

# The origin of silicate carbon stars: ISO/SWS observation of V778 Cygni\*

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Received 6 March 2000 / Accepted 15 September 2000

**Abstract.** The origin of silicate carbon stars has been a mystery ever since their discovery. We discuss here a full grating spectrum between 2.4 and 45  $\mu\text{m}$  of the silicate carbon star V778 Cyg obtained by the ISO/SWS. The spectrum, taken about 14 years after the IRAS LRS observation, confirms the complex nature of the object. The spectrum is clearly divided into a short wavelength ( $\lambda < 6.5 \mu\text{m}$ ), carbon-rich part and long-wavelength, oxygen-rich part. No obvious change of the 10 and 18  $\mu\text{m}$  silicate features is observed between IRAS and ISO spectra, indicating that the silicate dust is in a steady structure. The 2.7  $\mu\text{m}$  H<sub>2</sub>O band and the 15  $\mu\text{m}$  CO<sub>2</sub> bands are tentatively detected. The near-infrared part of the spectrum indicates that the present-day mass-loss rate is very low. The silicate features can only be fitted by optically thin dust emission from sub-micron size grains. The total oxygen-rich dust mass seen at infrared wavelengths is  $2\text{--}10 \times 10^{-6} M_{\odot}$ , of which  $3\text{--}50 \times 10^{-8} M_{\odot}$  is warm (300–600 K). If the dust is heated by radiation from the central star, the dust should be located as close as about 12 stellar radii from the star. We suggest that the dust responsible for the emission features is in a steady outflow from the system. We show that the dust cannot be located in a circum-binary disk, but is stored in a disk around the companion star during the previous O-rich mass-loss phase. The duration of silicate emission is estimated as  $\sim 10^4$  yr. It is compatible with the fact that not all J-type carbon stars show silicate emission. The evolution of the central star and formation of the disk in AGB binary systems largely depends on the orbital separation. V778 Cyg and other “IRAS discovered” silicate carbon stars probably have wide orbits. In such a case, a disk is formed around the companion. Close-binary systems such as the Red Rectangle form massive equatorial O-rich disks, and the evolution of the central star is largely influenced by the binarity.

**Key words:** stars: AGB and post-AGB – stars: carbon – stars: circumstellar matter – stars: individual: V778 Cyg – infrared: stars

## 1. Introduction

Silicate carbon stars were first discovered in studies of IRAS LRS (Low-Resolution Spectrometer) spectra (Willems & de Jong 1986; Little-Marenin 1986). The LRS spectra of these carbon stars exhibit emission features of amorphous silicate dust at 10 and 18  $\mu\text{m}$ , typical for an oxygen-rich environment. Subsequently, H<sub>2</sub>O and OH masers were detected from some silicate carbon stars (Nakada et al. 1987; Little-Marenin et al. 1988, 1994; te Lintel Hekkert et al. 1991; Engels & Leinert 1994), confirming the O-rich chemistry in the circumstellar material of these stars. No detection of SiO or HCN pure-rotational lines has been reported (Little-Marenin et al. 1994). Further searches in the LRS data (Chan & Kwok 1991; Kwok & Chan 1993; Kwok et al. 1997) have resulted in the discovery of 19 stars in this peculiar class.

The nature of the silicate carbon stars is still unclear. Little-Marenin (1986) proposed that the objects are binaries consisting of a carbon-rich and an oxygen-rich giant. This idea is now thought to be unlikely, since there is no evidence of O-rich giants in the objects from spectroscopic observations (Lambert et al. 1990) or infrared speckle interferometry (Engels & Leinert 1994). Willems & de Jong (1986; also Chan & Kwok 1991) suggested that these objects have just experienced a transition from oxygen-rich to a carbon star by a recent ( $\leq 100$  years) thermal pulse, and that the oxygen-rich matter is the remnant of a previous mass-loss phase. This quick transition model has also been criticized, especially from the evolutionary point of view (Lloyd Evans 1990).

The most widely accepted idea nowadays to explain the phenomenon is the following (Morris 1987; Lloyd Evans 1990). Suppose these are all binaries with an unseen companion star, probably a main-sequence star. While the star was an oxygen-rich giant, some portion of the mass ejected was captured and stored in a disk around the companion star. Then, the central

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\* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA. The SWS is a joint project of SRON and MPE.

star experienced thermal pulses and evolved to a carbon star. The numerical calculations by Mastrodemos & Morris (1998) show that a permanent disk around the companion can actually be formed. On the other hand, Kahane et al. (1998) proposed a circum-binary reservoir, i.e. a disk surrounding the whole system. Radial velocity variations have been detected in two silicate carbon stars, BM Gem and EU And (Barnbaum et al. 1991), confirming the binarity of these objects.

It is known that most, if not all, silicate carbon stars are J-type carbon stars, i.e. carbon stars with enhanced  $^{13}\text{C}$  and depletion of *s*-process elements (Willems & de Jong 1986; Lloyd Evans 1990). However, not all J-type carbon stars show silicate dust features.

Observations with the Infrared Space Observatory (ISO; Kessler et al. 1996) have revealed that many evolved stars show evidence of a complex chemistry in their circumstellar material. Waters et al. (1998) reported that the spectrum of a post-AGB binary system, the Red Rectangle, taken by the Short-Wavelength Spectrometer (SWS; de Graauw et al. 1996), shows both Polycyclic-Aromatic Hydrocarbons (PAH) features and crystalline silicate features. Mid-infrared images show that the PAH features arise from the bipolar mass flow, i.e. oxygen-rich materials are probably located in the equatorial disk, while PAHs are in the present-day stellar wind. Another remarkable example is IRAS 09425–6040 (Molster et al. 2000). The nature of this object is not well understood. The SWS spectrum up to  $\sim 15 \mu\text{m}$  looks like that of a *normal* carbon star with a moderate mass-loss rate, showing a clear SiC dust feature at  $11.3 \mu\text{m}$ . However, the spectrum longward of  $15 \mu\text{m}$  is dominated by strong crystalline silicate bands. Indeed, the object has the highest fraction of crystalline silicates (about 75 percent of the silicate is in crystalline form) that has ever been observed by ISO. The presence of a circumstellar disk is strongly suggested in order to achieve such a high rate of crystallization (Molster et al. 1999). Trams et al. (1999) report the discovery of a silicate carbon star IRAS 04496–6958 in the Large Magellanic Cloud, although it is still not clear that this object has the same origin as the silicate carbon stars in our Galaxy.

Thanks to its large wavelength coverage and improved spectral resolution, observations with the ISO/SWS are expected to provide further information to clarify the nature of the silicate carbon stars. Unfortunately, many silicate carbon stars bright enough for SWS spectroscopy were not visible during the life span of ISO. The only available star, V778 Cyg, was observed in the guaranteed time programme AGBSTARS (P.I. T. de Jong). V778 Cyg is of spectral type C4,5J (Yamashita 1975).  $\text{H}_2\text{O}$  and OH masers have been detected (Nakada et al. 1987; Little-Marenin et al. 1988; Deguchi et al. 1988; Engels & Leinert 1994).

In this paper, we present the result of the ISO/SWS observation of V778 Cyg both on the dust features (Sect. 3) and the molecular features (Sect. 4). A possible origin of the silicate emission is proposed (Sect. 5). The formation and stability of disks in binary systems (Sect. 6), and possible solutions for V778 Cyg and other objects are discussed (Sect. 7). Finally, we elaborate on the nature of the silicate carbon stars (Sect. 8).

## 2. Observational data

V778 Cyg was observed on 1997 May 1, using the SWS full-grating scan mode (AOT 01, speed 3). The spectrum covers the wavelength range between  $2.38\text{--}45.2 \mu\text{m}$  with a resolution  $\Delta\lambda/\lambda \sim 600$ . The data were reduced in July 1999 using the SWS Interactive Analysis package developed by the SWS Instrument Dedicated Team, using the latest calibration parameters and procedures. Small residuals in flux level between different instrumental bands are corrected by scaling the bands with respect to band 1B ( $2.6\text{--}3.0 \mu\text{m}$ ). The correction factor was always within a few percent in band 1 ( $< 4 \mu\text{m}$ ), up to 20 percent in band 2 ( $4\text{--}12 \mu\text{m}$ ), and 5–10 percent in band 3 ( $> 12 \mu\text{m}$ ). The additional stars used in this study are all processed in the same manner.

Fig. 1 shows the ISO/SWS spectrum of V778 Cyg between  $2.38 \mu\text{m}$  and  $27.5 \mu\text{m}$ . The bands 3E and 4 ( $\geq 27.5 \mu\text{m}$ ) are not shown because of low quality. In Fig. 1 two other stars are also shown for comparison: the O-rich Mira variable *o* Cet with “typical” silicate emission bands at  $10$  and  $18 \mu\text{m}$ , and the carbon star RY Dra with the same spectral type (C4,5J, Yamashita 1975) as V778 Cyg but without silicate emission. Both stars were observed in the same mode (AOT01 speed 3).

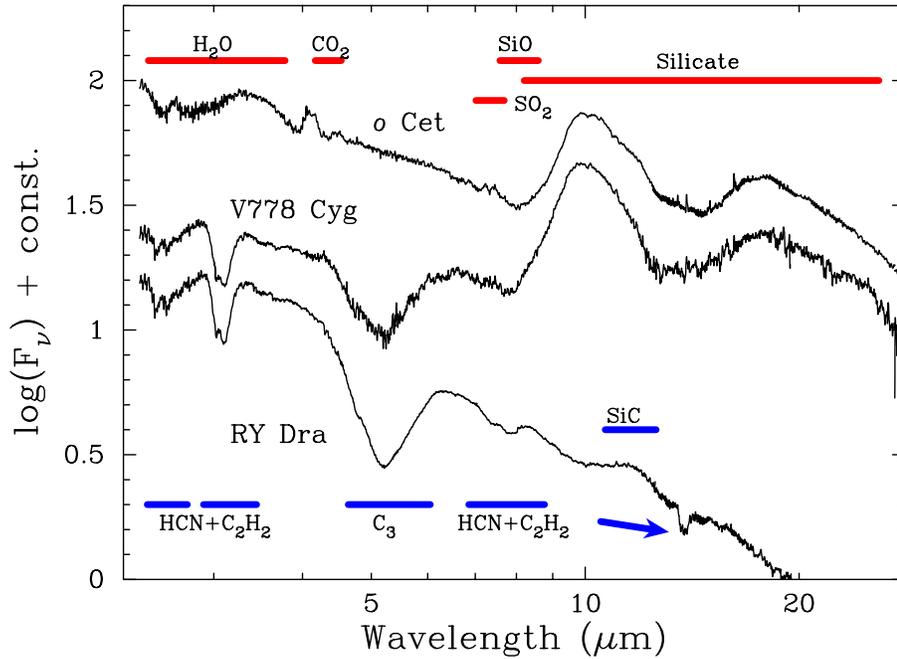
A comparison of these three spectra reveals the complexity of V778 Cyg. The spectrum up to  $\sim 6.5 \mu\text{m}$  is almost identical to that of the carbon star, RY Dra, characterized by the carbon-bearing molecular features. On the other hand, the spectrum of V778 Cyg longward of  $\sim 6.5 \mu\text{m}$  is dominated by strong silicate emission. No obvious molecular features longward of  $6.5 \mu\text{m}$  either O-rich or C-rich, are recognized in the spectrum (but see the discussion in Sect. 4).

## 3. The silicate dust features in V778 Cyg

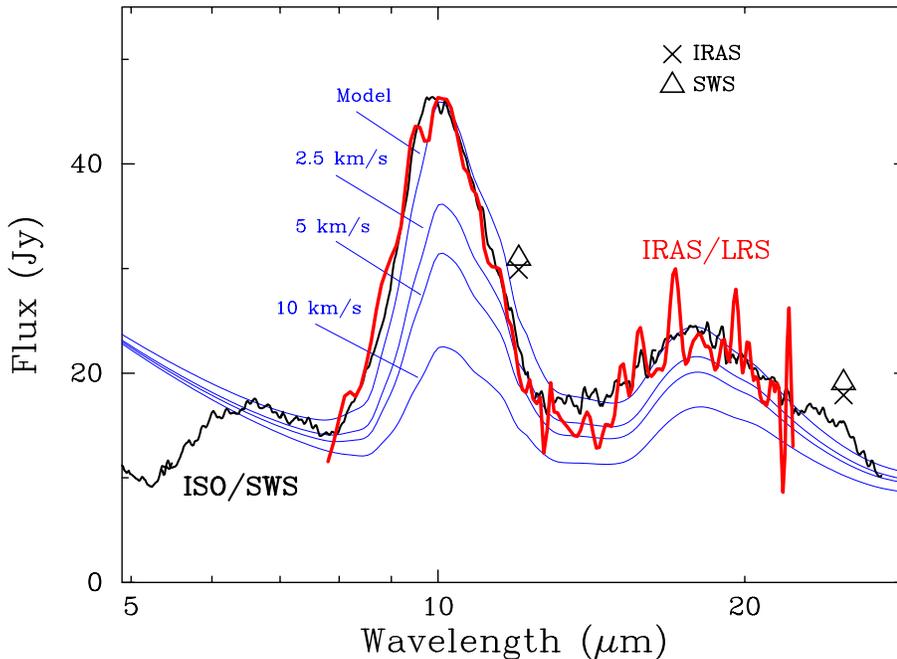
The present ISO/SWS spectrum is compared with that taken by the IRAS/LRS (Fig. 2). LRS data were retrieved from the Groningen IRAS data server<sup>1</sup> and reduced using the standard procedures of GIPSY (van der Hulst et al. 1992). The spectrum is scaled with respect to the IRAS  $12 \mu\text{m}$  flux. The SWS spectrum and the LRS spectrum perfectly agree in the wavelength region between  $8\text{--}23 \mu\text{m}$ . Also, the corresponding flux for the IRAS  $12$  and  $25 \mu\text{m}$  filters measured on the present ISO/SWS spectrum ( $31.0$  and  $19.1$  Jy, respectively) are consistent with those of the IRAS measurement ( $29.9$  and  $17.9$  Jy).

The IRAS and ISO observations were carried out with an interval of about 14 years. The central star is a semi-regular variable with a period of  $\sim 300$  days and amplitude of  $\Delta V = 0.3\text{--}0.5$  mag (Little-Marenin et al. 1992; Alksnis & Žaime 1993). The variation of the silicate features due to variability of the central

<sup>1</sup> The IRAS data were obtained using the IRAS data base server of the Space Research Organisation of the Netherlands (SRON) and the Dutch Expertise Centre for Astronomical Data Processing funded by the Netherlands Organisation for Scientific Research (NWO). The IRAS data base server project was also partly funded through the Air Force Office of Scientific Research, grants AFOSR 86-0140 and AFOSR 89-0320.



**Fig. 1.** The ISO/SWS spectrum of V778 Cyg compared with the spectra of the O-rich giant *o* Cet, and with the J-type carbon star RY Dra. Major molecular/dust features are indicated. The spectra of *o* Cet and RY Dra are scaled arbitrarily in flux. The spectrum of V778 Cyg shortward of  $\sim 6.5 \mu\text{m}$  is almost identical to that of RY Dra, while the spectrum longward of that wavelength, in particular the silicate emission, is quite similar to *o* Cet.



**Fig. 2.** The silicate emission bands in the spectra of V778 Cyg observed by the ISO/SWS and the IRAS/LRS. The LRS is scaled on the basis of IRAS  $12 \mu\text{m}$  photometry flux. The agreement between the two spectra is remarkable. The IRAS 12 and  $25 \mu\text{m}$  photometry flux ( $\times$ ) and corresponding flux measured on the present SWS spectrum ( $\triangle$ ) also agree very well. The thin lines indicate dust model spectra, and the expected change of the dust features during 14 years, assuming that the dust is in a detached shell expanding with velocities as indicated.

star is thus expected to be small (cf., Onaka et al. 1998). Therefore, the similarity of the two spectra separated by 14 years indicates that the dust is in a steady state.

In order to estimate the dust mass in V778 Cyg, we have modeled the observed spectrum by single temperature, optically thin dust emission. The dust opacity “set 1” (warm O-deficient circumstellar silicate) in Ossenkopf et al. (1992) is applied. The  $10 \mu\text{m} / 18 \mu\text{m}$  peak intensity ratio requires a lower limit to the dust temperature of 300 K. The dust mass in this case is  $5 \times 10^{-7} M_{\odot}$ . In order to satisfy the IRAS  $60 \mu\text{m}$  flux level (1.94 Jy), an additional  $8 \times 10^{-6} M_{\odot}$  with a temperature of

100 K is required. A similar profile can also be obtained with a combination of  $3 \times 10^{-8} M_{\odot}$  of 600 K and  $2 \times 10^{-6} M_{\odot}$  of 200 K dust.

We emphasize that the dust emission observed in V778 Cyg must be optically thin. Once the dust component becomes optically thick, the  $10 \mu\text{m}$  and  $18 \mu\text{m}$  feature profiles get distorted. Also, the dust grains showing the silicate features should not be larger than  $1 \mu\text{m}$ , in order to satisfy the Rayleigh limit.

We also modeled the spectrum by a single, uniform shell with a constant mass-loss rate (i.e. the density in the shell changes proportional to  $r^{-2}$ ). The central star is assumed to

be a 2500 K blackbody with a radius of  $R_* = 3 \times 10^{13}$  cm, and the dust temperature is calculated by solving the radiative equilibrium in the optically thin dust shell. The inner radius of the shell is  $12 R_* = 3.6 \times 10^{14}$  cm, where the dust temperature is about 600 K. The outer radius is not well constrained, but  $2300 R_*$  gives a reasonable flux level at  $60 \mu\text{m}$ . The present model parameters give a distance to the star of 1.4 kpc. The spectrum of V778 Cyg is quite well fitted by this simple spherical model (Fig. 2). In the figure, we plot the expected change of the silicate feature in 14 years, if the silicate dust is in an expanding detached shell. Even for an expansion velocity of  $2.5 \text{ km s}^{-1}$ , the change is significant, which is not observed. The total dust mass in the shell is  $1 \times 10^{-5} M_\odot$ . This value depends largely on the adopted outer radius of the shell. If we ignore the  $60 \mu\text{m}$  flux and fit only in the SWS spectral range, the minimum outer radius allowed is  $\sim 500 R_*$ . The total dust mass is then  $2 \times 10^{-6} M_\odot$ , i.e. similar to what was found above.

In summary, the silicate dust features in V778 Cyg are fitted by optically thin dust emission from *normal* sub-micron size grains. The total dust mass is  $2\text{--}10 \times 10^{-6} M_\odot$ , of which  $3\text{--}50 \times 10^{-8} M_\odot$  is warm (300–600 K).

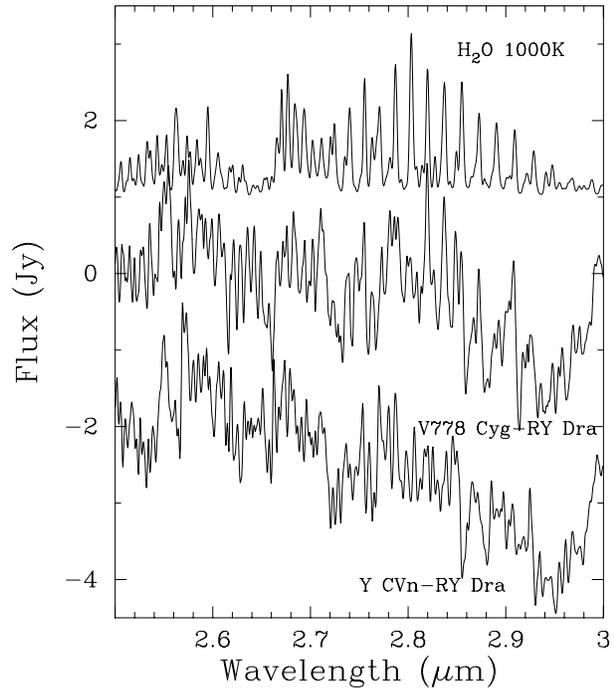
#### 4. Molecular features

As described in Sect. 2, the spectrum of V778 Cyg shortward of about  $6.5 \mu\text{m}$  indicates the carbon-rich nature of the central star. All the molecular features recognized in RY Dra, mainly due to  $\text{C}_2\text{H}_2$ , HCN,  $\text{C}_3$ , are also seen in V778 Cyg. On the other hand, the O-rich molecules observed in *o* Cet such as  $\text{H}_2\text{O}$ , SiO,  $\text{CO}_2$ ,  $\text{SO}_2$  (Yamamura et al. 1999a, 1999b) are not seen in V778 Cyg. This confirms the absence of a nearby O-rich giant star within the SWS aperture ( $14'' \times 20''$  for the instrumental band 1 & 2 ( $\leq 12.0 \mu\text{m}$ )).

The  $5.2 \mu\text{m}$   $\text{C}_3$  band is a good indicator of the mass-loss rate of carbon stars (Yamamura et al. 1998). The band is very strong when the mass-loss rate is lower than  $10^{-7} M_\odot \text{ yr}^{-1}$ , while it almost disappears in the stars with  $\dot{M} \sim 10^{-6} M_\odot \text{ yr}^{-1}$ . The near-infrared color temperature can also be used to estimate the present-day mass-loss rate (Willems & de Jong 1988; Groenewegen et al. 1992; Yamamura et al. 1998). The resemblance of V778 Cyg to RY Dra; a deep  $\text{C}_3$  feature and high ( $> 2000$  K) color temperature, strongly suggests that the present-day mass-loss rate of V778 Cyg is very low, of the order of  $10^{-8} M_\odot \text{ yr}^{-1}$ .

In Yamamura et al. (1997), we reported the non-detection of oxygen-rich molecular bands in the near-infrared part of the SWS spectrum of V778 Cyg. The improvement of data reduction techniques and new data since the previous study motivate us to analyze the data again in more detail.

In order to search for weak molecular features embedded in the strong C-rich molecular bands, we compare the spectrum of V778 Cyg with RY Dra. The comparison is done in the band 1 ( $< 4 \mu\text{m}$ ) region, where both spectra have the highest quality ( $\text{S/N} > 100$ ). The spectrum of RY Dra is scaled to the flux level of V778 Cyg at  $\sim 2.7 \mu\text{m}$ , then subtracted from the V778 Cyg spectrum. The result is presented in Fig. 3. For comparison, we also plot the synthesized spectrum of  $\text{H}_2\text{O}$ . The spectrum is

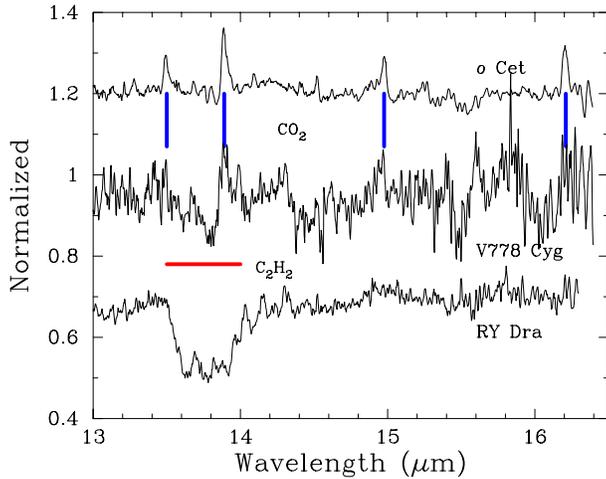


**Fig. 3.** Residual spectra of V778 Cyg (*middle*) and Y CVn (*bottom*) with respect to the J-type template star RY Dra, after scaled at  $2.7 \mu\text{m}$ . The spectrum of Y CVn is scaled by 1/50 to match the flux level of V778 Cyg. The residual shows sharp emission lines, which may correspond to the  $\text{H}_2\text{O } \nu_3$  band. The  $\text{H}_2\text{O}$  model spectrum (*top*) is calculated assuming LTE at  $T_{\text{ex}} = 1000$  K. The correlation co-efficient between the residuals and the model  $\text{H}_2\text{O}$  spectrum between  $2.65$  and  $2.95 \mu\text{m}$  is  $0.55$  for V778 Cyg, and  $0.27$  for Y CVn.

calculated assuming local thermodynamic equilibrium (LTE) at an excitation temperature of 1000 K. The temperature is very crudely estimated from the lines which might be seen in the spectrum. The residual spectrum of V778 Cyg – RY Dra shows some sharp peaks at the positions of  $\text{H}_2\text{O}$  lines. In order to check the reliability of the detection, we show the results of the same procedure for another J-type carbon star Y CVn (C5,5J, Yamashita 1975). The object was observed using AOT07 (full resolution grating scan). The residual of Y CVn – RY Dra does not show the  $\text{H}_2\text{O}$  features that appear in V778 Cyg. The correlation co-efficient between the residual spectra and the  $\text{H}_2\text{O}$  model spectrum calculated between  $2.65$  and  $2.95 \mu\text{m}$  are  $0.55$  for V778 Cyg, and  $0.27$  for Y CVn, respectively. Although the detection is quite marginal, the result is consistent with the fact that the star shows  $\text{H}_2\text{O}$  maser emission at radio wavelengths.

The intensities of the lines do not agree well with the model spectrum. This may be due to the remaining carbon-rich molecular features. However, it is also likely that the molecules are not in LTE, and are radiatively excited (Gonzalez-Alfonso & Cernicharo 1999).

Fig. 4 shows the spectra of V778 Cyg and two reference stars between  $13.0$  and  $16.5 \mu\text{m}$ . The spectra are normalized to the local *continuum* in the wavelength range. The star *o* Cet shows  $\text{CO}_2$  emission bands at  $13.9$ ,  $15.0$ ,  $15.4$ , and  $16.2 \mu\text{m}$  etc. (Justtanont et al. 1998). Although the low S/N ratio of the



**Fig. 4.** The continuum normalized spectra of V778 Cyg, *o* Cet, and RY Dra between 13.0 and 16.5  $\mu\text{m}$  are shown. Emission bands of  $\text{CO}_2$  are tentatively detected, indicating the presence of O-rich molecules. There is a weak and rather broad dip around 13.7  $\mu\text{m}$ , which can be interpreted as photospheric  $\text{C}_2\text{H}_2$  absorption diluted by the silicate dust emission.

V778 Cyg spectrum does not allow us to make a clear statement, the bands are tentatively detected in the object. These  $\text{CO}_2$  bands are nicely reproduced with  $T_{\text{ex}} = 1000$  K optically thin  $\text{CO}_2$  gas. As is always the case for oxygen-rich stars, the 15  $\mu\text{m}$  fundamental band is weak relative to the 14 and 16  $\mu\text{m}$  satellite bands.

Between 13.5 and 14.0  $\mu\text{m}$  there is a shallow and broad dip in the spectrum of V778 Cyg. This might be the photospheric  $\text{C}_2\text{H}_2$  band veiled by the strong silicate emission. By comparing with RY Dra, we estimate that the dust emission in V778 Cyg is about 5 times larger than the stellar flux at this wavelength range, i.e. the observed depth of the 14  $\mu\text{m}$  feature is  $\sim 1/5$  of that expected for the photosphere only. On the other hand, cool  $\text{C}_2\text{H}_2$  molecules in the outer atmosphere and the circumstellar envelope produce a narrow absorption feature centered at 13.7  $\mu\text{m}$  (Yamamura et al. 1998; Aoki et al. 1999), which is not observed in the spectrum of V778 Cyg. This also supports our conclusion that the present-day mass-loss rate of the object is very low.

## 5. Origin of the silicate dust emission

On the basis of the ISO/SWS observation of V778 Cyg, two early ideas for the origin of the silicate features associated with carbon stars can be rejected. No evidence for an O-rich giant companion is found (Little-Marenin 1986). The stability of the silicate features in 14 years is not in agreement with the fact that the silicate dust is in a detached expanding envelope, which is the remnant of an O-rich phase continued until quite recently (Willems & de Jong 1986).

Skinner et al. (1990) suggested that a chemical instability in the outflow may occur if the C/O ratio of the central star is close to unity. Furthermore, Yamamura et al. (1999c) discussed the possibility that the chemistry in the outflow could be influenced

by the secondary, when the C/O ratio of the primary is close to 1 and the secondary provides a certain amount of oxygen in the outflow. This is not likely, since the present-day mass-loss rate of the primary should be much smaller than that derived from the O-rich dust model (Sect. 4). Also, the SWS spectrum of V778 Cyg confirms that the central star is rather carbon-rich (cf., Aoki et al. 1998), and the companion would need to provide an unrealistically high amount of oxygen to reverse the C/O ratio locally.

The observed SWS spectrum and modeling of the silicate dust features lead us to conclude; (1) the silicate dust must be in a steady structure, (2) the dust temperature is as high as 600 K, (3) the dust emission should be optically thin, and (4) dust grains are *normal* sub-micron size.

These results are to some extent mutually contradictory. If the dust is heated by the radiation from the AGB star, (2) implies that it is located at a distance of only 12  $R_*$ . This setting is very similar to that of a mass-losing AGB star in which the dusty wind material is expelled by radiation pressure at velocities of 5–20 km/s. We will show in the next section that it is impossible to keep sub-micron dust grains in an optically thin setting close to an AGB star. Instead we suggest that the material which produces the observed silicate features is indeed being driven out in an outflow, but that the material is continuously replenished from a reservoir at or inside 12  $R_*$ . Since the star is now carbon-rich, the oxygen-rich material must originate from a reservoir which was filled during an earlier phase of the star’s evolution. A similar idea has been proposed by Jura & Kahane (1999). It has been suspected for some time that a binary system can provide such a storage mechanism, and it is usually assumed that the storage occurs in a disk (e.g. Morris 1987).

In the following section we present a general and quantitative discussion of the formation of disks in AGB binary systems. Then, we apply the arguments to the case of V778 Cyg. Our basic assumption that the primaries of silicate carbon stars are in the AGB phase, will be discussed in Sect. 8 with a possible evolutionary scenario of these objects.

## 6. The location of the oxygen-rich reservoir

Let us to consider a binary system consisting of an AGB star and a main-sequence companion. In such a binary system, there are 3 possible locations for a disk which can be used to store material.

1. A circum-binary disk: a disk surrounding the whole binary system.
2. A circum-primary disk: a disk around the primary (AGB) star, but inside the orbit of the secondary.
3. A disk around the secondary (main-sequence companion) star.

It is clear that the interaction with the companion star must be responsible for the formation of the disk. Depending on the separation of the two stars we can distinguish two main groups of systems with different mechanisms for disk formation. If the system is a close-binary, the AGB size of the primary will reach

or exceed the diameter of the system. In this case a massive interaction between the AGB star and the secondary has to be expected which will severely affect the mass-loss rate, evolution, and geometry of the system. These processes are not well understood today, but it seems feasible that a massive circum-binary disk may be formed in a very short time by this process.

If the separation between the two stars is much larger than the AGB size of the star, the direct influence of the secondary on the mass-loss process will be limited. The formation of an O-rich disk in this case needs to rely on an interaction of the secondary with the *stellar wind* from the AGB star. As we will show in the following, it is unlikely that such an interaction can produce a significant dusty *circum-binary* or *circum-primary* disk. Instead, the formation of a disk around the *secondary* is the more likely scenario.

### 6.1. Capturing a wind into a circum-binary disk

#### 6.1.1. Effects of radiation pressure

The wind from an AGB star contains dust grains formed within the wind, typically at a dust-to-gas ratio of  $f_{\text{dust/gas}} \lesssim 10^{-2}$  by mass.

If we ignore optical depth effects, the acceleration of a dust grain due to the stellar radiation is  $g_{\text{rad}} = 3L_p Q / (16\pi r_p^2 a c \rho_{\text{dust}})$ , where  $L_p$  is the luminosity of the primary,  $a$  the dust grain radius,  $r_p$  the distance from the primary,  $\rho_{\text{dust}}$  the specific density of the grain material and  $Q$  is the extinction efficiency of the dust averaged over the primary's stellar spectrum ( $Q \sim 0.2$  for the dust opacity in Ossenkopf et al. (1992) and a 2500 K blackbody). Comparing this acceleration with the gravitational acceleration from the star  $g_{\text{grav}} = GM_p/r_p^2$ , we find the well-known equation

$$\beta_{\text{dust}} = \frac{3L_p Q}{16\pi GM_p c a \rho_{\text{dust}}} = 1146 \frac{L_p}{10^4 L_\odot} \frac{1 M_\odot}{M_p} \frac{Q}{0.2} \frac{1 \mu\text{m}}{a} \frac{1 \text{g/cm}^3}{\rho_{\text{dust}}}. \quad (1)$$

Therefore, for an AGB star, the radiation pressure on grains exceeds the gravitational attraction from the star by a factor of a thousand. Since the absorption coefficient of the gas can be ignored when compared to the dust, the value for  $\beta$  for the gas/dust mixture is  $\beta \approx \beta_{\text{dust}} \times f_{\text{dust/gas}}$ . If dust and gas are momentum coupled, the radiative acceleration of the dust-gas mixture is still 10 times higher than the gravitational acceleration from the star. The net force on the material is directed outwards, and radiation pressure on dust grains with momentum coupling of dust and gas can drive a wind.

In order to form a circum-binary disk, the secondary must interact with the wind originating from the primary, stop the outward motion of the material and add angular momentum to make the material orbit the system. However, even if the interaction between the wind and the secondary manages to bring the outward velocity down to zero, the radiative force will still act on the material. Lets assume the material stops right outside the orbit of the secondary. In order to stabilize

the material, the secondary must be able to interact with the material repeatedly every orbit. We may now ask how long it takes to move the material out to twice its distance and compare the result with the orbital time of the secondary. If the material starts out with velocity zero at the distance  $r_0$  from the star and experiences an acceleration  $(GM_p/r_p^2) \cdot (\beta - 1)$ , one can show that the time to reach a distance  $2r_0$  is given by

$$t_2 = \frac{r_0^{3/2}}{\sqrt{GM_p(\beta - 1)}} \left( 1 + \frac{\ln \sqrt{2}}{\sqrt{2}} \right). \quad (2)$$

Comparing this with the orbital period around the primary at a distance  $r_0$ ,  $t_k = 2\pi \sqrt{r_0^3/(GM_p)}$ , we find  $t_2/t_k \approx 1/(5\sqrt{\beta - 1}) \ll 1$ . Therefore the material will be removed from the vicinity of the secondary very quickly, and repeated gravitational interaction cannot be efficient in stabilizing the wind material in a circumstellar disk. A very similar analysis shows that it will not be possible to stabilize a disk of material inside the orbit of the secondary (i.e. a circum-primary disk).

The arguments above do not apply to an interaction between the stars in a close-binary system. First, the material pulled out from the AGB star in a close-binary system may contain little or no dust. The dust in these disks which is seen today may have formed later inside the disk as it cooled down. Even if the material does contain dust at a high concentration, it is possible that enough matter is removed in a single sweep for the forming disk to immediately become optically thick. In this case the radiation pressure from the primary will only act on the inner surface of the disk instead of the whole volume. Since  $\beta$  in the optically thin case is about 10, an optical depth of about 3 will be sufficient to shield the optically thick parts of the disk from the radiation of the primary, and the driving out of the material will be much slower. However, the dust grains would still receive enough radiation to drift through the gas disk with a speed of several km/s. An optical depth above 7 would be sufficient to drop  $\beta_{\text{dust}}$  below unity in the optically thick part of the disk. Under these conditions, the disk could be stable for an extended period of time. While the interaction of a wind with a distant companion certainly cannot produce such dense material, it seems possible that the massive interaction in a close-binary like the Red Rectangle can do so, and this may be the reason for the existence of a circum-binary disk in such close-binary systems.

#### 6.1.2. Large grains and coagulation

Another possibility to produce a stable orbiting cloud of dust grains is to increase the grain size. Sufficiently large grains absorb less radiation per unit mass, so that the radiative acceleration cannot exceed the gravitational acceleration. From Eq. (1) we see that this would require dust grains with radii in the range of cm. While such dust grains would not be driven out of the system by radiation pressure, this scenario meets other severe problems.

Even if the grains do not feel the radiation pressure, they can still be driven out by the drag force in a passing wind. Therefore the grains need to be stored in a protective environment during

the high mass-loss phase of the wind. Furthermore, the particles cannot grow to these large sizes by the normal chemical growth in the AGB wind (Dominik et al. 1989). Growth therefore must happen by coagulation. However, growth by coagulation initially leads to fluffy aggregates which do not significantly reduce the mass absorption coefficient (Dominik & Tielens 1997; Wurm & Blum 1998). Therefore, initial dust coagulation does not stabilize the grains at all. In order to grow up to large sizes, the grains need to be in an environment of sufficient density for a long time. An AGB wind does not provide such an environment, but a circumstellar disk can. To grow  $0.1 \mu\text{m}$  sized grains to compact cm-sized grains, at least 50 collisions are necessary (with mass-doubling in every collision). We can estimate the collision time scale in a disk in which the motion of the dust is not governed by its interaction with the gas. We consider the dust to be distributed in a cylindrical torus ranging from  $r_1$  to  $r_2$ . The particles fly in this cylinder on inclined orbits. Assuming circular orbits, the collisions are only due to the vertical motion of the grains, which is caused by the orbital inclinations. During each orbit a particle crosses the midplane twice and therefore can collide with the total surface dust density twice per orbit.

The Kepler velocity at the outer side of the cylinder is  $v_k = \sqrt{GM_p/r_p}$  and the time for one orbit is  $t_k = 2\pi\sqrt{r_p^3/GM_p}$ . If we distribute a dust mass  $M_{\text{dust}}$  of grains with a radius  $a$  in that cylinder, the total cross section of that dust is  $A_{\text{dust}} = N_{\text{dust}}\pi a^2 = 3M_{\text{dust}}/4\rho_{\text{dust}}$ . The collision probability during a single orbit is then 2 times the ratio between the total dust cross section and the cross section of the cylinder which contains the mass. The collision time scale is then

$$\begin{aligned} t_{\text{coll}} &= \frac{t_k}{p_{\text{coll}}} = \frac{4\pi^2}{3} \frac{a\rho_{\text{dust}}}{\sqrt{GM_p}} \frac{1}{M_{\text{dust}}} r_p^{7/2} \\ &= 7.45 \text{ yr} \frac{a}{1 \mu\text{m}} \frac{\rho_{\text{dust}}}{1 \text{ g/cm}^3} \left( \frac{1M_{\odot}}{M_p} \right)^{1/2} \\ &\quad \times \frac{10^{-8}M_{\odot}}{M_{\text{dust}}} \left( \frac{r_p}{10 \text{ AU}} \right)^{7/2}. \end{aligned} \quad (3)$$

Thus, collisions will have timescales of years, when the dynamical influence of the gas is neglected. Note that the time calculated is only the time for the first collision — later collisions will have still larger time scales due to the loss of total dust surface area in the coagulation process. Since as we have shown above, the wind and radiation pressure will drive out the material, on the timescale of a single orbit, there is not enough time to produce large grains which could be in a stable orbit.

If the disk is dominated by gas, then dust coagulation will have to rely on Brownian motion and on drift velocities due to settling or orbital decay. Brownian motion produces only very small relative velocities between dust grains, and the collision times will be much longer than calculated above. If the relative velocities are dominated by dust settling like in a proto-planetary disk, a dust grain can only collide with half the surface density of dust in the disk while settling to the midplane. The collision time scale due to dust settling will also be longer than the timescale calculated above for a gas-free disk.

Using a very similar calculation, Jura & Kahane (1999) concluded that there are enough collisions during the estimated lifetime of such a system to produce large grains and to stabilize the orbits in this way. However, they implicitly assume a stable disk which allows the dust grains to complete many orbits. This model therefore fits much better the situation in systems like the Red Rectangle and may indeed explain the large grains observed there. However, as we have shown above, this is not a valid process to stabilize the grains in the first place.

## 6.2. Capturing a wind into a companion disk

### 6.2.1. Stability of the disk around the secondary

For the stability of the disk around the secondary with respect to radiation pressure from the primary, we can use the equations derived above, with a slight modification. While the radiation pressure is still governed by the luminosity and distance from the primary, the gravitational force is determined by the mass ( $M_s$ ) of the secondary and the distance ( $r_s$ ) between the dust and the secondary. Thus we immediately find

$$\begin{aligned} \beta_{\text{dust}}^{(2)} &= \frac{3L_p Q r_s^2}{16\pi G M_s c a \rho_{\text{dust}} r_p^2} \\ &= 1146 \frac{L_p}{10^4 L_{\odot}} \frac{1M_{\odot}}{M_s} \frac{Q}{0.2} \frac{1 \mu\text{m}}{a} \frac{1 \text{ g/cm}^3}{\rho_{\text{dust}}} \left( \frac{r_s}{r_p} \right)^2. \end{aligned} \quad (4)$$

The dust can be in a stable orbit around the secondary if  $\beta_{\text{dust}}^{(2)}$  is below unity. For the quantities given in Eq. (4) this means that  $r_s/r_p \leq 0.03$ . Dust grains that close to the secondary can be in stable orbits and the radiation pressure of the primary will not be able to blow them out of the system.

The gas disk around the secondary can grow much bigger. Given the fact that  $\beta_{\text{gas}}$  is typically 0.4 for a  $1M_{\odot}$  star (Helling 1999), it is clear that the size of the gas disk around the secondary is not limited by the radiation pressure on the gas in the disk, but by the tidal interaction with the primary and by the ram pressure of the stellar wind. Presumably, in the beginning, the disk was formed at the region closest to the companion star, where gravity is strong enough to keep dust grains in stable orbits. With time, the gas disk grew and became optically thick, so that even small dust grains can be stored in the much larger disk. Numerical calculations of disk accretion in binary systems show that the size of the disk reaches of the order of 10 percent of the system size (Mastrodemos & Morris 1998).

### 6.2.2. Accretion of wind material onto disk around secondary

In this section we make a rough estimate of how much mass can be accreted onto the disk around the secondary. While this is a hydrodynamic problem, a simple estimate can be put forward by computing the gravitationally enhanced cross section of the secondary for wind material from the primary. After the disk formation has started, the geometrical cross section of the

secondary and its disk with a radius of  $r_d$  is  $\sigma_{\text{geom}} = \pi r_d^2$ . Gravitational focusing increases this to

$$\sigma = \pi p^2 \approx \pi r_d^2 \left( 1 + \left( \frac{v_{\text{esc}}(r_d)}{v_0} \right)^2 \right) \quad (5)$$

where  $v_0$  is the wind velocity (i.e. the initial velocity at which the wind material approaches the secondary) and  $v_{\text{esc}}(r_d) = \sqrt{2GM_s/r_d}$  is the escape velocity at the distance  $r_d$  from the secondary. The term with the squared velocities is the Safronov factor for gravitational cross section enhancement (see e.g. Wetherill 1990). The cross section is dependent upon the velocity. Wind material which is arriving at a speed much exceeding the escape speed from the disk will only see the geometrical cross section. Slower material will see enhanced cross section. If we assume that the secondary is far enough from the primary so that the sphere sector surface covered by the cross section of the disk can be approximated by the circle  $\pi p^2$ , the fraction of the wind material collected by the secondary disk is

$$\begin{aligned} f_{\text{acc}} &= \frac{1}{4} \frac{r_d^2}{D^2} \left( 1 + \left( \frac{v_{\text{esc}}(r_d)}{v_0} \right)^2 \right) \\ &= \frac{1}{400} \left( \frac{10}{D/r_d} \right)^2 \\ &\quad \times \left( 1 + 17.7 \frac{M_s}{1M_{\odot}} \frac{r_d}{1\text{AU}} \left( \frac{10\text{km/s}}{v_0} \right)^2 \right) \end{aligned} \quad (6)$$

which is no more than a few percent for typical arrangements.

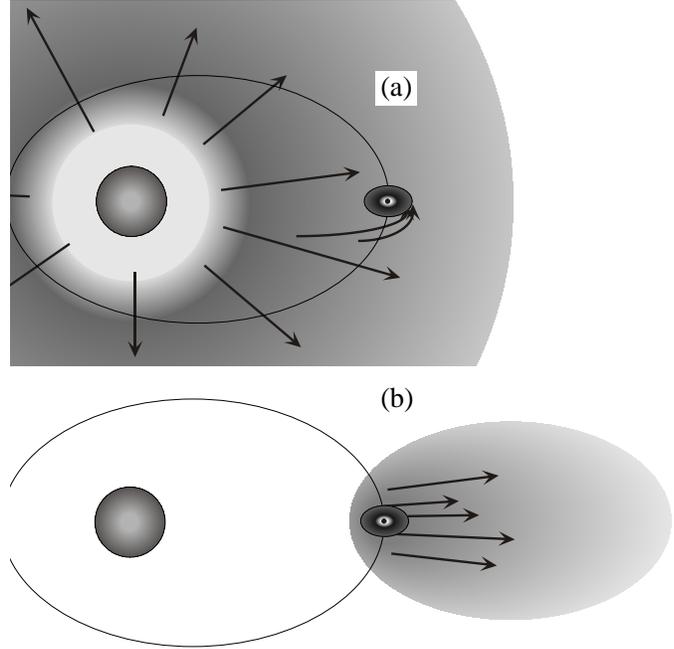
## 7. The dust disk of V778 Cyg

The arguments presented in the previous section suggests that the formation of the disk around the AGB binary system depends on the orbital separation: in a close-binary system, the strong binary interaction enables the formation of a circum-binary or circum-primary disk, while for the wide orbital separation, a disk around the secondary star can only be possible.

Which scenario is appropriate for V778 Cyg? We first note that there is no clear observational proof that V778 Cyg is a binary star. Careful radial velocity measurements by Barnbaum et al. (1991) only give an upper limit of  $1.5 \text{ km s}^{-1}$  for V778 Cyg. The other two similar stars they measured, BM Gem and EU And, show radial velocity variations of 6 and  $5 \text{ km s}^{-1}$ , respectively, in a period of about 500 days. The amplitude,  $v_p \sin i$ , of the primary's radial velocity variation in a binary system is (assuming circular orbits)

$$v_p \sin i = \sqrt{\frac{GM_s}{D}} \sqrt{\frac{M_s}{M_p + M_s}}, \quad (7)$$

where  $M_p$  and  $M_s$  are the masses of the primary and secondary,  $\sin i$  is the inclination and  $D$  is the distance between both stars. Assuming that the stars have both  $1 M_{\odot}$ , we find that the distance between the components is constrained by  $D/(\sin i)^2 > 110 \text{ AU}$ . Therefore, unless the inclination is extremely small, the components are separated by many AU. Our



**Fig. 5a and b.** A schematic view of the V778 Cyg system. **a** A part of mass-loss wind was captured in the disk around the companion star while the star was O-rich. **b** The central star evolved to become carbon-rich and decreased its mass-loss rate. The silicate dust in the companion disk is gradually blown out by radiation pressure of the central star.

model analysis of the dust features expects that the dust is located at  $12 R_{\star}$  or  $24 \text{ AU}$  from the central star. This is well beyond the dust forming radius, and it is clear that the solution for V778 Cyg to keep O-rich material is the companion disk. The companion disk itself is too small to emit sufficient flux. In addition, the disk may be optically thick. We repeat that an outflow arising from the disk is essential for the silicate emission seen in the infrared spectra of V778 Cyg.

Fig. 5 sketches the evolutionary scenario of V778 Cyg. The companion disk had been formed while the central star was still O-rich (Fig. 5a). The dust mass now seen in the infrared is of the order of  $10^{-5} M_{\odot}$  (Sect. 3). Suppose that the star experienced mass loss with a rate of  $10^{-6} M_{\odot} \text{ yr}^{-1}$  which lasted for  $10^5$  years. Assuming a mass accretion efficiency of a few percent and a dust-to-gas mass ratio of 0.01, the dust mass captured in the disk is estimated to be a few  $\times 10^{-5} M_{\odot}$ . The heavy mass loss stops when a thermal pulse turned the central star to be carbon-rich, but the dust in the companion disk keeps flowing out (Fig. 5b). With a mass-loss rate of  $5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$  (derived from the model for the expansion velocity of  $10 \text{ km s}^{-1}$ ), the disk would be consumed in 5000–10000 years. This time may be larger if there is a contribution from the cold silicates dust far from the star, which is the remnant of the previous mass-loss phase. In any case, the period when a star shows the silicate features is only the first  $\sim 10^4$  years after the star became a carbon star.

The question remains how the disk returns small grains into the outflow. This may depend upon the initial gas density in the disk. If the density is large enough and the relative speed of

dust grains is small, coagulation might occur in the disk, and the companion disk contains large grains. The interaction between gas and dust grains reduces, and the gas would be lost from the system, probably by accreting onto the companion, or being blown away. When the gas is gone, collisions may start grinding the big grains down, and the small grains leave the system in the outflow (see also, Jura & Kahane 1999). If coagulation does not take place and the small grains remain dispersed in the gas, the way to remove dust from the disk may be the slow peeling off of the disk surface: dust grains appear in the disk surface and are blown away by the radiation pressure.

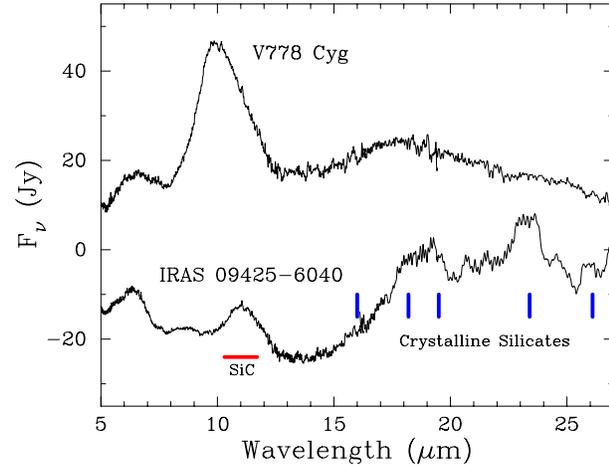
The situation seems quite different in the cases of the Red Rectangle and IRAS 09425–6040. The Red Rectangle is known to be a binary system with an orbital period of 318 days and an amplitude of the radial velocity variation of about  $25 \text{ km s}^{-1}$  (van Winckel et al. 1995). The orbital separation between the primary and the secondary is about 1 AU; smaller than the typical radius of an AGB star. It is suggested that the central star of the Red Rectangle has experienced an extreme binary evolution (Waelkens et al. 1996). There is direct evidence for a circum-binary disk in the Red Rectangle (Roddi er et al. 1995; Osterbart et al. 1997). On the other hand, no information about binarity in IRAS 09425–6040 has been reported. The presence of massive and cool dust disk in the object however implies a small binary separation, but probably not as close as the Red Rectangle, since the near-infrared nature of the star seems quite normal.

The infrared spectra of these objects show strong crystalline silicate features as well as high far-infrared/sub-mm flux ratio, indicating the presence of well-processed large dust grains. In contrast, V778 Cyg (and possibly all other “IRAS discovered” silicate carbon stars) shows no clear indication of crystals (Fig. 6) and has a steep decrease of flux density toward longer wavelengths. The amount of crystalline grains which can hide behind the strong amorphous features is no more than 20 percent in V778 Cyg, if we assume that crystalline silicate grains coexist with amorphous grains. This is similar to the normal O-rich outflow (Molster et al. 1999). On the other hand, about 75 percent of silicate is in crystalline form in IRAS 09425–6040 (Molster et al. 2000). Furthermore, the dust disk in the Red Rectangle and IRAS 09425–6040 are one order of magnitude more massive than that in V778 Cyg.

## 8. The primary star of V778 Cyg

The fact that all known silicate carbon stars are J-type indicates a close relation between the evolution of the primary star and the formation of the disk. In the previous sections, we assumed that the star is in the AGB phase and that the companion disk was formed during the previous O-rich mass-loss phase.

At least for some J-type carbon stars there exists observational evidence that they are luminous enough to be in the AGB phase. Westerlund et al. (1991) found that some J-type carbon stars in the Magellanic Clouds are located in the same or an even higher luminosity region in the HR diagram compared to *normal* carbon stars. The first silicate carbon star discovered in the



**Fig. 6.** The spectrum of V778 Cyg compared with IRAS 09425–6040, the “ISO discovered” silicate carbon star. IRAS 09425–6040 shows the crystalline silicate features longward of  $15 \mu\text{m}$ , while it has clear SiC dust feature at  $11.3 \mu\text{m}$ . The positions of major crystalline silicate features are indicated by thick grey lines. It is remarkable that V778 Cyg does not show any clear indication of crystalline silicates.

LMC, IRAS 04496–6958, is also very luminous ( $M_{\text{bol}} = -6.8$  mag), although it is not known whether this star is J-type or not (Trams et al. 1999). Recent luminosity estimates for carbon stars based on Hipparcos data (Wallerstein & Knapp 1998; Alksnis et al. 1998) show that two nearby J-type stars, namely Y CVn and RY Dra, are as luminous as other N-type (*normal*) carbon stars. The spectrum of V778 Cyg is quite similar to that of RY Dra (Fig. 1). Indeed, Ohnaka & Tsuji (1999) stated that they could not find any systematic difference between J-type carbon stars with and without silicate features. Both groups usually show a large  $\text{C}_2$  band index (Yamashita 1972, 1975) as well as relatively low  $T_{\text{eff}}$  (around 3000 K). We therefore conclude that the primary star of V778 Cyg and other silicate carbon stars are *likely* in the AGB phase.

We further speculate that all luminous J-type stars once had a companion disk filled with O-rich material and thus showed the silicate dust emission. Lloyd Evans (1990, 1991) observed carbon stars in the IRAS color region of  $[12] - [25] \geq 0.7$ . There are 24 J-type carbon stars in this sample of which about one half are identified as silicate carbon stars. Only a few show strong silicate emission features. According to our scenario the silicate emission features are only seen during a limited period after the transition from O-rich to C-rich. Presumably, J-type stars with little or no silicate emission are those that have exhausted the oxygen-rich dust in the companion disk. In the subsequent mass-loss phase, the disk will be refilled by carbon-rich material.

Why do we not see silicate features in *normal* (N-type) carbon stars? If our scenario that all J-type stars are binary and were once silicate carbon stars is true, it is likely that the evolution of the primary stars is influenced by binarity, like in the case of close-binary systems. In other words, J-type stars are only formed in binary systems with a relatively wide orbital separation, and all these systems eventually have a companion

disk and show silicate emission at some phase. More statistical analysis is required to confirm this hypothesis. In addition, it is also possible that the transition from O-rich stars to J-type stars goes more quickly than that to N-type carbon stars. The latter may experience an intermediate phase of S- or SC-type evolution. In that case the O-rich dust in the disk is replaced gradually by carbon-rich material. The quick transition scenario for single star evolution, originally proposed by Willems & de Jong (1988), fails on the basis of the short evolutionary timescale implied. However, adding the capacity to store O-rich dust in the system relaxes the constraints on the evolutionary timescale significantly.

Abia & Isern (2000) recently proposed that J-type carbon stars are low-mass stars in the early-AGB phase, and are produced by a special mixing mechanism called *cool bottom processing* (Wasserburg et al. 1995). This mechanism is able to create a  $^{13}\text{C}$ -rich carbon star without (detectable) s-process elements. This is compatible with our scenario that the silicate carbon stars became carbon-rich relatively recently.

It has been suggested that J-type stars have evolved from R-type stars and thus have lower luminosity than AGB stars (Lloyd Evans 1986, 1990; Lambert et al. 1990). This scenario is attractive from the point of view that R-type stars show similar abundance characteristics to J-type stars, except at higher effective temperature ( $T_{\text{eff}}$ ) and lower luminosity. R-type stars are thought to be formed by an extremely energetic He-core flash (Dominy 1984). If this scenario were true, these stars have become carbon-rich long ago. Storage of the O-rich material has taken place when the star was still in Red Giant Branch (RGB) or at the He-core flash. Our arguments in the previous section would still hold even in such a case. Mass capturing takes place in the dusty stellar wind phase, and thus results in a companion disk. Lambert et al. (1990) estimated that the mass ejected until the He-core flash in a star with an initial mass of  $1 M_{\odot}$  is up to  $0.5 M_{\odot}$ . The disk has been stable until recently when the star became luminous enough to blow the dust out.

## 9. Conclusions

The ISO/SWS observation of the silicate carbon star V778 Cyg revealed that there has been little change in the spectral profile of the silicate features in the last 14 years, since the IRAS/LRS observation.  $\text{H}_2\text{O}$  and  $\text{CO}_2$  molecules marginally detected in emission, are probably located in the circumstellar environment. The near-infrared spectrum indicates that the present-day mass-loss rate is small. The silicate features can only be fitted by optically thin emission from small (sub-micron size) dust grains. We propose that the features arise from the continuous dust outflow from a companion disk, as dust grains spill out from the gravitational restriction and are blown away by the radiation pressure from the central star. We discussed formation of a disk in a binary system under the strong radiation field from the central star. It turned out that the orbital separation is a key parameter which determines the fate of the system. A heavy circum-binary disk is formed when the system is a close-binary, while a disk around the companion star results for the wide

separation system. V778 Cyg is of the latter case. Objects such as the Red Rectangle and IRAS 09425–6040 are probably formed by the former mechanism. The primary of V778 Cyg is likely in the AGB phase. We assume that the oxygen-rich material was stored during the previous AGB mass-loss phase, but the conclusion does not change even if the material was provided in the earlier phase, during RGB or at the He-core flash. The dust mass in the disk of V778 Cyg is of the order of  $10^{-5} M_{\odot}$ , which will be consumed in about  $10^4$  years after the primary star became a luminous carbon star. We suspect that all luminous J-type stars have once been silicate carbon stars. Those who show little or no silicate emission might have exhausted the dust in the disk. Presumably, binarity influences the evolution of the primary star even for wide orbital separation.

*Acknowledgements.* The authors thank to K. Ohnaka for discussion on J-type stars. I.Y., C.D., and L.B.F.M.W. acknowledge financial support from an NWO PIONIER grant. F.J.M. is supported by an NWO grant 781-71-052.

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