated by Table 3, which presents the masses and temperatures of WDs in the Hyades cluster. Except for V471 Tau itself, the data are taken from the literature, as indicated in the notes to the table. Masses are available from three different techniques: (1) spectroscopic binary orbits, which yield dynamical masses, are available for V471 Tau (this paper) and for HZ 9 (which does not eclipse, making it necessary to assume a mass for the cool companion from its spectral type); (2) gravitational redshifts (where the center-of-mass velocity is known from the assumption that the WD shares the motion of the Hyades cluster), and (3) spectroscopic temperatures and surface gravities, which yield a mass when combined with a theoretical mass-radius relation. The columns in Table 3 contain the following information: (1)-(2) the star name and Villanova WD catalog number; (3) the dynamical mass; (4) the mass derived from the gravitational redshift; (5) the mass derived from the spectroscopic gravity; and (6) the effective temperature.

In Figure 8 we plot the WD masses vs. effective temperatures. We have omitted HZ 9 from the figure, because, as just noted, the mass of its cool companion must be assumed from its spectral type, and the pitfalls of this assumption have been demonstrated vividly
by V471 Tau.

Figure 8 dramatically illustrates the paradox of the WD in V471 Tau. We expect there to be a strong correlation between temperature and mass, because the coolest WDs in the cluster should be the oldest ones; in turn, these should be the most massive, since they are descended from the most massive progenitor stars. And indeed such behavior is exhibited by all but one of the Hyades WDs. V471 Tau flagrantly violates the correlation: it is both the hottest WD in the Hyades and the most massive\(^5\). (Note that, if anything, the fact that V471 Tau has emerged from a CE interaction makes the paradox even worse, since in the absence of the binary interaction the WD’s mass would have grown to an even higher value.)

There are several possible astrophysical explanations for the high \(T_{\text{eff}}\) value of the V471 Tau WD. We discuss the plausibility of each scenario in the following subsubsections.

7.5.1. Recent Star Formation

It has been suggested (e.g., Eggen & Iben 1988; see also Barstow et al. 1997, their §6.1) that the paradox of the hot WD in V471 Tau could be resolved if the system really is much younger than other members of the Hyades, having been formed in a late burst of star formation in the cluster. However, Perryman et al. (1998), in their detailed study of the Hyades H-R diagram based on Hipparcos parallaxes, found that the stars within 10 pc of the cluster center can be fit (after removing known binary systems) with a single-age isochrone with an age of \(625 \pm 50\) Myr. There is thus no independent support for any recent star-forming activity in the cluster core.

7.5.2. Accretion

Can the WD heating arise from accretion from the stellar wind of the dK component? The observed luminosity of the WD is \(L_{\text{WD}} = 0.15 L_\odot\). The luminosity available from accretion at a rate of \(\dot{M}\) is

\[
L_{\text{accr}} \simeq 0.5 GM_{\text{WD}} \dot{M}/R_{\text{WD}} \simeq 0.12 \left( \frac{M_{\text{WD}}}{0.8 M_\odot} \right) \left( \frac{R_{\text{WD}}}{0.01 R_\odot} \right)^{-1} \left( \frac{\dot{M}}{10^{-10} M_\odot \text{yr}^{-1}} \right) L_\odot, \quad (15)
\]

\(^5\)Curiously, the Praesepe cluster also contains a high-mass WD, LB 5893, that is anomalously hot for its mass, as shown by Reid (1996), Claver, Liebert, & Bergeron (1997), and Claver et al. (2001); although LB 5893 is a single WD, it presents a paradox similar to that of V471 Tau.
so that it would take an accretion rate of $\sim 10^{-10} M_\odot \, \text{yr}^{-1}$ to provide the luminosity. The entire mass-loss rate from the dK star due to its stellar wind is probably smaller than this (Mullan et al. 1989; Bond et al. 2001), and moreover we would expect only a small fraction of the wind ($\approx 10^{-2}$) to be captured by the WD, even in the absence of magnetic effects. In fact, however, our GHRS observations of the photospheric Si III line (Sion et al. 1998) indicate that the actual accretion rate onto the WD is less than $10^{-17} M_\odot \, \text{yr}^{-1}$ (as supported also by the EUV observations of Dupuis et al. 1997); we argued on this basis that most of the material that attempts to accrete is rejected by a magnetic propeller effect.

Thus it appears that accretion luminosity is inadequate for explaining the high temperature of the WD.

### 7.5.3. Recent Nova

Could the WD in V471 Tau still be hot following a recent nova outburst?

The possibility of a relatively recent nova event received some support when Bruhweiler & Sion (1986) and Sion et al. (1989) reported absorption lines with large negative velocities ($-260$, $-590$, and $-1200 \, \text{km s}^{-1}$) in IUE spectra of the binary; these authors suggested that the lines might arise in a shell ejected during an ancient nova eruption, although for the two lower-velocity components they could not rule out ejection events associated with the K dwarf. They also pointed out that Chinese observers recorded a possible nova in the year 396, lying near the location of V471 Tau in the sky (cf. Pskovskii 1979 and references therein). Clark & Stephenson (1977) place the 396 event at the approximate position $(\alpha, \delta)_{1950} = 4^h, +20^\circ$, as compared with $3^h48^m, +17^\circ06'$ for V471 Tau. The brightness of the event was roughly consistent with that of a DQ Her-type classical-nova outburst at the distance of V471 Tau, according to Hertzog (1986). On the other hand, Clark & Stephenson state that the event was “at best a probable nova,” and it remains possible that the ancient report refers to a supernova, comet, or some other transient event unrelated to V471 Tau, or to a nova outburst of a different object. Moreover, the S/N of the claimed IUE detection of high-velocity lines was quite low, and our GHRS observations reported here along with a preliminary examination of more recent spectra obtained with the Space Telescope Imaging Spectrograph (to be discussed in a separate paper) have not confirmed the existence of these features. In addition, there is no evidence for an ejected nova shell in deep, wide-angle Hα direct imaging of the environment around V471 Tau (J. Gaustad, 1999 private communication).

In a theoretical study, Prialnik & Shara (1986) found that a $1.25 M_\odot$ WD will cool to
the effective temperature of V471 Tau in \( \lesssim 10^3 \) yr following a nova outburst, assuming that mass transfer from the cool companion drops to zero following the explosion—a debatable proposition for classical novae, but appropriate for V471 Tau. The probability of catching the system in an immediate post-nova stage is thus extremely low.

The post-nova cooling timescales are somewhat longer for lower-mass WDs, such as that in V471 Tau. Theoretical studies indicate that a WD with the mass of that in V471 Tau must accrete a hydrogen-rich envelope of \( \sim 3 \times 10^{-4} M_\odot \) in order to initiate a thermonuclear runaway (see Table 1 of Gehrz et al. 1998). The star's subsequent nuclear-burning timescale (i.e., the time required to burn the envelope) would then be of order \( 10^3 \) yr (Gehrz et al.), and it would take somewhat longer to cool to the observed temperature in V471 Tau. However, this still leaves the probability of observing the system at the present epoch quite low.

If we were to suppose that the WD in V471 Tau was actually formed some \( 5 \times 10^8 \) yr ago, then it could have built an envelope mass of \( 3 \times 10^{-4} M_\odot \) with an accretion rate of \( \dot{M} \approx 6 \times 10^{-13} M_\odot \text{yr}^{-1} \). Curiously, this value of \( \dot{M} \) is close to what the Bondi-Hoyle rate would be for a total mass-loss rate from the K dwarf of \( \sim 10^{-11} M_\odot \text{yr}^{-1} \), which is the lower limit reported by Mullan et al. (1989) from IUE absorption-line observations obtained when the WD was just above the surface of the K star. However, our GHRS observations of the WD (Sion et al. 1998) show that the magnetic propeller mechanism actually limits the accretion rate to several orders of magnitude lower than this; thus the WD would not be expected to have accumulated enough hydrogen for even one nova outburst within the age of the Hyades cluster.

On the other hand, it is not impossible that the WD emerged from the CE event with a hydrogen envelope already close to the mass necessary for a nova outburst. Conceivably, also, the time-averaged accretion rate could be higher than what it happened to be during our GHRS observations, due to episodic flaring activity on the dK star. In sum, it turns out to be surprisingly difficult to rule out categorically that V471 Tau has had a nova outburst in the recent past, although we deem this possibility to be unlikely from a probabilistic standpoint.

### 7.5.4. Blue-Straggler Scenarios

The paradox of the hot WD in V471 Tau is, of course, reminiscent of the general problem of blue stragglers in open and globular clusters. Blue stragglers are stars on or near the MS, but lying above the MS turnoff and thus apparently younger than the bulk of the cluster members. The possible connection to V471 Tau is that a blue straggler should eventually
evolve to become an anomalously hot WD in the cluster. There is a general consensus that many blue stragglers are merged binaries. However, a straightforward binary merger scenario cannot explain V471 Tau, which contains a WD in a system that is still a close but detached binary.

Iben & Tutukov (1999) have proposed a scenario that solves this problem by having V471 Tau belong initially to a triple system. Unlike hierarchical triples, whose orbits can remain stable for long intervals, the proposed progenitor system in their scheme was among the \(~10–20\%\) of triples that are non-hierarchical and was thus on the brink of instability.

In the Iben-Tutukov scenario, the initial system contained an Algol-type close binary, while the K dwarf orbited the Algol at a larger distance. The WD progenitor in the Algol system began with a mass similar to (or perhaps slightly less than) that of the present-day MS turnoff stars in the Hyades (\(~2.5\,M_\odot\); Weidemann et al. 1992), and the hypothetical donor companion had an initial mass somewhat above the MS turnoff. The donor evolved to fill its Roche lobe, and conservative mass transfer ensued. As the mass transfer proceeded it increased the mass of the WD progenitor. Once the mass ratio was inverted, the orbital separation in the Algol binary would begin to increase, until it exceeded the limit of stability. At that point, one of the stars, most likely the one of lowest mass, which would now be the Algol donor, was ejected from the system, leaving a binary composed of a MS primary, now a blue straggler with a mass that could approach twice the turnoff mass, and the K companion. This system would then evolve into a CE event as outlined above, giving rise to a much closer pair consisting of the WD core of the Algol accretor and the K star.

Two possible objections to this scenario arise immediately, however. One is that the system should have received a recoil velocity of order the orbital speed (scaled appropriately by the masses) when one star was ejected, yet the binary’s space motion is measured to be within a few \(\text{km s}^{-1}\) of the cluster velocity. The other is that several authors (Beavers, Herczeg, & Liu 1986; İbanoğlu et al. 1994; Guinan & Ribas 2001) have proposed that V471 Tau has a distant third companion, with an orbital period of \(~30\,\text{yr}\) and eccentricity \(\sim0.3\). This suggestion is based on eclipse timings that show a periodic variation in the orbital period; if attributed to the light travel-time effect, the third companion’s mass is only \(M_3\sin i_3 \sim 0.04\,M_\odot\), according to Guinan & Ribas. It would appear unlikely that such a loosely bound third body would have survived the triple-star interaction outlined above, without at least having acquired a very large orbital eccentricity, although of course detailed modelling would be required to support this statement. Alternatively, one might argue that this third body is the putative former donor object, although again one might expect a larger eccentricity, and also in the Iben-Tutukov scenario the subgiant removed from the Algol system has a mass about an order of magnitude larger than inferred for the present-
day distant companion. Actually, however, only about one cycle of the proposed 30-yr orbit has been observed, so it may be premature even to conclude that there is a third body (as opposed to intrinsic period variability, which has been seen in many other close binaries).

In any case, we suggest that an alternative and simpler triple-star scenario may account for all of the properties of V471 Tau without violating any known constraints. Suppose that the initial system consisted of a very close pair of MS stars, with the original primary somewhat more massive than the current MS turnoff and the original secondary somewhat less massive. The current dK star would, again, be a more distant companion. A sufficiently close MS pair will evolve into a “Case A” Algol-type system when the primary expands to fill its Roche lobe. As shown in the recent simulations by Nelson & Eggleton (2001), many Case A systems evolve eventually into a contact configuration. This will lead to a merger of the close pair and formation of a blue straggler. The straggler would subsequently evolve into an AGB star, at which point it would fill the Roche lobe of its orbit with the more distant dK star, enter into a CE interaction, eject the envelope as a planetary nebula, and evolve into the present V471 Tau configuration.

Fortuitously, Nelson & Eggleton (2001, their Fig. 4) present a simulation that comes remarkably close to accounting for the evolution of the inner pair in V471Tau, under our Case A scenario. They start with a ZAMS pair of masses 2.8 and 2.5 $M_\odot$ and an initial orbital period of 1.6 day. The original primary in this binary commences Roche-lobe overflow at an age of 370 Myr, the mass ratio quickly inverts, and the system becomes a contact binary at 490 Myr when the original secondary evolves to fill its own Roche lobe. Just before coming into contact, the masses are 2.0 and 3.3 $M_\odot$. The ensuing merger would produce a blue straggler of 5.3 $M_\odot$, which would have a MS lifetime of $\sim$100 Myr. Thus, at an age of $\sim$600 Myr (very close to the age of the Hyades), the merged object would evolve to the AGB stage, and enter into a CE event with the putative more distant dK companion. The outcome would be a very close pair, consisting of the dK MS star and a hot WD with a mass that could approach that of a remnant of a single 5.3 $M_\odot$ star.

Such a scenario is admittedly *ad hoc* and has few, if any, observationally testable consequences, apart of course from the very existence of the present-day V471 Tau system\. We can, however, point out that catalogs of field triple (or higher multiplicity) systems have been presented by Fekel (1981), Chambliss (1992), and Tokovinin (1997). Among these multiples are some that have parameters more or less similar to that of the proposed progenitor of

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\textsuperscript{6}The rotation speed of the V471 Tau WD, $v \sin i \simeq 80$ km s$^{-1}$, is near the high end of the range observed in single WDs (see Koester et al. 1998) and might be thought to support a binary-merger scenario, but a small amount of mass accretion from the bloated dK component near the end of the CE interaction might also account for the WD’s high angular momentum.
V471 Tau. For example, Algol (β Persei) itself consists of an inner eclipsing pair with a total mass of \( \sim 4.5 M_\odot \), orbited by an outer F dwarf with a period of 1.9 yr (see Fekel 1981, Nelson & Eggleton 2001, and references therein). The triple system of δ Librae is also quite similar to Algol (Worek 2001), with an outer late G dwarf orbiting the close eclipsing pair in a 2.8-yr period. Hence it is clear that nature does occasionally create real triples with properties similar to those proposed here.

8. Implications for Common-Envelope Evolution

As discussed in §1, one of the motivations for this study was to determine \( \alpha_{\text{CE}} \), the efficiency with which orbital energy went into ejecting matter from the V471 Tau system during its recent CE interaction, as defined in our equation (1). Our initial expectation was that this determination would be straightforward: because of the high temperature and short cooling age of the WD, we could simply assume the total mass of the WD progenitor (hereafter we refer to this object as “the AGB star”) to have been equal to that of Hyades MS turnoff stars. The AGB star’s core mass would be taken to be the current mass of the WD, and the radius and binding energy of the AGB star’s envelope could be calculated easily from stellar models. Then, knowing all parameters of the post-CE binary, we could calculate \( \alpha_{\text{CE}} \) entirely from known quantities. (It should be noted that in this section we consider only the CE interaction of the AGB star with its dK companion, apart from any previous events that might have created or altered the AGB star, as discussed in the previous section.)

Unfortunately, however, the evolutionary paradox of the WD in V471 Tau forces us to abandon the assumption that the AGB star had an initial mass equal to the current Hyades turnoff mass. Instead, it was very probably higher.

Although V471 Tau has now become a less ideal laboratory for CE evolution than previously thought, we can still place useful limits on the value of \( \alpha_{\text{CE}} \), since the range of possible AGB star masses is fairly limited. A recent observational study of the WD initial-mass/final-mass relation (IMFMR) by Jeffries (1997) indicates (for Hyades metallicity) that the WD mass of 0.84 \( M_\odot \) in V471 Tau corresponds to an initial MS mass of \( \sim 4 M_\odot \). From the older Weidemann (1987) IMFMR the initial mass would have been higher, \( \sim 5.8 M_\odot \). These values are, of course, lower limits on the AGB star’s mass in V471 Tau, since the CE evolution would if anything have limited the growth of the core mass to a value below that attainable by an undisturbed single star of the same initial mass. However, if our Algol merger scenario is correct, the initial mass would have been limited to about twice the current Hyades turnoff mass.
We have chosen to estimate $\alpha_{\text{CE}}$ for a range of assumed AGB star masses from 3.5 to 5.5 $M_\odot$, with the low end extended slightly below the Jeffries lower limit to allow for the possibility of some stellar-wind mass loss prior to the CE event, and the upper limit corresponding to slightly more than twice the turnoff mass. We determine the luminosity of the AGB star at the moment of Roche-lobe overflow by taking $M_{\text{core}}$ to be the current WD mass of 0.84 $M_\odot$, and using the theoretical AGB core-mass/luminosity relation of Vassiliadis & Wood (1994):

$$L_{\text{AGB}}/L_\odot = 56694 [(M_{\text{core}}/M_\odot) - 0.5],$$

which implies an AGB luminosity of $L_{\text{AGB}} = 19275 L_\odot$. For the radius of the AGB star at the beginning of the CE interaction we use a formula based on Hurley, Pols, & Tout (2000):

$$R_{\text{AGB}}/R_\odot = 1.218 M_{\text{AGB}}^{-0.34} [(L_{\text{AGB}}/L_\odot)^{0.41} + 0.335(L_{\text{AGB}}/L_\odot)^{0.75}],$$

which applies for Hyades metallicity, as set forth in detail by Hurley et al. We can thus calculate the radius of the AGB star and equate it to the radius of its Roche lobe, $R_L$, at the onset of mass transfer to the dK companion. Next, for each assumed value of $M_{\text{AGB}}$, we can calculate the initial orbital separation, $a_i$, from the Eggleton (1983) formula

$$R_L = \frac{0.49 q^{2/3} a_i}{0.6 q^{2/3} + \ln(1 + q^{1/3})},$$

where $q = M_{\text{AGB}}/M_2$ and $M_2$ is the mass of the companion. To proceed, we need to calculate the binding energy of the AGB star’s envelope at the beginning of the CE event and the change in orbital energy (potential plus kinetic) from the beginning to the end of the event.

The binding energy can be calculated explicitly from stellar models. However, as discussed by, e.g., Han, Podsiadlowski, & Eggleton (1995) and Livio (1996), in practice two significantly different approximations have been used in the literature:

1. de Kool (1990) writes the binding energy, $\Delta E_{\text{bind}}$, of the AGB star’s envelope as

$$\Delta E_{\text{bind}} = \frac{GM_{\text{AGB}} M_{\text{env}}}{\lambda R_{\text{AGB}}},$$

where $M_{\text{env}}$ is the envelope mass of the AGB star, given by $M_{\text{env}} = M_{\text{AGB}} - M_{\text{core}}$, and $\lambda$ is a constant of order 0.5, according to de Kool’s comparison with detailed stellar models. This formulation neglects the (relatively small) contribution to the gravitational potential well from the companion star. It also assumes that the envelope material is ejected at just the escape velocity.

The CE interaction is assumed to eject $M_{\text{env}}$ from the system, leaving a much closer binary composed of the AGB star’s core and the secondary star. In de Kool’s formulation,
the change in the orbital energy as a result of the interaction is given by

\[ \Delta E_{\text{orb}} = \frac{GM_{\text{core}} M_2}{2a_f} - \frac{GM_{\text{AGB}} M_2}{2a_i}, \tag{20} \]

where \( a_f \) is the final orbital separation and \( M_2 \) is assumed to be unchanged during the interaction.

Adopting the remaining observational quantities of \( M_2 = 0.93 M_\odot \) and \( a_f = 3.3 R_\odot \), we now have all of the information needed to calculate \( \alpha_{\text{CE}} \) as a function of assumed \( M_{\text{AGB}} \), using equations (1) and (16)–(20). The results are presented in Table 4, in which the calculated efficiency parameter is denoted \( \alpha_{\text{CE, deKool}} \).

Table 4 indicates that the V471 Tau progenitor system had an orbital period of several years, with the AGB star having a radius of about half the orbital separation. The calculated de Kool \( \alpha_{\text{CE}} \) lies between about 0.3 and 1, depending on the assumed mass of the AGB star. Recent detailed hydrodynamical calculations of CE interactions for systems with parameters similar to those that are likely for the V471 Tau progenitor (Yorke, Bodenheimer, & Taam 1995; Sandquist et al. 1998) have yielded values of \( \alpha_{\text{CE}} \) of \( \sim 0.3–0.6 \), in good agreement with our empirical results.

(2). In a separate series of papers, Tutukov, Yungelson, Iben, Livio, and collaborators have used a different pair of equations to approximate the binding and orbital energies (see the review by Iben & Livio 1993). They write the envelope’s binding energy as

\[ \Delta E_{\text{bind}} = \frac{G(M_{\text{AGB}} + M_2) M_{\text{env}}}{2a_i}, \tag{21} \]

i.e., they consider the stage at which the CE has already grown to a radius of \( a_i \), and they include the contribution of the secondary star to the potential as well. A smaller difference is that these collaborators write the change in orbital energy as

\[ \Delta E_{\text{orb}} = \frac{GM_{\text{core}} M_2}{2a_f} - \frac{GM_{\text{core}} M_2}{2a_i}, \tag{22} \]

that is, they consider only the change in the orbital energy of the degenerate core and the MS companion, and not the additional (but small) contribution from the orbital energy of the AGB envelope. We calculated the CE efficiency for V471 Tau using equations (21)–(22) instead of (19)–(20), and tabulate the results, denoted \( \alpha_{\text{CE, Tutukov}} \), in the last column of Table 4. In this case, the efficiency parameter is found to be of order 0.1. As pointed out by Han et al. (1995) and Livio (1996), \( \Delta E_{\text{bind}} \) calculated in this fashion is significantly smaller than calculated using de Kool’s approximation—by a factor of \( \sim 6 \) in the case of V471 Tau; thus the derived \( \alpha_{\text{CE}} \) is also smaller by the same factor.
9. Summary and Discussion

This paper reports HST/GHRS spectroscopy at Lyα of the hot component in the eclipsing DA+dK pre-cataclysmic binary V471 Tau. The Lyα radial velocities of the WD, combined with ground-based measurements of eclipse timings and of the radial velocities and rotational velocity of the dK star, constrain the orbital inclination to be \( \sin i = 0.976 \). The resulting dynamical masses for the components are \( M_{\text{WD}} = 0.84 \) and \( M_{\text{dK}} = 0.93 \) \( M_\odot \). Both values are significantly larger than adopted in previous investigations, which had to rely (erroneously) on an assumed mass for the K star based on its spectral type.

The dK component is remarkable in being about 18% larger than a normal Hyades dwarf of the same mass. We attribute the expansion to the large (\( \sim 25\% \)) fractional coverage of the star’s surface by starspots. In response to this covering, the star has expanded in order to radiate the luminosity generated in its core.

Although such an expansion is predicted theoretically, our observations are probably the clearest demonstration yet that the phenomenon does exist. The oversized radius will have important implications for the future evolution of V471 Tau and other pre-cataclysmic binaries, if it is a general property of such systems. For example, V471 Tau will become a cataclysmic variable earlier than otherwise expected, since it will fill its Roche lobe earlier. Moreover it is probably incorrect to assume a normal main-sequence relationship between mass, radius, and spectral type for the cool components of cataclysmic and pre-cataclysmic binaries (cf. Smith & Dhillon 1998).

The effective temperature of the WD was determined by model-atmosphere fitting to the Lyα profile, and was found to be 34,500 K. The radius of the WD, \( 0.0107 \, R_\odot \), was determined from a radiometric analysis and from eclipse ingress timings. Availability of direct measurements of the radius and mass of the star allow the most stringent comparisons yet with the theory of WD structure. The position of the star in the mass-radius plane is shown to be in full accord with the predictions of theory for a degenerate carbon-oxygen WD with a surface temperature equal to that observed. The position of the WD in the H-R diagram is also fully consistent with that expected for a WD with our dynamically measured mass. The inferred cooling age of the WD is close to \( 10^7 \) yr.

The high effective temperature, high mass, and apparent short cooling age of the WD present an evolutionary paradox. The WD is the most massive known in the Hyades, but also the hottest, in direct conflict with theoretical expectation. We examined possible resolutions of the paradox, and concluded that the WD is probably indeed very young (rather than being anomalously hot through some more exotic mechanism, such as a recent nova outburst). Most probably it is descended from a blue straggler. A plausible scenario is that the progenitor...
system was a triple, with a close inner pair of main-sequence stars whose masses were both similar to that of the present cluster turnoff. These stars first became an Algol-type binary, which merged after several hundred million years to produce a single star of about twice the turnoff mass. When this star evolved to the AGB phase, it underwent a common-envelope interaction with a distant dK companion, spiralled down to its present separation, and ejected the envelope. We estimate that the common-envelope efficiency parameter, $\alpha_{\text{CE}}$, was of order 0.3–1.0, in good agreement with hydrodynamical simulations.

In the widely quoted approximation used by Tutukov and collaborators, however, our estimated $\alpha_{\text{CE}}$ is of order 0.1. A value this low makes it easier to produce short-period post-CE systems, including CVs and double-degenerate binaries that may be Type Ia supernova progenitors. A specific, and testable, prediction from the population syntheses of Yungelson et al. (1993) is that, with $\alpha_{\text{CE}} \simeq 0.1$, the orbital periods of close-binary nuclei of planetary nebulae will typically range from 0.3 to 30 days.

The Space Telescope Imaging Spectrograph (STIS) is now available onboard HST, and covers the entire UV spectrum rather than a small window around Ly\(\alpha\). We are currently undertaking followup observations of V471 Tau using STIS, and have also obtained STIS spectra of HZ 9, the other known pre-cataclysmic binary in the Hyades. We hope that these data will provide even more accurate radial velocities (through observations of photospheric metallic lines), including a direct measurement of the gravitational redshift. These observations should allow us to test, refine, and expand upon the results reported here for this endlessly fascinating binary system.

This paper had a long gestation period, during which we benefitted from the assistance of many people. The initial concepts for the observing program arose from discussions between HEB and John Stauffer. The demanding HST scheduling was accomplished by many talented people at STScI, including Dustin Manning and Denise Taylor. Lengthy initial assessments of the data and preliminary analyses were carried out by Karen Schaefer and Rex Saffer. We had useful discussions with, among others, Fuhua Cheng, Chris Clemens, Jean Dupuis, Ed Guinan, Colleen Henry, Steve Hulbert, Icko Iben, Steve Kawaler, Jim Liebert, Mario Livio, Dermott Mullan, Dina Prialnik, Neill Reid, and Matt Wood. Ivan Hubeny very kindly provided his atmosphere code and much assistance and advice in running it. John Gaustad generously obtained wide-field H\(\alpha\) images of the V471 Tau field and provided them in advance of publication. The referee, Stephane Vennes, made several comments that helped us improve the paper.

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Stauffer, J.R. 1987, AJ, 84, 996
Fig. 1.— Our twelve GHRS Lyα spectra of V471 Tau, shifted vertically for clarity. The spectra are presented in order of orbital phase, labelled on the right. The 4 pre-COSTAR spectra obtained in 1993 have noticeably lower S/N. Note the orbital motion of the broad Lyα wings of the white dwarf, the out-of-phase motion of the chromospheric emission core from the K dwarf, and the stationary interstellar absorption core. The bottom spectrum shows a transient absorption line of Si III, due to a mass ejection from the dK star passing in front of the white dwarf (Bond et al. 2001).
Fig. 2.— Ly$\alpha$ spectrum of V471 Tau, obtained by summing the eight post-COSTAR spectra without any velocity shifts. The various features seen superimposed on the broad absorption wings of the white dwarf are labelled.
Fig. 3.— The V471 Tau Lyα profile, obtained by coaddition of the eight post-COSTAR spectra, after shifting the individual spectra to zero velocity. Superimposed as a noise-free line is a model-atmosphere profile calculated for $T_{\text{eff}} = 34,500$ K and $\log g = 8.3$. Note the excellence of the fit. A weak Si III 1206 Å line is present in the coadded sum, due to a combination of a photospheric feature (Sion et al. 1998) and the transient line due to silhouetted mass ejections from the K star.
Fig. 4.— Radial velocity versus orbital phase for the white-dwarf and K-dwarf components of V471 Tau. Velocities for the white dwarf are from the eight post-COSTAR HST observations discussed here, and the numerous velocities for the K star are from the ground-based measurements of Bois et al. (1988). Solid lines show the best-fitting sinusoidal fits for each component.
Fig. 5.— The mass-radius plane for the K-dwarf component of V471 Tau. Values of the orbital inclination \(i\) corresponding to the mass coordinate are labelled at the top. The curve marked “Hyades ZAMS” shows the main-sequence mass-radius relation for Hyades dwarfs (see text). Dark shading marks the excluded regions on the right-hand side corresponding to \(i > 90^\circ\) and at the lower left below the Hyades ZAMS curve. Horizontal lines indicate the radius of the star based on radiometry and the assumption that the indicated fraction \(f_{\text{spot}}\) of the surface area is covered with dark starspots. The nearly vertical curve labelled \(\Delta t_{\text{ecl}} = 2891\) s (and the associated error limits and lightly shaded areas) delimit the allowed values based on measurements of the duration of the total eclipse. The more nearly horizontal curve marked \(v \sin i = 91\) km/s (and its associated error limits and light shading) show allowed values based on the measured rotational velocity. The intersection of the two curves shows our final solution for the mass, radius, and orbital inclination, and the small white parallelogram shows the error limits.
Fig. 6.— Position of the white-dwarf component of V471 Tau in the mass-radius plane. For comparison we plot theoretical relations for C and O white dwarfs of zero temperature and 35,000 K surface temperature (Wood 1995), and zero-temperature Mg and Fe white dwarfs (Hamada & Salpeter 1961). The agreement with the 35,000 K CO relation is excellent.
Fig. 7.— The position of the V471 Tau white dwarf in the theoretical H-R diagram. Also shown are cooling tracks for CO white dwarfs of various masses from Wood (1995). Dashed lines show the cooling ages. The position of V471 Tau is in excellent agreement with that expected from its dynamically measured mass of $0.84 M_\odot$. Its cooling age is close to $10^7$ yr.
Fig. 8.— Positions of the single Hyades white dwarfs and of the white dwarf in V471 Tau in the effective temperature vs. mass diagram. Data are taken from Table 3; gravitational-redshift masses are plotted for the single white dwarfs, and our dynamical mass for V471 Tau. The single white dwarfs show the expected increase in mass with decreasing temperature, but V471 Tau flagrantly violates the trend.
Table 1. V471 Tau GHRS Spectra and Radial Velocities

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<th>Orbital Phase (mid-exposure)</th>
<th>$V_{\text{WD}}$ (km s$^{-1}$)</th>
<th>$\sigma_V$ (km s$^{-1}$)</th>
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$^a$Pre-COSTAR observations, STScI Program ID 4344; all others are post-COSTAR, STScI Program ID 5468.
Table 2. Measured and Derived V471 Tauri System Parameters

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</tr>
<tr>
<td>$L_{\text{dK}}$</td>
<td>0.40 $\pm$ 0.02 $L_{\odot}$</td>
<td>§6</td>
</tr>
<tr>
<td>$L_{\text{WD}}$</td>
<td>0.146 $\pm$ 0.016 $L_{\odot}$</td>
<td>§7.3</td>
</tr>
<tr>
<td>$t_{\text{cool,WD}}$</td>
<td>$10^7$ yr</td>
<td>§7.3</td>
</tr>
</tbody>
</table>

*Sections in this work, unless otherwise indicated.*
Table 3. Properties of the Hyades White Dwarfs

<table>
<thead>
<tr>
<th>Name</th>
<th>WD</th>
<th>$M_{\text{dyn}}/M_\odot^a$</th>
<th>$M_{\text{GR}}/M_\odot^b$</th>
<th>$M_{\text{sp}}/M_\odot^c$</th>
<th>$T_{\text{eff}}$ (K)$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V471 Tau</td>
<td>0347+171</td>
<td>0.84 ± 0.05</td>
<td>...</td>
<td>...</td>
<td>34,500 ± 1,000</td>
</tr>
<tr>
<td>HZ 4</td>
<td>0352+096</td>
<td>...</td>
<td>0.74 ± 0.04</td>
<td>0.72 ± 0.03</td>
<td>14,770 ± 350</td>
</tr>
<tr>
<td>LB 227</td>
<td>0406+169</td>
<td>...</td>
<td>0.80 ± 0.06</td>
<td>0.80 ± 0.04</td>
<td>15,190 ± 350</td>
</tr>
<tr>
<td>VR 7</td>
<td>0421+162</td>
<td>...</td>
<td>0.70 ± 0.02</td>
<td>0.68 ± 0.03</td>
<td>19,570 ± 350</td>
</tr>
<tr>
<td>VR 16</td>
<td>0425+168</td>
<td>...</td>
<td>0.69 ± 0.01</td>
<td>0.68 ± 0.03</td>
<td>24,420 ± 350</td>
</tr>
<tr>
<td>HZ 9</td>
<td>0429+176</td>
<td>0.51 ± 0.10</td>
<td>...</td>
<td>...</td>
<td>20,000 ± 2,000</td>
</tr>
<tr>
<td>HZ 7</td>
<td>0431+125</td>
<td>...</td>
<td>0.67 ± 0.02</td>
<td>0.65 ± 0.03</td>
<td>21,340 ± 350</td>
</tr>
<tr>
<td>LP 475-242</td>
<td>0437+138</td>
<td>...</td>
<td>0.75 ± 0.04</td>
<td>...</td>
<td>12,600</td>
</tr>
<tr>
<td>HZ 14</td>
<td>0438+108</td>
<td>...</td>
<td>0.66 ± 0.04</td>
<td>0.68 ± 0.03</td>
<td>27,390 ± 350</td>
</tr>
</tbody>
</table>

$^a$Dynamical masses. Sources: V471 Tau: this paper; HZ 9: Stauffer (1987).

$^b$Gravitational-redshift (GR) masses from Reid (1996).


Table 4. Calculations of Common-Envelope Efficiency, \( \alpha_{CE} \)

<table>
<thead>
<tr>
<th>( M_{AGB} ) (( M_\odot ))</th>
<th>( q )</th>
<th>( R_{AGB} ) (( R_\odot ))</th>
<th>( a_i )</th>
<th>( P_{orb,i} ) (yr)</th>
<th>( \alpha_{CE, deKool} )</th>
<th>( \alpha_{CE, Tutukov} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>3.76</td>
<td>486</td>
<td>979</td>
<td>4.6</td>
<td>0.33</td>
<td>0.05</td>
</tr>
<tr>
<td>4.0</td>
<td>4.30</td>
<td>464</td>
<td>915</td>
<td>3.9</td>
<td>0.47</td>
<td>0.07</td>
</tr>
<tr>
<td>4.5</td>
<td>4.84</td>
<td>446</td>
<td>862</td>
<td>3.4</td>
<td>0.64</td>
<td>0.10</td>
</tr>
<tr>
<td>5.0</td>
<td>5.38</td>
<td>431</td>
<td>818</td>
<td>3.0</td>
<td>0.84</td>
<td>0.13</td>
</tr>
<tr>
<td>5.5</td>
<td>5.91</td>
<td>417</td>
<td>780</td>
<td>2.7</td>
<td>1.07</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Notes: Col. 1: assumed total mass of the AGB star in the V471 Tau system at the onset of the common-envelope (CE) interaction; its core mass is taken to be 0.84 \( M_\odot \). Col. 2: mass ratio relative to the 0.93 \( M_\odot \) dK secondary star. Col. 3: radius of the AGB star at CE onset. Cols. 4 & 5: orbital separation and period of the AGB and dK stars at the onset of the CE event. Cols. 6 & 7: the efficiency of conversion of orbital energy into ejecting matter from the system, calculated as described in the text according to the formulations of de Kool and of Tutukov and collaborators, respectively.