

The 21 μm and 30 μm circumstellar dust features in evolved C-rich objects

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(Received xxxx xx, 2008; Revised xxxx xx, 2008; Accepted xxxx xx, 2008; Online published Xxxxx xx, 2008)

The 21 μm and 30 μm bands are the strongest dust emission features detected in evolved low- and intermediate-mass C-rich stars (i.e. asymptotic giant branch [AGB] stars, proto-planetary nebulae [PPN], and planetary nebulae [PN]). While the 21 μm feature is rare and exists only in the transient PPN phase, the 30 μm feature is more common and seen in the entire late stage of stellar evolution, from AGB to PPN and PN phases, as well as in the low-metallicity galaxies: the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). The carriers of these features remain unidentified. Eleven of the twelve well-identified 21 μm sources also emit in the 30 μm band, suggesting that their carriers may be somewhat related.

Key words: AGB stars, post-AGB stars, circumstellar dust, infrared

1. Introduction

The circumstellar chemistry of the low- and intermediate-mass stars from AGB on is dichotomized into O-rich and C-rich classes according to the C/O abundance ratio, since C and O would combine at relatively high temperature to form the very stable molecule CO. The dominant dust species in O-rich circumstellar envelope (CSE) is silicate, abundant in both amorphous and crystalline forms. In C-rich objects, the C-bearing molecules (e.g. C₂, C₃, CN, and some hydrocarbon compounds) dominate, while the most common dust feature should be assigned to the SiC 11.3 μm band detected in more than 700 stars most of which are C-rich objects. However, the strongest and most enigmatic spectral features of C-rich objects are the 21 μm and 30 μm emission bands. The combined contribution of these two bands can amount to more than 20% of the total infrared flux, so they greatly influence the CSE evolution. Furthermore, the dispersion of the CSE dust to the interstellar medium (ISM) brings the dust for these features enter into the recycling of cosmic dust.

2. The 21 μm feature

The 21 μm feature was first identified in 4 PPNe from the IRAS/LRS spectra in 1989 (Kwok et al. 1989). Later, from the high resolution spectra taken by ISO/SWS, this feature is accurately measured to have a peak wavelength at $\sim 20.1 \mu\text{m}$. But the tradition to name it as the 21 μm feature is retained. As one of the rarest dust features, so far, this feature has been well identified only in a dozen sources (see Kwok et al. 1999). Consistent with its rare appearance, the 21 μm sources all are at a short phase in stellar evolution, i.e. PPN, which lasts only several $\sim 10^3$ years. They show a double-peaked spectral energy distribution (SED), with one optical peak arising from the radiation of the central star (with an effective temperature of $\sim 5500\text{--}7500\text{K}$) and the other (usually mid-) infrared (IR) peak from the low-temperature dust envelope. Besides, all these 21 μm PPNe are C-rich, metal-poor but rich in s-process elements, a quite small subgroup of PPNe (Kwok et al. 1999).

Since its discovery, the 21 μm feature has attracted much attention for its unidentified carrier. The number of proposed carrier candidates exceeds the number of the feature emitters (i.e. a dozen). The proposed candidates fall into three broad categories: (i) organic dust, (ii) oxides, and (iii) the silicon and carbon compound. Because the 21 μm emission band is found only in C-rich sources, the C-bearing organic dust species are naturally considered as the carrier candidates, including hydrogenated fullerenes, polycyclic aromatic hydrocarbon (PAH), hydrogenated amorphous carbon (HAC), synthetic carbonaceous macromolecules, and amides (especially urea). In addition, inorganic candidates are proposed: diamonds, iron oxides ($\gamma\text{-Fe}_2\text{O}_3$, Fe_3O_4 , FeO), SiS₂, titanium carbide nanoclusters, doped SiC, and SiC core-SiO₂ mantle particles, some of which also contain carbon atoms. Posch et al. (2004) discussed in details many of these proposed candidates. The proposal for these materials to be the 21 μm feature candidate is generally based on their experimental

spectra which show a feature around 20 μm similar to the observed 21 μm feature profile. But a valid carrier needs not only to be able to reproduce the observed feature, but also (1) to be abundant enough to account for the observed intensity and (2) to not have any associated features, consistent with the observational fact the 21 μm band has no appreciable associated features. For example, since titanium is a rare element in the universe, Ti-bearing dust species are often examined in terms of the required abundance (relative to H), e.g., titanium carbide (TiC) nanoclusters were rejected because the cosmic Ti abundance is not enough to account for the intensity of the observed 21 μm emission feature (see Li 2003, Hony et al. 2003, Chigai et al. 2003).

2.1 Carrier

We have investigated the feasibility of all the inorganic carrier candidates based on their elemental abundance requirement and the possible presence of any associated features (see Zhang et al. 2008 for details). The mass of the carrier, m_d , which is directly related to the abundance of the elements composing the carrier, is the key parameter to determine the emitted power of the feature through

$$E_{\text{tot}} = m_d \int_{21 \mu\text{m band}} \kappa_{\text{abs}}(\lambda) \times 4\pi B_\lambda(T_d) d\lambda \quad (1)$$

where E_{tot} is the total emitted power of the 21 μm feature, $\kappa_{\text{abs}}(\lambda)$ is the mass absorption coefficient of the proposed dust carrier, $B_\lambda(T_d)$ is the Planck function at wavelength λ and dust temperature T_d (here we assume that the 21 μm feature-emitting dust has a single temperature of T_d). The abundance of element X locked up in dust $[X/H]$ to account for the observed power is then

$$[X/H] \equiv \frac{n_X m_d / \mu_d m_H}{M_H / m_H} = \frac{n_X E_{\text{tot}}}{\mu_d M_H \int_{21 \mu\text{m band}} \kappa_{\text{abs}}(\lambda) \times 4\pi B_\lambda(T_d) d\lambda} \quad (2)$$

where n_X is the number of X atoms per molecule, μ_d is the molecular weight of the dust, M_H is the total H mass of the circumstellar envelope of the star.

Therefore, with the mass absorption coefficient κ_{abs} experimentally measured or theoretically calculated, the required abundance of specific element X can be calculated from the observed feature intensity. For the strongest 21 μm feature source HD 56126 (also known as IRAS 07134+1005), the total power emitted through the 21 μm band is $E_{\text{tot}} \approx 10^{36} \text{ erg s}^{-1}$ (i.e., about $300 L_\odot$). From this abundance requirement, both the TiC nanoclusters and the fullerenes coordinated with Ti atoms originally suggested by Kimura et al. (2005b) are disqualified to be the carrier due to the shortage of element Ti; the same fate is for SiS_2 from the shortage of element S (SiS_2 also can not satisfy the criterion on the associated features) (Zhang et al. 2008).

Although the 21 μm feature is discovered only in C-rich sources that exhibit additional spectral features arising from C-bearing molecules, it has no clear association with any other features. As we will discuss later, ten among the twelve known 21 μm sources emit at the 30 μm feature as well, but their intensities are not correlated at all. On the other hand, the proposed carrier candidates often exhibit additional spectral feature(s) (aside from the 21 μm feature). A typical example is the SiC dust (responsible for the most popular dust feature in C-rich sources at 11.3 μm). The suggestion for SiC to be the 21 μm feature carrier must pass the examination that the expected intensity ratio of the 11.3 μm feature to the 21 μm feature should agree with the observed value of $I(11.3 \mu\text{m})/I(21 \mu\text{m}) < 0.01$ (Jiang et al. 2005).

Detailed calculations have shown that this is impossible from the optical properties of SiC (Jiang et al. 2005). The same examination has been applied to other inorganic carrier candidates. This requirement rules out all the candidates which exhibit associated feature(s), e.g., SiS_2 with an associated feature at 16.8 μm , SiC dust with carbon impurities at 11.3 μm , carbon and silicon mixtures at 9.5 μm , SiC core- SiO_2 mantle grains at 8.3 μm and 11.3 μm , Fe_2O_3 at 9.2 μm , 18 μm and 27.5 μm , Fe_3O_4 at 16.5 μm and 24 μm are all rejected as a viable candidate (see Zhang et al. 2008 for details). This lack of agreement is evident since the 21 μm feature is usually weak compared to the associated features in the experimental spectra of the proposed candidate materials while in the observation it is the opposite.

With the two criteria (i.e. the requirement of abundance to account for the observed high intensity of the 21 μm feature and the requirement of no clear associated feature) taken into account, among the inorganic carrier candidates only FeO (as originally proposed by Posch et al. 2004) survives, as both Fe and O are rich elements and FeO has no associated feature. However, it is not clear how FeO can form and survive in a C-rich environment where all O atoms are consumed to form CO. The summary of the examination results on the inorganic carrier candidates is described in Zhang et al. (2008).

The same examination procedure should be performed for the organic carrier candidates. From the abundance point of view, the organic materials are not expected to have problem since they are composed mainly of carbon and hydrogen, both of which are abundant elements. But they may have a big problem due to displaying associated features that are not observed in the 21 μm sources. For example, PAHs, as one of the organic carrier candidates, show a distinctive series of features at 3.3, 6.2, 7.7, 8.6 and 11.3 μm . In fact, ten among the twelve 21 μm sources have such PAH features (mostly around 3.3, 7.7,

and 11.3 μm), which makes it reasonable to list PAHs as a carrier candidate. But the intensity ratios of the 21 μm feature to the prominent features at 3.3–11.3 μm of PAHs can be problematic. Other organic species may have similar dilemma.

2.2 Search for new emitters

Although the twelve well-accepted 21 μm emitters are all PPNe, a few PNe and extreme AGB stars have been reported to have this feature as well. Hony et al. (2001) argued that the 21 μm feature is seen in two PNe. Volk et al. (2000) reported the detection of this feature in two highly evolved carbon stars. It is therefore necessary to search new 21 μm emitters in both PPNe and objects in other late stages of stellar evolution. To clarify the stellar evolutionary stages for this feature to exist, which discloses the physical and chemical conditions of the carrier, would be very helpful in the identification of the carrier.

We used the *Spitzer* Space Telescope to search for new 21 μm emitters. The adopted criteria which could potentially detect new 21 μm emitters was to find the sources with an emission excess around 21 μm which may come from the 21 μm feature. The mid-IR space project Midcourse Space Experiment (MSX) provided an opportunity to choose such sources because one of its broad photometric bands, band E, has a central wavelength of 21.34 μm and a bandwidth of 6.24 μm that covers the entire wavelength range of the 21 μm feature. So the task of picking out the objects with 21 μm emission excess was transferred to searching for the sources with excess in the MSX-E band. To be more explicit, the observed objects were selected based on the following procedure:

- 1) Pick up the evolved stars from the IRAS PSC (*Point Source Catalog*). Since the 21 μm sources are not necessarily limited to the post-AGB phase, stars in a broad evolutionary stage, from evolved AGB stars to PNe, are selected based on the IRAS color indices; specifically, $\log F_{25}/F_{12} > -0.2$ and $\log F_{60}/F_{25} < 0$. The combination of these two color indices are to exclude YSOs and galaxies and leave with us only evolved stars (van der Veen & Habing 1988). The selected stars should have high-quality IRAS photometry at 12 μm , 25 μm , and 60 μm .
- 2) Look for the counterparts of these sources in the MSX PSC catalog. The cross-association is done by position-matching. Only those sources in the sky area surveyed by MSX, mostly in the Galactic plane, are left. The selected sources should have high quality MSX photometry in the MSX C (12.13 μm) and E (21.34 μm) bands.
- 3) Find the sources with excess in the MSX E band. Fig. 1 is the color-color diagram of $\log F_{25}/F_{12}$ vs. $\log F_{\text{msxE}}/F_{\text{msxC}}$ of the sources chosen above. We fit these data by a quadratic line which approximately represent the mean values of the $\log F_{\text{msxE}}/F_{\text{msxC}}$ color. Apparently, the objects lying above this line are more likely to have the 21 μm emission feature. As the MSX C band (12.13 μm) is an analog to the IRAS 12 μm band, and the dust continuum radiation in the MSX E band (21.34 μm) should not differ much from that in the IRAS 25 μm band, the objects lying above the fitting line are considered to have an excess emission in the MSX E band.
- 4) Choose the sources whose colors are similar to those of the known 21 μm sources. Because most of the known 21 μm sources are at high latitudes, they were not observed by MSX. We therefore calculate $\log F_{\text{msxE}}/F_{\text{msxC}}$ for the known 21 μm sources by convolving their ISO/SWS spectra with the MSX Relative Spectral Response function. It can be seen that, as expected, these known 21 μm sources (denoted by asterisks) are lying mostly above or on (depending on the strength of the feature) the fitting line. In comparison, the C-rich PPN IRAS 19477+2401 without 21 μm emission (denoted by a triangle) is well below the fitting line. In addition, the color indices $\log F_{25}/F_{12}$ of the known 21 μm sources are all larger than 0.5 (because the dust is cold). Therefore, the sources with $\log F_{25}/F_{12}$ between 0.5 and 1.0 are chosen.
- 5) Exclude the sources which are O-rich or other early-type objects according to the SIMBAD database. A few of the above-selected sources, which are previously observed and found to be OH/IR stars or Wolf-Rayet objects, are rejected.
- 6) Exclude the sources brighter than 100 Jy in the MSX E band. This is to avoid the saturation problem in the IRS high resolution mode.

As the result, we were left with 18 sources which are possibly evolved AGB stars, PPNe and PNe and have excess emission around 21 μm . They are shown in Fig. 1 as diamond-surrounded dots. Two of the 18 sources were listed in others' *Spitzer* GO (General Observer) proposals with higher priority. The other 16 sources were observed from our *Spitzer* proposal (ID P-30403). They were observed using the Infrared Spectrograph (IRS) with two modules: Short-High (SH) and Long-High (LH) during Cycle-3 from October 2006 to May 2007. The data were taken in "staring mode" with two nod positions along each IRS slit. Due to the anticipated high brightness of the objects, no specific off-set observations were dedicated. Our observations found no new objects showing the 21 μm emission feature, while some objects have features attributed to crystalline silicates which bring about at least part of the MSX-E band excess (Jiang et al. 2008). It's worthy noting that

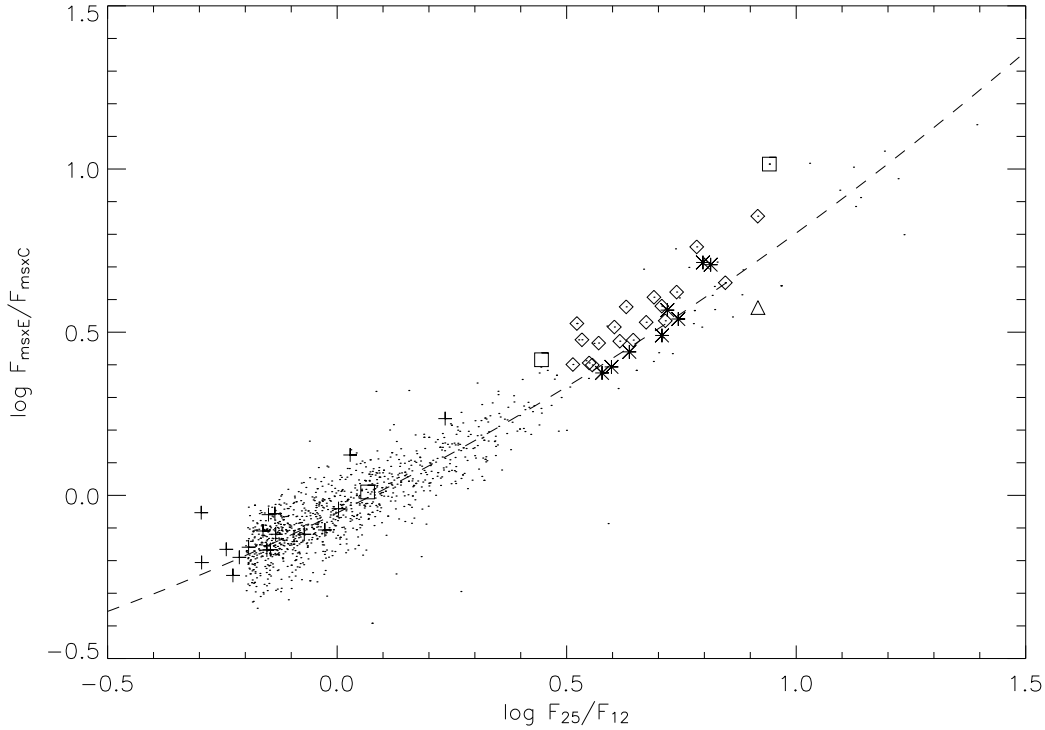


Fig. 1. Color-color diagram of the sources with good quality measurements both in the IRAS 12, 25 μm bands, and in the MSX C (12.13 μm) and E (21.34 μm) bands, with the dashed line being a quadratic fit to these data. The selected candidates are labelled by diamond-surrounded dots. Others symbols – asterisk: known strong 21 μm sources; cross: AGB stars with 10 and 20 μm silicate emission; square: O-rich PPNe with silicate emission; triangle: C-rich PPN without 21 μm emission.

Hrivnak et al. (2008) reported two new detections of the 21 μm feature based on their *Spitzer* observations. Although we are not yet at a position to conclude that the 21 μm feature exists only in C-rich PPNe, it at least suggests that this feature appears only under rigorous conditions and the sources are really rare.

In summary, we conclude that the carrier candidates suggested up to now are mostly unacceptable and the conditions for the existence of the 21 μm feature are not very clear either. To make progress in the study of this feature, more laboratory experiments are needed to search for materials that can meet the abundance and spectral requirements. In addition, sophisticated dust model may be helpful. From the observational side, larger scale surveys should be performed to the objects sharing the characteristics of the 21 μm sources, i.e. metal-poor, the s-process elements enhanced, C-rich, PPN and so on. But the *Spitzer* spectral surveys of the evolved stars in LMC and SMC did not find new emitters. Since the evolved stars in LMC and SMC are mainly C-rich and very likely metal-poor, this result may indicate that these two characteristics are not the key or not enough. Perhaps a survey of the C-rich PPN would be a nice project to discover new 21 μm emitters.

3. The 30 μm feature

The 30 μm feature is not as rare as the 21 μm feature. Since its discovery (Low et al. 1973) from ground-based observations, this feature has been detected in 63 Galactic objects: 36 evolved carbon stars, 14 PPNe and 13 PNe (Hony et al. 2002), thanks to *KAO* (Kuiper Airborne Observatory), *ISO* (Infrared Space Observatory) and *Spitzer*. Moreover, the 30 μm emission feature is also found in evolved stars of other galaxies, including 17 carbon-rich stars in the LMC (Zijlstra et al. 2006) and 8 carbon-rich stars in the SMC (Sloan et al. 2006; Lagadec et al. 2007).

The 30 μm feature shows up not only in the PPN phase, but also in the AGB and PN phases. The conditions for its presence is not as strict as the 21 μm feature. However, like the 21 μm feature, it shows up only in C-rich environment. Meanwhile, they do not form a special sub-group of the evolved C-rich objects, at least partly due to the lack of a detailed analysis of the 30 μm sources. Nevertheless, there seems to be a borderline of dust temperature for the 30 μm emission. In our Galaxy, this feature occurs from extreme AGB stars on to later stages. In LMC and SMC, only in the coolest stars was this feature detected. Given the uncertainties in determining the specific dust temperature, the highest dust temperature

of the 30 μm emitters should not exceed 700 K. The temperature upper limit means the feature carrier exists only in low temperature.

The spectral profile, both the peak and width, of the 30 μm feature changes in different objects. The feature peak shifts to longer wavelengths with lower dust temperature for the Galactic sources. The shape changes significantly from object to object that it even causes debates about the feature profile. One suggestion is that the feature is composed of two sub-features at different wavelengths according to the *ISO* observation of some PPNe (Volk et al. 2002); the other suggestion is that the feature is monolithic but varies with the temperature and shape of the dust carrier (Hony et al. 2002). The experimental absorption spectra of MgS, a promising carrier candidate, show great dependence on dust shape (Kimura et al. 2005a).

MgS seems to be a widely accepted carrier of the 30 μm feature, although other candidates have also been proposed (including organic molecules naturally present in C-rich environment). MgS was first brought forward by Goebel & Moseley (1985) based on its IR resonance band. Later observations of the 30 μm band were often explained in terms of the MgS dust in the radiative transfer modelling, but the modelling results bring about a few questions on MgS as the carrier.

Shape Spherical-shaped dust can not fit the observations well, while CDE (continuous distribution of ellipsoids) can, because the optical properties of MgS change greatly with the dust shape. However, the shape of the MgS dust formed in laboratory is often roundish, network-like or cubic other than ellipsoidal (Kimura et al. 2005a). Moreover, the CDE shape distribution is difficult to explain the observed sub-structures (but see Zhukovska & Gail 2008). It thus leads to the suspicion of the reality of the ellipsoidal shape assumption.

Abundance For the sources in the Galaxy, the required abundances of Mg and S to account for the observed intensity of the 30 μm feature is usually much less than cosmic abundances of these elements. For example, Jiang et al. (1999) found that 10% of the cosmic S abundance is sufficient. Thus the MgS abundance seems to have no problem. Nevertheless, the detection of the 30 μm feature in LMC and SMC needs to re-consider the abundance issue since these two galaxies are much more metal-poor than our Galaxy, in particular the metallicity of the SMC is only about 10% of our Galaxy. No modelling efforts have been taken for the 30 μm features detected in the Magellanic clouds (MCs) partly due to the lack of abundance measurements of these sources. Quantitative modelling will be very helpful. Besides, whether sulfur is mainly tied to MgS is unknown. From the examination of the Wild 2 dust collected by *Stardust*, most of the sulfur in the anhydrous dust is concentrated in iron sulfides while no MgS dust was found; besides, some of the anhydrous silicates are Mg-rich (Flynn 2008). This suggests that both Mg and S may be tied to dust species other than MgS. However, Zhukovska & Gail (2008) pointed out that FeS is abundant only in O-rich environments; while in C-rich environment, MgS is more stable than FeS, and Mg should neither be tied to silicates formed in O-rich environment. This may alleviate the problem of abundance caused by consuming Mg and S to form other molecules.

Associated features The experimental IR spectra of MgS exhibit some sub-structures although the associated features depend on dust shape (Kimura et al. 2005a). This might be a piece of good news for the argument that the 30 μm feature is composed of two sub-features, but whether the observed and experimental sub-structures agree with each other needs careful comparison.

4. Comparison of the 21 μm and 30 μm features

The 21 μm and 30 μm features are the strongest dust features in evolved C-rich sources. They share some characters such as to influence the final evolution of stars. But they are different in several aspects as mentioned in previous sections. Here a detailed comparison is summarized.

Profile The 21 μm feature is not symmetrical, but has a steep rise in blue wing and a long tail at the red end $\sim 23\text{--}24 \mu\text{m}$. It is certainly a one-component feature. More importantly, the profile of this feature is universal, i.e. there is no clear change from source to source. This leads one to believe that the carrier should be a single sort of dust material with universal properties in various sources. On the other hand, the profile of the 30 μm feature changes so greatly from source to source that a two-component structure was proposed as discussed above. The change of the profile could be caused either by the dust properties such as the shape and size distributions that lead to the change of optical properties, or by the physical and chemical conditions such as the temperature and metallicity. From the analysis of the 30 μm sources in our Galaxy, Hony et al. (2002) found that the feature profile is related to the dust temperature. In the low-metallicity SMC, this feature appears to be weaker than in our Galaxy (Sloan et al. 2006), but there is no significant difference in LMC and in our Galaxy (Zijlstra et al. 2006) even though LMC is clearly metal poor compared to our Galaxy. Therefore, it seems that the metallicity is not directly correlated with the strength of the 30 μm feature.

Emitters First of all, both features are detected only in C-rich sources, and in the very late stages of evolution. The 21 μm feature is detected only in PPNe, the very short transient phase of stellar evolution, while the 30 μm feature shows up from AGB to PPN and PN phases. In addition, the 30 μm feature is discovered in LMC and SMC where the metallicity is low. Meanwhile there has been no report on the discovery of the 21 μm feature in the MCs although the 21 μm sources in our Galaxy are metal-poor, but this may be caused by the observation bias: so far only evolved AGB stars (not PPNe) have been observed in the MCs. It implies that the carrier of the 21 μm feature can survive only in a narrow range of physical conditions. On the contrary, the dust for the 30 μm feature can live in various environments, in particular, its survival to the PN phase would bring it to the ISM to participate in the cosmic dust re-cycling.

Table 1. The 21 μm feature sources. The numbers under the “30 μm ” and “21 μm ” labels are the fractions of the total IR flux emitted in the 30 μm feature or the 21 μm feature (in case no numbers are given, \checkmark : detected, ...: not yet detected).

Object	30 μm	21 μm	Ref.
02229+6208	20	1	Hrivnak et al. 2000
04296+3429	22	5	Szczerba et al. 1999
05113+1347	...	\checkmark	Kwok 1999
07134+1005	12	8	Hrivnak et al. 2000
16594-4656	22	7	Hrivnak et al. 2000
19500-1709	24	1	Volk et al. 2002
20000+3239	19	1	Hrivnak et al. 2000
AFGL 2688	\checkmark	\checkmark	Omont et al. 1999
22223+4327	\checkmark	\checkmark	Volk et al. 2002
22272+5435	24	3	Szczerba et al. 1999
22574+6609	19	2	Hrivnak et al. 2000
23304+6147	24	5	Volk et al. 2002

Co-existence Among the twelve 21 μm feature sources, ten sources show the 30 μm emission feature. Early in 1995, the 16–46 μm spectra were taken for five 21 μm emitters by KAO. It was found that the 30 μm feature is present in all of them, while the intensity of these two bands are not correlated (Omont et al. 1995). Later, from the ISO/SWS spectra, Hrivnak et al. (2000) discovered new 30 μm emitters and quantitatively analyzed the percentage of the total IR flux emitted in the two features (see Table 1). Up to now, 11 of the twelve 21 μm emitters are reported to have the 30 μm emission feature. The only source that was not classified as with the 30 μm feature is IRAS 05113+1347 which was not observed in this spectral range. Therefore, the 11/12 ratio is a lower limit of the percentage of the 30 μm feature in the 21 μm sources and a 12/12 ratio is possible. Such an almost 100 percentage that the 30 μm feature appears in the 21 μm emitters may lead to the proposition that their origins are related. But this is challenged by the fact that their strengths are not correlated. The most promising candidate carrier of the 30 μm feature MgS is neither suggested as that of the 21 μm feature as it does not exhibit any features around 21 μm . Nevertheless, the carriers for both features are not well identified. They may (partly) share some organic molecules as the carrier, or their carrier may co-exist.

Acknowledgments. BWJ and KZ are supported in part by China’s grants 2007CB815406 and NSFC 10473003. BWJ thanks the LOC for financial support. AL is supported in part by NASA/*Spitzer* Theory Programs and NSF grant AST 07-07866. We thank Drs. B. Hrivnak and Y. Kimura for helpful suggestions.

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