Unidentified Species in Envelopes around Carbon Stars

B. W. Jiang\textsuperscript{1}, A. Li\textsuperscript{2}, K. Zhang\textsuperscript{3}, J. M. Liu\textsuperscript{1}, J. Gao\textsuperscript{1} and A. Mishra\textsuperscript{2}

\textsuperscript{1}Department of Astronomy, Beijing Normal University, Beijing 100875, China
e-mail: bjiang@bnu.edu.cn
\textsuperscript{2}Department of Physics and Astronomy, University of Missouri, Columbia, MO 65211, USA
\textsuperscript{3}Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA

Abstract. The infrared (IR) spectra of many evolved carbon-rich stars exhibit two prominent dust emission features peaking around 21\,$\mu$m and 30\,$\mu$m, with the former exclusively seen in proto-planetary nebulae (PPNe), while the latter seen in a much wider range of objects, including AGB stars, PPNe and planetary nebulae (PNe). The 30\,$\mu$m feature is seen in all the 21\,$\mu$m sources, but no correlation is found between these two features. Over a dozen carrier candidates have been proposed for the 21\,$\mu$m feature, but none of them has been widely accepted and the nature of the 21\,$\mu$m feature remains a mystery. The carrier of the 30\,$\mu$m feature also remains unidentified. MgS dust, once widely accepted as a valid carrier, was ruled out because of the sulfur budget problem. In this work we examine nano-sized FeO dust as a carrier for the 21\,$\mu$m feature. We calculate the IR emission spectrum of FeO nanodust which undergoes single-photon heating in PPNe. It is found that the 21\,$\mu$m feature emitted by FeO nanodust is too broad to explain the observed feature. For the 30\,$\mu$m feature, we argue that graphite could be a viable carrier. Graphite, provided its d.c. conductivity $\sigma_{d.c.}$ exceeds $\sim$100 ohm\,$^{-1}$ cm\,$^{-1}$, exhibits a pronounced band at 30\,$\mu$m.

Keywords. stars: carbon, (stars:) circumstellar matter, dust, infrared: stars

1. Introduction

In the late stage of evolution, the low- and intermediate-mass stars lose a large amount of mass and produce circumstellar shells. Various dust species are present in the cold and dense shells of asymptotic giant branch (AGB) stars, post-AGB stars and planetary nebulae (PNe), among which silicate dust in O-rich shells and SiC dust in C-rich shells are well identified through their spectral features.

There are two prominent spectral features respectively peaking around 21\,$\mu$m and 30\,$\mu$m. Both features are observed in circumstellar shells of C-rich stars in both the Milky Way and the Magellanic Clouds (MC). So far, the 21\,$\mu$m feature is detected in about 18 Galactic objects (Cerrigone \textit{et al.} 2011) and 9 MC objects (Volk \textit{et al.} 2011). The 21\,$\mu$m feature is only seen in proto-planetary nebulae (PPNe), a transient phase in stellar evolution. In contrast, the 30\,$\mu$m feature is detected in the whole late stage of stellar evolution, from AGB to post-AGB to PN (Hony \textit{et al.} 2003).

All the 21\,$\mu$m sources also display the 30\,$\mu$m emission feature as well as the so-called “unidentified infrared (UIR)” emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3\,$\mu$m. The UIR bands are commonly attributed to polycyclic aromatic hydrocarbon (PAH) molecules (Léger & Puget 1984, Allamandola \textit{et al.} 1985). As shown in Figure 1, the 30\,$\mu$m feature does not correlate with the 21\,$\mu$m feature, implying that their carriers are not related. Figure 1 also shows that the 21\,$\mu$m feature does not correlate with the UIR features. This argues against large PAH clusters as a possible carrier for the 21\,$\mu$m feature. Moreover, it appears that the 30\,$\mu$m feature and the UIR features weakly anti-correlate, suggesting...
2. FeO nanodust as a carrier of the 21 µm feature

Zhang et al. (2009a) examined nine inorganic carrier candidates for the 21 µm feature, including nano TiC, fullerenes with Ti, SiS2, doped SiC, the SiC and SiO2 mixture, FeO, Fe2O3 and Fe3O4. We found that except FeO nanodust, they are all problematic: they
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Figure 3. Upper panel: the opacity of graphite with a d.c. conductivity of \( \sigma_{d.c.} = 100 \text{ ohm}^{-1} \text{ cm}^{-1} \). A prominent 30 \( \mu \text{m} \) feature with a FWHM of \( \sim 10 \ \mu \text{m} \) is clearly seen. Lower panel: the emission profiles of graphite with \( \sigma_{d.c.} = 100 \text{ ohm}^{-1} \text{ cm}^{-1} \) at \( T = 80, 100, 120, 140 \ \text{K} \). Dot-dashed line: the \( T = 100 \ \text{K} \) blackbody.

either require too much material (i.e., violating the abundance constraint) or produce extra features which are not seen in astronomical objects.

FeO seems to be a promising candidate carrier for the 21 \( \mu \text{m} \) feature for two reasons: (1) Fe is an abundant element; and (2) FeO has a pronounced spectral feature around 21 \( \mu \text{m} \) (Posch et al. 2004, Zhang et al. 2009a). However, it is not clear how FeO forms in C-rich environments as the 21 \( \mu \text{m} \) sources are all C-rich. Posch et al. (2004) argued that FeO nanodust could form in these environments. We therefore model the excitation and emission processes of FeO nanodust in PPNe. As FeO nanodust will experience temperature fluctuation, we calculate its temperature probability distribution function \( dP/dT \) and then calculate its emission spectrum from \( dP/dT \).

Taking a 3-D Debye model (with a Debye temperature of \( \Theta_D = 430 \ \text{K} \)) for the specific heat of FeO and the refractive indices at \( T = 10 \ \text{K}, 100 \ \text{K}, 200 \ \text{K} \) and \( 300 \ \text{K} \) from Henning & Mutschke (1995, 1997), we calculate \( dP/dT \) and the emergent spectrum of spherical FeO of radius \( a = 10 \ \text{Å} \) for HD 56126, a proto-typical 21 \( \mu \text{m} \) source (see Figure 1). The IR emission spectrum exhibits a strong band at 21 \( \mu \text{m} \). However, it is too broad (with FWHM \( \sim 4 \ \mu \text{m} \)) to explain the observed FWHM of \( \sim 2.2–2.3 \ \mu \text{m} \) (see Kwok et al. 1989). For nonspherical dust, the predicted 21 \( \mu \text{m} \) feature is even broader. Finally, to account for the power emitted from the 21 \( \mu \text{m} \) feature in HD 56126, the FeO model
requires Fe/H \approx 4.3 \times 10^{-6}, exceeding the iron budget of Fe/H \approx 3.2 \times 10^{-6} available in HD 56126. Therefore, FeO nanodust is unlikely a valid carrier for the 21 \mu m feature.

3. Graphite as a carrier for the 30 \mu m feature

The 30 \mu m feature, extending from \sim 24 to \sim 45 \mu m, is very strong and accounts for up to \sim 30\% of the total IR luminosity of the emitter. MgS dust, once widely accepted as a carrier (Begemann et al. 1994), was ruled out by Zhang et al. (2009b) who showed that the MgS model would require too much S. Even with a very generous assumption of UV/optical absorbing coefficient, the required MgS dust exceeds what is available by over an order of magnitude. This was later confirmed by Messenger et al. (2013) (but also see Lombaert et al. 2012).

We propose graphite as a carrier of the 30 \mu m feature seen in evolved stars. Graphite has been identified as a presolar stardust species in primitive meteorites through its isotropic anomaly. Graphite is also key component in standard interstellar grain models. A feature around 30 \mu m is already recognizable in the absorption coefficient of graphite (Draine & Lee 1984). Depending on its d.c. conductivity \sigma_{d.c.}, the 30 \mu m feature could be very strong. Our preliminary calculations show that graphite could account for the observed 30 \mu m feature, provided \sigma_{d.c.} > 100 \text{ohm}^{-1} \text{cm}^{-1} (see Figure 1). Experiments have shown that graphite can have a wide range of \sigma_{d.c.}, ranging from \sim 1 to \sim 200 \text{ohm}^{-1} \text{cm}^{-1} (Primak 1956).

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