

## ON MAGNESIUM SULFIDE AS THE CARRIER OF THE 30 $\mu\text{m}$ EMISSION FEATURE IN EVOLVED STARS

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### ABSTRACT

A large number of carbon-rich evolved objects (asymptotic giant branch stars, protoplanetary nebulae, and planetary nebulae) in both the Milky Way galaxy and the Magellanic Clouds exhibit an enigmatic broad emission feature at  $\sim 30 \mu\text{m}$ . This feature, extending from  $\sim 24 \mu\text{m}$  to  $\sim 45 \mu\text{m}$ , is very strong and accounts for up to  $\sim 30\%$  of the total infrared luminosity of the object. In literature it is tentatively attributed to magnesium sulfide (MgS) dust. Using the prototypical protoplanetary nebula around HD 56126 for illustrative purpose, however, in this work we show that in order for MgS to be responsible for the 30  $\mu\text{m}$  feature, one would require an amount of MgS mass substantially exceeding what would be available in this source. We therefore argue that MgS is unlikely the carrier of the 30  $\mu\text{m}$  feature seen in this source and in other sources as well.

*Key words:* circumstellar matter – dust, extinction – infrared: stars – stars: AGB and post-AGB – stars: individual (HD 56126)

*Online-only material:* color figures

### 1. INTRODUCTION

In carbon-rich evolved objects, there are two prominent, mysterious emission features known as the “21  $\mu\text{m}$ ” and “30  $\mu\text{m}$ ” features (e.g., see Jiang et al. 2009). The 21  $\mu\text{m}$  feature is seen almost exclusively in 16 protoplanetary nebulae (PPNe) and its identification is notoriously difficult (see Posch et al. 2004; Zhang et al. 2009). The 30  $\mu\text{m}$  feature, first discovered by Forrest et al. (1981) in the *Kuiper Airborne Observatory* spectrometry of C stars and planetary nebulae (PNe), is very broad and strong, extending from  $\sim 24 \mu\text{m}$  to  $\sim 45 \mu\text{m}$  and accounting for up to  $\sim 30\%$  of the total infrared (IR) luminosity of the object (Volk et al. 2002).<sup>3</sup> More ubiquitously seen in C-rich objects than the 21  $\mu\text{m}$  feature, the 30  $\mu\text{m}$  feature has now been detected in 63 Galactic and 25 Magellanic objects (see Jiang et al. 2009 and references therein), including asymptotic giant branch (AGB) stars, post-AGB stars and PNe.<sup>4</sup>

Compared to the 21  $\mu\text{m}$  feature for which over a dozen carrier candidates have been proposed, the identification of the 30  $\mu\text{m}$  feature has not received the attention it deserves. Magnesium sulfide (MgS) solids were first proposed by Goebel & Moseley (1985) as a carrier of the 30  $\mu\text{m}$  feature, based on (1) the similarity of the observed emission spectral profiles and the laboratory spectra of MgS (Nuth et al. 1985), and (2) the considerations of C-rich equilibrium condensation chemistry which predicts the condensation of MgS in C-rich stars (Lattimer et al. 1978). The MgS proposition gains further support from detailed modeling of the 30  $\mu\text{m}$  feature of a large number of C-rich sources obtained by the *ISO* (Jiang et al. 1999; Szczerba et al. 1999; Hony et al. 2002).

A valid carrier candidate should not only reproduce the observed emission spectra but also satisfy the abundance constraints (i.e., the amounts of elements required to lock up in the carrier should not exceed what are available in the 30  $\mu\text{m}$  sources). The absorption profile  $Q_{\text{abs}}(\lambda)$  of MgS dust with a distribution of ellipsoidal shapes exhibits a broad band around 30  $\mu\text{m}$ . To fit the observed 30  $\mu\text{m}$  emission spectra, one often compares the observed spectra with  $Q_{\text{abs}}(\lambda) B_{\lambda}(T)$ , the product of the absorption efficiency and a blackbody with an assumed temperature  $T$  (e.g., see Hony et al. 2002).

The MgS temperature is an essential parameter: it not only affects the shape and peak wavelength of the model emission spectrum but also determines the total amount of MgS dust  $M_{\text{MgS}}$  required to account for the flux  $F_{\lambda}$  emitted from the 30  $\mu\text{m}$  band:  $M_{\text{MgS}} \propto F_{\lambda} / [Q_{\text{abs}}(\lambda) B_{\lambda}(T)]$ . Previous models based on MgS do not seem to have a sulfur (S) budget problem (Jiang et al. 1999; Szczerba et al. 1999; Hony et al. 2003). However, the MgS temperatures adopted in these models were often treated as a free parameter and were derived from matching the spectral profiles of the observed 30  $\mu\text{m}$  feature with  $Q_{\text{abs}}(\lambda) B_{\lambda}(T)$  by varying  $T$  (e.g., see Hony et al. 2002). Due to the lack of the dielectric functions in the ultraviolet (UV), visible and near-IR wavelength ranges for MgS dust, it is not possible to calculate the precise thermal equilibrium temperatures of MgS dust in the 30  $\mu\text{m}$  sources. Therefore, the previously derived S budget may be questionable.

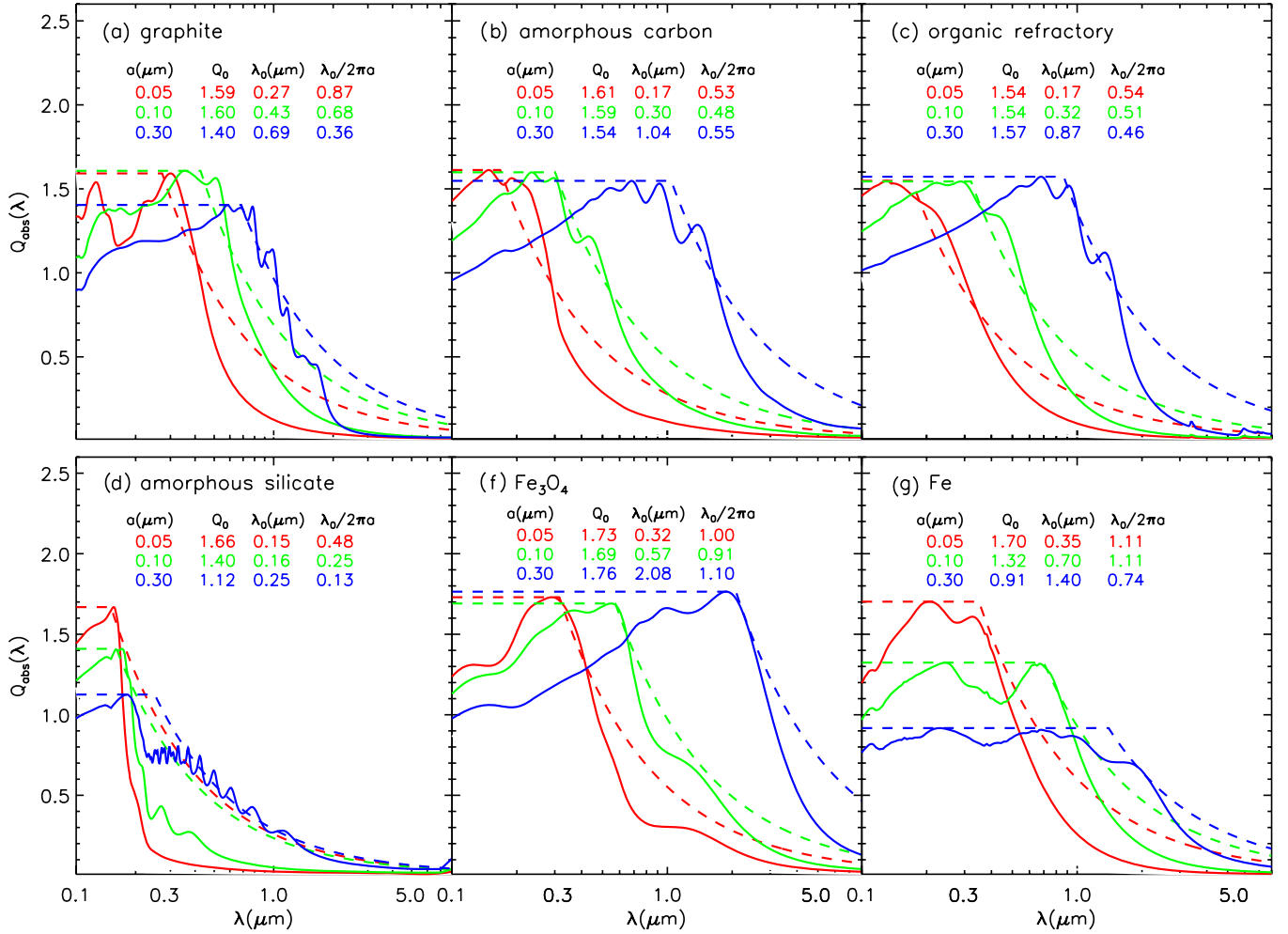
In this work, we make a rather generous estimation of the UV/visible absorptivity of MgS and calculate its temperatures in the circumstellar shell of HD 56126, a prototypical source of the 21  $\mu\text{m}$  and 30  $\mu\text{m}$  features. It is shown that the required MgS dust mass exceeds what would be available by a substantial amount. We therefore argue that MgS is unlikely the carrier of the 30  $\mu\text{m}$  feature.

### 2. OPTICAL PROPERTIES OF MgS DUST

In order to calculate the temperature of a dust species, the knowledge of its optical properties over a wide wavelength range is required. Unfortunately, the dielectric functions of MgS

<sup>3</sup> The *Infrared Space Observatory* (*ISO*) spectroscopy suggested that the 30  $\mu\text{m}$  feature consists of two subfeatures: a narrow feature at 26  $\mu\text{m}$  and a broad one at 33  $\mu\text{m}$  (Hrivnak et al. 2000; Volk et al. 2002). But this was not confirmed by *Spitzer* (Hrivnak et al. 2009).

<sup>4</sup> The 21  $\mu\text{m}$  sources all exhibit the 30  $\mu\text{m}$  feature. But these two features do not appear to correlate in their strengths (see Jiang et al. 2009). Unlike the 21  $\mu\text{m}$  feature which displays little shape variation, the 30  $\mu\text{m}$  feature varies in its peak wavelength and width among different sources (e.g., see Hrivnak et al. 2000; Hony et al. 2002).



**Figure 1.** Absorption efficiencies  $Q_{\text{abs}}(\lambda)$  of both dielectric (amorphous carbon, organic refractory, amorphous silicate) dust and metallic dust (graphite, iron, and magnetite) calculated from Mie theory for three sizes:  $a = 0.05$  (red),  $0.1$  (green), and  $0.3 \mu\text{m}$  (blue). Also shown are the best fits (dashed lines) given by Equation (1) (with  $Q_0$  and  $\lambda_0$  treated as free parameters).

(A color version of this figure is available in the online journal.)

have only been experimentally determined in the IR (e.g., see Begemann et al. 1994; Hofmeister et al. 2003). The UV/visible absorptivities of MgS dust are essential since they determine how much energy will be absorbed by a given MgS grain (when exposed to starlight) which in turn determines how much energy will be emitted in the IR. It is this balance of energy between absorption and emission that determines the grain temperature.

We take the following procedure to approach the UV/visible absorption efficiency  $Q_{\text{abs}}^{\text{UV}}(\lambda)$  of MgS dust:

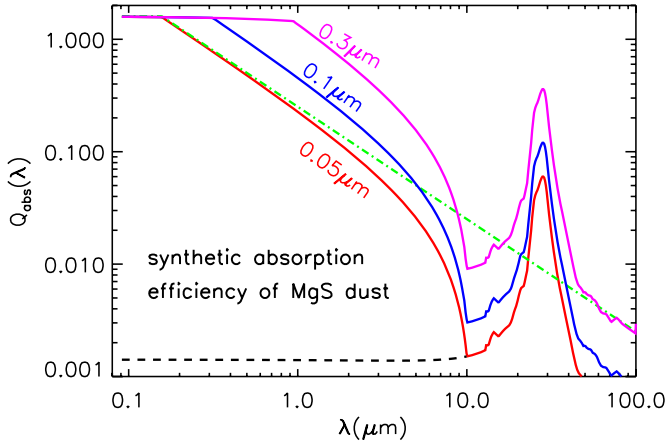
$$Q_{\text{abs}}^{\text{UV}}(\lambda) = \begin{cases} Q_0, & \lambda \leq \lambda_0; \\ Q_0 (\lambda_0/\lambda), & \lambda > \lambda_0, \end{cases} \quad (1)$$

where  $Q_0$  is a constant and the cut-off wavelength  $\lambda_0$  depends on grain size (and material). What would be the reasonable  $Q_0$  and  $\lambda_0$  values for MgS? To shed light on this, we use Mie theory to calculate the UV to near-IR absorption efficiencies for spherical grains of various compositions and sizes. We consider both dielectric (amorphous silicate, amorphous carbon, organic refractory) and metallic materials (graphite, iron Fe, magnetite  $\text{Fe}_3\text{O}_4$ ). We then approximate the calculated absorption profiles  $Q_{\text{abs}}(\lambda)$  with Equation (1). For submicron-sized dust, as shown in Figure 1, while  $Q_0 \approx 1.6$  is a reasonable estimation for

both dielectric and metallic dust, the cut-off wavelength for a given size  $a$  is generally shorter for dielectric dust ( $\lambda_0 \approx \pi a$ )<sup>5</sup> than that for metallic dust ( $\lambda_0 \approx 2\pi a$ ). For MgS dust of size  $a$ , we thus adopt  $Q_0 = 1.6$  and  $\lambda_0 = \pi a$ . We note that, as can be seen in Figure 1, Equation (1) with  $Q_0 = 1.6$  and  $\lambda_0 = \pi a$  (or  $\lambda_0 = 2\pi a$ ) almost always overestimates the actual UV/visible absorptivities of all six dust species, particularly at  $\lambda < \lambda_0$ . This suggests that the MgS temperatures derived using the UV/visible absorptivity of Equation (1) would be overestimated and thus one would underestimate  $M_{\text{MgS}}$  (since it is most likely that Equation (1) also overestimates the actual UV/visible absorptivity of MgS).

In the IR, we will use the dielectric functions of  $\text{Mg}_{0.9}\text{Fe}_{0.1}\text{S}$  measured by Begemann et al. (1994) in the 10–200  $\mu\text{m}$  wavelength range to calculate the absorption efficiencies  $Q_{\text{abs}}^{\text{IR}}(\lambda)$  of MgS. At longer wavelengths, we will extrapolate assuming  $Q_{\text{abs}}^{\text{IR}}(\lambda) \propto \lambda^{-2}$ . We will consider both spherical dust and dust with a continuous distribution of ellipsoids (CDE) shape distribution (Bohren & Huffman 1983). Finally, we smoothly

<sup>5</sup> For amorphous silicate dust larger than  $\sim 0.07 \mu\text{m}$  in size,  $\lambda_0$  is much smaller than  $\pi a$ . This is due to the sudden rise in absorption caused by the electronic transition at  $\lambda \sim 0.1\text{--}0.2 \mu\text{m}$  (Kim & Martin 1995).



**Figure 2.** Synthetic absorption efficiencies of MgS dust of  $a = 0.05$  (red),  $0.1$  (blue),  $0.3 \mu\text{m}$  (magenta). For  $a = 0.05 \mu\text{m}$ , we also show the UV/visible component  $Q_{\text{abs}}^{\text{UV}}$  (green dot-dashed line) and the IR component  $Q_{\text{abs}}^{\text{IR}}$  (black dashed line) alone.

(A color version of this figure is available in the online journal.)

join  $Q_{\text{abs}}^{\text{UV}}(\lambda)$  and  $Q_{\text{abs}}^{\text{IR}}(\lambda)$  through

$$Q_{\text{abs}}(\lambda) = (1 - \xi_{\text{IR}}) Q_{\text{abs}}^{\text{UV}}(\lambda) + \xi_{\text{IR}} Q_{\text{abs}}^{\text{IR}}(\lambda), \quad 912 \text{ \AA} < \lambda < 1 \text{ cm} \quad (2)$$

$$\xi_{\text{IR}}(\lambda) = \min [1, (\lambda/10 \mu\text{m})^3]. \quad (3)$$

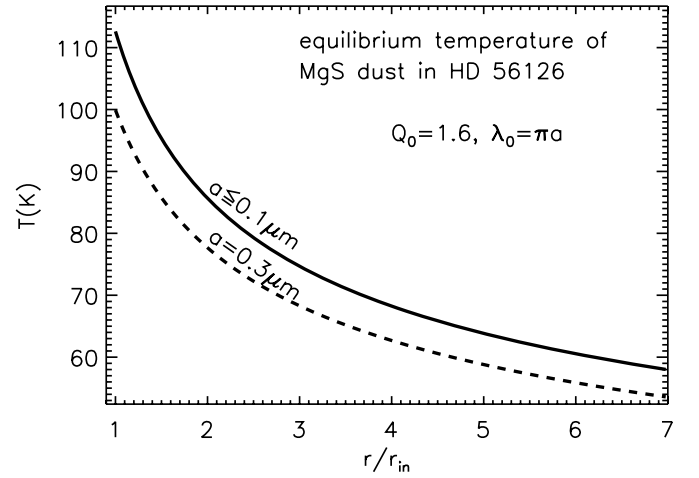
The absorption efficiency synthesized from Equation (2) is dominated by  $Q_{\text{abs}}^{\text{UV}}(\lambda)$  at  $\lambda < 5 \mu\text{m}$  and by  $Q_{\text{abs}}^{\text{IR}}(\lambda)$  at  $\lambda > 10 \mu\text{m}$  (see Figure 2).

### 3. THE TESTER: HD 56126

A successful candidate carrier should be able to explain the observed  $30 \mu\text{m}$  feature in all sources. A failure in a single source would be sufficient to rule out the candidate. To examine whether the carriers can account for the observed feature strength we choose HD 56126, a prototypical source of the  $21 \mu\text{m}$  and  $30 \mu\text{m}$  features and one of the best studied post-AGB stars, as a tester.

Van Winckel & Reyniers (2000) performed a homogeneous photospheric abundance analysis for HD 56126, and derived the abundances of sulfur and carbon to be  $\text{S}/\text{H} \approx 4.07 \times 10^{-6}$ , and  $\text{C}/\text{H} \approx 4.47 \times 10^{-4}$ . HD 56126 has a radius of  $r_{\star} \approx 49.2 r_{\odot}$  ( $r_{\odot}$  is the solar radius), and a luminosity of  $L_{\star} \approx 6054 L_{\odot}$  ( $L_{\odot}$  is the solar luminosity). We approximate the stellar radiation by the Kurucz model atmospheric spectrum with  $T_{\text{eff}} = 7250 \text{ K}$  and  $\log g = 1.0$ . We adopt a distance of  $d \approx 2.4 \text{ kpc}$  from Earth to HD 56126.

The size and mass of the circumstellar envelope of HD 56126, which are important for determining the quantity of MgS dust available in the envelope, are still controversial. Hony et al. (2003) suggested that the dust is confined to the envelope with a radius between  $1''.2$ – $2''.6$  based on their mid-IR imaging at  $11.9 \mu\text{m}$ . Their detailed radiative transfer model derived a circumstellar envelope mass of  $M_{\text{H}} \sim 0.16$ – $0.44 M_{\odot}$ , depending on the assumed gas-to-dust ratio ( $\sim 220$ – $600$ ). Meixner et al. (2004) found a more extended envelope (with radius between  $1''.2$ – $7''$ ) based on their CO  $J = 1 - 0$  line emission images. They derived a much smaller mass for the envelope ( $M_{\text{H}} \sim 0.059 M_{\odot}$ ).



**Figure 3.** Equilibrium temperatures of MgS dust in the HD 56126 envelope. For dust with  $a \lesssim 0.1 \mu\text{m}$ ,  $T$  is insensitive to  $a$  (see Footnote 7).

### 4. HOW MUCH MgS DUST IS REQUIRED?

By assuming the envelope is optically thin,<sup>6</sup> we calculate the temperature  $T(r, a)$  of MgS dust of size  $a$  at a distance  $r$  from the central star from the energy balance between absorption and emission

$$\left(\frac{r_{\star}}{2r}\right)^2 \int_0^{\infty} \pi a^2 Q_{\text{abs}}(a, \lambda) F_{\lambda}^{\star} d\lambda = \int_0^{\infty} \pi a^2 Q_{\text{abs}}(a, \lambda) 4\pi B_{\lambda}(T[r, a]) d\lambda, \quad (4)$$

where  $F_{\lambda}^{\star}$  is the stellar atmospheric flux which is approximated by a Kurucz model. In Figure 3, we show the equilibrium temperatures of MgS dust of  $a = 0.1, 0.3 \mu\text{m}$  as a function of the distance from the central star.<sup>7</sup> We see that for  $a \lesssim 0.1 \mu\text{m}$   $T$  decreases from  $\sim 110 \text{ K}$  at the inner most shell to  $\sim 50 \text{ K}$  at the outer boundary, significantly lower than that adopted by Hony et al. (2002),  $T = 150 \text{ K}$ . Larger dust has a lower  $T$  (e.g., for dust of  $a = 0.3 \mu\text{m}$ ,  $T$  is lower than that of  $a = 0.1 \mu\text{m}$  by about  $\sim 10 \text{ K}$ ).

The IR emission per unit mass of MgS dust of size  $a$  is

$$F_{\text{MgS}}(\lambda) = \int_{r_{\text{in}}}^{r_{\text{out}}} [3 Q_{\text{abs}}(a, \lambda) / 4a\rho_{\text{MgS}}] \times 4\pi B_{\lambda}(T[r, a]) dn(r)/dr 4\pi r^2 dr, \quad (5)$$

where  $\rho_{\text{MgS}} \approx 2.84 \text{ g cm}^{-3}$  is the mass density of MgS dust,  $r_{\text{in}} \approx 1''.2$  and  $r_{\text{out}} \approx 7''$  are respectively the inner and outer radius of the dust shell of HD 56126 (Meixner et al. 2004), and  $dn(r)/dr$  is the MgS dust spatial density distribution. We will consider two spatial distribution functions: (1)  $dn/dr \propto r^{-2}$ , which means the mass loss of the central star is constant during the whole process;<sup>8</sup> and (2)  $dn/dr \propto r^{-1}$ , which was shown by

<sup>6</sup> If the envelope is not optically thin, the conclusion of this work would be strengthened since when exposed to an attenuated starlight radiation, the MgS model would require more MgS dust to account for the same  $30 \mu\text{m}$  feature strength.

<sup>7</sup> For dust in the size range of  $0.01 < a < 0.1 \mu\text{m}$ ,  $T$  is insensitive to  $a$  since both  $Q_{\text{abs}}^{\text{UV}}/a$  and  $Q_{\text{abs}}^{\text{IR}}/a$  are independent of  $a$ . This is because for  $\lambda > 0.3 \mu\text{m}$  where there is significant stellar radiation,  $Q_{\text{abs}}^{\text{UV}} \propto \lambda_0 \propto a$ , while in the IR the dust is in the Rayleigh regime and therefore  $Q_{\text{abs}}^{\text{IR}} \propto a$ .

<sup>8</sup> The much more complicated function adopted by Meixner et al. (2004) to reproduce the observed dust IR emission spectral energy distribution (SED) and mid-IR images of HD 56126 is actually similar to  $dn/dr \propto r^{-2}$ .

**Table 1**

$M_{\text{MgS}}^{\text{req}}$  (in unit of  $10^{-5} M_{\odot}$ )—The MgS Mass Required to Account for the Power Emitted in the 30  $\mu\text{m}$  Feature in HD 56126

Spherical Dust (Mie Theory)		
Dust Size ( $\mu\text{m}$ )	$dn/dr$ $\propto r^{-2}$	$dn/dr$ $\propto r^{-1}$
0.01	46.1	84.9
0.05	46.1	84.9
0.1	47.5	87.5
0.3	87.3	164
CDE		
0.01	34.7	64.3
0.05	34.7	64.3
0.1	35.7	64.3
0.3	65.9	126

Hony et al. (2003) to closely fit the observed SED and mid-IR images (with the dust confined to a narrow zone of  $1''.2$ – $2''.6$  from the star).

The power output per unit mass in the 30  $\mu\text{m}$  band is calculated by integrating  $F_{\text{MgS}}(\lambda)$  over the entire band (with the continuum subtracted)

$$E_{\text{MgS}}^{30\mu\text{m}} = \int_{30\mu\text{m band}} F_{\text{MgS}}(\lambda) d\lambda. \quad (6)$$

The MgS mass  $M_{\text{MgS}}^{\text{req}}$  required to account for the observed 30  $\mu\text{m}$  emission in HD 56126 is

$$M_{\text{MgS}}^{\text{req}} = E_{30\mu\text{m}}^{\text{obs}} / E_{\text{MgS}}^{30\mu\text{m}}, \quad (7)$$

where  $E_{30\mu\text{m}}^{\text{obs}} \approx 2 \times 10^{36} \text{ erg s}^{-1}$  is the total power emitted from the 30  $\mu\text{m}$  feature of HD 56126 (Hony et al. 2003).

We calculate  $M_{\text{MgS}}^{\text{req}}$  and tabulate the results in Table 1. We see that for dust with a size  $a \gtrsim 0.1 \mu\text{m}$ ,  $M_{\text{MgS}}^{\text{req}}$  increases with  $a$  because the dust temperature  $T$  decreases with  $a$  (see Figure 3). But for  $a < 0.1 \mu\text{m}$ ,  $M_{\text{MgS}}^{\text{req}}$  is insensitive to  $a$  (since  $T$  is insensitive to  $a$  as long as  $a$  is not in the nanosize range, and the dust will not undergo stochastic heating by single photons). The required MgS mass is also affected by the adopted dust spatial density distribution: the  $dn/dr \propto r^{-1}$  distribution requires more MgS (since it places more MgS grains in the cool, outer envelope region). But in general,  $M_{\text{MgS}}^{\text{req}}$  is in the order of several tens of  $10^{-5} M_{\odot}$ ,<sup>9</sup> exceeding what would be available in HD 56126 roughly by one order of magnitude (see Section 5).

The 30  $\mu\text{m}$  feature arising from spherical MgS dust is too sharp to be comparable with the 30  $\mu\text{m}$  feature seen in C-rich objects. This is why a CDE shape distribution is often invoked (e.g., see Hony et al. 2002). Unfortunately, the simple formula of Bohren & Huffman (1983) for calculating the absorption cross sections of CDE dust is only valid in the Rayleigh regime (i.e.,  $a \ll \lambda$ ). There is no precise way to derive the UV/visual absorption efficiencies of CDE dust (which are crucial to determine its heating rate and equilibrium temperature). We therefore simply adopt the equilibrium temperatures calculated for its spherical counterpart. The MgS mass required to account for the observed 30  $\mu\text{m}$  emission power is derived from Equations (5)–(7) with  $Q_{\text{abs}}^{\text{IR}}$  calculated from the CDE shape

<sup>9</sup> This also appears unreasonably too high in view that the total dust mass in the envelope is just  $M_{\text{dust}} \approx 7.4 \times 10^{-4} M_{\odot}$  (Hony et al. 2003; Meixner et al. 2004).

**Table 2**

$M_{\text{MgS}}^{\text{ava}}$  (in unit of  $10^{-5} M_{\odot}$ )—The MgS Mass that Could be Available in the Envelope of HD 56126, with the Assumption that All S Atoms are Tied Up in MgS

$M_{\text{dust}}$ ( $10^{-4} M_{\odot}$ )	Gas/Dust ( $r_{\text{g/d}}$ )	$M_{\text{env}}$ ( $M_{\odot}$ )	$M_{\text{MgS}}^{\text{ava}}$ ( $10^{-5} M_{\odot}$ )	References
7.8	75	0.059	0.96	Meixner et al. (2004)
7.4	220	0.16	2.60	Hony et al. (2003)
7.4	600	0.44	7.16	Hony et al. (2003)
7.4	380	0.28	4.56	This work

distribution (Bohren & Huffman 1983). As shown in Table 1, the CDE model requires  $\sim 30\%$  less MgS mass than the spherical model, but still needs much more than what could be available in HD 56126.

## 5. HOW MUCH MgS DUST WOULD BE AVAILABLE IN HD 56126?

Let  $M_{\text{MgS}}^{\text{ava}}$  be the MgS dust mass available in the circumstellar envelope of HD 56126. Let  $M_{\text{env}}$ ,  $M_{\text{H}}$ , and  $M_{\text{dust}}$  be the total gas, hydrogen, and dust mass in the envelope. If we know the sulfur abundance  $[\text{S}/\text{H}]_{\star}$ , the fraction of sulfur depleted in MgS  $\phi_{\text{MgS}}^{\text{S}}$ , and the gas-to-dust ratio  $r_{\text{g/d}}$  of HD 56126, we can estimate  $M_{\text{MgS}}^{\text{ava}}$  from

$$M_{\text{MgS}}^{\text{ava}} = \mu_{\text{MgS}} M_{\text{H}} [\text{S}/\text{H}]_{\star} \phi_{\text{MgS}}^{\text{S}}, \quad M_{\text{H}} = M_{\text{env}} / 1.4, \quad (8)$$

$$M_{\text{env}} = r_{\text{g/d}} M_{\text{dust}},$$

where  $\mu_{\text{MgS}}$  is the molecular weight of MgS, and the factor of 1.4 accounts for He whose abundance is  $\sim 10\%$  of H.

While both Hony et al. (2003) and Meixner et al. (2004) derived the circumstellar dust mass to be  $M_{\text{dust}} \approx 7.4 \times 10^{-4} M_{\odot}$ , they adopted a very different gas-to-dust ratio  $r_{\text{g/d}}$ . Assuming that all C atoms are locked up in CO, Meixner et al. (2004) estimated  $M_{\text{env}} \approx 0.059 M_{\odot}$  from the millimeter interferometry images of the CO  $J = 1 - 0$  line. This corresponds to a gas-to-dust ratio of  $r_{\text{g/d}} \approx 75$ , lower by a factor of  $\sim 3$  than the typical gas-to-dust ratio of  $r_{\text{g/d}} \sim 200$  for carbon stars (Jura 1986). Hony et al. (2003) argued for a much higher gas-to-dust ratio, with  $r_{\text{g/d}} \sim 220$ – $600$ .

If we assume that all S atoms are tied up in MgS (i.e.,  $\phi_{\text{MgS}}^{\text{S}} = 1$ ), with  $[\text{S}/\text{H}]_{\star} \approx 4.07 \times 10^{-6}$  (Van Winckel & Reyniers 2000) and  $M_{\text{dust}} \approx 7.4 \times 10^{-4} M_{\odot}$ , the total amount of MgS mass available in HD 56126 would be  $M_{\text{MgS}}^{\text{ava}} \approx 9.60 \times 10^{-6}$ ,  $2.60 \times 10^{-5}$ , and  $7.16 \times 10^{-5} M_{\odot}$  respectively for  $r_{\text{g/d}} = 75$ , 220, and 600 (see Table 2). Even with  $r_{\text{g/d}} = 600$ ,  $M_{\text{MgS}}^{\text{req}}$  appreciably exceeds what is available in HD 56126. Therefore, it is secure to conclude that MgS is unlikely the carrier of the 30  $\mu\text{m}$  feature.

## 6. DISCUSSION

While the gas-to-dust ratio of  $r_{\text{g/d}} = 600$  adopted by Hony et al. (2003) may be in the high end,  $r_{\text{g/d}} \approx 75$  (Meixner et al. 2004) is probably too low.<sup>10</sup> The problem probably lies in the fact that Meixner et al. (2004) could have underestimated the total gas mass  $M_{\text{env}}$  by assuming that all carbon atoms are in

<sup>10</sup> With  $r_{\text{g/d}} \approx 75$  (corresponding to  $M_{\text{env}} \approx 0.059 M_{\odot}$ ), the star (whose mass is  $\sim 0.6 M_{\odot}$ ) would have a zero-age main sequence mass of just  $M_{\star} \approx 0.66 M_{\odot}$ . Such a low-mass star, even with a metallicity  $[\text{Fe}/\text{H}] = -1$  cannot evolve to the tip of RGB in the cosmic age (Demarque et al. 2008), not to mention the post-AGB phase.

CO. As a matter of fact, a considerable fraction of the C atoms are in atomic carbon (CI): Knapp et al. (2000) observed the  $609 \mu\text{m } ^3P_1 \rightarrow ^3P_0$  line of CI in the envelope of HD 56126 and estimated the CI to CO abundance ratio to be  $[\text{CI}/\text{CO}] \approx 0.4$ . In addition, a small fraction of the C atoms should be  $\text{C}_2$ ,  $\text{C}_3$ , and CN (Bakker et al. 1996; Hrivnak & Kwok 1999).

Let us assume that CO, CI, and amorphous carbon dust are the major sinks of C (i.e., we neglect in  $\text{C}_2$ ,  $\text{C}_3$ , CN, and PAHs). The C budget in the envelope of HD 56126 is

$$[\text{C}/\text{H}]_\star = [\text{C}/\text{H}]_{\text{CO}} + [\text{C}/\text{H}]_{\text{CI}} + [\text{C}/\text{H}]_{\text{AC}}, \quad (9)$$

where  $[\text{C}/\text{H}]_\star \approx 4.47 \times 10^{-4}$  is the stellar C abundance of HD 56126 (Van Winckel & Reyniers 2000),  $[\text{C}/\text{H}]_{\text{CO}} = M_{\text{CO}}/[\mu_{\text{CO}}M_{\text{H}}]$ ,  $[\text{C}/\text{H}]_{\text{CI}} \approx 0.4[\text{C}/\text{H}]_{\text{CO}}$  (Knapp et al. 2000), and  $[\text{C}/\text{H}]_{\text{AC}} = M_{\text{AC}}/[\mu_{\text{C}}M_{\text{H}}]$ , are respectively the C abundances tied up in CO, CI and amorphous carbon, where  $M_{\text{CO}} \approx 5.54 \times 10^{-4} M_\odot$  (Meixner et al. 2004) and  $M_{\text{AC}} \approx 7.4 \times 10^{-4} M_\odot$  (Hony et al. 2003; Meixner et al. 2004) are respectively the masses of CO and amorphous carbon in the HD 56126 envelope,  $\mu_{\text{CO}}$  and  $\mu_{\text{C}}$  are the molecular (atomic) weights of CO and C, respectively. We estimate the total hydrogen mass to be

$$M_{\text{H}} = \frac{1.4 M_{\text{CO}}/\mu_{\text{CO}} + M_{\text{AC}}/\mu_{\text{C}}}{[\text{C}/\text{H}]_\star} \approx 0.20 M_\odot. \quad (10)$$

This corresponds to a total envelope mass  $M_{\text{env}} \approx 0.28 M_\odot$  and a gas-to-dust ratio of  $r_{\text{g/d}} \approx 380$ . With all the sulfur atoms in MgS (i.e.,  $\phi_{\text{MgS}}^{\text{S}} = 1$ ), we obtain  $M_{\text{MgS}}^{\text{ava}} \approx 4.56 \times 10^{-5} M_\odot$ . This is much smaller than  $M_{\text{MgS}}^{\text{req}}$ , the amount of MgS mass required to explain the power emitted at the  $30 \mu\text{m}$  feature (see Table 1).

We should note that the actual available MgS mass could be even lower since it is likely that some S atoms are tied up in gas molecules such as SiS and CS. In the C-rich AGB star CW Leo (IRC +10216), SiS and CS consume a substantial fraction of the S atoms (Glassgold 1996; Millar et al. 2001). If this also holds for HD 56126, the shortage of MgS dust mass would become more severe. It does not help if MgS mixes with amorphous carbon.<sup>11</sup> As illustrated in Figure 1,  $Q_0 = 1.6$  and  $\lambda_0 = \pi a$  (adopted for MgS) also overestimate the UV/visible absorptivity of amorphous carbon. The mixture of amorphous carbon and MgS would have a lower temperature since the IR emissivity of amorphous carbon is much larger than that of MgS. Therefore, one would expect a larger  $M_{\text{MgS}}^{\text{req}}$ . We should also note that HD 56126 is not the strongest  $30 \mu\text{m}$  feature source. The MgS budget problem would be more severe for objects with a stronger  $30 \mu\text{m}$  band and cooler MgS dust (e.g., IRAS 19454, a post-AGB star, requires  $T \approx 50 \text{ K}$ ; see Hony et al. 2002).

Zhukovska & Gail (2008) recently performed a detailed study of the condensation of MgS in the outflows from C-rich stars on the tip of the AGB. They found that MgS can only be formed by precipitating on pre-existing grains and therefore one would expect MgS to form as a mantle on the SiC core. However, these grains would exhibit a feature at  $\sim 33\text{--}38 \mu\text{m}$  which is not seen in C-rich objects.

Hony et al. (2003) and Hony & Bouwman (2004) assumed an analytic formula for the UV/visible absorption efficiency of MgS dust, which differs from Equation (1) in that theirs have

an appreciable absorbing power at  $0.3 < \lambda < 2 \mu\text{m}$ :

$$Q_{\text{abs}}^{\text{UV}}(\lambda) = \begin{cases} 1, & \lambda \leq 1 \mu\text{m}; \\ 2 - \lambda, & 1 < \lambda \leq 2 \mu\text{m}; \\ 0, & \lambda > 2 \mu\text{m}. \end{cases} \quad (11)$$

With this kind of  $Q_{\text{abs}}^{\text{UV}}(\lambda)$  and assuming a spatial distribution of  $dn/dr \propto r^{-1}$  (within a narrow zone of  $1''2\text{--}2''6$  from the star) for the dust and a gas-to-dust ratio of  $r_{\text{g/d}} = 600$ , Hony et al. (2003) performed detailed radiative transfer modeling calculations for HD 56126 and found that the S abundance constraint was not violated.

If we adopt the UV/visible absorption efficiency  $Q_{\text{abs}}^{\text{UV}}(\lambda)$  of Hony et al. (2003), for MgS dust of  $a = 0.1 \mu\text{m}$ , we would need  $M_{\text{MgS}}^{\text{req}} \approx 8.38 \times 10^{-4} M_\odot$  and  $4.56 \times 10^{-4} M_\odot$  respectively for the dust spatial distributions of  $dn/dr \propto r^{-1}$  and  $dn/dr \propto r^{-2}$ , far exceeding the maximum amount of MgS dust  $M_{\text{MgS}}^{\text{ava}}$  that could be available in HD 56126 (see Table 2).<sup>12</sup> For  $a = 0.01 \mu\text{m}$ , the required MgS mass is reduced to  $M_{\text{MgS}}^{\text{req}} \approx 8.01 \times 10^{-5} M_\odot$  and  $4.69 \times 10^{-5} M_\odot$  respectively for  $dn/dr \propto r^{-1}$  and  $dn/dr \propto r^{-2}$ , and appears comparable to  $M_{\text{MgS}}^{\text{ava}}$ . However, we note that (1)  $M_{\text{MgS}}^{\text{ava}}$  is already an upper limit, and (2) we are not sure if Equation (11) is a reasonable approximation for the UV/visible absorption properties of MgS dust of  $a = 0.01 \mu\text{m}$ . As shown in Figure 1, the UV/visible absorption cut-off wavelength  $\lambda_0$  varies with dust size  $a$ . For the dust species listed in Figure 1, Equation (1) seems to be a more reasonable approximation than Equation (11) for their  $Q_{\text{abs}}^{\text{UV}}(\lambda)$ . We call on laboratory measurements of the UV/visible/near-IR dielectric functions of MgS dust.

Finally, we calculate  $E_{\text{abs}}^{\text{tot}}$  ( $\text{erg s}^{-1} \text{g}^{-1}$ )—the total power absorbed by 1 g MgS dust of size  $a$  from

$$E_{\text{abs}}^{\text{tot}} = \frac{r_\star^2 \ln(r_{\text{out}}/r_{\text{in}})}{2 r_{\text{out}}^2 - r_{\text{in}}^2} \int_{912 \text{ \AA}}^\infty [3 Q_{\text{abs}}(a, \lambda)/4a\rho_{\text{MgS}}] \times F_\lambda^\star d\lambda, \text{ for } dn/dr \propto r^{-1}; \quad (12)$$

$$E_{\text{abs}}^{\text{tot}} = \frac{r_\star^2}{4 r_{\text{in}} r_{\text{out}}} \int_{912 \text{ \AA}}^\infty [3 Q_{\text{abs}}(a, \lambda)/4a\rho_{\text{MgS}}] \times F_\lambda^\star d\lambda, \text{ for } dn/dr \propto r^{-2}. \quad (13)$$

If we assume the absorbed energy is *all* radiated away through the  $30 \mu\text{m}$  feature, we would require a total MgS mass of  $M_{\text{MgS}}^{\text{min}} = E_{30 \mu\text{m}}^{\text{obs}}/E_{\text{abs}}^{\text{tot}}$ —apparently, this is absolutely a lower limit since the absorbed energy will not be *exclusively* emitted from the  $30 \mu\text{m}$  feature (a fraction of the energy will be radiated away at other wavelengths and through the continuum underneath the  $30 \mu\text{m}$  feature). In Table 3, we tabulate  $E_{\text{abs}}^{\text{tot}}$  and  $M_{\text{MgS}}^{\text{min}}$ . We see in all cases  $M_{\text{MgS}}^{\text{min}} > M_{\text{MgS}}^{\text{ava}}$ , indicating that we simply do not have enough MgS to account for the observed emission power.

## 7. SUMMARY

We have investigated the hypothesis of MgS as a carrier of the prominent  $30 \mu\text{m}$  emission feature seen in numerous C-rich evolved objects, using HD 56126 as a test case. It is found that, in order to account for the enormous power emitted from this feature, one requires a much higher MgS dust mass than

<sup>11</sup> Goebel & Moseley (1985) argued that MgS could form via chemical surface reactions on carbon grains.

<sup>12</sup> Following Meixner et al. (2004), we assume the dust to be distributed in a broader zone, i.e.,  $1''2\text{--}7''$  from the star.

**Table 3**  
 $M_{\text{MgS}}^{\text{min}}$  – The Minimum Amount of MgS Dust Required

Dust Size ( $\mu\text{m}$ ) $a$	$dn/dr \propto r^{-2}$		$dn/dr \propto r^{-1}$	
	$E_{\text{abs}}^{\text{tot}}$ ( $\text{erg s}^{-1} \text{g}^{-1}$ )	$M_{\text{MgS}}^{\text{min}}$ ( $M_{\odot}$ )	$E_{\text{abs}}^{\text{tot}}$ ( $\text{erg s}^{-1} \text{g}^{-1}$ )	$M_{\text{MgS}}^{\text{min}}$ ( $M_{\odot}$ )
0.01	$2.85 \times 10^6$	$3.53 \times 10^{-4}$	$1.62 \times 10^6$	$6.20 \times 10^{-4}$
0.05	$2.85 \times 10^6$	$3.53 \times 10^{-4}$	$1.62 \times 10^6$	$6.20 \times 10^{-4}$
0.1	$2.77 \times 10^6$	$3.62 \times 10^{-4}$	$1.58 \times 10^6$	$6.38 \times 10^{-4}$
0.3	$1.57 \times 10^6$	$6.42 \times 10^{-4}$	$8.90 \times 10^5$	$1.13 \times 10^{-3}$

**Notes.** This is obtained by assuming that the energy absorbed by a MgS grain is exclusively emitted through the 30  $\mu\text{m}$  band (see Section 6). Also tabulated is  $E_{\text{abs}}^{\text{tot}}$  ( $\text{erg s}^{-1} \text{g}^{-1}$ ), the power per unit mass absorbed by MgS dust. We see in all cases  $M_{\text{MgS}}^{\text{min}} > M_{\text{MgS}}^{\text{ava}}$ .

available in this object. We therefore argue that MgS is unlikely the carrier of the 30  $\mu\text{m}$  feature.

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