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Detached cold dust shell around the early R star (warm carbon star) HD 100764

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Abstract. From IRAS observations of early R stars (warm-carbon stars) detached cold dust shell has been detected around the early R star HD 100764. In addition to the cold dust (140 K to 50 K) there is also warm dust (~ 1000 K) around HD 100764. The total shell mass is estimated to be of the order of $0.5\,10^{-4}\,M_{\odot}$. The presence of dust shell around the early R star HD 100764 suggests that it has experienced significant mass loss in the recent past. The luminosity of the star is too low ($M_V = +0.4$) to be on the AGB. The present dust shell around HD 100764 may be the result of mass loss experienced by the star during the helium core flash.

The dust shell around HD 100764 appears to be oxygen-rich (silicate dust shell). The oxygen-rich dust shells around J-type carbon stars may also be the result of mass loss experienced by them in the recent past during the helium core flash.

Key words: stars: carbon – stars: early R – infrared radiation stars: evolution of – stars: mass loss

1. Introduction

The red giant stars appear to evolve along the asymptotic giant branch (AGB) through M→MS→S→SC→C sequence. Along this sequence the abundance of ^{12}C increases by the mixing of helium-burning products to the stellar surface. Recently from an analysis of IRAS data Willems & de Jong (1986), Little-Marenin (1986) & Vardya (1989) detected few carbon stars with oxygen-rich circumstellar dust shells. Willems & de Jong (1986, 1988) suggested a new scenario for carbon star evolution. They suggested that the carbon stars with oxygen-rich circumstellar dust shells are very recently formed carbon stars and that they are the result of direct transition from M-type to C-type rather than through an intermediate S star phase. Whether all red giants go through the M→MS→S→SC→C sequence or some skip the intermediate stages and become carbon stars is not yet fully understood. Among the carbon stars there are few groups that do not fit the above mentioned sequence. These are the early R stars (warm carbon stars) and the ^{13}C rich or J-type carbon stars. The early R stars do not fit the sequence and the AGB because their luminosities are too low for the AGB and also the early R stars and J-type carbon stars are ^{13}C rich (^{12}C/^{13}C = 4 to 15) and show no over abundance of s-process elements (Dominy 1984; Utsumi 1985). There are several types of peculiar red giants which have enhanced s-process elements and/or carbon but which cannot be explained by mixing during helium shell flashing in the late stages of AGB evolution. These are Ba II stars, CH stars and subgiant CH stars. All these peculiar red giants have absolute magnitudes which range down to zero and fainter. The early R stars differ from many of the other peculiar red giants in that they do not show enhanced s-process abundances. The early R stars lie in the same region of H-R diagram, as the Ba II, CH, and normal field G-K giant stars (Scalo 1986). The early R stars belong to the old disk population and their space density is of the order of 1% of the normal field G-K giants (Blanco 1965). Blanco estimated that the space density of R stars is 10 times that of N stars near the Sun, while Stephenson (1973) finds a decline in the space density of N stars but probably not of R stars in the direction of the galactic centre. Unlike Ba II and CH stars, all the early R stars are not binaries (McClure 1989) and the over abundance of carbon (C/O > 1) and low ^{12}C/^{13}C cannot be explained as due to mass transfer in a binary system because the early R stars have a normal binary frequency (McClure 1989). These early stars are too faint ($M_V = +0.4$, Vandervort 1958, Richer 1975, Gordon 1968, Eggen 1972) and low in mass (0.7 to 1.0 $M_{\odot}$) to explain their peculiarities on the basis of helium-shell flashing on the AGB. If the present early R stars were once luminous and pulsating AGB stars and experienced significant mass loss then we expect to see circumstellar dust around them. The near infrared observations of early R stars by Mendoza & Johnson (1965) suggest for excess flux in the 3.5 μm region in some of these stars. Mendoza (1968) and Alksne & Ikaunieks (1981) attribute the excess flux in the 3.5 μm region in some early R stars to the presence of circumstellar material reprocessing photospheric flux to longer wavelengths. In order to detect far infrared (IRAS) sources associated with early R stars the IRAS point source catalogue was searched.

In this paper the detection of circumstellar dust shell around the early R star HD 100764 is reported.

2. IRAS observations

Searched the IRAS point source catalogue (Beichman et al. 1985) for the IRAS counter parts of early R stars listed by Vandervort (1958) and Mendoza & Johnson (1965) (see also Dominy 1984). Only one early R star HD 100764 was found to show significant far infrared excess fluxes at 12 μm, 25 μm, 60 μm and 100 μm. Two other early R stars HD 16115 and HD 156074 were found to

Table 1. IRAS observations of early R stars

	V	R type	C type	Observed IRAS fluxes (Jansky)			
				12 μm	25 μm	60 μm	100 μm
HD 16115	8.07	R3-R5	C2, 3J	0.33	0.25	—	—
HD 100764	8.8	Ro	C1, 1	7.83	10.24	9.01	5.89
HD 156074	7.61	Ro	C3, 1	0.51	0.25	—	—

show flux at 12 μm. The uncertainty in the 12 μm, 25 μm, 60 μm and 100 μm fluxes of HD 100764 are 4%, 8%, 12%, and 12% respectively. The uncertainty in the 12 μm flux of HD 16115 and HD 156074 is 12%. The IRAS positions of these three sources are in very good agreement with their SAO positions. The IRAS fluxes of these three sources are given in Table 1.

3. Analysis

The 0.36 μm to 100 μm flux distribution of HD 100764 is shown in Fig. 1. The *UBVRIJKL* observations of HD 100764 shown in Fig. 1 are from Mendoza & Johnson (1965), and Eggen (1972). From a detailed spectroscopic analysis of HD 100764 Dominy (1984) found $T_{\rm eff}=4850$ K, $\log g=2.2$ and $[{\rm Fe/H}]=-0.6$. The star HD 100764 is not a pulsating variable. The *UBVR* observations of Mendoza & Johnson (1965), Eggen (1972) and the narrowband scanner fluxes obtained by Yorka (1983) agree with one another and show no evidence for variability, which is in agreement with the characteristics of early R stars. The reddening in the direction of HD 100764 is very low. Eggen (1972) derived $E(B-V)=0.02$ which is consistent with the high galactic latitude of this star. Richer (1975) obtained the Ca II K line region spectrum of HD 100764 and employing Wilson Bappu effect, he derived the absolute visual magnitude $M_{\rm V}=+0.3$, which is in agreement with the absolute magnitude estimate of early R stars by Vandervort (1958), and Baumert (1974). Employing $M_{\rm V}=+0.3$ and $E(B-V)=+0.02$ the distance is found to be 500 parsecs. The flux distribution of a star with $V=8.8$, $T_{\rm eff}=4850$ K $\log g=2.0$, and $[{\rm Fe/H}]=-0.5$ is shown in Fig. 1. The observed and computed fluxes match fairly well from 0.36 μm to 1.0 μm. Beyond 1.0 μm the observed flux of HD 100764 deviates from that expected from a star with no circumstellar dust shell. The flux received above the earths atmosphere from HD 100764 alone is found to be $10.1\,10^{-12}$ W m^{-2} (the excess flux in the near and far infrared is not included). Adopting a distance of 500 parsecs the luminosity L is found to be 87 $L_\odot$. The dust shell around HD 100764 absorbs the radiation from the star and reemits the radiation in the infrared. The flux distribution (Fig. 1) from 1.2 μm to 100 μm is rather flat, which suggests for the presence of temperature gradient in the dust envelope. The excess flux in the near and far infrared regions suggests for the presence of warm and cold dust. In the Van der Veen & Habing (1988) far

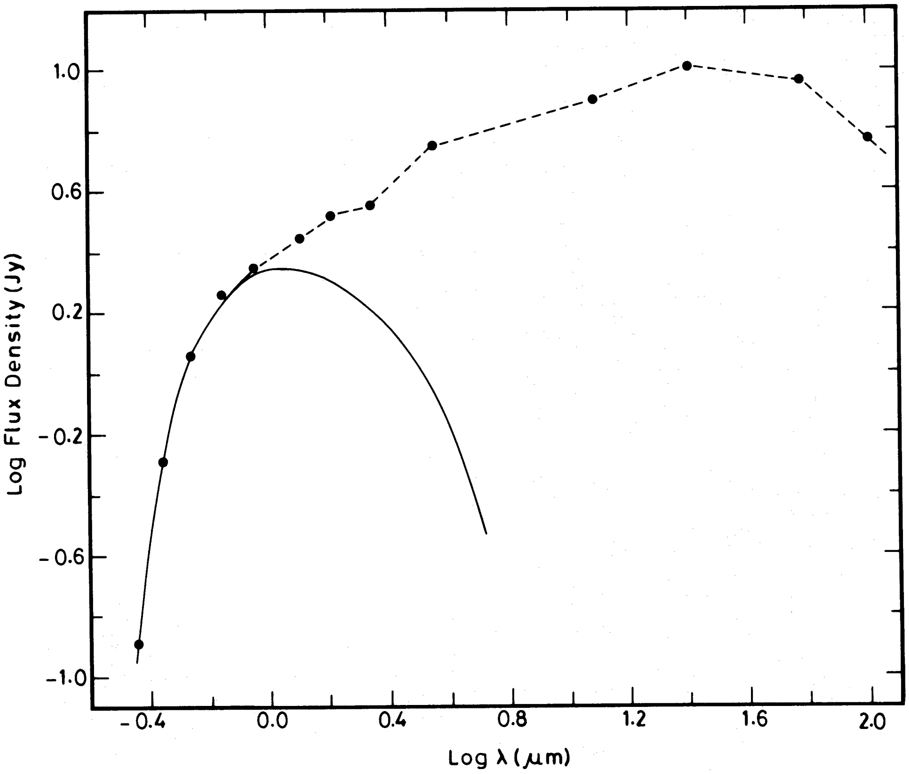

Fig. 1. Flux distribution of early R star HD 100764. Filled circles represent the observed fluxes. The continuous dark line represents the flux distribution of a star with the parameters $V=8.8$, $T_{\rm eff}=4850$ K, $\log g=2.0$, $[{\rm Fe/H}]=-0.5$

infared (IRAS) colour-colour diagram, HD 100764 is in box VIb which is characterized by stars with relatively hot dust close to the star and relatively cold dust at large distance. Some of the objects with far infrared colours similar to that of HD 100764 are found to be oxygen-rich. The infrared flux (from the dust shell around HD 100764) between 3 μm to 100 μm received above the earth's atmosphere was integrated and found to be $6.8\,10^{-12}\ \mathrm{W\,m^{-2}}$. Using the distance of 500 pc the total far-infrared luminosity L_{IR} of the dust shell was found to be $L_{\mathrm{IR}} = 54\ L_{\odot}$. If only the IRAS 12 μm, 25 μm, 60 μm, and 100 μm fluxes are considered the integrated (12 μm to 100 μm) flux was found to be $2.2\,10^{-12}\ \mathrm{W\,m^{-2}}$ and $L_{\mathrm{IR}}(\mathrm{IRAS}) = 17\ L_{\odot}$. The infrared is nearly certainly energy absorbed by the dust shell from the star, it must be concluded that the shell has considerable optical depth in the visual and near UV spectral range. A value of $\tau_{\mathrm{vis}} = 0.5$ is necessary. However the ultraviolet blue, and visual region fluxes (Eggen 1972) show no significant reddening. The absorption could be wavelength independent and therefore not cause any observable reddening. This could happen if the absorbing particles are larger than normal interstellar grains. But very large particles are not required. According to Draine & Lee (1984) minimum grain sizes of between $3\,10^{-5}$ and 10^{-4} cm will suffice. The assumption of spherical symmetry and that the infrared emission comes from a relatively thin shell can be used together with the optical depth in the visual discussed above, and the measured infrared fluxes to determine the radius of the emitting shell R_{d}, the dust temperature T_{d} and the dust mass M_{d} (Hildebrand 1983, Barlow 1983). The equations used are

$$\tau_{\nu} = \frac{3}{2\Pi}\left(\frac{d}{R_{\mathrm{d}}}\right)^{2}\frac{F_{\nu}}{B_{\nu}(T_{\mathrm{d}})}$$

and

$$M_{\mathrm{d}} = \frac{4}{3}\frac{\alpha\rho}{Q_{\nu}}\frac{d^{2}F_{\nu}}{B_{\nu}(T_{\mathrm{d}})}$$

where d is the distance to the source, F_{ν} the observed flux density, $B_{\nu}(T_{\mathrm{d}})$ the planck function with dust temperature T_{d}, a (10^{-5} cm) and ρ ($3\ \mathrm{gm\,cm^{-3}}$) are the radius and mean density of the emitting dust grains which have an emissivity $Q\ (\nu_{\mathrm{max}})$ at the peak of the infrared energy distribution ($Q_{25\,\mu\mathrm{m}} = 3\,10^{-3}$). The infrared flux distribution cannot be fitted by a single temperature. The near infrared flux distribution suggests the presence of warm dust (800–1000 K). In the far infrared (12 μm to 100 μm) a mean dust temperature $T_{\mathrm{d}} = 140$ K can be used as a rough global parameter. The 60 μm to 100 μm flux ratio and the presence of significant flux at 100 μm suggest the presence of cold dust with the dust temperature T_{d} in the range of 100 K to 50 K. Observations beyond 100 μm will be useful to study the cold dust component. The radius of the dust shell is estimated to be $1.7\,10^{4}\ R_{\odot}$. It may be composed of multiple shells of different dust temperatures. If we adopts $T_{\mathrm{d}} = 140$ K, the dust mass M_{d} turns out to be $0.5\,10^{-6}\ M_{\odot}$. The determination of the dust mass depends on the distance, the flux density, T_{d}, $Q(\nu)$ and the size of the dust grains. The accuracy of the dust mass determination is limited primarily by the uncertainties in distance, grain size and emissivity. The estimate of dust mass can be considered as a lower limit. If the ratio of gas to dust mass is about 100, as it is in the interstellar medium the total minimum shell mass is of the order of $0.5\,10^{-4}\ M_{\odot}$.

From an analysis of mass loss from carbon stars Jura (1986) suggested that pulsations may levitate the matter above the photosphere, and then grains form, with the consequence that the radiation pressure on the dust expels the matter to infinity. However, early R stars including HD 100764 are not pulsating variables. The CNO and $^{12}\mathrm{C}/^{13}\mathrm{C}$ abundances ([C] = +0.47, [N] = 0.44, [O] = −0.53, $^{12}\mathrm{C}/^{13}\mathrm{C} = 4$, [Fe] = −0.59), (Dominy (1984) of HD 100764 clearly suggest that it is an evolved star. The lack of oxygen depletion indicates that the CNO cycle operating near equilibrium is not responsible for the fact that C/O > 1. The low value of $^{12}\mathrm{C}/^{13}\mathrm{C}$ suggests deep mixing. Dominy (1984) suggested that early R stars resulted from mixing at the time of or closely following helium core flash. At the time of helium core flash the luminosity may be higher than the present luminosity and helium core flash might have triggered significant mass loss. The dust shell around HD 100764 may be the result of mass loss during the helium core flash. The presence of dust shell around HD 100764 suggests that it has experienced helium core flash only recently. The dust shells around most of the early R stars may have been dissipated. However several early R stars show evidence for the presence of warm dust (Mendoza 1968, Alksne & Ikaunieks 1981) which may be the remnant of the dissipated dust shell. The normal oxygen abudance in the atmosphere of HD 100764 and other early R stars (Dominy 1984) suggests that the circumstellar dust shell around HD 100764 may be oxygen-rich. Oxygen-rich circumstellar dust shells have been detected in few J-type carbon stars (Little-Marenin 1986, Willems & de Jong 1986, Vardya 1989) which have low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio and no over-abundance of s-process elements similar to early R stars. The evolutionary connection between early R stars and J-type carbon stars is not clear. It may be that some early R stars may evolve into J-type carbon stars. Little-Marenin (1986) suggested that the carbon stars with oxygen-rich circumstellar dust shells are binaries in which the observed dust shell is around the M-type star. However Willems & de Jong (1986, 1988) suggested that these stars are recently formed carbon stars and that they evolved directly from M stars, and the oxygen-rich dust shell was formed when the star was in M star phase and it is not yet dissipated. Vardya (1989) suggested that an unusual chemical equilibrium exists such that an O-rich environment is produced following grain formation in a C-rich shell.

Willems & de Jong (1986) suggested that the carbon stars with silicate dust shells are J-type ($^{12}\mathrm{C}/^{13}\mathrm{C} \simeq 4$, ^{13}C rich) carbon stars. From a detailed analysis of these stars Lloyd Evans (1990) and Lambert et al. (1990) found that all seven of the known carbon stars having silicate emission feature are J-type carbon stars. The location of HD 100764 in the far infrared colour-colour diagram of Van der Veen & Habing (1988), and the lack of oxygen depletion in the photosphere (Dominy 1984) suggests that HD 100764 has a silicate dust shell, which makes it the less luminous and warm carbon star with silicate dust shell.

Zuckerman & Maddalena (1989) on the basis of absence of OH maser emission from six optically identified carbon stars with 60 μm emission, and combined with two additional arguments that relate to time scale for evolution on AGB and also the properties of S-type stars suggested that the scenario for carbon star evolution developed by Willems & de Jong (1988) is incorrect. However de Jong (1989) in response to the objections raised by Zuckerman & Maddalena has shown that their objections are unfounded. de Jong (1989) has shown that the negative results of search for OH maser emission in six carbon stars are inconclusive, and the S stars fit quite naturally in the evolution scenario, and also the probability for both stars in a binary system to be on the AGB is much too small to account for the observed number of carbon stars with oxygen-rich circumstellar shells.

Recently H_2O maser emission has been detected from four carbon stars with silicate dust shells (V 778 Cyg, EU And MC 79-11, C 2123) (Little-Marenin et al. 1988, Nakada et al. 1987, 1988, Deguchi et al. 1988, 1989). OH maser, the main line 1665 and 1667 MHz OH maser lines were seen from V778 Cyg (Little-Marenin et al. 1988). These observations further confirm that the dust shells around these stars are oxygen-rich. The silicate feature of the dust shell and the water maser originate from the remnant shell of the past oxygen-rich stage of the star. Recently Deguchi et al. (1990) observed several IRAS sources in the CO $J=1-0$ and SiO $J=2-1$, $v=1$ including the five southern carbon stars with silicate dust shells. They found no SiO and CO emission from four of these stars. SiO masers are usually associated with stellar H_2O/OH maser sources. The non-detection of SiO masers in carbon stars with silicate emission seems to argue against the binary hypothesis. If these stars are a binary pair of M and C stars, SiO masers in the envelope of the M star should be present. Deguchi et al. (1990) conclude that the transition phase hypothesis advocated by Willems & de Jong (1986) explains the non-detection of SiO masers from these stars.

Recently Olofsson et al. (1990) made CO observations of several bright carbon stars. They found large thin detached circumstellar envelopes indicating that the mass loss has occurred episodically. They suggest that the detached circumstellar envelopes around the carbon stars studied by them are the natural consequence of a recent helium shell flash. However the J-type carbon stars are less luminous ($M_{\rm bol}\simeq -3.5$) compared to the average luminosity of normal carbon stars ($M_{\rm bol}\simeq -5$). Even though the present luminosities of J-type carbon stars are relatively low when compared with normal carbon stars they also might have experienced helium shell flash recently and the silicate dust shells around them may be the result of mass loss experienced by these stars recently as a result of first or initial helium shell flash. However the low luminosity of J-type carbon stars and the low ratio of $^{12}C/^{13}C$, and also the absence of over abundance of s-process elements suggests an evolutionary connection between R stars and J-type carbon stars. Their low luminosities suggest that they are low mass stars. The R stars and J-type carbon stars may be the result of helium core flash. Paczynski & Tremaine (1977) were the first to suggest that the R stars may be the result of core helium flash. The silicate dust shells around the J-type carbon stars and the R-star HD 100764 may be the result of mass loss experienced by these stars during the core helium flash, which has taken place recently. This is in agreement with the suggestion of Willems & de Jong (1986) that these stars have turned into carbon stars only recently. A binary model with a red giant companion as the source of silicate dust shell was suggested by Little-Marenin (1987). This model appears to be invalid in view of the absence of SiO maser emission from carbon stars with silicate dust shells (Deguchi et al. 1990) and also the absence of SiO bands in the 4 μm region spectra of these stars (Lambert et al. 1990). Lloyd Evans (1990) (see also Lambert et al. 1990) suggested that the material expelled from the carbon star starting while it still had an oxygen-rich envelope has accumulated in a disc around a hypothetical companion. Lloyd Evans proposed this model in order to account for the absence of significant reddening of the carbon star flux in the blue visual region. The scheme sketched by Lambert et al. (1990) for the origin of carbon stars with silicate dust shells is similar to that proposed by Lloyd Evans (1990). Lambert et al. (1990) suggest that the present silicate dust shell was ejected by the progenitor of the J-type carbon star about 10^8 years ago and it has formed a disc around a less luminous companion. Now it is well understood that barium stars are binaries and the over abundance of s-process elements are due to mass transfer or accretion. However the barium stars do not have dust shells or discs around them (Dominy et al. 1986). The above model of Lambert et al. (1990) requires to form the disc around the low mass companion and to maintain it for about 10^8 years.

If we exclude the binary model and accept that the silicate dust shell is around the carbon star, the carbon star optical region flux may not show significant reddening if the absorption by the dust grains is wavelength independent and the dust shell is in the form of thin disc around star. The neutral extinction of the carbon star optical region fluxes can be accounted if the absorbing particles are larger than normal interstellar grains. But very large particles are not required. According to Draine & Lee (1984) minimum grain sizes of between $3\,10^{-5}$ and 10^{-4} cm will suffice to produce neutral extinction. Some of the RV Tauri stars have very red far-infrared colours (Lloyd Evans 1985) but the stars in the optical region do not show large reddening. From IRAS data few stars have been found with detached cold dust shells with far infrared colours similar to planetary nebulae. The optical counterparts of these sources do not show large reddening of their fluxes in the ultraviolet, blue and visual regions (Parthasarathy & Pottasch 1986, Pottasch & Parthasarathy 1988). The star HD 100764 has warm and cold dust shells and the far infrared colours are very red similar to that observed in J-type carbon stars with silicate dust shells. The optical region fluxes of HD 100764 do not show evidence for significant reddening. Eggen (1972) derived $E(B-V)=0.02$ for HD 100764. It may be that the dust shells are not optically thick, the dust grain size is relatively large and dust is confined in the form of thin disc around the star and hence less reddening.

The silicate dust shell around the warm J-type carbon star HD 100764 and the silicate dust shells around the J-type carbon stars may be the result of mass loss experienced by these stars in the recent past during the helium core flash. The luminosity of these stars may be too low to experience helium shell flashes and corresponding mass loss (Olofsson et al. 1990). Iben & Renzini (1984) in their review indicate that first major core flash is followed by a series of roughly a dozen thin shell flashes that occur successively closer to the center and resemble the thermal pulses which occur in AGB stars. During these thin shell flashes the luminosity of the star increases and it may experience mass loss. The possible occurrence of dredge-up following the main flash is controlled by the same sort of physics as in AGB stars of small core mass (Iben & Renzini 1984).

The recent sets of evolutionary models calculations by Lattanzio (1989), Sackmann & Boothroyd (1990), Hollowell (1987) show that they have succeeded in producing carbon stars of quite low luminosity. It is only recently that dredge-up has been found in theoretical models of low mass stars (Sackmann & Boothroyd (1990). Also recent evolutionary model calculations show that a single dredge-up episode produced a carbon star (Sckmann & Boothroyd 1990). The possibility that J-type carbon stars are the low luminosity AGB stars cannot be ruled out, and the silicate dust around them may be the result of mass loss experienced by them during the first few shell flashes. Recently Lattanzio's (1989) AGB models produced carbon stars without enhancement of s-process elements which is a characteristic of J-type carbon stars. Another possibility is that J-type carbon stars have lost significant mass before becoming carbon stars. It has been shown that in models with smaller envelope masses when carbon dredge-up begins the reduced envelope mass means a smaller dilution of the added carbon. Hence less carbon is needed to form a carbon star and thus fewer shell flashes (thermal pulses) and therefore no over abundances of s-process elements.

4. Conclusions

The presence of dust shell around the early R star (warm carbon star) HD 100764 suggests that it has experienced significant mass loss in the recent past. The present dust shell around HD 100764 may be the result of mass loss experienced by star during the helium core flash. The oxygen-rich dust shells around some J-type carbon stars may also be the result of mass loss experienced by these stars during helium core flash.

The CO ($J=1-0$ and 2–1) millimetre wave observations and SiO, OH and H_2O maser observations of HD 100764 may enable us to further understand its evolutionary stage and circumstellar dust characteristics.

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