

On the use of $^{12}\text{CO}/^{13}\text{CO}$ as a test of common-envelope evolution

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Abstract. We present *K*-band echelle spectra of the cataclysmic variable SS Cyg and the pre-cataclysmic variable V471 Tau in order to measure the strengths of the ^{12}CO and ^{13}CO bands at 2.3525 and 2.3448 μm , respectively, and so perform the observational test of the common-envelope model of close binary star evolution proposed by Sarna et al. (1995). Although we find evidence of an absorption feature coincident with the expected wavelength of ^{13}CO in both objects, we attribute it instead to a cluster of neutral atomic absorption features (primarily due to Ti I) possibly arising from star-spots on the surfaces of the rapidly rotating secondary stars in these systems, thereby rendering the test inconclusive. We present a modified observational test of common-envelope evolution, based on the observation of the ^{13}CO bands at 2.3739 and 2.4037 μm , which is insensitive to spectral contamination by star-spots.

Key words. binaries: spectroscopic – stars: individual: SS Cyg – stars: individual: V471 Tau – novae, cataclysmic variables – infrared: stars – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Well over half of all stars are believed to be binary or multiple systems, with about half of these, in turn, consisting of close binary systems where the two component stars are unable to complete their normal evolution without being influenced by the presence of the other (see Duquennoy & Mayor 1991 and references therein). The orbital separations of close binary systems containing at least one compact object – such as the cataclysmic variables (CVs) and low-mass X-ray binaries (LMXBs) – are significantly smaller than the radii of the stars which were the progenitors of the compact objects in these systems. This means that significant orbital shrinkage must have occurred, probably in a process known as common-envelope (CE) evolution. According to the CE model of close binary star evolution (in this case, as applied to CVs; Paczyński 1976), the more massive (primary) star fills its Roche lobe when it reaches its giant or asymptotic giant branch phase, while its lower mass (secondary) companion remains on the main sequence. Under these conditions, mass transfer to the secondary is dynamically

unstable and occurs at such a high rate that the transferred material cannot be accreted by the secondary and so forms a CE, in which the binary is immersed. Through the action of drag forces, the main-sequence star spirals towards the core of the giant, generating luminosity which drives off the CE. What remains is often called a post-common envelope binary (PCEB), with typical orbital periods of a few days. These systems are thought to become CVs or LMXBs when magnetic braking or gravitational radiation extracts sufficient orbital angular momentum for the main-sequence secondary star to fill its Roche lobe (Spruit & Ritter 1983; Rappaport et al. 1983). The theory of CE evolution is therefore of fundamental importance in astrophysics, and is probably a key step in the production of some of the most exotic inhabitants of our Galaxy, including the binary radio pulsars, black-hole X-ray binaries and Type Ia supernovae. For a recent review of CE evolution, see Iben & Livio (1993).

Although there is general agreement that most close binary systems have evolved through a CE phase, there is little direct evidence to support the CE model. The best evidence to date for the reality of CE evolution comes from the observation of planetary nebulae with close binary nuclei (Iben & Livio 1993; Livio 1996; Bond 1992). There is no direct evidence, however, that whole classes of important objects such

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as LMXBs, CVs and their immediate precursors, the so-called pre-CVs (e.g. Catalán et al. 1994), have in fact evolved through a CE phase. As a result, Sarna et al. (1995) proposed a direct observational test of CE evolution. The idea is based on the fact that the ratio of $^{12}\text{C}/^{13}\text{C}$ decreases from a value of 84 in main-sequence stars like the Sun (Harris et al. 1987) to a value of about 17 in giants (Harris et al. 1988), due to the different nuclear burning and mixing processes which occur in these stars. During the CE phase, the main-sequence secondary effectively exists within the atmosphere of the giant primary and will accrete material from it, thereby altering the $^{12}\text{C}/^{13}\text{C}$ ratio from solar-like values towards giant-like values. By measuring the $^{12}\text{C}/^{13}\text{C}$ ratio it is therefore possible to determine whether a binary has passed through a CE stage. This test has already been performed by Dhillon & Marsh (1995), who made a tentative detection of ^{13}CO in the *K*-band spectrum of the pre-CV V471 Tau. To confirm this detection, we observed V471 Tau again, along with the CV SS Cyg. The results of these new, much higher quality observations are presented in this paper, together with a discussion of the recent results of Catalán et al. (2001), who independently performed similar observations to the ones we describe here.

2. Observations and data reduction

On the night of 1995 October 22 we obtained 2.3338–2.3662 μm echelle (15 km s^{-1} resolution) spectra of the detached binary/pre-CV V471 Tau, the semi-detached binary/CV SS Cyg and the field stars G1105A (a K3 dwarf) and BS86 (a K3 giant) with CGS4 (Wright 1994) on the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. This was followed by additional UKIRT+CGS4 observations on the night of 2000 June 19, when we obtained 2.3310–2.3481 μm echelle spectra of the field stars G1406 (an M6 dwarf) and GJ1190 (a K5 dwarf) at a resolution of 8 km s^{-1} . Regular observations of nearby standards with featureless spectra were obtained on both nights to correct for the effects of telluric absorption and to provide flux calibration. The data were reduced following the procedures described by Dhillon & Marsh (1995).

3. Results

The observed spectra are presented in Fig. 1. The spectral features of interest are the first-overtone, vibrational-rotational molecular bands of ^{12}CO (4–2) at 2.3525 μm and ^{13}CO (2–0) at 2.3448 μm , where the wavelengths refer to the position of the band-head. Given that the ratio of $^{12}\text{C}/^{13}\text{C}$ is approximately 84 in solar-like stars and 17 in giants, one would expect ^{13}CO to be significantly stronger in the spectrum of a K3III star than in a K3V star. This is precisely what is observed in Fig. 1 – the ^{12}CO band is prominent in both G1105A and BS86, but the ^{13}CO band does not appear in the former whereas it is clearly visible in the latter (see also Table 1). The spectrum of the detached binary V471 Tau in Fig. 1 also shows prominent ^{12}CO . This is to be expected, given that this 12.5 hr-period pre-CV has a secondary star with an estimated spectral type of

K2V (Young & Nelson 1972)¹. The spectrum of V471 Tau also shows a prominent absorption feature coincident with the expected wavelength of ^{13}CO , with a strength relative to ^{12}CO similar to that observed in BS86 (see Table 1). This is in agreement with the detection of such a feature by Dhillon & Marsh (1995) and Catalán et al. (2001). The absorption feature is also observed in the spectrum of SS Cyg in Fig. 1; the (albeit noisier) spectrum of this 6.6 hr-period CV with a K4V secondary star (Ritter & Kolb 1998) shows enhanced absorption around 2.3448 μm , once again in agreement with the somewhat uncertain detection by Catalán et al. (2001).

One interpretation of the above result is that we have detected enhanced ^{13}CO , thereby confirming that V471 Tau and SS Cyg have evolved through a CE phase. This interpretation would almost certainly be incorrect, however, as the spectra of both objects show evidence of contamination by star-spots. This can be understood by inspecting the NaI features at 2.3355 μm and 2.3386 μm in Fig. 1. The NaI doublet in both V471 Tau and SS Cyg is stronger than one would expect given the spectral type of the secondary stars in these objects (compare the strength of NaI in V471 Tau and SS Cyg with its strength in the K3V star in Fig. 1). It is straightforward to explain this excess NaI absorption as being due to star-spot contamination, as the cooler star-spots would contribute to spectral features seen in stars of a later spectral type (and hence strengthen NaI in the spectra of V471 Tau and SS Cyg; compare the strength of NaI in the K3V spectrum with the K7V and M2V spectra in Fig. 1). This interpretation is supported by the Doppler imaging experiments of Ramseyer et al. (1995), who find that the secondary star in V471 Tau exhibits extensive star-spot coverage ($\sim 25\%$ of the stellar surface, according to O’Brien et al. 2001). Webb et al. (2002) also find evidence for $\sim 22\%$ star-spot coverage of the secondary star of SS Cyg. They see a similar effect to the one described in this paper; in their case, TiO absorption from star-spots is introduced into the optical spectrum of the K4 secondary star (and TiO absorption is not normally seen in stars earlier than K7).

It should be pointed out that star-spots are not the only explanation for the anomalous strength of NaI absorption in our spectra of V471 Tau and SS Cyg; differences in temperature, gravity or abundances between the secondary stars and the spectral-type templates in Fig. 1 could also cause such an effect. Given that we already know star-spots are present in V471 Tau and SS Cyg, however, this seems to be the simplest explanation. If we accept that the enhancement in NaI line strength is due to contamination by star-spots, this then implies that the feature at 2.3448 μm in Fig. 1 may not be due to ^{13}CO . This can be seen by examining the rotationally broadened K7V, M2V and M6V spectra in Fig. 1, which shows a prominent absorption feature around 2.3448 μm . This absorption feature is dominated by the neutral atomic line of Ti I (Wallace & Hinkle 1996) and happens to fall at the same position in the spectrum (2.3448 μm) as ^{13}CO . Furthermore, it can be seen that the Ti I feature increases in strength with later spectral type. As a result, the absorption feature at 2.3448 μm in V471 Tau and SS Cyg

¹ This spectral type estimate is far from accurate, however, being based solely on the *U* – *B* and *B* – *V* colours.

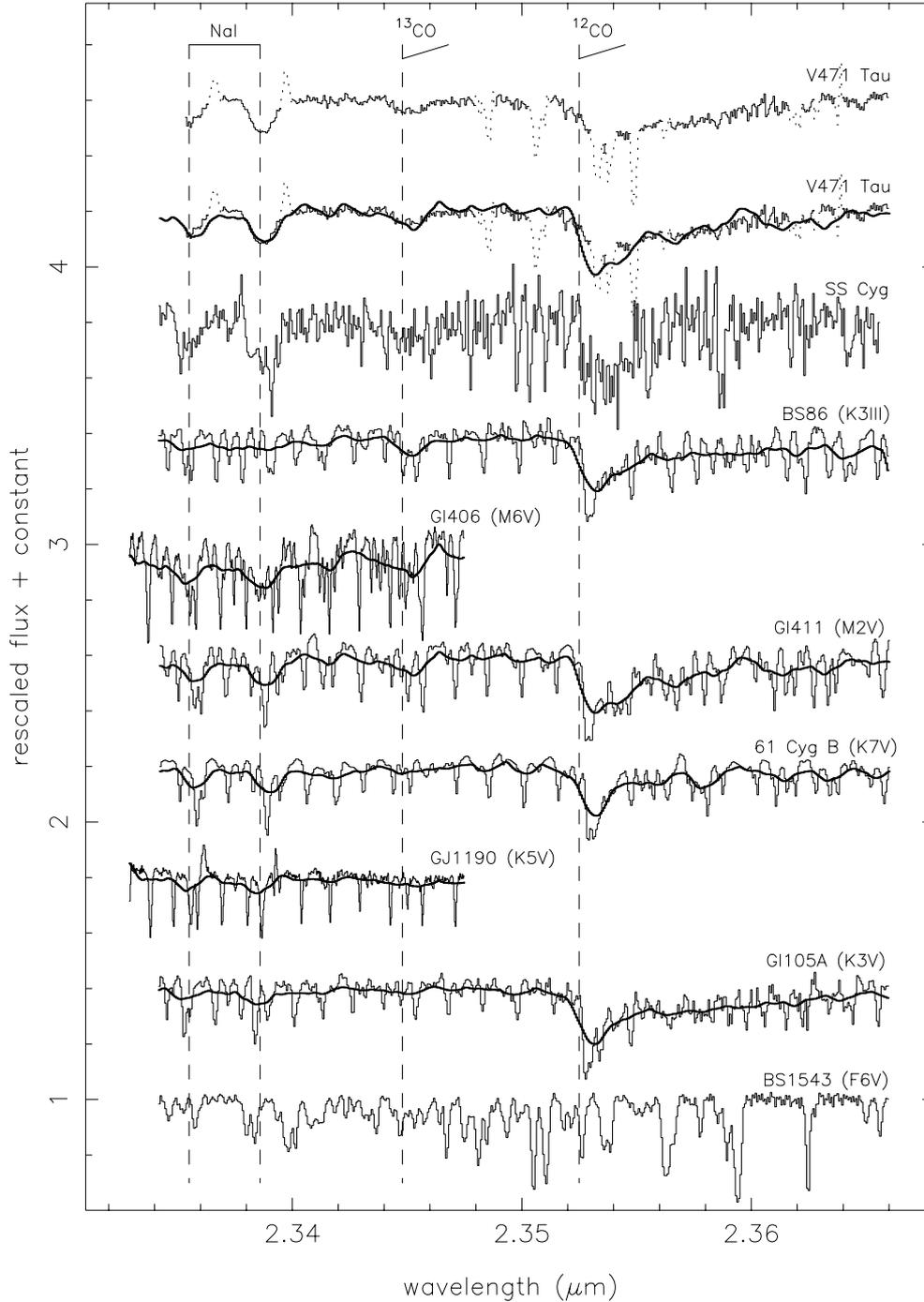


Fig. 1. Averaged K -band echelle spectra of (from top to bottom) the pre-CV V471 Tau (top two spectra), the CV SS Cyg, a K3 giant (BS86), and dwarf stars of spectral type M6–K3. The spectra of G1411 and 61 Cyg are taken from the atlas of Wallace & Hinkle (1996), and have been binned to exhibit the same resolution as the other spectra. All spectra have been normalized by dividing by a spline fit to their continua. Despite the number of lines in each spectrum, identifying the continuum was not difficult because it is essentially flat due to the short wavelength range covered. To account for the contribution of non-secondary star light in the binaries, the spectra have also been scaled to ensure that the ^{12}CO bands are of an equivalent depth (thereby enabling a direct comparison of the $^{12}\text{CO}/^{13}\text{CO}$ ratios in each object). All spectra have been offset on the ordinate by adding a constant to each spectrum. The bottom spectrum is that of an F6 dwarf (BS1543), normalized by dividing by a spline fit to the continuum regions, which indicates the location of telluric absorption features. The thick, solid curves superimposed on the spectra of the dwarf and giant stars show these spectra rotationally broadened by 90 km s^{-1} . The thick, solid curve superimposed on the lower spectrum of V471 Tau is the rotationally broadened spectrum of the M2 dwarf G1411. The dotted lines in the spectrum of V471 Tau denote bad pixels and regions where the telluric correction was poor.

Table 1. Flux deficits of the molecular bands in V471 Tau, SS Cyg and two representative spectral-type templates. The flux deficits were measured by integrating the flux in the continuum-subtracted spectra between 2.3445–2.3465 μm for ^{13}CO and between 2.3515–2.3600 μm for ^{12}CO (with an appropriate correction for the Doppler shift in V471 Tau and SS Cyg). Note that the spectra suffer from slit losses and hence the individual flux deficits are only lower limits; the flux deficit ratios given in the right-hand column, however, are secure. Equivalent width measurements are not presented due to contaminating emission from the white dwarf and the effects of irradiation in V471 Tau and SS Cyg.

| Object | ^{13}CO ($\times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$) | ^{12}CO ($\times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$) | $^{13}\text{CO}/^{12}\text{CO}$ |
|--------------|--|--|---------------------------------|
| V471 Tau | 0.122 \pm 0.008* | 1.331 \pm 0.017 | 0.092 \pm 0.006* |
| SS Cyg | 0.015 \pm 0.002* | 0.123 \pm 0.006 | 0.122 \pm 0.017* |
| G1105A (K3V) | 0.019 \pm 0.003 | 1.290 \pm 0.006 | 0.015 \pm 0.002 |
| BS86 (K3III) | 0.341 \pm 0.004 | 3.520 \pm 0.009 | 0.097 \pm 0.001 |

* The identification of the absorption band with ^{13}CO in these systems is not secure – see text for details.

most probably arises at least partly from Ti I. To illustrate this point we have plotted the rotationally-broadened spectrum of G1411, an M2 dwarf star, on top of the spectrum of V471 Tau in Fig. 1. The spectrum of the M2 dwarf not only provides a good match to the strengths of both Na I and ^{12}CO in V471 Tau, but also an adequate match to the absorption feature at 2.3448 μm . Given the uncertainty in the spectrum of the star-spots, the fraction of the surface they cover and the temperature of the surrounding photosphere, it is not possible to reliably disentangle the Ti I absorption in V471 Tau and SS Cyg from any ^{13}CO that may be present. In other words, it is impossible to reliably distinguish between the effects of CE evolution and star-spot contamination using the spectra presented in Fig. 1.

The test proposed by Sarna et al. (1995) still remains viable, however. Figure 2 shows high-resolution *K*-band library spectra taken from the spectral atlas of Wallace & Hinkle (1996). Over-plotted in thick lines are the same spectra rotationally broadened by 90 km s $^{-1}$, corresponding to the projected rotational velocity of the secondary star in V471 Tau (Ramseyer et al. 1995). Prominent in the spectrum of the K1 giant, α Boo, are the absorption bands of ^{12}CO at 2.3525 and 2.3830 μm , as well as the absorption bands of ^{13}CO at 2.3448, 2.3739 and 2.4037 μm . The ^{13}CO bands are not present in the spectrum of the K7 dwarf, but the rotationally broadened M2 dwarf spectrum shows an absorption feature at 2.3448 μm – as seen in the spectra presented in Fig. 1. However, the rotationally broadened M2 dwarf spectrum displays no absorption features at wavelengths corresponding to the ^{13}CO bands at 2.3739 and 2.4037 μm . Observations of V471 Tau and SS Cyg at these wavelengths (particularly the latter, stronger feature) would therefore be free of star-spot contamination and would allow a successful test of the CE model.

4. A comment on the results of Catalán et al. (2001)

Independently of the work presented in this paper, Catalán et al. (2001) observed V471 Tau, SS Cyg and four other binaries in order to confirm the results of Dhillon & Marsh (1995). They found evidence for the spectral feature at 2.3448 μm in V471 Tau, SS Cyg and one other detached binary (Feige 24). They

attribute this to a positive detection of ^{13}CO ; for the reasons discussed above, we believe this is erroneous and that the feature is most probably due to star-spots. The data of Catalán et al. (2001) cover a wider wavelength range than the data presented here, including the ^{13}CO band at 2.3739 μm . They have therefore partially performed the new observational test of CE evolution that we describe in this paper and they report a detection of the ^{13}CO band at 2.3739 μm in the binary Feige 24. However, their detection is at a very low signal-to-noise, the feature does not appear to lie at the correct wavelength (see their Fig. 2), and they do not detect this band in any of the other binaries observed. Therefore, we believe that Catalán et al. (2001) present no strong evidence for the presence of ^{13}CO and, unfortunately, their wavelength coverage does not extend to the much stronger ^{13}CO feature at 2.4037 μm that we propose should be observed in future observational tests.

5. Conclusions

Our *K*-band echelle spectra of the CV SS Cyg and the pre-CV V471 Tau show evidence of a spectral feature at 2.3448 μm . This is coincident with where we would expect to observe the ^{13}CO (2–0) molecular band, which would imply that these objects have passed through a CE phase during their evolution. However, our spectra also show enhanced Na I absorption, which can be attributed to star-spots. These star-spots also contribute to a cluster of strong, neutral atomic absorption features around 2.3448 μm , rendering our test of CE evolution inconclusive. We therefore propose a new test based on the measurement of the ^{13}CO bands at 2.3739 and 2.4037 μm , which we show would be uncontaminated by star-spots. We intend to perform this revised test in the near future.

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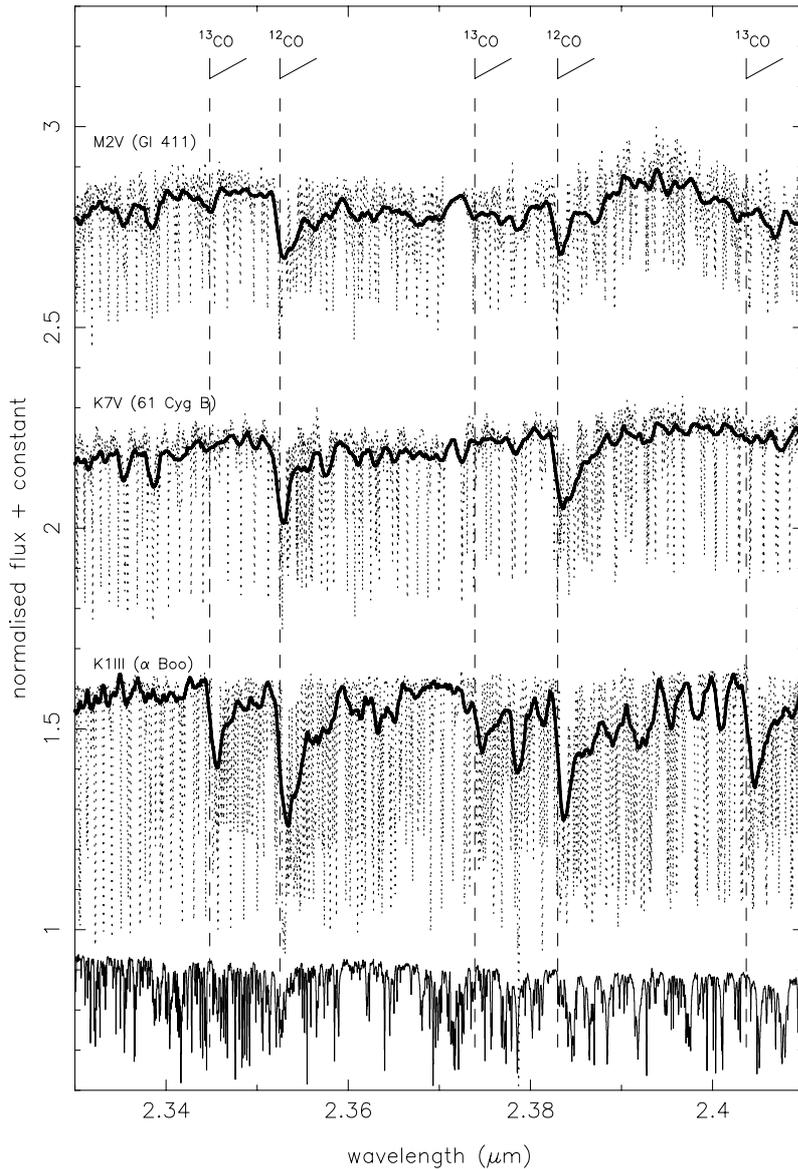


Fig. 2. The dotted curves show the high resolution K -band spectra of (from top to bottom) the M2 dwarf Gl 411, the K7 dwarf 61 Cyg B and the K1 giant α Boo, taken from the atlas of Wallace & Hinkle (1996). The spectra have been normalised by dividing by the flux at $2.37 \mu\text{m}$ and offset on the ordinate by adding a constant to each spectrum. The thick, solid curves superimposed on the spectra of the dwarf and giant stars show these spectra rotationally broadened by 90 km s^{-1} . The bottom spectrum is an atmospheric transmission function obtained from the ratios of two stellar spectra taken at different airmasses – the details of this process are given in Wallace & Hinkle (1996).

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