UIR bands in the ISO SWS spectrum of the carbon star TU Tauri^{★,★★}

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ABSTRACT

Polycyclic Aromatic Hydrocarbon (PAH) molecules are thought to form in the ejecta of carbon-rich Asymptotic Giant Branch (AGB) stars. Fifty ISO SWS spectra of warm carbon-rich AGB stars have been investigated for the Unidentified IR (UIR) emission due to fluorescence by PAH molecules. In this sample the binary star TU Tau, which has a blue companion, shows interesting spectral structure in the appropriate wavelength regions. The profiles of the UIR bands in TU Tau have been derived by comparing to suitable carbon-star spectra.

The presence of the UIR bands in TU Tau is attributed to UV photons originating from the A2 companion star which are necessary to excite PAH molecules. The absence of the UIR bands in the remainder of the sample is ascribed to the lack of UV (or visible) photons in their environment. Hence, the absence of UIR bands does not necessarily imply the absence of circumstellar PAHs in these sources.

The derived UIR band profiles have been compared to UIR band profiles from Reflection Nebulae, Planetary Nebulae (PNe), HII regions, Young Stellar Objects, evolved stars and Galaxies. The profiles of TU Tau are shown to have the most resemblance to those from PNe. Integrated band flux ratios have also been determined and compared to object type flux ratio correlations found in other studies. Here no definite match was found.

TU Tau is the only binary with a blue companion in this sample of AGB stars. In line with earlier studies, we suggest that the blue photons provided by this companion are required for efficient excitation of PAH molecules in AGB ejecta. In addition, we argue that these blue photons may promote complex chemistry in the ejecta of TU Tau.

The similarity in the peak profiles observed in the spectrum of TU Tau with those in the spectra of PNe indicates that PAHs are formed in the circumstellar envelope of carbon-rich AGB stars and make it largely unmodified into the PNe phase. The variations in the band strength ratios between the different objects has been linked to the ionization state of PAHs and reflects the different physical environments between this AGB star and PNe. In contrast, the variation in UIR band profiles between stellar ejecta and the Interstellar Medium (ISM) are largely attributed to chemical modifications during the ISM phase.

Key words. stars: carbon – stars: circumstellar matter – stars: individual: TU Tau – ISM: evolution – infrared: stars – infrared: ISM

1. Introduction

Emission features around 3.3, 6.2, 7.6, 7.9, 8.6, 11.2 and 12.7 μm , called the Unidentified IR (UIR) bands (Gillett et al. 1973; Geballe et al. 1985; Cohen et al. 1986), are commonly ascribed to Polycyclic Aromatic Hydrocarbons (PAHs): large molecules of many fused aromatic rings (Leger & Puget 1984; Cohen et al. 1985; Puget & Leger 1989; Allamandola et al. 1989). PAHs are excited through absorption of a single UV photon (Sellgren 1984). The absorbed energy is redistributed over the molecule and the molecule relaxes through photon

emission at characteristic infrared wavelengths, leaving fingerprints by which they can be identified in spectra.

The presence of these large molecules in space is of great influence on many aspects of the Interstellar Medium (ISM) (Omont 1986). These aspects include interstellar (surface) chemistry due to their large surface area, heating and cooling of the ambient ISM through photo-electric ejection, infrared emission and gas-grain collisions and the charge balance, which in its turn influences the equilibrium state for chemical reactions.

PAHs are believed to be formed in the Circumstellar Envelopes (CSE) of carbon stars and to be subsequently injected into the ISM through the stellar winds. However, the presence of these molecules in the CSE of carbon stars is virtually undetected to date. The detection of the PAHs around most of these stars may well be hampered by the lack of UV photons in their environment. The current evidence for the presence of PAHs in the ejecta of carbon-rich giants is only twofold and

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** Figures 4 to 18 are only available in electronic form at <http://www.edpsciences.org>

indirect. First, spectra from carbon-rich proto-planetary nebulae and Planetary Nebulae (PNe) show strong IR emission features. These objects are the descendants of carbon-rich AGB stars and their circumstellar material originates from matter lost during the AGB phase (Shklovsky 1956; Salpeter 1971; Habing 1990). Second, analysis of star-dust grains isolated from meteorites – whose isotopic composition betrays an origin in carbon-rich AGB stars – have revealed the presence of (specific) small PAHs with an isotopic composition similar to that of the parent grain (Messenger 2003). However, one of the key question remains: “are PAHs formed efficiently in the outflow of carbon rich giants?”.

Prior research in this area, by Speck & Barlow (1997) and Buss et al. (1991) using respectively UKIRT and IRAS spectra, showed tantalizing evidence for the existence of weak UIR band emission in a particular binary system TU Tau. This system harbors an AGB star with a carbon-rich outflow and a blue companion star that produces some UV photons. These UV photons may enable PAHs to be detected.

We build on the work of Speck & Barlow (1997) and Buss et al. (1991) but we use spectra obtained by the Short Wavelength Spectrometer (SWS) on board of ESA’s Infrared Space Observatory (de Graauw et al. 1996). These spectra have higher spectral resolution and a wider wavelength coverage, which allows us to search for the complete family of IR emission features in TU Tau. Also, the C–H bands in the previously studied 8–13 μm region, are known to vary in strength and therefore may present only limited tracers for the presence of circumstellar PAHs. In addition, it is known that the 5–9 μm range exhibits strong spectral variations reflecting their environment. Hence, the access to this regions provides us with a powerful tool for studying the origin and evolution of the UIR bands in TU Tau.

2. The sample

For this study we have examined the ISO SWS spectra of 26 warm, optically bright carbon-rich AGB stars (available electronically at EDP Sciences). The spectra of these stars are characterized by many strong and broad absorption bands due to molecules in their photosphere and outflows as well as emission features due to dust grains at larger wavelengths (e.g. SiC). The UIR bands of interest are located in four distinctive regions: 3–4 μm , 4–7 μm , 7–10 μm and 10–13 μm . We verified by visual inspection that TU Tau is unique in the sample, because of its spectral structure around the appropriate UIR wavelengths. A subsample was defined for use as template stars in direct comparison to TU Tau. In order to better understand the observed spectral differences in the UIR bands and to assess their reality, three comparison stars have been selected: W Ori as a star with the most similar spectrum; S Sct as a star with the second most similar spectrum; and VX And as a star with the least similar spectrum. Data on the four stars are presented in Table 1 and Fig. 1 presents the four ISO SWS spectra from 2.38–20 μm .

Table 1. The subsample. Presented are the Astronomical Observing Template used, the classification by Kraemer et al. (2002), the classification by Alksnis et al. (2001) and the fitted blackbody temperature.

SWS NAME	AOT (Speed)	Kraemer	Alksnis	T_{bb} (K)
TU Tau	SWS01(2)	2.CE	N2 + A	1912
W Ori	SWS01(3)	2.CE	N5; C5,4	2092
S Sct	SWS01(2)	2.CE	N3	2395
VX And	SWS01(2)	2.CE	N7; C4,5	2379

Fig. 1. ISO SWS spectrum for TU Tau, W Ori, S Sct and VX And from 2.38–20 μm (same scale). The units on the Y-axis have been chosen to emphasize the apparent spectral structure. Indicated with the gray curves are fitted continua for 4–10 μm and 10–14 μm , see Sect. 3 for details.

2.1. Data reduction

Astronomical observations with the SWS instrument were done using Astronomical Observing Templates (AOT). The carbon star spectra in this work were observed using AOT SWS01, so obtaining low resolution spectra over the entire instrument range 2.38–45.2 μm .

The data in this work have been processed with OLP version 10.1. Further data reduction consisted of extensive bad data removal. Glitches in the data were removed by inspecting the detector read outs in time and comparing the signal of each detector with the average signal from the other detectors in each sub-band in wavelength. Simultaneous jumps or glitches in all detectors of a sub-band have been isolated by comparing the independent up and down scan and removing the discrepant data. After cleaning the data have been re-binned to a regular wavelength grid with a resolving power ($\lambda/\Delta\lambda$) of 300 and four times oversampled.

Fig. 2. ISO SWS spectrum for TU Tau and the re-constructed spectrum from W Ori. The inset presents the UIR band emission in TU Tau. Indicated with the dashed lines are the centers of the UIR bands. The units on the Y-axis have been chosen to emphasize the apparent spectral structure.

The re-binned spectra have been spliced with the sub-bands to form a continuous spectrum from 2.3 to 45.2 μm . At high flux levels the uncertainty in the absolute flux calibration is the dominant cause of discontinuities between neighboring sub-bands. While at low flux levels offsets due to dark-current corrections are thought to dominate. Scaling factors have been applied to those bands with a median flux level over 20 Jy and offset to bands with lower flux levels. In general the necessary corrections in offset and scaling are small and in accordance with the quoted uncertainties for the SWS instrument.

2.2. TU Tau

This study focuses on TU Tau, a carbon-rich AGB star classified C 5 II (Richer 1971). The ISO SWS spectrum of TU Tau is presented as the gray curve in Fig. 2. TU Tau was shown to have a composite spectrum by Shane (1925), indicating a binary system. TU Tau's companion is a hot A star classified A2 IV by Olson & Richer (1975). The angular separation between the two stars is $0.170 \pm 0.025''$ (Perryman et al. 1997). The system is measured to have a radial velocity of 24 km s^{-1} (Wilson 1953). The mass-loss rate of TU Tau is estimated at $1.5 \times 10^{-7} M_{\odot} \text{yr}^{-1}$ by Claussen et al. (1987); they put the star at the distance of 0.9 kpc, which is in good agreement with the parallax of 1.12 mas measured by Hipparcos (Perryman et al. 1997).

3. Determining the UIR band profiles

The spectra of carbon-rich AGB stars contain various components. The principal component being the stellar continuum. Besides the continuum radiation, carbon-rich AGB stars exhibit

emission and absorption bands due to the molecules and dust in the photosphere and CSE.

Line formation is a complex interplay of the diffusion of energy outward mediated by the absorption, scattering, and re-emission due to photospheric gases. The spectrum of TU Tau, or any other carbon-rich AGB star, is not that of a simple continuum with superimposed circumstellar absorption bands. Indeed, many of the molecular absorption bands that are seen, mainly form in the photosphere. Rather than developing a stellar atmosphere model for carbon-rich AGB stars to derive an appropriate continuum, this problem is approached phenomenologically by assuming an appropriate standard star with added circumstellar absorption and emission components. The resultant spectrum can then be approximated as

$$F_{\star}(\nu) = F_{C\text{-star}}(\nu)e^{-\tau_{\star}(\nu)}, \quad (1)$$

with $F_{C\text{-star}}(\nu)$ being the standard star and $\tau_{\star}(\nu)$ the optical depth in the molecular bands, which is dependent on the physical conditions in the CSE and most importantly, on the abundances of the different species present. In addition, for TU Tau an extra component due to the UIR bands is suspected. Therefore, the observed spectrum of TU Tau can be written as the sum of two parts

$$F_{\text{TUTau}}(\nu) = R_{\text{TUTau}}(\nu) + F_{C\text{-star}}(\nu)e^{-\tau_{\text{TUTau}}(\nu)}, \quad (2)$$

where the residual component $R_{\text{TUTau}}(\nu)$ represents the contribution due to PAHs.

3.1. Molecular absorption band corrections

For the determination of the UIR band profiles of TU Tau we take the stars from the subsample as templates for TU Tau without UIR bands. We find, however, the need to correct for the

Table 2. Fitted parameters and their values, see text for details. The linear correlation coefficient is given, where applicable, between brackets.

SWS NAME	c	γ	t	a	b	d
TU Tau	622 (0.849)	-1.35		40	-1.2	
W Ori	717 (0.845)	-1.45	1.22 (0.996)	260	-10	0.10
S Sct	419 (0.584)	-1.03	1.44 (0.993)	125	-7	0.71
VX And	559 (0.759)	-1.19	2.12 (0.989)	118	-7	0.71

general slope of the continuum and the depth of the molecular absorption bands. In matching the spectrum of the template star to TU Tau, we will adopt a power-law continuum and scale the optical depth with a constant factor. For the observed optical depth we can write

$$\tau_{\star}(\nu) = \ln(c_{\star}\nu^{-\gamma_{\star}}/F_{\star}(\nu)), \quad (3)$$

where $c_{\star}\nu^{-\gamma_{\star}}(\nu)$ is the adopted power-law continuum for the template star. For TU Tau we can then write

$$R_{\text{TUTau}}(\nu) = F_{\text{TUTau}}(\nu) - c_{\text{TUTau}}\nu^{-\gamma_{\text{TUTau}}}e^{-t\tau_{\star}(\nu)}, \quad (4)$$

where $c_{\text{TUTau}}\nu^{-\gamma_{\text{TUTau}}}$ is the adopted power-law continuum for TU Tau and t is the constant scaling factor.

3.2. SiC feature corrections

The broad $11.2 \mu\text{m}$ SiC is in emission and appears to be optically thin. The observed SiC profile of a template star can then be approximated, when adopting a linear continuum, by

$$\begin{aligned} P_{\star}(\nu) &= F_{\star}(\nu) - F_{\text{C-star}}(\nu) \\ &= F_{\star}(\nu) - (a_{\star} + b_{\star}\nu), \end{aligned} \quad (5)$$

where $(a_{\star} + b_{\star}\nu)$ is the adopted linear continuum. In this case the reference spectrum is constructed by scaling the profile with a constant factor d . For the residual component for TU Tau R_{TUTau} we then write

$$R_{\text{TUTau}}(\nu) = F_{\text{TUTau}}(\nu) - (a_{\text{TUTau}} + b_{\text{TUTau}}\nu) - d \cdot P_{\star}(\nu), \quad (6)$$

where $(a_{\text{TUTau}} + b_{\text{TUTau}}\nu)$ is the adopted linear continuum for TU Tau and d the constant scaling factor.

3.3. Results

The methods outlined above have been applied to the $4\text{--}10 \mu\text{m}$ and $10\text{--}14 \mu\text{m}$ regions respectively. The adopted continua are presented in Fig. 1 (gray curves) and the derived values for c, γ, t, a, b and d are listed in Table 2.

Figure 2 presents the spectrum of TU Tau together with the reference spectrum constructed using W Ori as template star, indicated are the molecular line positions, dust features and the UIR bands. In the inset of Fig. 2 the residual spectrum is plotted. While minor discrepancies around 5.5 and $7 \mu\text{m}$ can still be seen the method outlined above works well and most of the absorption and emission features, except for the UIR bands have been corrected for. The residual spectrum shows clear $6.2, 7.7, 8.6$ and $11.2 \mu\text{m}$ bands. This is in agreement with earlier ground-based and space born studies, which identified the 11.2 and $7.7 \mu\text{m}$ bands in the spectrum of TU Tau (Buss et al. 1991; Speck & Barlow 1997).

The reference spectrum constructed using S Sct (available electronically at EDP Sciences) shows less agreement with TU Tau, which is predominantly due to exceptionally strong absorption in the overtone bands of C_2H_2 between 3.4 and $4.0 \mu\text{m}$ in this spectrum.

Also, the constructed spectra work equally well in the SiC range although this range is more affected by the intrinsically higher noise-level of the used spectra.

Note that the $3.28 \mu\text{m}$ UIR band is located within the strong blended C_2H_2 and HCN absorption bands. This region is further complicated by the absorption band at $3.28 \mu\text{m}$ of CH_4 . Hence, we have refrained from detailed fits of this region. Although a weak emission feature can be seen in the residual spectrum in Fig. 2, its reality is doubtful as this band only becomes apparent *after* subtraction of the reference spectrum.

4. The UIR spectrum of TU Tau

The top panels in Fig. 3 presents the UIR bands in TU Tau. The profiles, as derived from the three template stars, are indicated separately (gray curves) and give some indication of the systematic uncertainties introduced by the applied method.

The uncertainties in the profiles have been put in terms of the residual profiles obtained after subtracting a best, a second best and a worst “appropriate” comparison star. In all cases, emission features are apparent. We deem the profile obtained with W Ori the best because of overall similarities between the spectra of W Ori and TU Tau as indicated by fitted blackbody temperatures (1912 K versus 2092 K) and the good linear correlation coefficients returned when fitting the optical depth.

We recognize the difference in profiles derived using S Sct and VX And. However, after subtraction of an additional “continuum” component the residual profiles are very similar to those obtained for W Ori. This extra “continuum” reflects the difficulty in defining the true continuum in regions where the spectrum is dominated by strong molecular absorption bands (see Fig. 1).

The $6.2 \mu\text{m}$ profile shows no variation in peak position and overall shape when comparing the profiles derived using the different template stars. For the $7.6/7.8 \mu\text{m}$ complex the $7.8 \mu\text{m}$ component remains dominant, the relative scale and peak position of the $8.6 \mu\text{m}$ profile does show some variation with the strength of the complex. The variation in shape of the $11.2 \mu\text{m}$ profile is attributed to noise, which may also cause the slight shifts in peak position.

Fig. 3. *Top:* the 6.2, 7.7 complex, 8.6 and 11.2 μm UIR band profiles in TU Tau. An indication of their uncertainties is given by the gray curves. The solid and the dotted gray line are obtained using S Sct and VX And as template stars, respectively.

4.1. Profiles and band strengths

Studies of the detailed profiles of the UIR bands in the spectra of a large sample of stellar sources, PNe, Reflection Nebulae (RNe), HII regions and galaxies have revealed that the bands in the 6–9 μm range show strong variation in peak position and profiles. Specifically, Peeters et al. (2002) classified 6–9 μm spectra from RNe, HII regions, Young Stellar Objects (YSO), evolved stars and galaxies based on profile and peak position. They find that the variations in the UIR bands correlate with object type. In Peeters et al. (2003) the variation in the 3.3 and 11.2 μm bands, due to C–H bending and stretching modes, are studied and classified. The observed variation are shown to be more modest than those in the 6–9 μm region and the object correlation in the C–H modes is not as tight as for the C–C modes. The bottom panel of Fig. 3 shows the main classes as defined by Peeters et al. (2002) and Peeters et al. (2003) for comparison with the obtained profiles for TU Tau (top panel). Table 3 gives a quantitative analyses.

With a peak position of 6.27 μm for the 6.2 μm band and a stronger 7.8 than 7.6 μm component, the C–C modes for TU Tau match best those of class *B*. While the derived 11.2 μm profile for TU Tau has a large intrinsic uncertainty, the 11.2 μm

Table 3. Classifications for the 6.22, 7.7 complex, 8.6 and 11.2 μm profiles, λ_c indicates the peak positions in μm . The 7.7 μm complex is classified by dominant component. Compiled from Peeters et al. (2002) and Peeters et al. (2003).

The 5–9 μm region				
Class	Object	$\lambda_{6.2}$	$\lambda_{7.7}$	$\lambda_{8.6}$
<i>A</i>	HII, RNe	6.2	7.6/equal	8.6
<i>B</i>	PNe	6.24–6.28	“7.8”	>8.62
<i>C</i>	post-AGB stars	6.3	8.22	none
–	TU Tau	6.27	7.6/7.8	8.61
The 11.2 μm region				
Class	Object	$\lambda_{11.2}$	$FWHM_{11.2}$	
<i>A</i> _{11.2}	HII, Herbig, YSOs	11.20–11.24	0.17	
<i>A(B)</i> _{11.2}	Galaxies, PNe	11.20–11.24	0.21	
<i>B</i> _{11.2}	Galaxies, PNe, post-AGB	11.25	0.20	
–	TU Tau	11.25–11.27	0.05–0.2	

profile matches best with class *B*_{11.2} in peak position and width. As far as the influences of the systematic variations are concerned; only the derived 11.2 μm profile shows strong enough variation in peak position for some ambiguity to exist in its

classification. Overall however, the systematic variations in all bands are small.

Hony et al. (2000) measured the bands strength ratios of various UIR bands. These authors present spectra from HII, YSOs, RNe and PNe. They find that several of the UIR band strength ratios correlate with object type. Such correlations are found for $I_{3.3}/I_{6.2}$ with $I_{11.2}/I_{6.2}$, $I_{6.2}/I_{11.2}$ with $I_{12.7}/I_{11.2}$ and I_{PAH}/I_{IR} with $I_{12.7}/I_{11.2}$. Since for TU Tau of these bands only the $F_{6.2}$ and $F_{11.2}$ can be reliably measured the full potential of these correlations can not be used. We calculate the 6.2 and 11.2 μm band strengths by integrating between 6.1 to 6.6 and 10.8 to 11.9 μm , respectively. We then find a ratio of 11.2/6.2 equal to 0.59. This ratio falls in the range observed for star forming regions but is significantly smaller (by a factor of 3) than the average found for carbon-rich PNe (~ 1.6). In conclusion, the band profiles of TU Tau match those of PNe, while the determined band strength ratios differ significantly from those of PNe and are closer to those found for HII regions.

5. Discussion

The observed large variation in peak position, profile and relative strength of the UIR bands in the sample of PNe, post-AGB objects, YSOs, HII regions and RNe are attributed to global changes in the physical and chemical characteristics of the emitting PAH family. Specifically, variations in the peak positions of the 6.2 μm band are thought to reflect incorporation of nitrogen in the aromatic ring structure (Peeters et al. 2002; Bauschlicher 2002). The 7.6/7.8 μm are likely also related to chemical modifications, because they correlate well with the 6.2 μm variations. In contrast, variations in the ratio of the C–H modes to the C–C modes (e.g. 11.2/6.2 μm) are attributed to variation in the charge state of the emitting PAHs (Allamandola et al. 1999a; Hony et al. 2001; Bakes et al. 2001).

The UIR band profiles of TU Tau seem to indicate incorporation of N. The similarity between the 11.2/6.2 μm ratio of TU Tau and those observed for the ISM suggest similar charge states.

5.1. The 6–9 μm region

Molecular composition and in particular chemical impurities are thought to form the basis of the profile changes in the 6–9 μm region. The effects on the IR spectra depend on the substituted atom and the location of the substitution (Bauschlicher 2002). The best candidate for substitution is nitrogen, basically for two reasons; 1) incorporation of nitrogen into the PAH doesn't compromise the aromatic stability of the π bond; 2) nitrogen is relatively abundant. Incorporation of N in the C-skeleton has been shown to shift the peak position of the “6.2” μm band to shorter wavelength; e.g. from ~ 6.3 to ~ 6.2 μm .

Given that the PAH family present in TU Tau is similar to that in PNe suggests that PAHs remain largely unmodified from the AGB phase into the PNe phase and contains little N. On the other hand, the different spectral characteristics between TU Tau/PNe and interstellar objects suggests that subsequent chemical processing, incorporating N in the PAH structure, occurs in the ISM, perhaps very rapidly.

5.2. The 11.2/6.2 μm ratio and the PAH charge state

The influence of PAH ionization is most striking between 5–10 μm . The peak positions of the profiles is hardly effected, but the intensity changes remarkably (Allamandola et al. 1999b; Szczepanski & Vala 1993; Langhoff 1996; Kim et al. 2001; Hudgins & Allamandola 1999, and refs. therein). The emission in this region originates from aromatic C–C stretching modes. The charge redistribution in the π electron system upon the ionization results in a oscillating dipole in the C-skeleton. In contrast, the strength of the oscillating dipole moments for the C–H bonds are reduced. The 11.2/6.2 μm ratio observed in TU Tau is very similar to that observed in ISM sources, but distinctly smaller than observed in PNe. The ionization balance of PAHs is regulated by G_0/n_e . We derive values for G_0 and n_e to investigate the charge state of the PAHs in the CSE of TU Tau.

The incident UV flux, G_0 , on the CSE, in terms of the interstellar radiation field, is estimated by calculating the energy emitted by the companion at a distance of 152 AU. With a luminosity of $52 L_\odot$, we estimate a bolometric flux at the inner edge of the TU Tau dust shell $F_{\text{bol}} \approx 1.5 \times 10^3 \text{ erg cm}^{-2} \text{ s}^{-1}$. Only including the radiation emitted between 3.1–13.6 eV based upon a black body with $T_{\text{eff}} = 9700 \text{ K}$, we arrive at $G_0 \approx 9 \times 10^5$.

A zeroth-order estimate for the electron density n_e is found considering the ionization balance for Na, which is the dominant electron donor in view of abundance and ionization potential considerations. From the mass-loss rate, we derive

$$n_i(r) \approx \frac{\dot{M}X_i}{4\pi r^2 m_{\text{HV}}} = n_i(r_0) \left(\frac{r_0}{r} \right)^2, \quad (7)$$

where r_0 is taken the PAH and dust formation region and X_i is an abundance. We adopt $r_0 = 10^{14} \text{ cm}$ and estimate $n_{\text{Na}}(r_0) \sim 87 \text{ cm}^{-3}$ using the solar abundance for Na, the observed mass-loss rate for TU Tau and an outflow velocity of 11 km s^{-1} (Loup et al. 1993). Photo ionization drives the ionization in the CSE. Solving the ionization balance indicates all sodium is ionized and $n_e \approx 87 \text{ cm}^{-3}$ and hence $G_0/n_e \sim 1.0 \times 10^4 \text{ cm}^3$.

For comparison, for diffuse clouds typically $G_0/n_e \approx 500 \text{ cm}^3$, for RNe $G_0/n_e \approx 10^3 \text{ cm}^3$ and for PDRs associated with HII regions $G_0/n_e \approx 5 \times 10^3 \text{ cm}^3$ (Bakes et al. 2001; Hollenbach & Tielens 1997). For comparison, for the planetary nebula NGC 7027, G_0/n_e in the PDR is estimated to be $\approx 3 \times 10^4 \text{ cm}^3$ and an order of magnitude larger for the dense toroid surrounding the ionized gas (Hollenbach & Tielens 1999), where most of the UIR emission in this source originates. The estimates made here are very crude, but seem in line with the determined 11.2/6.2 μm ratio that suggest a high degree of ionization for the PAHs in the CSE of TU Tau.

5.3. PAH formation in stellar atmospheres

If PAHs are present in the stellar outflow of TU Tau it means that PAHs are formed in the CSE of TU Tau. However, does this imply that PAHs are present around other carbon-stars, and in particular, those that do not have hot companions? To affirm this question we have to consider the influence of the nearby companion on the formation of PAHs.

The rate limiting step in the formation of PAHs in carbon-star ejecta is linked to the initiator of acetylene polymerizations through the formation of small radicals; e.g. $C_2H_2 + M \xrightarrow{k_M} H_2CC : + M$ (Frenklach & Feigelson 1989, Cherchneff et al. 2000). The UV radiation field of the companion may accelerate this polymerization process, most likely through $C_2H_2 + \gamma_{\text{fuv}} \xrightarrow{k_{\text{uv}}} C_2H + H$, where C_2H is generally considered an important intermediate in soot and PAH production (Harris & Weiner 1985). The parameter that presents a first order estimate on the influence of the companion's radiation field is

$$\chi \equiv \frac{[C_2H_2] \cdot k_{\text{UV}}}{[C_2H_2][M] \cdot k_M} = \frac{k_{\text{UV}}}{k_M} \cdot \frac{1}{[M]}, \quad (8)$$

where k_{UV} is the reaction rate for the ethynyl radical to form under the influence of photon interactions and k_M is the reaction rate for the vinylidene radical to form through collisional interactions. k_{UV} is estimated as $6.3 \times 10^{-10} \text{ s}^{-1}$ from Le Teuff et al. (2000) based upon the value for G_0 derived above. k_M is estimated as $2.18 \times 10^{-18} \text{ cm}^3 \text{ s}^{-1}$ from Frenklach & Feigelson (1989) at 800 K; the temperature of the CSE (Allain et al. 1997). Then, at a density of 10^8 cm^{-3} for the collisional partner (H or H_2) we calculate $\chi \sim 10^7$, indicating that the influence of the companion dominates.

Note however that in shocked regions the density of the collisional partner and the temperature increase considerably (Cherchneff et al. 1992; Cau 2002). This effectively increases the efficiency of the collisional reaction and possibly shifts χ in these regions to values smaller than unity.

Clearly, detailed theoretical studies on the PAH formation in the ejecta of TU Tau are required to access the influence of the companion star on the formation rates.

6. Summary and conclusions

Spectral features around 3.3, 6.2, 7.6, 7.9, 8.6, 11.2 and $12.7 \mu\text{m}$ are usually assigned to PAHs. PAH molecules need UV photons to get excited, therefore the features in the so called UIR bands are commonly not found in spectra of carbon-rich AGB stars.

We have studied the ISO SWS spectrum of the carbon star TU Tau which has a hot companion star. This hot A star provides the UV photons able to excite the PAHs.

By comparing the spectrum of TU Tau with a group of suitable reference spectra we confirm that UIR band emission is present and detectable in all major UIR bands except for the $3.3 \mu\text{m}$ band which is located inside a deep absorption band caused by HCN and C_2H_2 .

Deduced profiles, found using reference spectra, show that the profiles strongly resemble those found in PNe. This suggests that the UIR emitters in the PNe phase have been formed during the AGB phase and survive relatively unmodified into the PNe phase.

However, the relative band strength differs significantly from those found in PNe. Whereas, to first order, the profile shape is a measure of the molecular structure (chemistry), the UIR band strength ratios are a measure of the ionization state (environment). This suggests that the physical conditions in the

CSE of TU Tau differ significantly from PNe conditions, but that similar molecules are playing a role.

As for the future, VISIR can yield a better S/N for the $11.2 \mu\text{m}$ regions which allows to determine a more accurate profile. More suitable comparison stars like W Ori will put the derived profiles on a firmer footing. More extensive studies on the CSE of TU Tau should give the definite answer on the influence of the companion star on the PAH formation. Of course, more binary systems like TU Tau are needed to determine how universal the evolutionary scenario is that is painted here.

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Fig. 4. ISO–SWS spectra for HD19557, TX PSC, TX PSC and V AQL.

Fig. 5. ISO-SWS spectra for Y CVN, TU Tau, S Sct and V460 Cyg.

Fig. 6. ISO–SWS spectra for V460 CYG, T Ind, T Ind and W Ori.

Fig. 7. ISO-SWS spectra for RY Dra, SS 485, VX And and R For.

Fig. 8. ISO–SWS spectra for RU Vir, CS 3070, V CRB and V CRB.

Fig. 9. ISO–SWS spectra for V CRB, V CRB, V CRB and V CRB.

Fig. 10. ISO–SWS spectra for SS Vir, AFGL 933, CS 2429 and T Dra.

Fig. 11. ISO–SWS spectra for T Dra, T Dra, T Dra and T Dra.

Fig. 12. ISO–SWS spectra for T Dra, T Dra, T Dra and U Cam.

Fig. 13. ISO–SWS spectra for S Cep, S Cep, V Cyg and V Cyg.

Fig. 14. ISO–SWS spectra for V Cyg, V Cyg, V Cyg and V Cyg.

Fig. 15. ISO–SWS spectra for R Scl, R Scl, R Scl and R Scl.

Fig. 16. ISO–SWS spectra for R Scl and R Scl.

Fig. 17. ISO SWS spectrum for TU Tau and the re-constructed spectrum from S Sct. The inset presents the UIR band emission in TU Tau. Indicated with the dotted dashed lines are the centers of the UIR bands. The units on the *Y*-axis have been chosen to emphasize the apparent spectral structure.

Fig. 18. ISO SWS spectrum for TU Tau and the re-constructed spectrum from VX And. The inset presents the UIR band emission in TU Tau. Indicated with the dotted dashed lines are the centers of the UIR bands. The units on the *Y*-axis have been chosen to emphasize the apparent spectral structure.