A&A 377, 994–998 (2001)
DOI: 10.1051/0004-6361:20011164

Astronomy & Astrophysics

Detection of the unusual 3.5 μm feature in the Herbig Be star MWC 297

H. Terada[1], M. Imanishi[2], M. Goto[1], and T. Maihara[3]

[1] Subaru Telescope, National Astronomical Observatory of Japan, Hilo, Hawaii 96720, USA
[2] National Astronomical Observatory, Mitaka, Tokyo, 181-8588, Japan
[3] Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan

Received 2 September 1999 / Accepted 20 August 2001

Abstract. We present spectroscopic observations of MWC 297 with medium spectral resolution in the 2.1–4.1 μm region, that show the unusual emission band at 3.53 μm as well as gaseous emission lines of the Brackett, Pfund and Humphrey series of hydrogen. A unique aspect of the measured 3.53 μm emission band is the fact that, within our detection limit, it is not accompanied by the 3.3 and 3.4 μm emission band. We suggest that the 3.53 μm feature could be emitted by highly dehydrogenized carbonaceous dust particles that were processed under the influence of the strong radiation field of the central star.

Key words. infrared: stars – ISM dust – stars: individual: MWC 297 – stars: circumstellar matter

1. Introduction

There are few Herbig Ae/Be stars (hereafter HAeBe stars) which possess spectral emission features at 3.4–3.5 μm, although many HAeBe stars have the 3.3 μm emission feature which is commonly attributed to carbonaceous dust. Representative stars of the class with the 3.4–3.5 μm bands are Elias 1 (V892 Tau) and HD 97048. These stars have three distinct peaks at 3.3, 3.42, and 3.53 μm. The intensity ratio of the 3.53 to the 3.3 μm features observed is different from one star to another. It should be noted that the objects that show the relatively intense 3.53 μm feature are pre-main sequence stars of the Herbig Ae/Be class. Weaker 3.53 μm emission features have been observed in a few post-AGB stars. In this paper, we present new spectroscopic observations of MWC 297 in the 2.1–4.1 μm region, and show that only the 3.5 μm feature of carbonaceous dust is present in this source.

2. Observation and data reduction

Spectroscopic observations of MWC 297 were made with a cooled grating spectrograph (hereafter referred as LEWIS, a name taken from L, M band Echelle Wide coverage Intermediate-resolution Spectrometer), which utilizes a 256×256 InSb array together with an echelle-type aluminum grating (Imanishi et al. 1996).

Observations were made with the 60 inch telescope of Steward Observatory on Mount Lemmon, Arizona, in the L-band on May 26 and 29, and in the K-band on May 29. Slit widths were 7.6″ and 3.8″ in these observations, with a spectral resolving power of ∼650 and ∼1300 respectively. In both cases, the height of the rectangular slit was 7.6″.

Throughout the observations we utilized the f/45 chopping secondary for sky subtraction, and in addition, we adopted the standard telescope nodding technique to compensate for the sky emission gradient and telescope emission. The total on-source integration time in the L-band was 448 s, and in the K-band it was 200 s.

For spectral calibration, we observed a bright star, BS 6866 (G8III) by which we eliminated the terrestrial absorption and obtained the spectrophotometric flux level of the object. The wavelength calibration was made by occasionally measuring a neon discharge lamp during the observations.

Send offprint requests to: H. Terada,
e-mail: terada@subaru.naoj.org

3. Results

3.1. Hydrogen recombination lines

The reduced spectrum of MWC 297 taken on May 26, 1996 is shown in Fig. 1. A number of emission lines is detected such as Brackett α (4.052 μm), Pfund γ (3.741 μm), Pfund δ (3.297 μm), Pfund ϵ (3.039 μm), and at least eleven lines from the Humphrey series, ranging from 24–6 at 3.501 μm to 14–6 at 4.021 μm. These hydrogen recombination lines are thought to originate either from the outflowing wind or from the partially ionized boundary region between the atmosphere and the circumstellar envelope (Nisini et al. 1995; Benedettini et al. 1998; Suto et al. 1989).

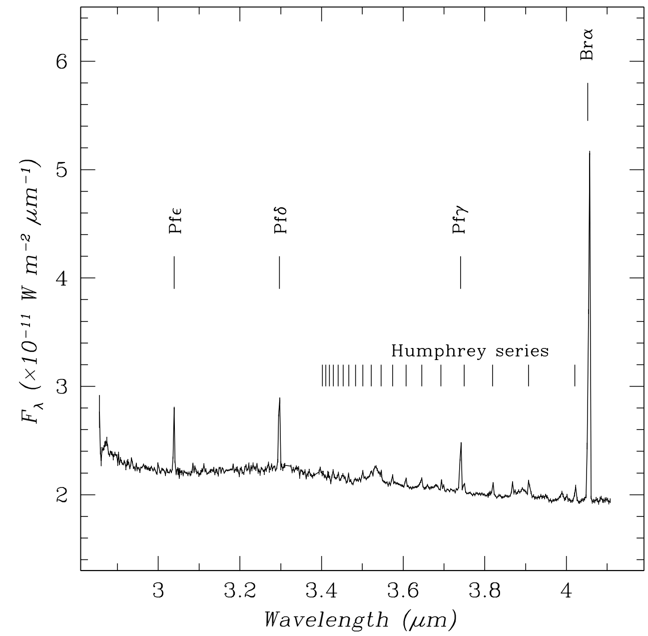

Fig. 1. The 2.8–4.1 μm spectrum of MWC 297. H I recombination lines are indicated.

The detailed analysis of these emission lines will be discussed elsewhere.

3.2. The 3.1 μm absorption feature

A shallow, but definite, absorption feature around 3.1 μm is also seen in Fig. 2, which is attributed to H_2O ice particles (Gillett & Forrest 1973; Smith et al. 1989). The optical depth of the ice absorption is estimated as $\tau_{3.1} = 0.066 \pm 0.008$, assuming a 1300 K blackbody between 2.1–3.4 μm (Fig. 3). The blackbody temperature is consistent with the photometry of Bergner et al. (1988). From observations in four molecular clouds (ρ Ophiuchi, Taurus, R CrA and Serpens molecular cloud), $\tau_{3.1}$ is known to be related to the visual extinction $A_{\rm V}$ by $\tau_{3.1} = q \times (A_{\rm V} - A_0)$ (Whittet et al. 1988; Tanaka et al. 1990, 1994; Eiroa & Hodapp 1989; Chen & Graham 1993). Except for the case of ρ Ophiuchi dark cloud ($q = 0.06$, $A_0 = 10$–15 mag) which is thought to have an intense UV radiation field, the values of q, A_0 are almost the same for the other molecular clouds ($q = 0.09$–0.1, $A_0 = 3$–6 mag), whose averaged values are 0.094, 4.3 respectively. $A_{\rm V}$ toward MWC 297 has been estimated as 8.3 mag derived from the $E(B-V)$ value (Hillenbrand et al. 1992). A portion of $A_{\rm V}$ may be attributed to the cold intracloud dust with H_2O ice mantle ($A_{\rm VI}$), and another portion may be attributed to the warmer circumstellar dust with no H_2O ice mantle ($A_{\rm VC}$) as a result of the intense UV radiation from MWC 297. If the intracloud absorption around MWC 297 has the same nature as the Taurus, R CrA and Serpens molecular clouds, we can estimate $A_{\rm VI}$ to be $\sim$5.0 mag by adopting $q = 0.094$, $A_0 = 4.3$. Hence $A_{\rm VC}$ $\sim$3.3 and more than 1/3 of the total absorption can be attributed to circumstellar origin.

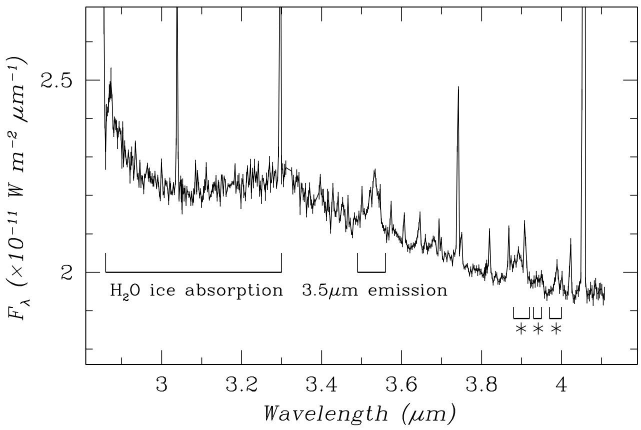

Fig. 2. Same as Fig. 1 but with expanded scale. The broad 3.53 μm emission feature and the 3.1 μm absorption band are indicated. Spurious emission features are marked by $*$, which is caused by molecular absorptions (mostly O$-$H) in the standard star (BS 6866; G8III). These absorption features have been detected in late-type stars (Ridgway et al. 1984; Smith 1991).

3.3. The 3 μm emission features

A broad emission feature at 3.53 μm is clearly detected in the MWC 297 spectrum as shown in Fig. 2. From the width of the spectral feature as well as its wavelength, we attribute it to the 3.53 μm emission feature observed in Elias 1 and HD 97048. In fact, the 3.53 μm feature is almost identical to the profile found in these stars as well as in two post AGB stars, HR 4049 and HD 52961. Referring to the phenomenological classification of spectra of the 3 μm emission, these objects are in class C (Aitken & Roche 1981; Whittet et al. 1984; Geballe 1997; Oudmaijer et al. 1995), having the prominent 3.53 μm emission feature in comparison to other 3 μm features in the 3.3–3.5 μm region. Recently HD 142527 and HD 100546 have been reported as candidates for class C objects (Waelkens et al. 1996; Malfait et al. 1998). However, HD 100546 has weaker 3.5 μm emission relative to the 3.3 μm emission, and seems to be a class A object with "normal" dust features rather than a class C object. The 3.5 μm emission in HD 142527 was not confirmed after reduction using more recent calibration data (Malfait et al. 1999). We argue that MWC 297 is the fifth object of this class. However, it is unique in that only the 3.53 μm is detected, at least at our detection level.

In Fig. 4, we compare the observed 3.53 μm profile of MWC 297 with that of Elias 1 observed by Tokunaga et al. (1991). They are quite similar. However, it is interesting to note that the feature found in the spectrum of the post AGB star HR 4049 has somewhat different characteristics in terms of the central peak as well as associated sub-peaks.

The observed spectrum was dereddened based on the estimated $A_{\rm V}$ by using the extinction law given by Rieke & Lebofsky (1985). Then the intensities of the 3.3, 3.4, 3.5 μm features were measured by subtracting the underlying continuum from the integrated strengths of the features in the intervals 3.215–3.365 μm for the 3.3 μm

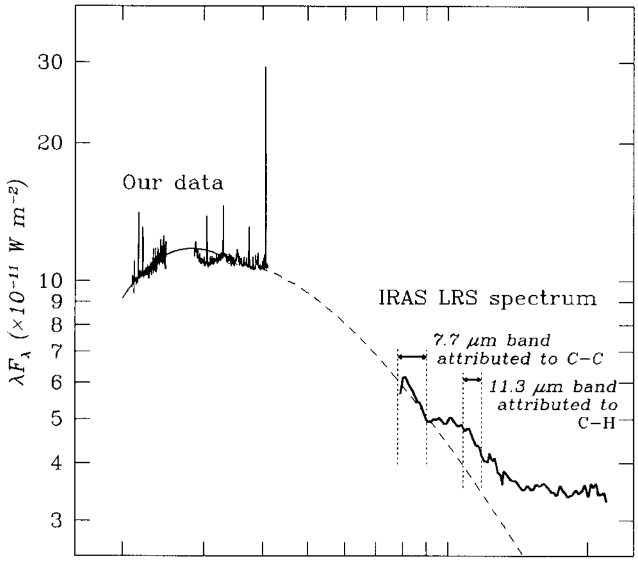

Fig. 3. The 2.1–22.0 μm spectrum of MWC 297. The dereddened 2.1–4.1 μm spectrum from this paper and the 7.7–22.0 μm spectrum from the IRAS/LRS data base are shown. The solid line shows a blackbody emission of 1300 K. The dashed line shows emission from the standard disk model with a temperature distribution of $T(R) \propto R^{-3/4}$ and well explains the photometric data from near-infrared to far-infrared (Hillenbrand et al. 1992).

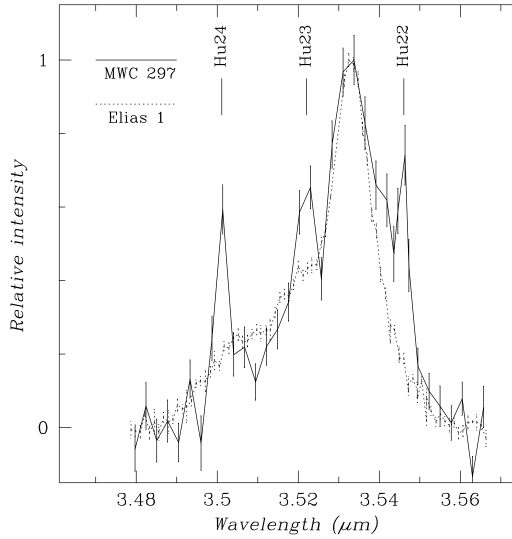

Fig. 4. A comparison of the normalized 3.53 μm emission profiles in MWC 297 and Elias 1. The data for Elias 1 are taken from Tokunaga et al. (1991).

band, 3.360–3.475 μm for the 3.4 μm band, and 3.478–3.567 μm for the 3.5 μm band. Since MWC 297 has Hu24 (3.501 μm), Hu23 (3.522 μm), and Hu22 (3.546 μm) in the 3.5 μm band, we estimate its flux excluding these lines. The results are summarized in Table 1. As for the 3.3 and 3.4 μm features, those upper limits (1σ) are given for features of the same width as Elias 1.

4. Discussion

As mentioned in Sect. 3, the 3.5 μm emission features in HAeBe stars and post AGB stars are not perfectly identical, and may be essentially different due to the difference in the evolutionary stage of the carbonaceous dust. In the following discussion we concentrate on the dust emission feature seen in HAeBe stars.

4.1. Relative intensities of 3.5 to 3.3 μm features

We estimate the fluxes of the 3.3–3.5 μm emission of HD 97048 and Elias 1 in the same way for MWC 297 (Table 1). Clearly, the relative intensities of the 3.5 to the 3.3 μm features vary in three HAeBe stars. First, let us examine the correlation between the intensity ratio and the spectral type of central stars. The stellar parameters of these objects are listed in Table 2. As the distance and spectral type for MWC 297 are still disputable, we adopt them from two sources (Hillenbrand et al. 1992; Drew et al. 1997). From Tables 1 and 2, it is seen that as the spectral type gets earlier, the relative intensity of the 3.5 μm feature to the 3.3 μm feature tends to be larger. Previous observations of the 3.3 μm feature in HAeBe stars have revealed that the higher the effective temperature of the star, the larger the spatial extent of the 3.3 μm feature around the star. Brooke et al. (1993) have estimated the dehydrogenization radius around HAeBe stars, showing that it is reasonable agreement with the radial extent of the 3.3 μm feature. This implies that inside this radius the materials or at least the responsible C-H bonds of the 3.3 μm feature are destroyed under the intense UV radiation from the central star. According to this hypothesis, we can calculate the dehydrogenization radius for these three objects with the following equation:

$$R_{\rm DH} = 6.9\times10^{-7}\left(\frac{10^{-9}\ {\rm cm^3\ s^{-1}}}{\alpha}\right)^{\frac{1}{2}}\left(\frac{5\times10^4\ {\rm cm^{-3}}}{n_{\rm H}}\right)^{\frac{1}{2}} \times\left(\frac{\sigma_{\rm UV}}{3\times10^{-16}\ {\rm cm^2}}\right)^{\frac{1}{2}}(N_{\rm UV})^{\frac{1}{2}},$$

where $N_{\rm UV}$ is the number of photons per sec responsible for the destruction of C-H bonds, $\sigma_{\rm UV}$ is the absorption cross section, α is the collision rate constant, and $n_{\rm H}$ is the hydrogen density. As for $\sigma_{\rm UV}$, α, and $n_{\rm H}$, we use the same value as Brooke et al. (1993). In a wavelength region of 912–1240 Å, $N_{\rm UV}$ is derived by assuming a blackbody emission of $T_{\rm eff}$ and the stellar radius R_* in Table 2. The results of the calculations of $R_{\rm DH}$ are shown in Table 2. The dehydrogenization radius $R_{\rm DH} \sim 10^5$ AU for MWC 297 is much larger than the aperture of our observation ($7.6'' \times 450$ pc = 3420 AU) using the distance and spectral type derived by Hillenbrand et al. (1992). We reach the same conclusion if we use the results of Drew et al. (1997).

Let us examine possible explanations for the origin of this feature. It has been suggested that the 3.53 μm band originates in combination and overtone bands of C-C

Table 1. Summary of 3 μm emission features.

Object Name	$F_{3.29}$ [10^{-15} Wm^{-2}]	$F_{3.43}$ [10^{-15} Wm^{-2}]	$F_{3.53}$ [10^{-15} Wm^{-2}]	$\frac{F_{3.53}}{F_{3.29}}$	$\frac{F_{3.53}}{F_{3.43}}$
Elias 1[a]	7.24 ± 0.16	6.27 ± 0.11	9.99 ± 0.07	1.4	1.6
HD 97048[b]	14	40	88	6.3	2.2
MWC 297	<5.59	<14.2	46.3 ± 2.1	>8.3	>3.3

Data from:
[a] Tokunaga et al. (1991).
[b] Aitken & Roche (1981); Baas et al. (1983).

Table 2. Stellar parameters and dehydrogenization radius.

Object Name	Spectral Type	A_V[a] [mag]	d [pc]	$\log(T_{\rm eff})$	R_*[a] [AU]	$R_{\rm DH}$ [AU/″]
Elias 1	A6[a]	4.1	140[b]	3.91[a]	0.5	13/0.092[d]
HD 97048	B9[a]	1.3	140[b]	4.03[a]	2.5	410/2.9[d]
MWC 297	O9[a] (B1.5[c])	8.3	450[a] (250[c])	4.53[a] (4.38[c])	9.1	98000/220[d] (43000/170[e])

[a]Hillenbrand et al. (1992).
[b]Brooke et al. (1993).
[c]Drew et al. (1997).
[d]Calculated from stellar parameter of Hillenbrand et al. (1992).
[e]Calculated from stellar parameter of Drew et al. (1997).

vibrations (Schutte et al. 1990), or the C-H stretch vibrations in the hydrogenated fulleranes such as $C_{60}H_{36}$ (Webster 1992). We interpret the 3.53 μm emission feature as combination and overtone bands of the C-C bonds that survive after dehydrogenization. Since the 7.7 μm emission is thought to originate from the C-C bonds, we expect that the 7.7 μm feature should be present in the mid-infrared spectrum of MWC 297. This is confirmed by the IRAS/LRS data shown in Fig. 3, although 7.7 μm is near the shortest wavelength available with LRS. On the other hand, the 11.3 μm emission is apparently absent in the same spectrum, whose upper limit (1σ) is estimated as 2.9×10^{-14} Wm^{-2}. From astronomical observations of various objects the 3.3 μm and 11.3 μm emission is well known to co-exist always, having a strong linear correlation, $F_{3.3}/F_{11.3} \approx 0.3$ in the same aperture (Jourdain de Muizon et al. 1990; Schutte et al. 1990; Hanner et al. 1998). Using this ratio, the corresponding upper limit of the 3.3 μm emission becomes 8.7×10^{-15} Wm^{-2}. Taking the LRS large aperture (30″) into account, this result is consistent with the upper limit of the 3.3 μm emission to our observation.

The spatial extent of the 3.5 μm emission has not been detected in Elias 1 and HD 97048. A speckle observation at the 3.5 μm band around HD 97048 shows that this emission feature originates from the inner ∼0.05″ around the central star (Roche et al. 1986). The spectroscopic imaging of the 3.5 μm emission of Elias 1 does *not* show any component larger than ∼1″ (Thornley et al. 1989). Schutte et al. (1990) have proposed a working hypothesis that the spatial distributions of carbonaceous dust around HAeBe stars are divided into at least three regions. In the innermost region (region I), perhaps even the C-C structure inherent to aromatic rings is destroyed, that is, the high energy radiation would photodestruct the aromatic ring itself. In the middle region (region II), the C-C bonds are intact, but dehydrogenization is the dominant process of the alteration of carbonaceous dust. The 3.5 μm emission feature should be strong here. In the outermost region (region III) carbonaceous dust, if any, is not altered, and therefore the 3.3 μm emission feature should be present. The distance from the central star to the border between region II and III corresponds to the dehydrogenization radius $R_{\rm DH}$. Adopting this framework, we can explain the variety of relative intensities of the observed 3.3 and 3.5 μm features in three HAeBe stars.

For example V921 Sco (B0) has been found to have a "normal" dust emission feature with 3.3 μm emission (Jourdain de Muizon et al. 1990; Benedettini et al. 1998); this is a HAeBe star with almost the same spectral type as MWC 297 (Brooke et al. 1993). This indicates that another alteration process may be needed to produce the carrier for the 3.53 μm emission.

4.2. Relative intensities of 3.5 to 3.4 μm features

The relative intensities of the 3.5 to the 3.4 μm feature have the same trend as the observed 3.5/3.3 μm ratio, but at a lower value. In fact the 3.4 and 3.5 μm features in

HD 97048 and Elias 1 are very similar in intensity ratio and also in profile shapes (Whittet et al. 1984). If the carrier of the 3.5 μm emission feature is combination and overtone bands of the C-C bonds, the laboratory experiments imply that the 3.4 μm emission should be detected (Schutte et al. 1990). Since the 3.4 μm emission is influenced by a Fermi resonance with 3.3 μm C-H stretch, the observed 3.5/3.4 μm ratio may vary according to the strength of the 3.3 μm emission feature.

5. Conclusion

We have obtained the 2.1–4.1 μm spectrum of MWC 297. We found the following conclusions:

1. The carbonaceous dust emission in MWC 297 was observed in the 3 μm band, in which only the 3.53 μm feature was detected. MWC 297 is the fifth object which has 3.53 μm feature;
2. The unusual 3.5 μm features in three Herbig Ae/Be stars are clearly identical in peak wavelength and profile shape. This indicates that the carrier of the 3.5 μm feature is the same in these stars;
3. The intensity ratio of the 3.3 μm to the 3.5 μm features varies in three objects, and the carrier of the 3.5 μm is overtone and combination bands of C-C vibrations;
4. No 3.4 μm emission feature could be detected. The 3.4 μm and 3.5 μm emission features may have a different origin, although high signal-to-noise spectra are needed to confirm this conclusion;
5. The 3.1 μm H_2O ice absorption feature is detected. The optical depth $\tau_{3.1} = 0.066$ with $A_V = 8.3$ indicates that more than 1/3 of the total absorption may be attributed to a circumstellar origin.

Note added in Proofs. After this paper was accepted, we became aware of the paper by Guillois et al. (1999, ApJL 521, 133) that suggests the 3.53 μm emission feature arises from diamond material.

Acknowledgements. We wish to thank the staff of the NASA/Steward Observatory 60 inch telescope on Mount Lemmon for the support of these observation. Our special thanks are due to A. Tokunaga for providing us with data for Elias 1 and helpful suggestions. This research was supported by the Grant-in-Aid for Scientific Research on Priority Areas of the Ministry of Education, Science, and Culture of Japan.

References

Aitken, D. K., & Roche, P. F. 1981, MNRAS, 196, 39
Baas, F., Allamandola, L. J., Geballe, T. R., Persson, S. E., & Lacy, J. H. 1983, ApJ, 265, 290
Benedettini, M., Nisini, B., Giannini, T., et al. 1998, A&A, 339, 159
Bergner, Y. K., Kozlov, V. P., Krivtsov, A. A., et al. 1988, Afz, 28, 313
Brooke, T. Y., Tokunaga, A. T., & Strom, S. E. 1993, AJ, 106, 656
Chen, W. P., Graham, J. A. 1993, ApJ, 409, 319
Drew, J. E., Busfield, G., Hoare, M. G., et al. 1997, MNRAS, 286, 538
Eiroa, C., & Hodapp, K.-W. 1989, A&A, 210, 345
Geballe, T. R. 1997, in From Stardust to Planetesimal, San Francisco, ed. Y. J. Pendleton, & A. G. G. M. Tielens, ASP Conf. Ser., 122, 119
Gillett, F. C., & Forrest, W. J. 1973, ApJ, 179, 483
Hanner, M. S., Brooke, T. Y., & Tokunaga, A. T. 1998, ApJ, 502, 871
Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, ApJ, 397, 613
Imanishi, M., Terada, H., Sugiyama, K., et al. 1996, PASP, 108, 1129
Jourdain de Muizon, M., d'Hendecourt, L. B., & Geballe, T. R. 1990, A&A, 227, 526
Malfait, K., Waelkens, C., Waters, L. B. F. M., et al. 1998, A&A, 332, L25
Malfait, K., Waelkens, C., Bouwman, J., De Koter, A., & Waters, L. B. F. M. 1999, A&A, 345, 181
Nisini, B., Milillo, A., Saraceno, P., & Vitali, F. 1995, A&A, 302, 169
Oudmaijer, R. D., Waters, L. B. F. M., van der Veen, W. E. C. J., & Geballe, T. R. 1995, A&A, 299, 69
Ridgway, S. T., Carbon, D. F., Hall, D. N. B., & Jewell, J. 1984, ApJS, 54, 177
Rieke, G. H., & Lebofsky, M. H. 1985, ApJ, 288, 618
Roche, P. F., Allen, D. A., & Bailey, J. A. 1986, MNRAS, 220, 7
Schutte, W. A., Tielens, A. G. G. M., Allamandola, L. J., Cohen, M., & Wooden, D. H. 1990, ApJ, 360, 577
Smith, R. G. 1991, MNRAS, 249, 172
Smith, J. D., Sellgren, K., & Tokunaga, A. T. 1989, ApJ, 344, 413
Suto, H., Mizutani, K., & Maihara, T. 1989, MNRAS, 239, 139
Tanaka, M., Sato, S., Nagata, T., & Yamamoto, T. 1990, ApJ, 359, 192
Tanaka, M., Nagata, T., Sato, S., & Yamamoto, T. 1994, ApJ, 430, 779
Thornley, M., Woodward, C. E., Pipher, J. L., et al. 1989, BAAS, 21, 1085
Tokunaga, A. T., Sellgren, K., Smith, R. G., et al. 1991, ApJ, 380, 452
Waelkens, C., Waters, L. B. F. M., de Graauw, M. S., et al. 1996, A&A, 315, L245
Webster, A. 1992, MNRAS, 257, 463
Whittet, D. C. B., McFadzean, A. D., & Geballe, T. R. 1984, MNRAS, 211, 29
Whittet, D. C. B., Bode, M. F., Longmore, A. J., et al. 1988, MNRAS, 233, 321