

# A cold detached dust envelope around an oxygen-rich Mira-type AGB star R Hydrae

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**Abstract.** The circumstellar structure of R Hydrae has been investigated in the IRAS survey scan data. R Hya is a late M-type Mira variable star whose IRAS LRS spectrum is classified as 15 (no feature). But, it shows a remarkable infrared excess in the IRAS photometric data, which cannot be explained by an oxygen-rich circumstellar dust envelope of a mass losing late-type star without showing a significant 10  $\mu\text{m}$  silicate feature in the LRS spectrum.

An extended emission component around R Hya is clearly found in the 60 and 100  $\mu\text{m}$  images produced by Pyramid Maximum Entropy (PME) image reconstruction techniques. It is also visible in the individual IRAS scan data at 25, 60 and 100  $\mu\text{m}$ . It firmly indicates the existence of an extended circumstellar dust envelope around R Hya. The IRAS data further suggest the dust envelope being detached from the central star. The detached circumstellar dust envelope is consistent with both the featureless LRS spectrum and the red colors in the IRAS photometric data. R Hya is likely to be experiencing a cessation of mass loss which has lasted for about one hundred years, and which has made the inner boundary of the dust envelope about sixty stellar radii, far from the region which is warm enough to produce the 10  $\mu\text{m}$  feature.

**Key words:** circumstellar matter – stars: AGB – stars: mass-loss – infrared: stars – stars: individual: R Hya

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## 1. Introduction

Mass loss phenomena are commonly seen, to some degree, for all late-type giant stars which have a core of carbon and oxygen with degenerate electrons in the final stage of stellar evolution. As these late-type stars are located on the Asymptotic Giant Branch (AGB) in the Hertzsprung-Russell diagram (HR diagram), they are called AGB stars. Most oxygen-rich AGB stars,

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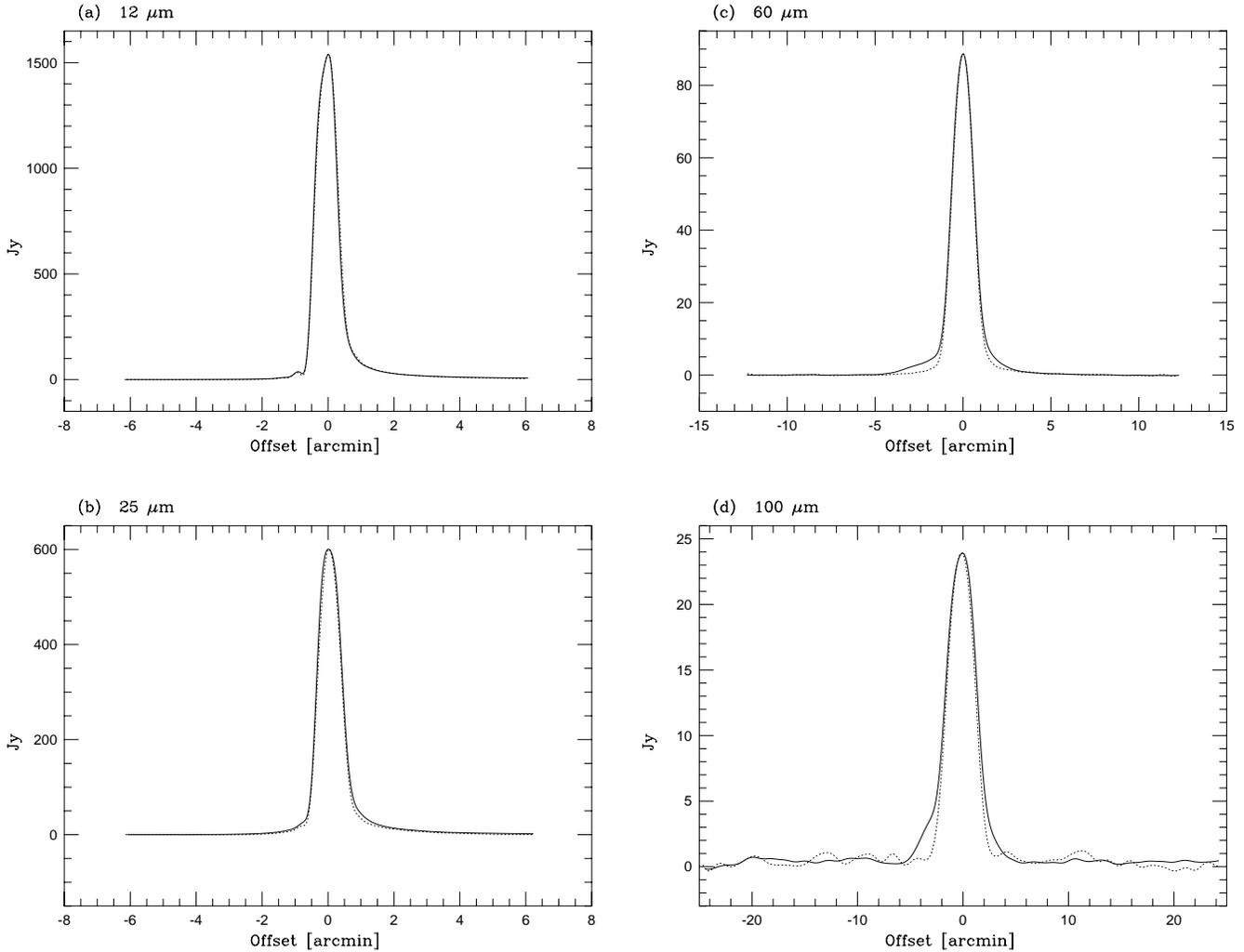
such as M-type Mira variables and OH/IR stars, often show a silicate band feature at 10  $\mu\text{m}$  in the spectra obtained by the low resolution spectrograph (LRS) on board IRAS (IRAS Science Team 1986) as well as remarkably red values in the IRAS photometric colors such as  $\log(S_{25}/S_{12})$  and  $\log(S_{60}/S_{25})$ , where  $S_\lambda$  is the flux density at a wavelength of  $\lambda$   $\mu\text{m}$ . These infrared properties are well understood in terms of a circumstellar dust envelope of silicate grains produced by the current continuous mass loss phenomena of those evolved stars (Bedijn 1987; Hashimoto et al. 1990a; Justtanont & Tielens 1992; Hashimoto 1994).

On the other hand, Hashimoto et al. (1990b) found that there are a number of optically visible M-type AGB stars which show no or very weak silicate band feature around 10  $\mu\text{m}$  in the LRS spectra (LRS class 1*n*; IRAS Science Team 1986), while they show remarkably red colors in the IRAS photometric data. The infrared properties of these M-type stars cannot be explained by a model of mass losing oxygen-rich AGB star with a circumstellar dust envelope of silicate grains (Hashimoto 1994). Some unknown physical conditions are required in the explanations of those M stars. Thus, detailed investigations of such M stars should give us a valuable information for the further understanding of the physical process in the mass loss phenomena and the evolution of the AGB stars.

In the present paper, we examine the circumstellar structure of R Hydrae, one of the M-type AGB stars which show remarkably red colors in the IRAS photometric data with no 10  $\mu\text{m}$  silicate band feature in the LRS spectra, through a re-analysis of IRAS data including high resolution images made with Pyramid Maximum Entropy (PME) techniques.

## 2. The red 1*n* M stars

There are a number of optically visible M-type stars whose LRS spectra are classified “1*n*” in the LRS catalog (IRAS Science Team 1986) showing (almost) no silicate band feature around 10  $\mu\text{m}$ . These optically visible 1*n* M-type stars have been regarded as oxygen-rich late-type stars which have no or optically very



**Fig. 1a–d.** Co-added profiles of the IRAS scan data of R Hya at wavelengths of 12  $\mu\text{m}$  **a**, 25  $\mu\text{m}$  **b**, 60  $\mu\text{m}$  **c**, and 100  $\mu\text{m}$  **d**. The point source profiles of  $\beta$  Gru scaled to those of R Hya are presented by dashed curves for comparison

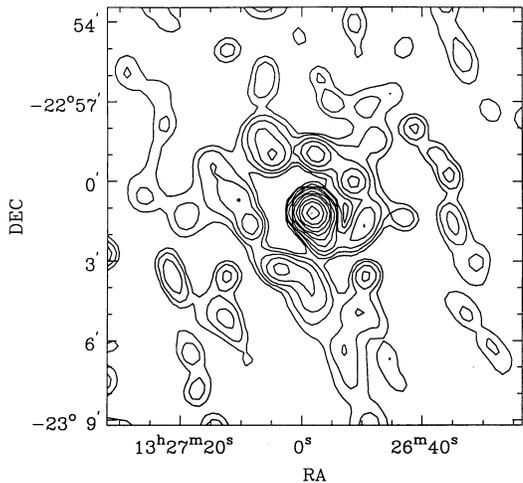
thin dust envelopes. The absence of the 10  $\mu\text{m}$  silicate band feature is interpreted as a small amount of optical thickness in the circumstellar dust envelope. As a matter of fact, a large number of M-type stars classified as  $1n$  show an IRAS color of  $\log(S_{25}/S_{12})$  between  $-0.65$  and  $-0.55$ , which can be well explained by simple models of no or optically very thin circumstellar dust envelopes with their weak mass loss activity. Further, the optical spectra of these  $1n$  M stars with  $\log(S_{25}/S_{12}) \sim -0.6$  are usually earlier than M5, indicating that they should be stars on the Red Giant Branch (RGB) rather than on the AGB. This is also consistent with their faint mass loss activity.

Hashimoto et al. (1990b) found, however, that a significant fraction of the optically visible  $1n$  M stars show remarkably red IRAS photometric colors. The  $1n$  M stars with  $\log(S_{25}/S_{12}) > -0.5$  are classified as the “red”  $1n$  M stars. Since the red  $1n$  M stars usually show an optical spectral type later than M5, they are most likely to be evolved stars on the AGB. Note that the large value of  $\log(S_{25}/S_{12})$  is almost as red as those of oxygen-rich AGB stars with a remarkable 10  $\mu\text{m}$  emission feature in

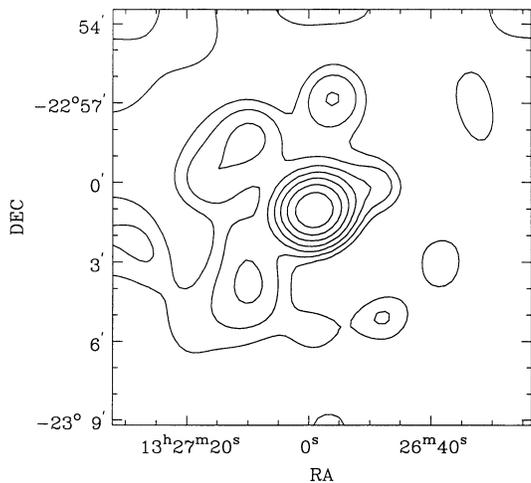
the LRS spectra, which indicates that their circumstellar dust envelopes are optically thick significantly. Hashimoto (1994) examined both the IRAS photometric and LRS data, comparing them with a large number of dust envelope models. It turned out impossible to reconstruct the IRAS properties of the red  $1n$  M stars with realistic physical parameters of the model envelopes of amorphous silicate grains. When the models are forced to fit the observed photometric colors, they imply also a strong silicate emission band at 10  $\mu\text{m}$ , which is not observed. It is, thus, very difficult to understand the infrared properties of the red  $1n$  M stars in terms of a circumstellar dust envelope of silicate grains surrounding a mass losing oxygen-rich AGB star.

### 3. Re-analysis of the IRAS data of R Hya

R Hydrae is a late M giant Mira-type variable star (M7–9 III), the brightest source among the red  $1n$  M stars with its LRS class 15 and  $\log(S_{25}/S_{12}) = -0.43$ . An s-process element Tc has been observed in R Hya, which indicates a third dredge-up happened



**Fig. 2a.** IRAS 60  $\mu\text{m}$  image of R Hya reconstructed by the PME techniques. Contour lines are 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024  $\text{MJy str}^{-1}$



**Fig. 2b.** IRAS 100  $\mu\text{m}$  image of R Hya reconstructed by the PME techniques. Contour lines are 1, 2, 4, 8, 16, 32, 64, 128 and 256  $\text{MJy str}^{-1}$

very recently (Little et al. 1987). This firmly evidences that R Hya is in the AGB phase with thermal pulses.

IRAS raw scan data of R Hya are re-examined in order to investigate its circumstellar structure. Co-added profiles of IRAS individual scan data around R Hya at  $\lambda = 12, 25, 60$  and  $100 \mu\text{m}$  are presented in Figs. 1a–d. The point source profiles of  $\beta$  Gru scaled to those of R Hya are also presented for comparison. There seems no significant evidence of an extended component in the  $12 \mu\text{m}$  profile of R Hya (Fig. 1a), while a slight but clear feature of extended component is seen in the  $25 \mu\text{m}$  profile (Fig. 1b). An extended emission component is clearly seen in the  $60 \mu\text{m}$  profile of Fig. 1c, as well as in the  $100 \mu\text{m}$  profile (Fig. 1d), which is consistent with the results of Young et al. (1993).

Pyramid Maximum Entropy (PME) program has been developed to reconstruct the IRAS survey data into high resolution

images (HIRAS; Bontekoe et al. 1991, 1994; Waters et al. 1994). We have applied HIRAS to the IRAS 60 and  $100 \mu\text{m}$  data in order to investigate the spatial structure around R Hya. The 60 and  $100 \mu\text{m}$  images of R Hya are shown in Fig. 2a and b, respectively. The  $60 \mu\text{m}$  image (Fig. 2a) shows a definite component of the extended emission around R Hya with an effective spatial resolution about 1 arc minute. The extended component is also seen in the  $100 \mu\text{m}$  image (Fig. 2b), though detailed discussion on the spatial structure cannot be made in the  $100 \mu\text{m}$  image since its spatial resolution and reliability are much poorer than those of the  $60 \mu\text{m}$  image.

In Fig. 2a the shape of the  $60 \mu\text{m}$  extended circumstellar emission component seems almost circular, though it is somewhat distorted to be stretched in the direction of IRAS scan. The size of its extent is about 3–4 arc minutes in radius, which coincides with the  $100 \mu\text{m}$  image. This corresponds to about seven thousand times of stellar radius, with assuming that the distance and stellar radius of R Hya are about 110 pc (Jura & Kleinmann 1992) and  $700 R_{\odot}$  (equivalently, a stellar luminosity  $L \sim 10^4 L_{\odot}$  with  $T_{\text{eff}} \sim 2200$  K), respectively.

Furthermore, there seems to be a cavity inside the extended  $60 \mu\text{m}$  emission component, though this structure seen in Fig. 2a may not be represented very precisely because of the existence of an extremely bright point source at the center and our limited knowledge of the response function (Kester & Bontekoe 1994). We must be careful when examining a structure with a size comparable to the resolution limit in a reconstructed image, in particular in the case when an extremely bright source is located very close to that structure. The radial size of the possible inside cavity seen in the  $60 \mu\text{m}$  image (Fig. 2a) is about 1 arc minute, which corresponds to a radius of about two thousand stellar radii. This, however, should indicate only an upper limit of the inner radius of the circumstellar dust envelope, since the grain temperature at such a large inner boundary distance is too low to produce the  $25 \mu\text{m}$  extended emission component as seen in the co-added scan profile of Fig. 1b. Note that the  $25 \mu\text{m}$  emission component in the co-added scan profile seems to extend even inside the 1 arc minute distance. The inner boundary of the extended dust envelope should not be much larger than a couple hundred stellar radii in order to produce such an extended circumstellar  $25 \mu\text{m}$  emission.

## 4. Discussion

### 4.1. Possible explanations

Four cases can be considered in order to explain the red  $1n$  M stars. (1) The red colors of the infrared continuum can be observed if the stellar photosphere has an intrinsic infrared excess. No circumstellar matter is required in this case. But, it is very difficult to explain the infrared excess of the photosphere itself. (2) The second possibility is that there may be some kind of dust grains which have no band features at  $\lambda \sim 10 \mu\text{m}$  as suggested by Hashimoto et al. (1990b). (3) Also, the red  $1n$  spectra may be fitted by models with amorphous silicate grains which are so cold that they do not produce a band feature at  $\lambda \sim 10 \mu\text{m}$  strong enough to be observed by the LRS. A detached inner

boundary is required for the circumstellar dust envelope in this case (Hashimoto 1994, 1995). (4) Or, some circumstellar mechanisms other than dust grains may produce the infrared excess. For example, strong line emission from circumstellar molecules such as  $\text{H}_2\text{O}$  may cause the reddening. In any case, there must be some physical conditions which are unknown in the red  $1n$  M stars.

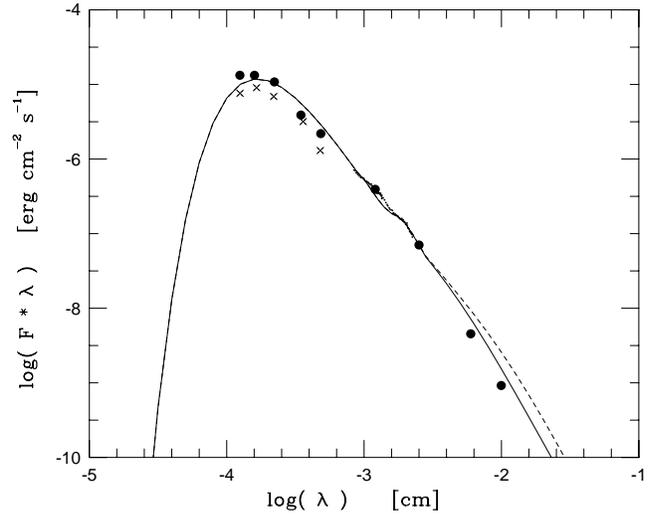
In the present analysis of the IRAS data of R Hya, it is most likely that R Hya really has an extended circumstellar envelope which shows a significant amount of infrared emission at wavelengths longer than  $\lambda \sim 25 \mu\text{m}$ . This observational fact rules out the first possibility of the intrinsic infrared excess of the stellar photosphere without any effects from the circumstellar envelope.

Generally speaking, the most effective source of the circumstellar emission at wavelengths from 25 to  $100 \mu\text{m}$  is dust grains in the circumstellar envelope. The extended circumstellar components seen in the IRAS data of R Hya are very likely to be the emission from the dust grains produced by a mass loss phenomenon of the central star. Though it is still rather difficult to completely rule out the possibility of the molecular emission in the envelope, it seems to have only small effect on the IRAS broad band photometric flux densities (IRAS Explanatory Supplement 1988). The most probable possibility would be that R Hya has an extended circumstellar dust envelope, which is observed as the extended components in the IRAS 25 –  $100 \mu\text{m}$  data. It is noted, however, that in the successful model fitting of the IRAS photometric and LRS data of the red  $1n$  M stars we have to introduce either a detached inner boundary for the circumstellar dust envelope of silicate-type grains or some exotic optical properties of oxygen-rich dust grains which do not have any features around  $10 \mu\text{m}$ .

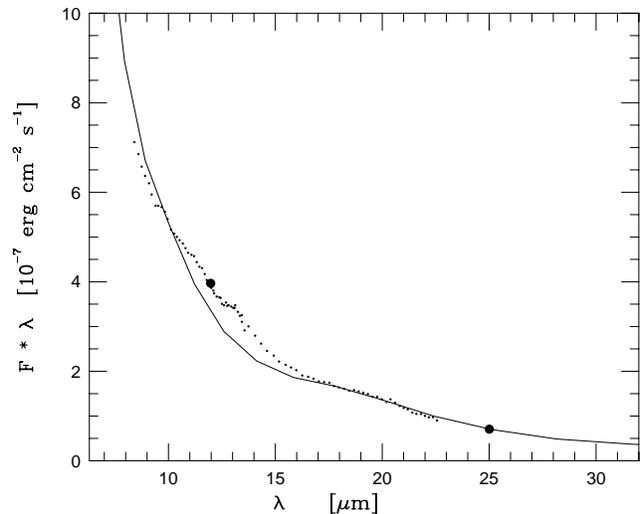
It is well known that most grains appearing in the circumstellar envelopes of mass losing oxygen-rich late-type stars are silicate-like grains such as amorphous silicates on the basis of grain formation theories (e.g. Gilman 1969; Kozasa et al. 1984) and of the observational characteristics of a large number of mass-losing oxygen-rich stars which show the 10 and  $18 \mu\text{m}$  band features of the silicate dust grains (e.g. Jones & Merrill 1976). As silicate-type grains which have no or extremely weak  $10 \mu\text{m}$  feature are not known in laboratory experiments, they should not exist in the universe as the major solid components of the circumstellar envelopes of a number of oxygen-rich AGB stars. Featureless solid grains other than silicates, such as aluminum oxide as proposed by Onaka et al. (1989), cannot explain the red  $1n$  M stars either. The abundance of such grains must be extremely large in order to produce an emission at least ten times stronger than the inevitably co-existing silicate grains to swamp the  $10 \mu\text{m}$  silicate feature. Eventually, the most probable case should be the detached dust envelope of usual silicate-type grains which have the  $10 \mu\text{m}$  band feature.

#### 4.2. Detached dust envelope

The models by Hashimoto (1994, 1995) indicate that the inner boundary of the dust envelopes of the red  $1n$  M stars should



**Fig. 3a.** Spectral energy distribution of R Hya. Both the brightest data (filled circle) and the faintest data (crosses) are plotted at  $J$ ,  $H$ ,  $K$ ,  $L$ , and  $M$  bands. IRAS photometric data at 12, 25, 60, and  $100 \mu\text{m}$  are presented by filled circles. The small dots are LRS measurements. The solid line is a model with  $T_* = 2200 \text{ K}$ ,  $\dot{M} = 1.5 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ ,  $r_i = 60 R_*$ , and  $r_o = 10^3 R_*$ . The same model but  $r_o = 10^4 R_*$  is presented by a dashed line



**Fig. 3b.** The same as Fig. 3a but presented in the LRS wavelength range with linear scales

be larger than about one hundred times of stellar radius if most grains are silicate-type grains with a usual  $10 \mu\text{m}$  band feature. In such a case the temperature of the silicate-type grains is less than  $300 \text{ K}$  at the inner boundary. A grain temperature less than  $300 \text{ K}$  cannot be expected at the inner boundary of the circumstellar dust envelope of a continuously mass losing oxygen-rich AGB star, since the grain formation temperature of silicate-type grains must be much higher than  $300 \text{ K}$ . Silicate grains are expected to be formed at about  $1000 \text{ K}$  (Gilman 1969; Kozasa et al. 1984), while Gail & Sedlmayr (1986) indicate lower temperature of about  $600 \text{ K}$ . But, a cessation of mass loss which has

lasted for a significant period can produce a large inner boundary with a low temperature since the circumstellar envelope is expanding outward.

In order to investigate the geometrical structure of the detached dust envelope, a numerical model by Hashimoto (1995) is employed in the analysis of the infrared data of R Hya. Spectral energy distribution of R Hya is presented in Fig. 3a. Since R Hya is a Mira-type variable star with a large amplitude variation in the near-infrared wavelengths, both the brightest and the faintest data at  $J$ ,  $H$ ,  $K$ ,  $L$ , and  $M$  bands are plotted in this figure. The brightest measurements (filled circle) are selected from Catalog of Infrared Observations (CIO; Gezari et al. 1993). The faintest near-infrared data (crosses) are from Fouqué et al. (1992). The IRAS photometric data at 12, 25, 60, and 100  $\mu\text{m}$  and LRS measurements are plotted in Fig. 3a by filled circles and small dots, respectively. A numerical model which well fits those observational data is presented by a solid line, though the fit is rather poor around  $L$  and  $M$  bands due to a lack of detailed treatment of molecular bands in the model calculation.

The same spectral energy distribution is presented again in the LRS wavelength range in Fig. 3b with linear scales. The model shows a quite fine fit in this wavelength region. There however remains a slight excess in the observation data against the model at the wavelengths around 13  $\mu\text{m}$ . It might be the emission from aluminum oxide grains as suggested by Onaka et al. (1989), though further detailed investigation is necessary for such a conclusion.

Through this model fitting, the inner boundary size of the dust envelope is estimated as  $r_i = 60R_*$  with a stellar effective temperature  $T_* = 2200$  K, while Hashimoto (1994) indicated  $r_i = 100R_*$  with  $T_* = 3000$  K without using near-infrared data. The grain temperature at the inner boundary is about 250 K. The total mass loss rate required to produce this extended dust envelope is about  $1.5 \cdot 10^{-7} M_{\odot}\text{yr}^{-1}$ , where the gas-to-dust mass ratio is assumed as 200. The outer size of the model dust envelope is estimated as about 1000 stellar radii, though it depends on the far-infrared optical properties of dust grains.

Assuming a typical expansion velocity of  $V_{\text{exp}} \sim 10 \text{ km s}^{-1}$  (Knapp & Morris 1985; Nyman et al. 1992), the inner boundary becomes as large as  $60 R_*$  when about one hundred years has passed since the termination of the mass loss which had produced the extended circumstellar dust envelope. The absence of the circumstellar component in the 12  $\mu\text{m}$  co-added scan data (Fig. 1a) also indicates very small amount of warm dust grains within a distance of  $60 R_*$ . The slight but significant extended component seen in the 25  $\mu\text{m}$  scan data (Fig. 1b) indicates the existence of dust grains with a temperature higher than about 120 K, suggesting that the inner boundary should not be much larger than  $300 R_*$  (see Hashimoto 1995). These observational characteristics are in good agreement with the estimation of the present model analysis.

The outer size of the circumstellar dust envelope measured in Fig. 2a is significantly larger than that derived from the model fitting (Fig. 3). It must be partly caused by our poor knowledge in the far-infrared optical constants of dust grains, but would also be caused by the spatial resolution in the IRAS observa-

tion. The emission from the outermost region of the extended circumstellar envelope would not be counted properly enough in the IRAS point source flux densities at the wavelengths of 60 and 100  $\mu\text{m}$ , since its extent is too large to be measured as a single point source in the IRAS observation. As only contribution from the central region within the effective spatial resolution of about 1 arc minute is reflected in the point source flux densities at 60 and 100  $\mu\text{m}$ , the outer size as small as the effective spatial resolution, i.e.  $\sim 1000R_*$  is derived in the model fit. A model with outer radius of  $10^4$  stellar radii (dashed line in Fig. 3a) is also calculated in order to estimate the total flux from the entire extended dust envelope. The total flux density at 60  $\mu\text{m}$  from the whole extended detached dust envelope is estimated as 19 Jy, which is in good agreement with 21.4 Jy of the measurement by Young et al. (1993).

R Hya has been detected in CO(2–1) molecular emission (Wannier & Sahai 1986) and SiO maser emission (Snyder & Buhl 1975). The mass loss rate obtained in our model analysis is in good agreement with the mass loss rate estimated from the CO observations by Wannier & Sahai (1986). Since the CO emission reflects whole gas materials in the entire extended envelope, the inner cavity within a distance of less than a few hundred stellar radii cannot be detected in the CO observation. Thus, the mass loss rate obtained by the CO observation should be the same as the losing rate in the detached envelope.

The detection of SiO maser may indicate a significant activity of the present mass loss. However, the intensity of SiO maser emission of R Hya is not so strong as measured for the mass losing oxygen-rich AGB stars with a strong 10  $\mu\text{m}$  emission band (Snyder & Buhl 1975), while the distance to this object is not very large ( $\sim 110$  pc). Thus, it may rather indicate that the present mass loss is not so active as to produce a large amount of dust grains in the inner region of the extended envelope. Note that a detection of SiO maser emission does not always correspond to a strong mass loss. The quantitative relationship between the SiO maser emission and the activity of mass loss has not been established clearly yet. The detection of SiO maser would not conflict with the detached dust envelope of R Hya with a halting of mass loss.

#### 4.3. AGB evolution with halting of mass loss

The mass loss rate of  $1.5 \cdot 10^{-7} M_{\odot}\text{yr}^{-1}$  estimated in the model analysis is just comparable with the typical rate of the moderate mass loss phenomena of Mira-type AGB stars (see Hashimoto 1994). Thus, R Hya should be a Mira-type AGB star before evolving into a phase of extremely strong mass loss, having stopped its moderate mass loss of  $\dot{M} \sim 1.5 \cdot 10^{-7} M_{\odot}\text{yr}^{-1}$  for about one hundred years. Such an evolutionary status of R Hya is in good agreement with the non-continuous mass loss process of oxygen-rich AGB stars indicated by Zijlstra et al. (1992) and Hashimoto (1994). As suggested from the analysis of the IRAS data (Hashimoto 1994) it is very likely that an oxygen-rich AGB star undergoes the phases of moderate mass loss of  $\dot{M} \sim 10^{-7} - 10^{-6} M_{\odot}\text{yr}^{-1}$  lasting for  $10^3 - 10^4$  years several dozen times with interruptions during the ordinary Mira-type

star phase. After this phase, if it does not become a carbon star, it should evolve into an OH/IR star with a mass loss rate exceeding  $10^{-5} M_{\odot} \text{yr}^{-1}$ .

Zijlstra et al. (1992) indicated that such an intermittent mass loss process with haltings can be understood in a picture of AGB evolution with the thermal pulse cycle (Vassiliadis & Wood 1992). In fact, Wood & Zarro (1981) have indicated that R Hya has experienced a thermal pulse process within a recent couple hundreds years. Further, an s-process element Tc, whose effective half-life in the interior of an evolved AGB star is estimated as less than 40 years, has been observed in R Hya (Little et al. 1987). This also indicates a recent third dredge-up with a thermal pulse. It is likely that the intermittent halting of mass loss is caused by a thermal pulse process occurred in R Hya a couple hundred years ago.

#### 4.4. Other bright red $1n$ M stars

Several other bright sources among the red  $1n$  M stars have been examined using their co-added IRAS profiles and high resolution  $60 \mu\text{m}$  images reconstructed with HIRAS (Hashimoto et al. 1995). A large fraction of them also show evidence of the extended circumstellar components, which is in good agreement with the picture of the red  $1n$  M stars with detached circumstellar dust envelopes. This supports the abovementioned AGB evolution with the haltings of mass loss.

### 5. Conclusions

Spatial structure around R Hya was examined using the IRAS raw survey data. An extended emission component is clearly found in both the high resolution  $60$  and  $100 \mu\text{m}$  images produced by PME image reconstruction techniques and the individual IRAS scan data at  $25$ ,  $60$  and  $100 \mu\text{m}$ .

It is most likely that R Hya really has a circumstellar dust envelope of silicate-type dust grains. The inner boundary of the dust envelope should be detached from the central star due to a halting of mass loss so that any significant  $10 \mu\text{m}$  feature is not observed in the LRS spectrum while showing remarkably red colors in the IRAS photometric data. R Hya is very likely to be experiencing a cessation of mass loss, which has lasted for about a hundred years, and which has made the inner boundary of the dust envelope too far away to be warm enough to produce the  $10 \mu\text{m}$  feature.

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