Astron. Astrophys. 326, 731–735 (1997)

ASTRONOMY AND ASTROPHYSICS

Common envelope evolution and Li in V471 Tauri*,**

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Received 7 March 1997 / Accepted 30 April 1997

Abstract. We have observed the spectral regions around the LiI resonance 670.8 nm and subordinate 610.4 nm lines of V471 Tau. This is an eclipsing post common-envelope (CE) binary system. A revision of several independent measurements of the parallax and proper motion of V471 Tau allow us to argue that this system is indeed a Hyades cluster member by examining and rejecting earlier, flawed results. Using spectral synthesis and taking into account NLTE effects, we have derived a photospheric Li abundance of log N(Li)=2.35±0.25 for the K dwarf, which is a factor $>$100 higher than single Hyades members of the same mass. We argue that two mechanisms are responsible for this: a) Accretion of a substantial amount of Li-rich material onto the K dwarf during CE evolution inside the giant precursor of the white dwarf. Recently, a number of Li-rich giants have been observed and they appear to undergo large mass-loss. We speculate that CE evolution could actually explain the properties of these giants as well. b) Reduced Li depletion in the K dwarf due to sustained fast rotation in a short-period tidally-locked orbit. This process accounts for the preservation of Li after CE evolution has ceased.

Key words: stars: abundances – binaries: eclipsing – stars: evolution; interiors; individual: V471 Tau

1. Introduction

V471 Tau (BD+16°516, V∼9.5) has been widely observed across the whole electromagnetic spectrum, and has been studied as a prototype of pre-cataclysmic variables having undergone common-envelope (CE) evolution. It is a detached eclising binary with a white dwarf (WD) and a K-type dwarf, and is thought to belong to our nearest open cluster, although this point has been controversial (see discussion below). The basic properties of V471 are summarized in Table 1. The data were taken from Bois, Lanning & Mochnacki (1988) and Ramseyer, Hatzes & Jablonski (1995). The period of the binary is 0.521 days, and it is syncronized and circularized as expected from tidal interaction.

Table 1. Properties of V471 Tau

Component	$M/M_\odot$	$R/R_\odot$	SpT.	T_{eff} (K)
WD	0.75	0.01	DA2	33500±500
RD	0.75	0.95	K2V	4800±200

We are carrying out a long-term programme aimed at investigating the depletion of Li in low mass stars, and its relationship with several parameters such as age and rotation (Martín et al. 1994, Martín & Claret 1996, Martín & Montes 1997). V471 Tau was included in our programme because its stellar parameters are known with high precision. However, our knowledge of its age and metallicity is based on its membership to the Hyades, which has been disputed by some researchers (e.g. Heintz 1991). Since it is very important for our study to be sure of the age, we have studied in detail the extant evidence for and against cluster membership.

1.1. Is V471 Tau a member of the Hyades cluster?

V471 Tau has coordinates that place it in the general area over which the Hyades stars are found. The systemic radial velocity reported by several authors are in good agreement with each other, e.g., 36.8 +/- 0.9 km s^{-1}(Young & Nelson 1972) and 37.4 +/- 0.5 km s^{-1}(Bois et al. 1988). The radial velocity of the Hyades stars varies from place to place in the sky, depending on the projection of the cluster space motion with the line of sight. At the position of V471 Tau the mean radial velocity of known members is 36±1.5 km s^{-1}(Griffin et al. 1988), which is perfectly consistent with the γ velocity of the binary system.

The proper motions are controversial, as one can judge by comparing the μ=0.”0898±0.0015 yr^{-1}, θ=94°.3±0.6 values given by Borgmann & Lippincott (1983), with μ=0.”125±0.002 yr^{-1} , θ=97°.1 obtained by Vilkki, Welty & Cudworth (1986). Heintz (1991) refined the Borgmann & Lippincott measurements with more data and concluded that V471 Tau is not a Hyades member because the proper motion that he measured was too large and 20° off in direction. Motivated by the controversy on the proper motion of V471 Tau, we enquired about measurements made by the Carlsberg Meridian Circle

* Based on data collected at the Isaac Newton telescope, operated by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos.
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(CAMC) at La Palma observatory. V471 Tau had been monitored by the CAMC in 1986 (position and magnitude given in CAMC Catalogue No.4). Using this position and the position at epoch 1900 from the Astrographic Catalogue, Leslie Morrison from the CAMC team kindly gave us the following proper motion: RA= +0".126±0.004 yr^{-1}, Dec= -0".021±0".004 yr^{-1}. Hence, V471 Tau is consistent with Hyades membership because of the independent and very precise proper motion by CAMC.

The parallax given by Heintz (0".006±0.0039) is much too small for a Hyades star, because it would place V471 Tau at a distance of 167±66 pc. However, the inconsistency of Heintz's proper motion with that of CAMC, also casts serious doubts about his parallax determination. Another problem with the parallax of Heintz is that it is so small that the K2 star would have to overfill its Roche lobe to provide the observed V-magnitude. This is ruled out by the absence of an acretion disk and the stellar radius derived by Ramseyer et al. (1995). Another value of the parallax, provided by Vilkki et al. (1986), is 0".017±0.0025 yr^{-1}, i.e. a distance of 58.8±7.5 pc. This is marginally consistent with the Hyades distance of 45.4±2.1 pc (Gunn et al. 1988). Bois et al. (1988) argued that the parallax determination may be affected by the presence of a third body in the binary system, and they used the temperature and radius of the white dwarf to derive a distance of 44±6 pc which would place the V471 Tau fully within the Hyades.

The probability that V471 Tau has just by chance systemic radial velocity and proper motion consistent with Hyades membership is less than 1% . Moreover, the best distance estimates are consistent with the known distance to the cluster. Thus, we can be reasonably confident that this binary does indeed belong to the Hyades cluster.

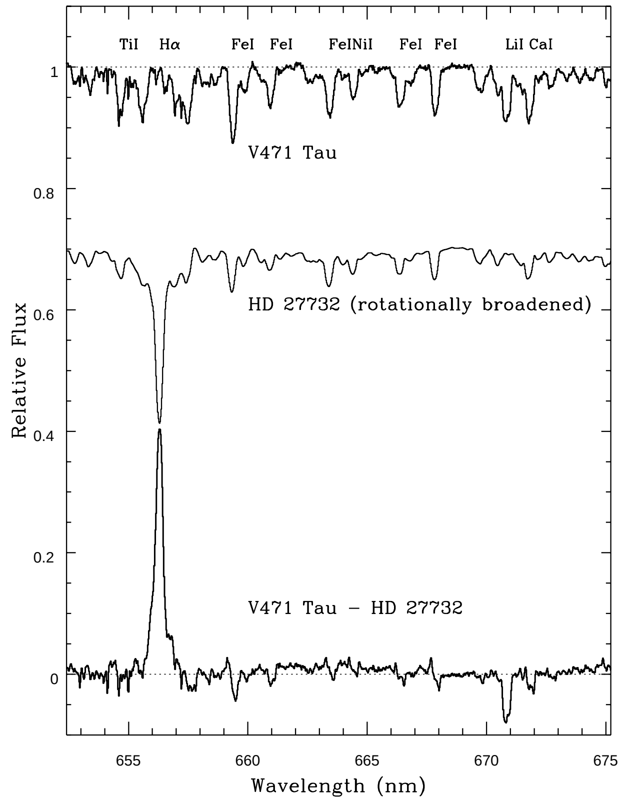

Fig. 1. From up to bottom we display the average spectrum of V471 Tau, the G9V Hyad HD 27732, and the residual of subtracting the two spectra above. We provide identification of the strongest features seen in the spectra. Note that in the difference spectrum the Li I λ670.8 feature has become the deepest absorption line, and H_α is strongly in emission (EW=-1.74 Å)

2. Spectroscopy

We observed V471 Tau with the Isaac Newton Telescope (INT) at La Palma observatory in October 1994. We used the IDS spectrograph with TEK 1024x1024 CCD, and gratings R1200R and H1800V, which gave dispersions of 0.39 and 0.24 Å/pix (R=8500–14000), respectively. The raw spectra were reduced using standard procedures; bias and flat field correction, wavelength calibration with CuNe arc exposures, and flux calibration using spectrophotometric standards. We also observed another two stars in the Hyades: Hz9, a pre-cataclismic variable with an M-type secondary, and HD 27732, a G9V single star. In Table 2 we present the observing log.

Table 2. Observing log

Name	Date	Dispersion (Å/pix)	texp (s)	Range (nm)
V471 Tau	15/10/94	0.24	1800	651.2–676.3
	17/10/94	0.24	1000	651.2–676.3
	17/10/94	0.24	1200	603.4–628.5
	19/10/94	0.39	500	650.0–689.8
Hz9	19/10/94	0.39	1800	650.0–689.8
HD27732	17/10/94	0.24	1000	651.2–676.3
	17/10/94	0.24	1000	603.4–628.5

Using the ephemerides of Young (1976) we have determined the orbital phases of V471 at the time of our spectroscopic observations. These are ϕ=0.74,0.28 and 0.22 for October 15, 17 and 19, respectively. The radial velocities of our spectra are in good agreement with the ephemerides of Young. Since the WD is quite hot, it emits an important amount of UV flux that could overionize the neutral lithium, especially in the face of the secondary that is always being irradiated. We have not noticed changes in the Li I λ670.8 equivalent width larger than our measurement error bars (±30 mÅ), but our phase coverage is too small to look for such an effect. The equivalent width in the spectrum obtained from averaging our three individual exposures of V471 Tau is 290 mÅ. Barrado y Navascués & Stauffer (1996) have measured a LiI equivalent width of 229 mÅ, which is significantly lower than our value. Their spectrum was obtained on 16 November 1994 (Barrado y Navascués 1997, private communication). The difference in the LiI equivalent width values might be due to variability of the line strength, perhaps related to variable irradiation of UV photons coming from the white dwarf or to intrinsic variability of the K dwarf.

Hz 9 is another short-period binary in the Hyades cluster (P=0.56433 days, Lanning & Pesch 1981). The main difference with V471 Tau is that Hz 9 has a cooler secondary (dM4.5). In Hz 9, we did not detect the Li I λ670.8 feature, and we can place an upper limit to its equivalent width of 140 mÅ.

3. Chemical abundances in V471 Tau

We computed LTE synthetical spectra using opacity-sampling model atmospheres obtained with the programme SAM71 (Pavlenko & Yakovina 1994). A metallicity [m/H]=+0.1 was assumed because of membership to the Hyades cluster. We carried out a differential analysis with respect to the Sun. The oscillator strengths of Kurucz's (1993, private communication) linelist had to be adjusted slightly (up to 30%) in a number of lines to match the solar spectrum for zero metallicity. Synthetical spectra for the Sun were computed by WITA2 program (Pavlenko et al. 1995) for microturbulent velocity v_t = 1 km/s and a Pavlenko & Yakovina model atmosphere. Synthetical spectra for V471 were computed for v_t = 2 km/s.

The Li I λ670.8 resonance feature is known to be very sensitive to T_{eff} . Thus, we used three different temperatures; 5000 K, 4800 K and 4600 K. We also tried two different values for the gravity; log g=4.0 and 4.5, but the computations were insensitive to this parameter. In Table 2 we give the LTE Li abundances that best fit the observed spectrum. The NLTE corrections were derived using the curves computed for our models following scheme used by Pavlenko et al. (1995). As shown in Fig. 2, we obtained a good reproduction of the spectrum without changing the abundances of the other elements (Al, Ca, Fe, Si) present in the synthesized spectral domain. Thus, we could not identify any chemical peculiarity in V471 Tau besides the high Li abundance. We did several trials using different element abundances, and we estimate that the metallicity of V471 Tau is the same as that of other Hyades stars within $\pm$0.1 dex. The synthetic fits using the three T_{eff} values were essentially of the same quality. These temperatures cover the possible range of temperature for the estimated spectral type of K2V. Hence, we adopt a mean value of log N(Li)$_{NLTE}$=2.35$\pm$0.25 for the Li abundance inferred from the LiI resonance line, where the error bar comes mainly from the uncertainty in temperature. Barrado y Navascués & Stauffer (1996) obtained log N(Li)$_{LTE}$=2.20, which is similar to our result.

Note in Fig 2, that the observed photospheric lines present some asymmetries in the core. We think that they are real because our line profiles should be accurate to a few percent. This is probably due to thermal inhomogeneities in the stellar surface. The Li I λ670.8 resonance feature might be used for obtaining a Doppler map, as it is quite sensitive to temperature changes, but its probable dependence also on the ionization due to UV flux impinging on the K dwarf could complicate the interpretation.

The subordinate LiI line at 610.4 nm was also observed in order to check the Li abundance derived from the resonance line. Due to the rotational broadening, the subordinate line is completely blended with three strong lines; FeI λ610.22, CaI λ610.27 and FeI λ610.32. We tried to estimate the Li abundance by fitting the observed spectrum with synthetic spectra with different Li abundances. A T_{eff} of 5000 K or 4800 K fit the spectrum of V471 Tau much better than a T_{eff} of 4600 K in this region. After trying abundances in the range log N(Li)$_{LTE}$=2.0 – 3.3, we realized that the contribution of the LiI line to the blend is so small that we cannot derive a meaningful Li abundance from our observed spectrum. It would be interesting in the future to observe the LiI subordinate line at 812.6 nm. In order to check the feasibility of this observation we have computed theoretical equivalent widths using curves of growth. In Table 3 we provide our results. As can be seen, the line at 812.6 nm is considerably weaker than the two lines considered in this work. Nevertheless, it is not severely blended with strong lines, and it could be possible to detect it with high resolution, high S/N ratio spectroscopy, which is feasible for a ninth-magnitude star using 4 m-class telescopes and state of the art spectrographs. It would be worthwile to observe this line as a check to the Li abundance inferred from the resonance line. We note that there

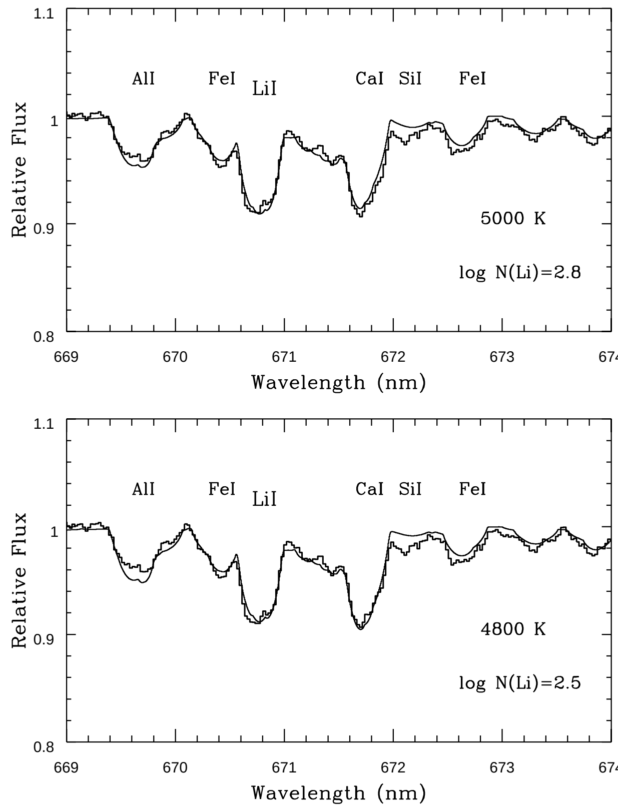

Fig. 2. LTE synthetic fits to the Li I λ670.8 region of V471 Tau. Upper panel shows the fit using T_{eff} = 5000 K, and lower panel the result of using T_{eff} = 4800 K. The main effect is in the Li abundance needed for producing a good fit. The observed spectrum shown is the average of the three observed.

Table 3. Li abundances for V471 Tau

Model	log N(Li)	log N(Li)
T_{eff} /log g	LTE	NLTE
4600/4.5	2.2	2.15
4800/4.5	2.5	2.35
5000/4.5	2.8	2.62
5000/4.0	2.8	2.63

Table 4. Theoretical equivalent widths for LiI lines (mÅ)

Model	log N(Li)	$EW_{670.8}$ LTE/NLTE	$EW_{610.4}$ LTE/NLTE	$EW_{812.6}$ LTE/NLTE
4800/4.5	2.2	206.2/214.7	9.4/7.8	2.0/1.8
4800/4.5	2.4	237.8/263.3	14.5/12.2	3.2/2.8
4800/4.5	2.8	296.7/353.9	33.8/28.8	7.9/7.1
4800/4.5	3.2	359.7/435.3	71.1/62.9	19.2/17.5
4800/4.5	3.6	447.5/530.9	126.5/119.9	44.2/41.8
5000/4.5	2.6	232.0/257.1	16.2/13.8	3.6/3.3
5000/4.5	3.0	292.1/347.3	37.3/32.3	8.9/8.1
5000/4.5	3.6	393.8/468.9	103.7/96.6	32.6/30.8

are some telluric lines in this spectral region, and care should be taken to remove them accurately.

4. Discussion

4.1. Preservation of lithium

In the Hyades cluster, tidally-locked binaries (TLBs) tend to have systematically higher Li abundances than wide binaries and single stars (Thorburn et al. 1994). The TLBs avoid Li depletion in two ways. First, for stars with masses 0.8–0.7 $M_\odot$ pre-main-sequence (PMS) Li depletion is due to convective mixing, which is thought to be less efficient in fast rotating stars (Martín & Claret 1996). The mass of the K dwarf in V471 Tau lies in the mass domain where high rotation effectively reduces PMS depletion. Second, during main-sequence (MS) evolution Li can be depleted as a result of mixing induced by angular momentum loss (Pinsonneault, Deliyannis & Demarque 1992). At the age of the Hyades ($\sim$6 x 10^8 yrs), low-mass stars have suffered both PMS and MS mixing and consequently Li is observed to be greatly depleted. There is a tight relationship between Li and $T_{\rm eff}$ in the Hyades cluster, with only a few deviant stars which are all TLBs. Barrado y Navascués & Stauffer (1996) showed that in the $T_{\rm eff}$ range 4900-4500 K there are three TLBs with orbital periods ranging from 1.79 to 2.39 days and Li abundances higher by $\sim$1 dex than the single Hyades sequence. V471 Tau is remarkable because it has a Li abundance higher by about 1.5 dex than the TLBs of similar $T_{\rm eff}$. If this high Li abundance is a consequence of a higher preservation throughout the lifetime of the system, we would have to face two important problems: (1) Dramatic reduction of PMS Li depletion would have to take place from orbital periods of 1.79 days to 0.52 days. (2) V471 Tau would have had to be a short period binary when the K dwarf was only 10^7–10^8 years old and it was a PMS star. This contradicts current ideas about the recent evolution of the system. We discuss below in some detail this problem in connection with CE evolution theory and how it can be solved.

4.2. CE evolution and Li enrichment

V471 Tau is thought to be a post-CE evolution binary and the precursor of a cataclysmic variable (e.g. Sarna et al. 1995). The CE phase was a recent event in the life of V471 Tau since the temperature of the WD is so high for its mass that it must be quite young. A WD age of $\sim$3 x 10^7 yrs and a progenitor mass of 2.5 $M_\odot$ (Isern 1996, private communication) satisfy well the observational properties assuming that the binary system is coeval with the Hyades. Current CE evolution models start with an orbital period generally much longer than the final orbital period. However, as discussed above, the preservation of Li in the K dwarf during PMS evolution would imply that the orbital period was already very short when the system was very young. Hence, the remarkably short period of V471 Tau would not be a consequence of CE evolution, but an inborn property of the system.

The precursor of V471 Tau must have been a binary with two unequal mass components. When the primary evolved out of the MS, CE evolution eventually set in as the giant filled its Roche lobe and transfered mass onto the secondary. The high rate of mass transfer could not be incorporated by the MS star and a CE formed around the inner binary. Friction made the secondary to spiral in towards the core of the primary, releasing energy that expelled the CE, and resulting in a red – white dwarf system with orbital period shorter than the original one. If we want to preserve the initial Li abundance of the K dwarf, the initial period of V471 Tau must have been shorter than the other Hyades TLBs (P<1.8 days). Then, the ratio of the periods before and after CE would have been less than 3.5, implying a ratio of projected semimajor axis of less than 10. According to Tutukov & Yungelson (1979) the shrinkage of the binary orbit can be expressed with a free parameter α which is sometimes referred to as the CE evolution efficiency:

$$\alpha = \frac{M_1^2 \times a_f}{M_c \times M_2 \times a_i}$$

where, M_1, M_c and M_2 are the masses of the progenitor, the primary's core and the secondary, respectively, and a_i and a_f the initial and final semiaxis distance of the orbit. Assuming M_1=2.5$M_\odot$, M_c=M_{WD}=0.75$M_\odot$, M_2=0.75$M_\odot$ and a_f/a_i $\leq$ 10, we obtain $\alpha \geq 1$. If the value of α equals to 1, the spiral in generates just all the energy necessary for expelling the giant envelope. Larger values of α indicate that not only frictional energy but another source of energy contributes to the expulsion of the envelope, such as radiation pressure or magnetic fields. In fact, in order to inhibit Li depletion efficiently in V471 Tau, values of α >1 are needed. CE models consider only α values in the range 0.1 to 1. Therefore, the Li preservation hypothesis in V471 Tau clearly conflicts with current ideas about CE evolution.

A plausible explanation to the high Li abundance in V471 Tau is that the precursor of the WD was a Li red giant. Recently, a number of such stars have been discovered among otherwise normal giants, although there could be a connection with large mass-loss inferred from IRAS colours (De la Reza et al. 1996, 1997). A mechanism that brings out Li synthesized in the interior and simultaneously drives a strong wind has been invoked. The Li giants are believed to be single because no radial velocity variations have been detected at the 1 km s^{-1}level (de Medeiros, Melo & Mayor 1996). De la Reza et al. proposed that all single giants with masses in the range 1.0 to 2.5 $M_\odot$

could experience abrupt mixing events of so far unidentified origin. The stars would be Li-rich during a short time of $\sim 10^5$ years, compared to the total red giant lifetime (few 10^7 years). This would explain why most normal giants are Li-poor. In order to explain the Li observed in V471 Tau, we suggest that the origin of the mechanism linking Li production with mass-loss in some red giants could be CE binary evolution. The general properties of the known Li-rich giants appear to be consistent with CE evolution theory: 1) no radial velocity variations because the giant's photoshere surrounds both components of the short-period binary system, 2) strong mass-loss driven by the spiral-in of the secondary, 3) Li production due to rapid mixing also related to the spiral-in process, 4) short-timescale because of formation of a post CE binary like V471 Tau, 5) low or moderate surface rotation velocity because the giant's atmosphere can be decoupled from the fast rotating interior, 6) a Li abundance in V471 Tau similar to those of the Li giants (de la Reza et al. 1996),

If, as we are proposing, the K dwarf was enriched with Li during CE evolution, and came out of it with an abundance similar to what's presently observed, the processes discussed in the previous section can readily account for the preservation of lithium in a timescale of a few x 10^7 yrs. In the case of Hz9, we have not detected Li because the mass of the red dwarf is much lower than in V471 Tau. M-type stars have fully convective interiors and PMS Li burning is much more efficient than in K-type stars (Martín et al. 1994). After the end of the CE phase, the detectability of Li depends on the mass, post-CE age and orbital period of the secondary.

CE theory could explain not only V471 Tau and Hz9, but also some, or most, of the Li-rich red giants. While this hypothesis is still rather speculative, it can spur observations for testing it. For instance, Sarna et al. (1995) proposed that the $^{12}C/^{13}C$ ratio of V471 Tau should be low if the secondary has accreted a significant amount of mass from the giant's envelope. Our ideas about Li in V471 Tau make us expect that it indeed has a $^{12}C/^{13}C$ ratio lower than a normal dwarf.

5. Summary

We have obtained high-resolution spectra of V471 Tau in the Li I λ670.8 spectral region at three different orbital phases. No significant line strength variability is seen, although the line profile does change. Comparison with one equivalent width measurement obtained by Barrado y Navascués and Stauffer (1996) suggests that the LiI line may be variable at some orbital phases or in timescales somewhat longer than the span of our observations. We also observed the subordinate LiI line at 610.4 nm, but found it useless because it is too blended and weak. The spectrum around the Li I λ670.8 feature is well matched with a spectral synthesis having T_{eff} =4800 K, metallicity of +0.1 dex. solar and log N(Li)=2.5. Consideration of NLTE effects and uncertainties in effective temperature give log N(Li)=2.35$\pm$0.25. Such a Li abundance is more than a factor 100 higher than those of single Hyades stars of the same mass. It is also a factor $\sim$ 30 higher than those of Hyades TLBs with orbital periods $\geq$1.7 days.

We discussed the possibility that V471 Tau has preserved its initial Li abundance, and find two problems with this hypothesis: 1) it would require that the rate of Li depletion changes dramatically in Hyades TLBs from orbital periods of $\sim$1.7 days to the orbital period of V471 Tau (0.5 days), 2) it is inconsistent with current understanding of CE evolution. We propose that the precursor of V471 Tau was a Li-rich giant. The properties of known Li red giants are not inconsistent with being CE binaries. In fact, CE evolution could power a mechanism linking Li production and mass-loss. The high Li abundance of the K-type star in V471 Tau can be explained as the result of accretion of Li-rich material during the spiral-in of the secondary inside the giant's envelope. Subsequently, Li is preserved in the K-dwarf during the last $\sim$3 x 10^7 yrs (the age of the WD) because of its fast rotation.

Acknowledgements. We thank Leslie Morrison and Ron Webbink for sending us information on the space motion and parallax of V471 Tau, Jordi Isern for computing the age of the white dwarf primary, and Marek Sarna for interesting discussions about CE theory. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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Note added in Proof: The parallax and proper motion of V471 Tau given in the Hipparcos output catalog confirm membership in the Hyades cluster