

High-resolution speckle masking interferometry and radiative transfer modeling of the oxygen-rich AGB star AFGL 2290*

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Abstract. We present the first diffraction-limited speckle masking observations of the oxygen-rich AGB star AFGL 2290. The speckle interferograms were recorded with the Russian 6 m SAO telescope. At the wavelength $2.11 \mu\text{m}$ a resolution of 75 milli-arcsec (mas) was obtained. The reconstructed diffraction-limited image reveals that the circumstellar dust shell (CDS) of AFGL 2290 is at least slightly non-spherical. The visibility function shows that the stellar contribution to the total $2.11 \mu\text{m}$ flux is less than $\sim 40\%$, indicating a rather large optical depth of the circumstellar dust shell. The 2-dimensional Gaussian visibility fit yields a diameter of AFGL 2290 at $2.11 \mu\text{m}$ of $43 \text{ mas} \times 51 \text{ mas}$, which corresponds to a diameter of $42 \text{ AU} \times 50 \text{ AU}$ for an adopted distance of 0.98 kpc.

Our new observational results provide additional constraints on the CDS of AFGL 2290, which supplement the information from the spectral energy distribution (SED). To determine the structure and the properties of the CDS we have performed radiative transfer calculations for spherically symmetric dust shell models. The observed SED approximately at phase 0.2 can be well reproduced at all wavelengths by a model with $T_{\text{eff}} = 2000 \text{ K}$, a dust temperature of 800 K at the inner boundary r_1 , an optical depth $\tau_V = 100$ and a radius for the single-sized grains of $a_{\text{gr}} = 0.1 \mu\text{m}$. However, the $2.11 \mu\text{m}$ visibility of the model does not match the observation.

Exploring the parameter space, we found that grain size is the key parameter in achieving a fit of the observed visibility while retaining the match of the SED, at least partially. Both the slope and the curvature of the visibility strongly constrain the possible grain radii. On the other hand, the SED at longer wavelengths, the silicate feature in particular, determines the dust mass loss rate and, thereby, restricts the possible optical depths of the model. With a larger grain size of $0.16 \mu\text{m}$ and a higher $\tau_V = 150$, the observed visibility can be reproduced preserving the match of the SED at longer wavelengths. Nevertheless, the model shows a deficiency of flux at short wavelengths, which is attributed to the model assumption of a spherically symmetric dust distribution, whereas the actual structure of the CDS around AFGL 2290 is in fact non-spherical. Our study demonstrates the

possible limitations of dust shell models which are constrained solely by the spectral energy distribution, and emphasizes the importance of high spatial resolution observations for the determination of the structure and the properties of circumstellar dust shells around evolved stars.

Key words: stars: imaging – stars: individual: AFGL 2290 – stars: AGB and post-AGB – stars: mass-loss – stars: circumstellar matter – infrared: stars

1. Introduction

AFGL 2290 (OH 39.7+1.5, IRAS 18560+0638, V1366 Aql) belongs to the group of type II OH/IR stars, which can be defined as infrared point sources with a maximum of the spectral energy distribution (SED) around $6\text{--}10 \mu\text{m}$, with the $9.7 \mu\text{m}$ silicate band in absorption, and with OH maser emission in the 1612 MHz line (Habing 1996). Most of these objects show a long-period variability in the infrared and the OH maser emission (Engels 1982; Herman & Habing 1985), although also a small fraction either varies irregularly with small amplitude or does not vary at all. OH/IR stars are surrounded by massive circumstellar envelopes composed of gas and small solid particles (dust, grains). These circumstellar dust shells (CDS) are produced by the ejection of matter at large rates ($\dot{M} > 10^{-7} M_{\odot} \text{ yr}^{-1}$) and low velocities ($\sim 15 \text{ km s}^{-1}$), and in some cases they totally obscure the underlying star. Based on the luminosities ($\sim 10^4 L_{\odot}$), the periods (500d to 3000d) and bolometric amplitudes ($\sim 1 \text{ mag}$), the kinematical properties and galactic distribution, the majority of OH/IR stars are highly evolved low- and intermediate-mass stars populating the asymptotic giant branch (AGB) (Habing 1996). They extend the sequence of optical Mira variables to longer periods, larger optical depths and higher mass loss rates (Engels et al. 1983; Habing 1990; Lepine et al. 1995).

The improvements of the observational techniques, especially at infrared wavelengths, and the elaboration of increasingly sophisticated theoretical models have provided a wealth of new information on the structure, the dynamics, and the evolution of the atmospheres and circumstellar shells of AGB stars, although many details still remain to be clarified (see the review

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by Habing 1996). A general picture has become widely accepted in which both the large amplitude pulsations and the acceleration by radiation pressure on dust contribute to the mass loss phenomenon for AGB stars. From observations, correlations are found between the period and the infrared excess (indicating the mass loss rate) (DeGioia-Eastwood et al. 1981; Jura 1986), and between the period and the terminal outflow velocity (Heske 1990). On the theoretical side, hydrodynamical models showed that due to the passage of shocks generated by the stellar pulsation the atmosphere is highly extended, thus enabling dust formation and the subsequent acceleration of the matter (Wood 1979; Bowen 1988). The inclusion of a detailed treatment of dust formation revealed a complex interaction between pulsation and dust formation, which results e.g. in a layered dust distribution and affects the derived optical appearance (Fleischer et al. 1992, 1995; Winters et al. 1994, 1995).

Until now most interpretations of observations as well as most theoretical models are based on the assumption of a spherically symmetric dust shell, often motivated by the circularity of the OH maser maps. However, observations show that some objects have substantial deviations from spherical symmetry (e.g. Dyck et al. 1984; Kastner & Weintraub 1994; Weigelt et al. 1998). This suggests that the asymmetries observed in many post-AGB objects and planetary nebulae (cf. Iben 1995) may already start to develop during the preceding AGB phase, which provides new challenges for the modeling of the mechanisms and processes determining the structure of the dust shells around AGB stars.

High spatial resolution observations can yield direct information on important properties of the dust shells around AGB stars, such as the dimensions and geometry of the shell. Therefore, such observations contribute additional strong constraints for the modeling of these circumstellar environments, which supplement the information from the spectral energy distribution. Measurements of the visibility at near-IR wavelengths, for example, can be used to determine the radius of the onset of dust formation as well as to constrain the dominant grain size (Groenewegen 1997). To gain information on details of the spatial structure, in particular on asymmetries and inhomogeneities of the CDS, the interferometric imaging with large single-dish telescopes is especially well suited because one observation provides all spatial frequencies up to the diffraction limit of the telescope and for all position angles simultaneously, allowing the reconstruction of true images of the object.

We have chosen AFGL 2290 for our study because it represents a typical obscured OH/IR star with a high mass loss rate, whose location is not too far away from us. The distance to AFGL 2290 can be determined directly with the phase lag method (cf. Jewell et al. 1979), which gives $D = 0.98$ kpc (van Langevelde et al. 1990). For the bolometric flux at earth a value of $f_b \sim 2.4 \cdot 10^{-10} \text{ W m}^{-2}$ is derived by van der Veen & Rugers (1989) from infrared photometry between $1 \mu\text{m}$ and $12 \mu\text{m}$ and the IRAS fluxes. At 0.98 kpc the luminosity is $L = 7200 L_\odot$, which is within the typical range for an oxygen-rich AGB star. The long period of $P = 1424$ d determined from the variation of

the OH maser (Herman & Habing 1985) and the high mass loss rate suggest, that the star is in a late phase of its AGB evolution.

So far, Chapman & Wolstencroft (1987) reported the only high angular-resolution infrared observations of AFGL 2290. From 1-dimensional slit-scan speckle interferometry with the UKIRT 3.8 m telescope at $3.8 \mu\text{m}$ and $4.8 \mu\text{m}$ they derive 1-dimensional visibilities and determine Gaussian FWHM diameters. Radiative transfer models for the AFGL 2290 dust shell have been presented by Rowan-Robinson (1982), Bedijn (1987), Suh (1991) and recently by Bressan et al. (1998). These models yield dust shell properties within the typical range of OH/IR stars, e.g. a dust mass loss rate of about $4 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ (Bedijn 1987; Bressan et al. 1998), or an optical depth at $9.7 \mu\text{m}$ of about 10 (Bedijn 1987; Suh 1991). However, none of these studies includes constraints from high spatial resolution infrared measurements.

In Sect. 2 we present the results of our speckle masking observations of AFGL 2290. The approach for the radiative transfer modeling is described in Sect. 3 comprising a short description of the code, the selection of the photometric data and a discussion of input parameters for the models. In Sect. 4 we present the results of the radiative transfer modeling starting with the discussion of a model, which yields a good fit of the observed SED at all wavelengths but does not reproduce the observed $2.11 \mu\text{m}$ visibility. In search of an improved model the changes of the resulting SED and visibility under variations of the input parameters are investigated in the following sections. We finish the paper with a summary of the results and our conclusions in Sect. 5.

2. Speckle masking observations

The AFGL 2290 speckle data presented here were obtained with the Russian 6 m telescope at the Special Astrophysical Observatory (SAO) on June 14 and 16, 1998. We recorded a total number of 1200 speckle interferograms of AFGL 2290 (600 on June 14 and 600 on June 16) and 2400 speckle interferograms of the unresolved reference star HIP 93260 (1200 on each of the two nights) with our 256×256 pixel NICMOS 3 camera through an interference filter with center wavelength $2.11 \mu\text{m}$ and a bandwidth of $0.192 \mu\text{m}$. The exposure time per frame was 100 ms, the pixel size was 30.61 mas and the field of view $7''.8 \times 7''.8$. The $2.11 \mu\text{m}$ seeing was about $\sim 1''.2$. A diffraction-limited image of AFGL 2290 was reconstructed from the speckle data by the speckle masking bispectrum method (Weigelt 1977; Lohmann et al. 1983; Weigelt 1991). The process includes the calculation of the average power spectrum and of the average bi-spectrum and the subtraction of the detector noise terms from those. The modulus of the object Fourier transform was determined with the speckle interferometry method (Labeyrie 1970). The Fourier phase was derived from the bias-compensated average bispectrum.

Figs. 1 and 2 show the visibility function of AFGL 2290 at $2.11 \mu\text{m}$. The azimuthally averaged visibility decreases steadily to values below ~ 0.40 of the peak visibility at the diffraction cut-off frequency (13.5 arcsec^{-1}). Thus, the circumstellar

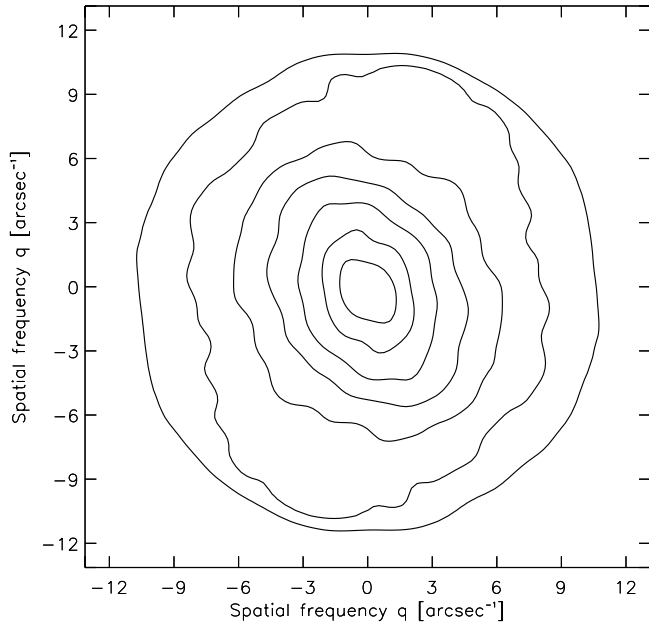


Fig. 1. Two-dimensional $2.11 \mu\text{m}$ visibility function of AFGL 2290 derived from the speckle interferograms. The contour levels are plotted from 20% to 80% of the peak value in steps of 10%.

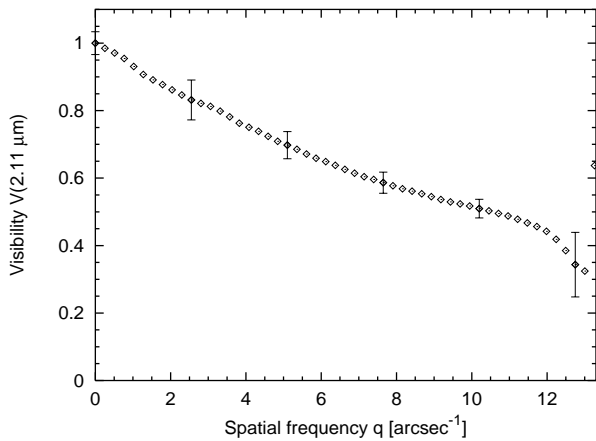


Fig. 2. Azimuthally averaged $2.11 \mu\text{m}$ visibility function of AFGL 2290 and errorbars.

dust shell is almost totally resolved, and the contribution of the unresolved stellar component to the monochromatic flux at $2.11 \mu\text{m}$ must be less than $\sim 40\%$, suggesting a rather high optical depth at this wavelength. In order to derive diameters for the dust shell, the object visibility function was fitted with an elliptical Gaussian model visibility function within a range of 1.5 arcsec^{-1} up to 7.5 arcsec^{-1} . We obtain a Gaussian fit diameter of $43 \text{ mas} \times 51 \text{ mas}$ for AFGL 2290 corresponding to $42 \text{ AU} \times 50 \text{ AU}$ for an adopted distance of 0.98 kpc or $5.7 r_* \times 6.8 r_*$ for an adopted distance of 0.98 kpc and an adopted stellar radius of $r_* = 7.5 \text{ mas}$ (cf. Sect. 4.1), respectively.

Fig. 3 shows the reconstructed $2.11 \mu\text{m}$ speckle masking image of AFGL 2290. The resolution is 75 mas . Fig. 4 shows the azimuthally averaged images derived from the reconstructed 2-dimensional images of AFGL 2290 and the reference star

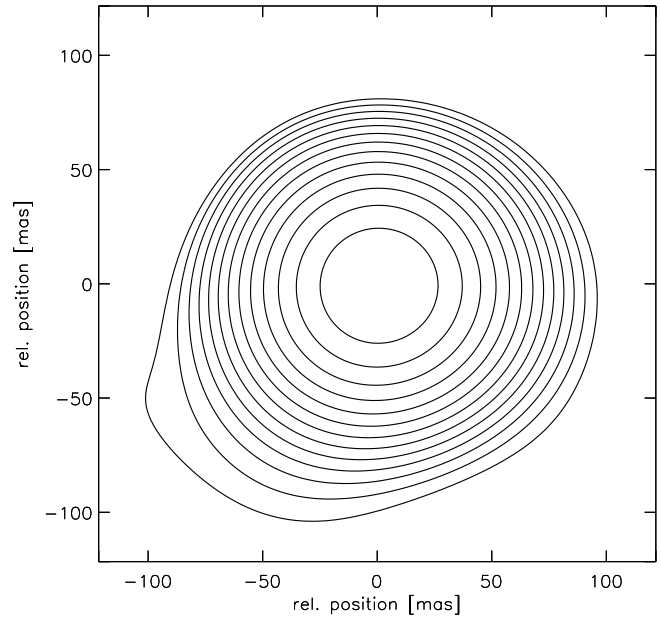


Fig. 3. Diffraction-limited $2.11 \mu\text{m}$ speckle masking image of the AFGL 2290. North is at the top and east to the left. The contours level intervals are 0.25 mag . The lowest contour level is 3.25 mag fainter than the peak intensity.

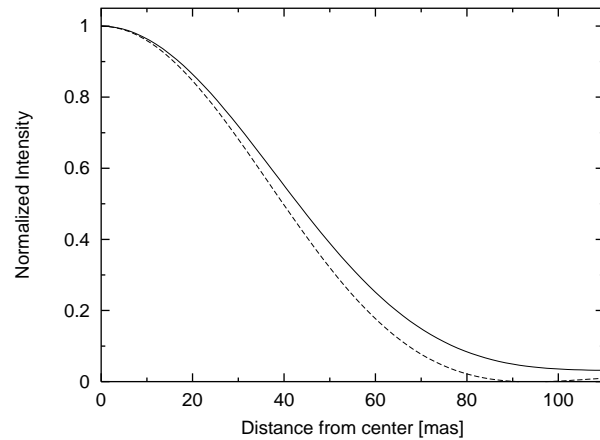


Fig. 4. Azimuthally averaged image of AFGL 2290 (solid line) and of the unresolved reference star HIP 93260 (dashed line).

HIP 93260. In the 2-dimensional AFGL 2290 image a deviation from spherical symmetry can be recognized. The intensity contours are elongated in the south-eastern direction along an axis with a position angle of 130° .

3. The radiative transfer modeling approach

3.1. The radiative transfer code

The radiative transfer calculations are performed with the code DUSTY developed by Ivezić et al. (1997), which is publicly available. The program solves the radiative transfer problem for a spherically symmetric dust distribution around a central source of radiation and takes full advantage of the scaling properties inherent in the formulation of the problem. The formulation of

the radiative transfer problem, the model assumptions and the scaling properties are described in detail by Ivezić & Elitzur (1997). Therefore, we give only a brief discussion here. The problem under consideration is a spherically symmetric dust envelope with a dust free inner cavity surrounding a central source of radiation. This geometry is not restricted to the dust shell of a single star. It can as well describe a dust envelope around a group of stars (e.g. a binary) or even around a galactic nucleus. The radial dependence of the dust density between the inner and outer boundary can be chosen arbitrarily. To arrive at a scale invariant formulation two assumptions are introduced: i) the grains are in radiative equilibrium with the radiation field, and ii) the location of the inner boundary r_1 of the dust envelope is controlled by a fixed temperature T_1 of the grains at r_1 . Due to radiative equilibrium this temperature is determined by the energy flux at r_1 , which in turn is controlled by the energy flux from the central source via the radiative transfer through the dusty envelope. Then prescribing the dust temperature at r_1 is equivalent to specifying the bolometric flux at the inner boundary, and the only relevant property of the input radiation is its spectral shape (Ivezić & Elitzur 1997). Similarly, if the overall optical depth of the dust envelope at some reference wavelength is prescribed, only dimensionless, normalized distributions describing the spatial variation of the dust density and the wavelength dependence of the grain optical properties enter into the problem.

This formulation of the radiative transfer problem for a dusty envelope is well suited for model fits of IR observations, because it minimizes the number of independent model parameters. The input consists of:

- the spectral shape of the central source of radiation, i.e. the variation of the normalized monochromatic flux with wavelength,
- the absorption and scattering efficiencies of the grains,
- the normalized density distribution of the dust,
- the radius of the outer boundary in units of the inner boundary,
- the dust temperature at the inner boundary,
- the overall optical depth at a reference wavelength.

For a given set of parameters, DUSTY iteratively determines the radiation field and the dust temperature distribution by solving an integral equation for the energy density, which is derived from a formal integration of the radiative transfer equation. For a prescribed radial grid the numerical integrations of radial functions are transformed into multiplications with a matrix of weight factors determined purely by the geometry. Then, the energy density at every point is determined by matrix inversion, which avoids iterations over the energy density itself and allows a direct solution of the pure scattering problem. Typically fewer than 30 grid points are needed to achieve a relative error of flux conservation of less than 1%. The number of points used in angular integrations is 2–3 times the number of radial grid points, and the build-in wavelength grid has 98 points in the range from $0.01 \mu\text{m}$ to 3.6 cm (see Appendix C in Ivezić & Elitzur 1997).

The distributed version of the code provides a variety of quantities of interest including the monochromatic fluxes and the spatial intensity distribution at wavelengths selected by the user, but not the corresponding visibilities. Since we want to employ the visibilities obtained from our high spatial resolution measurements as constraints for the radiative transfer models, we have supplemented the code with routines for the calculation of synthetic visibility functions.

3.2. Selection of photometric data

An important ingredient for the radiative transfer modeling of circumstellar dust shells around evolved stars is the spectral energy distribution (SED). Due to the variability of Miras and OH/IR stars, the SED of such objects ideally has to be determined from coeval observations covering all wavelengths of interest. Unfortunately, no such coeval photometric data set for the wavelength region from $\lambda \approx 1 \mu\text{m}$ to $\lambda \geq 20 \mu\text{m}$ is available in the literature for AFGL 2290. Thus, we have to define a ‘composite’ SED, which is derived from observations made by different authors at different epochs, but at about the same photometric phase (Griffin 1993).

From the infrared photometry of AFGL 2290 available in the literature, we selected those publications which specify the date of observation and present the fluxes in tabulated form, either in physical units (e.g. Jy) or in magnitudes with given conversion factors (at least as a reference). Table 1 lists the references, the date and phase of observation and the wavelengths. The phases were determined from the period $P = 1424 \text{ d}$ and the epoch of maximum, $\text{JD} = 244\,4860.8$, which has been derived from the monitoring of the OH maser emission by Herman & Habing (1985). Engels et al. (1983) determined periods of OH/IR stars from infrared observations and found that the periods and phases are in agreement for objects in common with the sample Herman & Habing (1985).

It can be seen from the entries in Table 1 that the wavelength range from $\lambda = 1.2 \mu\text{m}$ to $\lambda = 20 \mu\text{m}$ is only fully covered by observations around phase 0.2 (see entries 2, 4, 9, 12). The respective fluxes are shown in Fig. 5.

The measurements of Herman et al. (1984) and Nyman et al. (1993) match each other quite well at $\lambda = 3.8$ and $\lambda = 4.8 \mu\text{m}$, although the observations are separated by two periods. The fluxes of Price & Murdock (1976) and Gehrz et al. (1985) agree with the Herman et al. and Nyman et al. data within the errors given by the authors.

To represent the SED of AFGL 2290 we adopt the data of Herman et al. (1984), Gehrz et al. (1985), and Nyman et al. (1993). The scatter between the different data sets gives a rough estimate of the uncertainty of the ‘composite’ SED at phase 0.2 of ≈ 0.25 . We do not correct for interstellar extinction because the corrections are less than, or of the same order as, the uncertainty estimated above. For AFGL 2290 Herman et al. (1984) give a value of $A_V = 1.6$ for an adopted distance of 1.19 kpc which reduces to $A_V = 1.3$ at a distance of 0.98 kpc . With the wavelength dependence of the interstellar extinction in the infrared from Becklin et al. (1978) one obtains a correction

Table 1. Infrared photometry of AFGL 2290 ordered by the date of observation

No.	Julian Date 244 0000+	Phase* $P = 1424$ d	Ref.	Wavelengths [μm]										
1	1045	0.320 (-3)	1				4.2				11.0	19.8		
2	2295	0.198 (-2)	1								11.0	19.8		
3	2725	0.500 (-2)	2			2.2	3.6	5.0	8.4, 8.8	10.4	10.6	11.6	12.6	
4	3726	0.203 (-1)	3			2.3	3.6	4.9	8.7		10.0	11.4	12.6	19.5
5	3972	0.376 (-1)	4	1.25, 1.65		2.2	3.7	4.8						
6	4082	0.453 (-1)	3			2.3	3.6	4.9	8.7		10.0	11.4	12.6	19.5
7	4348	0.640 (-1)	3			2.3	3.6	4.9	8.7		10.0	11.4	12.6	19.5
8	4533	0.770 (-1)	4	1.25, 1.65		2.2	3.7	4.8	8.2	9.6	10.2		12.2	19.6
9	5146	0.200 (+0)	5				3.8	4.8	8.7	9.7	10.5	11.5	12.5	20
10	7816	0.075 (+2)	6	1.63	2.23	3.79								
11	7832	0.087 (+2)	7	1.26, 1.68	2.28	3.80								
12	8041	0.233 (+2)	8	1.24, 1.63	2.19	3.79	4.64							

References: 1) Price & Murdock 1976, 2) Lebofsky et al. 1976, 3) Gehrz et al. 1985, 4) Engels 1982, 5) Herman et al. 1984, 6) Noguchi et al. 1993, 7) Xiong et al. 1994, 8) Nyman et al. 1993.

* Numbers in parantheses give the cycle with respect to epoch JD 244 4860.8.

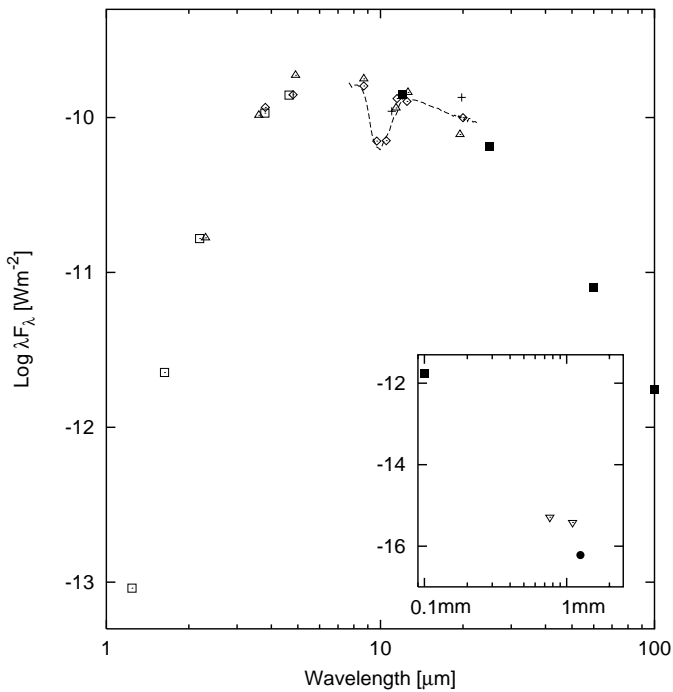


Fig. 5. IR-fluxes of AFGL 2290 observed about phase 0.2 and at phase 0.77. The data are taken from Price & Murdock 1976 (+), Herman et al. 1984 (\diamond), Gehrz et al. 1985 (\triangle), and Nyman et al. 1993 (\square). Also shown are the colour corrected IRAS fluxes adopted from van der Veen et al. 1995 (filled squares), and the IRAS low resolution spectra (dashed line). The IRAS data are multiplied by a factor of 1.95 in order to match the photometric data at $12 \mu\text{m}$. The insert shows mm measurements by Walmsley et al. 1991 (\bullet) and van der Veen et al. 1995 (∇ , 3σ upper limits).

factor of 1.35 at $\lambda = 1.25 \mu\text{m}$, 1.03 at $\lambda = 4.8 \mu\text{m}$, and 1.15 at $\lambda = 9.5 \mu\text{m}$.

AFGL 2290 was observed by IRAS (IRAS Point Source Catalog 1985). We adopt the colour corrected broadband fluxes

given by van der Veen et al. (1995) and the IRAS low resolution spectra from the IRAS Catalog of Low Resolution Spectra (1987). The latter are corrected according to Cohen et al. (1992). Since the broadband fluxes and spectra are averages of several measurements taken at different phases (IRAS Explanatory Supplement 1985), the flux levels, e.g. at $12 \mu\text{m}$, are lower than the fluxes from ground based observations around phase 0.2. Therefore, we multiply the IRAS data with a factor of 1.95 to join them with the ground based data.

Finally, observations at mm wavelengths were reported by Walmsley et al. (1991) who measured a flux of 0.025 Jy at $\lambda = 1.25 \text{ mm}$ at phase 0.18 (JD 2447960), and by van der Veen et al. (1995) who derived 3σ upper limits of 0.13 Jy and 0.14 Jy at 0.76 mm and 1.1 mm respectively for phase 0.25 (JD 2448069), which are consistent with the 1.25 mm flux.

3.3. Selection of input parameters

We represent the central star by a blackbody with an effective temperature T_{eff} . In contrast to the visible M type Mira variables with $T_{\text{eff}} \lesssim 3500 \text{ K}$, the effective temperature of OH/IR stars with optically thick dust shells cannot be directly determined. However, if OH/IR stars can be considered as an extension of the Mira sequence to longer periods and larger optical depths, one might extrapolate the period- T_{eff} relation for Mira variables derived by Alvarez & Mennessier (1997) to $P > 650 \text{ d}$, which yields $T_{\text{eff}} < 2500 \text{ K}$ in agreement with the values expected for the tip of the AGB.

The dust density distribution is obtained from the velocity law, which results from an approximate analytic solution for a stationary dust driven wind with constant mass loss rate (e.g. Schutte & Tielens 1989). If the gas pressure force is neglected and the flux averaged absorption coefficient is assumed to be constant with the radius r in the wind, the velocity distribution is given by

$$v(r) = v_\infty \sqrt{1 - \frac{r_1}{r} \left(1 - \left(\frac{v_1}{v_\infty}\right)^2\right)} \quad (1)$$

where v_1 denotes the velocity at the inner boundary r_1 , and v_∞ is the velocity at infinity. The relevant free parameter is the ratio of these velocities $\delta = v_1/v_\infty$, because only the normalized density distribution enters into the calculation.

We adopt this velocity law, because it accounts for the changing density gradient due to the acceleration of the matter by radiation pressure on dust in the innermost parts of the dust shell. Compared to a dust shell with a $1/r^2$ density distribution and equal optical depth the dust density at r_1 is higher by a factor of $0.5(1 + \delta)/\delta$ and the mass loss rate is lower by a factor of $0.5(1 + \delta)$ (cf. Le Sidaner & Le Bertre 1993). According to the theory of dust driven winds the velocity at the inner boundary, where efficient grain condensation takes place and the acceleration of the matter by radiation pressure on dust starts, is close to local sound velocity c_s (see Gail 1990). This is supported by observations of the velocity separation of the SiO maser emission in OH/IR stars (Jewell et al. 1984), which presumably originates from the dust forming region. With $c_s \lesssim 2 \text{ kms}^{-1}$ for temperatures of about 1000 K and with the measured outflow velocity of AFGL 2290 of $v_\infty = 16 \text{ kms}^{-1}$ (Herman & Habing 1985) one obtains $\delta \approx 0.12$, which we adopt as the standard value for δ .

As described in the previous section, the location of the inner boundary r_1 of the dust shell is determined by the choice of the dust temperature T_1 at r_1 . For the outer boundary r_{out} we adopt a default value of $r_{\text{out}} = 10^3 r_1$. As shown in the following section a larger outer boundary affects only the far infrared fluxes for $\lambda = 100 \mu\text{m}$ without altering the other properties of the model.

We consider spherical grains of equal size described by the grain radius a_{gr} . This is certainly a simplification because based on theoretical and observational arguments, one expects the presence of a grain size distribution $n(a_{\text{gr}})$. Therefore, a size distribution similar to the one observed in the ISM ($n(a_{\text{gr}}) \propto a_{\text{gr}}^{-3.5}$) is often assumed for radiative transfer models of circumstellar dust shells (e.g. Justtanont & Tielens 1992, Griffin 1993). Consistent models for *stationary* dust driven winds, which include a detailed treatment of (carbon) grain formation and growth, in fact yield a broad size distribution which can well be approximated by a power law (Dominik et al. 1989). However, in circumstellar shells around *pulsating* AGB stars the conditions determining the condensation of grains change periodically. The time available for the growth of the particles is restricted by the periodic variations of the temperature and density. This results in a narrower size distribution (Gauger et al. 1990, Winters et al. 1997) which might roughly be approximated by a single dominant grain size.

For the dust optical properties we adopt the complex refractive index given by Ossenkopf et al. (1992) for ‘warm, oxygen-deficient’ silicates. The authors consider observational determinations of opacities of circumstellar silicates as well as laboratory data and discuss quantitatively the effects of inclusions on

Table 2. Parameters and resulting properties of model A.

T_{eff} [K]	T_1 [K]	a_{gr} [μm]	r_{out}/r_1	$\tau_{0.55}$
2000	800	0.10	10^4	100
\dot{M}_d [$M_\odot \text{ yr}^{-1}$]	r_1 [R_*]	f_b [W m^{-2}]	θ_* [mas]	τ_{10}
$2.7 \cdot 10^{-7}$	7.80	$3.0 \cdot 10^{-10}$	7.50	7.49

the complex refractive index, especially at shorter wavelengths ($\lambda < 8 \mu\text{m}$). These constants yield a good match of the overall spectral shape of the observed SED of AFGL 2290, especially of the $9.7 \mu\text{m}$ silicate feature. However, we will also discuss the effects on the radiative transfer models resulting from different optical constants in the Appendix. With the tabulated values of the complex refractive index the extinction and scattering efficiencies are calculated from Mie theory for spherical particles assuming isotropic scattering.

Once a satisfactory fit of the spectral shape is achieved with suitably chosen values for the remaining input parameters T_{eff} , T_1 , a_{gr} , and $\tau_{0.55}$ (the optical depth at the reference wavelength $0.55 \mu\text{m}$) the match of the normalized synthetic SED with the observed SED determines the bolometric flux at earth f_b . Combined with the effective temperature one obtains the angular stellar diameter θ_* and thereby the spatial scale of the system. With an assumed distance D to the object, the luminosity L_* , the radius of the inner boundary in cm, and the dust mass loss rate \dot{M}_d can be calculated. The latter quantity is given by:

$$\dot{M}_d = 2\pi r_1 v_\infty (1 + \delta) \rho_{\text{gr}} \frac{\tau_d(\lambda)}{\tilde{Q}_{\text{ext}}(\lambda)} \quad (2)$$

where ρ_{gr} denotes the specific density of the grain material, $\tau_d(\lambda)$ is the dust optical depth at wavelength λ , and $\tilde{Q}_{\text{ext}} = \kappa_{\text{ext}}/V_{\text{gr}}$ is the extinction cross section κ_{ext} per unit volume V_{gr} of the grains. For single sized grains \tilde{Q}_{ext} is proportional to the extinction efficiency divided by the grain radius $Q_{\text{ext}}/a_{\text{gr}}$, and in the Rayleigh limit $2\pi a_{\text{gr}} \ll \lambda$ it is independent of the grain radius a_{gr} . For the specific density of silicate grains we adopt $\rho_{\text{gr}} = 3 \text{ g cm}^{-3}$ as a typical value. For the distance to AFGL 2290 we use $D = 0.98 \text{ kpc}$ (van Langevelde et al. 1990).

4. Radiative transfer modeling of AFGL 2290

4.1. A radiative transfer model for the SED of AFGL 2290

Starting with the parameters of previous radiative transfer models for AFGL 2290 presented by Rowan–Robinson (1982), Bedijn (1987), and Suh (1991), we achieved a satisfactory match of the observed SED with the set of parameters given in Table 2 after a few trials. Henceforth we will refer to this parameter set as model A, and we will first discuss its properties before we use it as a reference for an investigation of the sensitivity of the results on the parameters.

The SED of model A is shown in Fig. 6. Fig. 7 displays an enlargement of the 5–25 μm region with the $9.7 \mu\text{m}$ silicate feature. From the shortest wavelength at $\lambda = 1.25 \mu\text{m}$ up to $\lambda = 1.25 \text{ mm}$ model A provides a good fit to the observations.

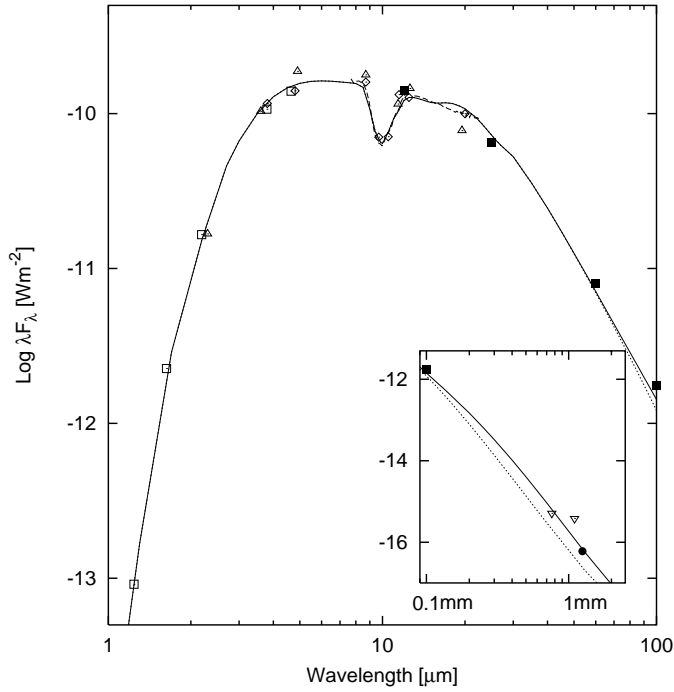


Fig. 6. Spectral energy distribution for model A (solid line) and adopted photometry of AFGL 2290 at about phase 0.2 (see Fig. 5 for the references and corresponding symbols). The insert shows the SED in the mm range. The dotted line displays the SED for a model with the parameters of model A and an outer boundary of $r_{\text{out}} = 10^3 r_1$.

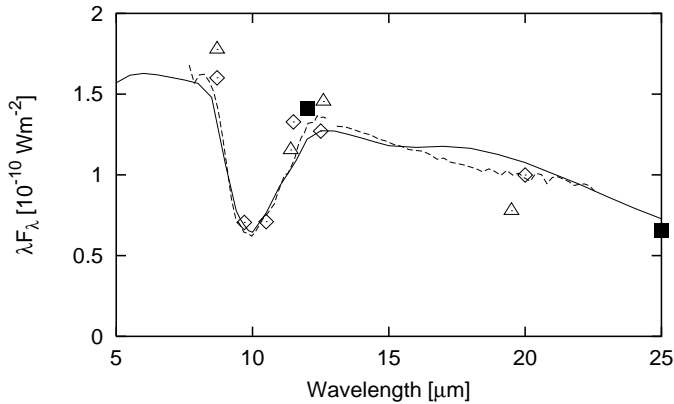


Fig. 7. 5–25 μm spectrum of model A (solid line) and the corrected IRAS LRS spectra (dashed lines). The IRAS data are scaled by a factor of 1.95 to match the ground based photometry (see Fig. 5 for the references and corresponding symbols).

The location, shape and strength of the silicate feature around 10 μm is well reproduced with the adopted optical data from Ossenkopf et al. (1992). Only in the 18 μm region is there a noticeable deviation because the model shows a weak, broad emission which is absent in the IRAS LRS spectrum.

In addition to the input parameters, Table 2 also lists the derived properties of model A. Our value for the bolometric luminosity at earth of $f_b = 3.1 \cdot 10^{-10} \text{ Wm}^{-2}$ is consistent with the values of $2.4 \cdot 10^{-10} \text{ Wm}^{-2}$ determined by van der Veen & Rugers (1989). With $T_{\text{eff}} = 2000 \text{ K}$ the angular stellar diameter

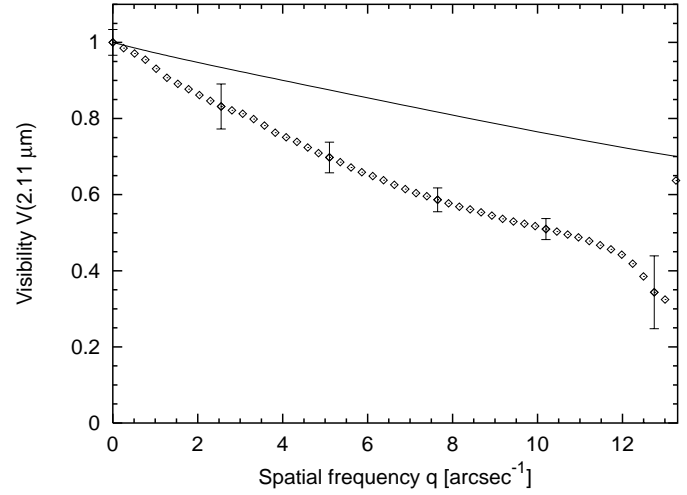


Fig. 8. Synthetic 2.11 μm visibility for model A (solid line) and the azimuthally averaged 2.11 μm visibility obtained from the speckle observation (squares).

is $\theta_* = 7.5 \text{ mas}$ and we obtain a stellar radius $R_* = 790 R_\odot$ and a luminosity $L_* = 9000 L_\odot$ adopting a distance $D = 0.98 \text{ kpc}$. The bolometric flux should be quite accurate considering the quality of the fit. However, the errors in the distance determination (e.g. $\sigma_D = 0.34$, van Langevelde et al. 1990) and the uncertainty in the determination of T_{eff} from the radiative transfer modeling (see Sect. 4.2.2) are rather large, resulting in correspondingly large uncertainties for L_* , R_* and \dot{M}_d .

The derived dust mass loss rate of $2.7 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ is close to the values derived from radiative transfer models by other authors. Bressan et al. (1998) obtain $4.5 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$, and the model of Bedijn (1987) yields¹ $4 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$. From a relation between the strength of the 10 μm feature and the color temperature Schutte & Tielens (1989) obtained $\dot{M}_d = 2.4 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ for AFGL 2290, and Heske et al. (1990) estimated $\dot{M}_d = 1.2 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ from the 60 μm IRAS flux.

All together the parameters and derived properties of model A lie in the typical range of values obtained from radiative transfer models for OH/IR stars showing the silicate feature in absorption. In the calculations of Lorenz–Martins & de Araújo (1997) T_{eff} ranges from 1800 K to 2400 K, T_1 from 650 K to 1200 K, and $\tau_{9.7}$ from 7 to 17. Justtanont & Tielens (1992) derive dust mass loss rates between $2.6 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ and $2.2 \cdot 10^{-6} M_\odot \text{ yr}^{-1}$, and optical depths $\tau_{9.7}$ between 4.85 and 19.6 for their sample of OH/IR stars.

In addition to model A with $r_{\text{out}}/r_1 = 10^4$, Fig. 6 also displays the SED for a model with the same parameters but with an outer boundary, which is ten times smaller, i.e. $r_{\text{out}}/r_1 = 10^3$ (dotted line). The spectra are virtually indistinguishable up to $\lambda \gtrsim 60 \mu\text{m}$. The additional cold dust due to the larger outer boundary of model A increases the far infrared fluxes (see insert of Fig. 6), but does not affect the SED at shorter wavelengths (cf. Justtanont & Tielens 1992). Since the values of the derived

¹ We have calculated \dot{M}_d from the values for r_1 and τ_{10} given by Bedijn (1987) adopting $\tilde{Q}_{\text{ext}}(10 \mu\text{m}) = 5.6 \cdot 10^3 \text{ cm}^{-1}$.

properties (f_b , \dot{M}_d , ...) are determined essentially by the shape of the SED below $60 \mu\text{m}$, they do not change for $r_{\text{out}}/r_1 \gtrsim 10^3$.

Fig. 8 shows a comparison of the $2.11 \mu\text{m}$ visibility calculated for model A with the azimuthally averaged $2.11 \mu\text{m}$ visibility V_{obs} derived from our speckle observations. Although model A yields a good fit to the observed SED, it fails to reproduce the observed visibility. The slope of the model visibility is much shallower than the slope of the observed one, and the model visibility levels off at $q \gtrsim 20 \text{ arcsec}^{-1}$ with $V_{2.11} = 0.6$. From the observed visibility we obtained an upper limit for the contribution of the star to the monochromatic flux at $2.11 \mu\text{m}$ of $\approx 40\%$, whereas model A yields 62% , indicating that the model optical depth of $\tau_{2.11} = 3$ at $2.11 \mu\text{m}$ is too low. Furthermore the steeper slope of V_{obs} suggests that a levelling-off should occur at a smaller spatial frequency compared to the model visibility, which means that the observed intensity distribution would be rather more extended than the intensity profile of model A.

To summarize, a dust shell model, which yields a visibility in agreement with the observations, requires a larger optical depth at $2.11 \mu\text{m}$ and a more extended intensity distribution compared to model A, but it has to produce the same spectral energy distribution. It turns out that these requirements can be partially fulfilled with suitably modified parameter values.

4.2. Effects of parameter variations on the calculated SED and the model visibility

In order to find a model which matches both the observed SED and the visibility, as well as exploring the sensitivity of the SED and the $2.11 \mu\text{m}$ visibility of the models on the input parameters, we have calculated various sequences of models. In each sequence one parameter was varied within a certain range, while the other parameters were kept fixed at the values of model A, except for the optical depth at the reference wavelength $\tau_{0.55}$. This quantity was adjusted for each model in order to obtain a match of the SED with the observation, especially with the observed strength of the $9.7 \mu\text{m}$ silicate feature. It turns out that models, for which the SED fit the feature equally well have (almost) equal dust mass loss rates, i.e. with our procedure we force the models in a sequence to have equal mass loss rates instead of equal $\tau_{0.55}$.

4.2.1. Effects of different dust temperatures at the inner boundary

The effects of different dust temperatures at the inner boundary on the calculated SED and the $2.11 \mu\text{m}$ visibility are displayed in Fig. 9. The dust temperature is varied between $T_1 = 600 \text{ K}$ and $T_1 = 1200 \text{ K}$, and the derived properties of the corresponding models are given in Table 3.

For the values of T_1 presented here, the SED is changed at wavelengths below $\lambda \approx 9 \mu\text{m}$. Compared to model A with $T_1 = 800 \text{ K}$ a smaller value of T_1 results in a higher flux below $\lambda = 3 \mu\text{m}$ and a deficiency of flux at wavelengths between $3 \mu\text{m}$ and $9 \mu\text{m}$. Values of $T_1 > 800 \text{ K}$ produce a deficiency of flux below $\lambda = 3 \mu\text{m}$ and an excess of flux between $3 \mu\text{m}$ and $9 \mu\text{m}$.

Table 3. Resulting properties for models with the parameters of model A, but with different dust temperatures at the inner boundary.

T_1 [K]	$\tau_{0.55}$	\dot{M}_d [$M_{\odot}\text{yr}^{-1}$]	r_1 [R_{\odot}]	τ_{10}	f_b [Wm^{-2}]
600	65	$2.86 \cdot 10^{-7}$	12.89	4.87	$2.60 \cdot 10^{-10}$
800	100	$2.66 \cdot 10^{-7}$	7.80	7.49	$3.00 \cdot 10^{-10}$
1000	150	$2.70 \cdot 10^{-7}$	5.27	11.23	$3.12 \cdot 10^{-10}$
1200	200	$2.66 \cdot 10^{-7}$	3.91	14.97	$3.25 \cdot 10^{-10}$

As a consequence, the bolometric fluxes are different for these models.

The changes of the SED for a variation of T_1 with fixed other parameters, including $\tau_{0.55}$, have been studied already by Ivezić & Elitzur (1997). For high $\tau_{0.55} > 100$ decreasing T_1 lowers the flux at shorter wavelengths, increases the strength of the silicate feature and raises the flux at larger wavelengths, similar to the changes produced by increasing $\tau_{0.55}$. Since we have adjusted $\tau_{0.55}$ for each value of T_1 to reproduce the observed strength of the $9.7 \mu\text{m}$ silicate feature, the model SED are only changed at shorter wavelengths in a modified way. This behaviour can be understood from the competition of the effects caused by lowering T_1 and simultaneously decreasing $\tau_{0.55}$. Up to $\lambda \lesssim 3 \mu\text{m}$ the increase of the monochromatic flux induced by the smaller optical depth more than compensates the decrease of the flux due to a lower T_1 , but in the region $3 \mu\text{m} \lesssim \lambda \lesssim 8 \mu\text{m}$ the effect of lowering T_1 dominates and the monochromatic flux decreases with T_1 .

The variation of T_1 mainly affects the slope of the $2.11 \mu\text{m}$ visibility $V_{2.11}$ via the different $\tau_{0.55}$. The optical depth increases with T_1 resulting in a broader intensity profile and a smaller stellar contribution to the monochromatic flux. This leads to a steeper decline of $V_{2.11}$ (see Ivezić & Elitzur 1996). The curvature of the visibility only noticeably changes at higher values of the spatial frequency. This change of the slope of the visibility indicates the onset of a levelling off of $V_{2.11}$, especially for the model with $T_1 = 600 \text{ K}$. Since its inner boundary is located at $12.9 R_{\odot}$ or 97 mas , the visibility should approach a constant value at $q \approx 13 \text{ arcsec}^{-1}$. An increase of T_1 above 1000 K yields only a marginally steeper slope of the visibility, although $\tau_{0.55}$ increases and the stellar contribution to the $2.11 \mu\text{m}$ flux correspondingly decreases. However, the inner boundary is shifted simultaneously to smaller radii, resulting in similar slopes of $V_{2.11}$ below $q \lesssim 13 \text{ arcsec}^{-1}$.

To summarize, the changes of the SED due to a variation of T_1 can in principle be compensated by a corresponding variation of $\tau_{0.55}$, but the presence of the silicate feature constrains the choice of the optical depth to values which reproduce the strength of the observed feature, i.e. to combinations of T_1 and $\tau_{0.55}$ which yield a fixed value for $\dot{M}_d \propto r_1 \tau_{10}$. Increasing T_1 yields a steeper slope of the $2.11 \mu\text{m}$ visibility. Above $T_1 = 1000 \text{ K}$, however, these changes are small and will not result in a model which matches the observed visibility.

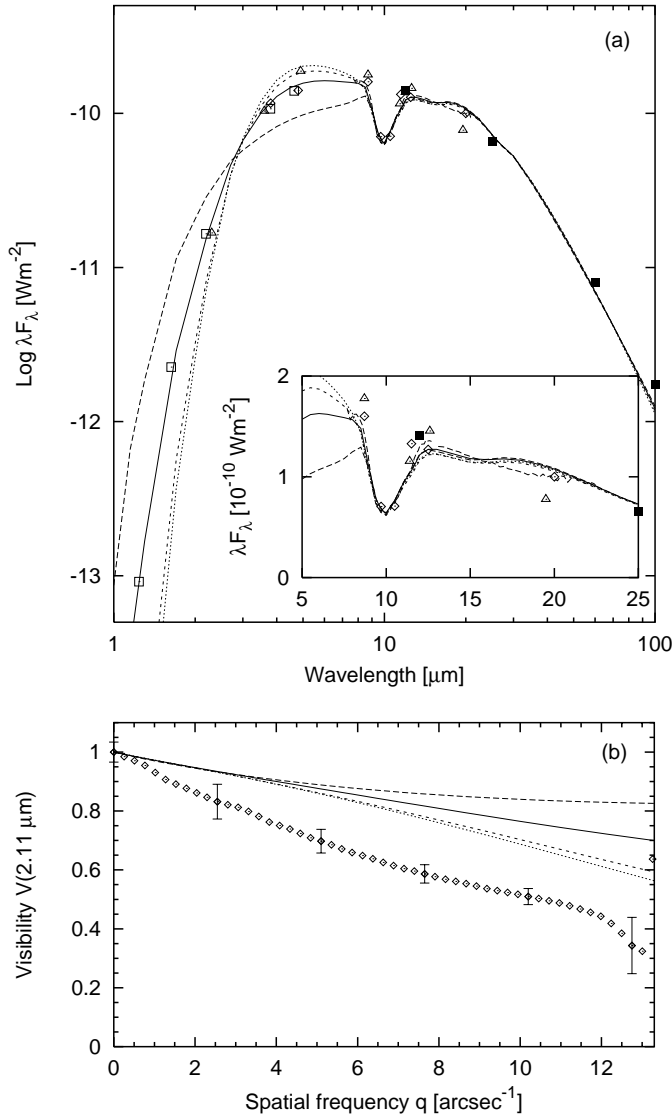


Fig. 9a and b. SED **a** and visibilities **b** for models with the parameters of model A, but with different dust temperatures at the inner boundary: $T_1 = 600$ K (long dashed line), 800 K (solid line), 1000 K (short dashed line), 1200 K (dotted line). The corresponding optical depths and derived model properties are given in Table 3. The spectra have been scaled with different f_b to match the observations at $\lambda > 8 \mu\text{m}$. The symbols denote the observations (see Figs. 2 and 5).

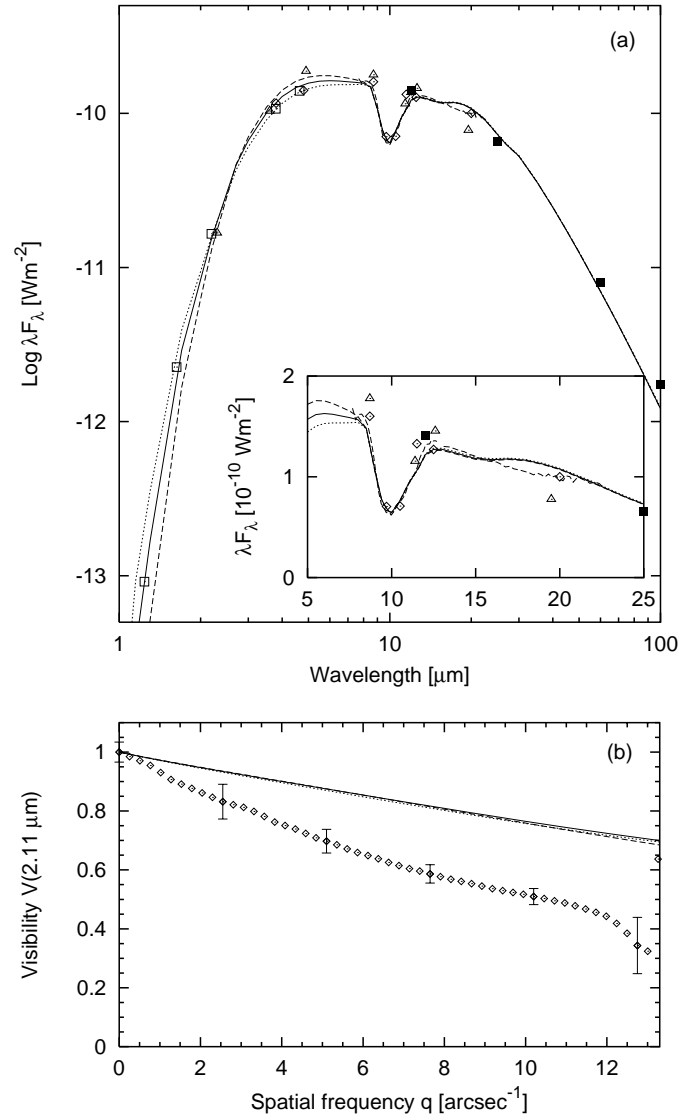


Fig. 10a and b. SED **a** and visibilities **b** for models with the parameters of model A, but with different effective temperatures: $T_{\text{eff}} = 1600$ K (dashed line), 2000 K (solid line), 2400 K (dotted line). The corresponding optical depths and derived properties are given in Table 4. The spectra have been scaled with different f_b to match the observations at $\lambda > 8 \mu\text{m}$. The symbols denote the observations (see Figs. 2 and 5).

4.2.2. Effects of different effective temperatures on the SED and the visibility

Fig. 10 displays the effects of different effective temperatures on the calculated SED and the $2.11 \mu\text{m}$ visibility. The effective temperature is varied between $T_{\text{eff}} = 1600$ K and $T_{\text{eff}} = 2400$ K. The derived properties of the corresponding models are given in Table 4.

The effects of the variation of T_{eff} on the model SED are qualitatively similar to the effects induced by a variation of T_1 . Lowering T_{eff} from 2400 K to 1600 K decreases the monochromatic flux below $\lambda \lesssim 2.5 \mu\text{m}$ and increases the flux at longer wavelengths up to $\lambda = 8 \mu\text{m}$. The main cause for these changes

is the shift of the wavelength λ_m , where the stellar (black-body) spectrum reaches its maximum, from $\lambda_m = 1.5 \mu\text{m}$ to $\lambda_m = 2.3 \mu\text{m}$. The monochromatic flux of the ‘hotter’ star is larger below a certain wavelength, which is, in addition, affected by the slightly different optical depths. However, for the large optical depths considered here, the effects of different T_{eff} on the SED are small as already shown by e.g. Rowan–Robinson (1980). It is interesting to note that the changes of the SED due to a variation of T_1 can be compensated for by a corresponding variation of T_{eff} , at least within a certain range of values.

The variation of T_{eff} has only a negligible effect on the $2.11 \mu\text{m}$ visibility for the temperature range considered here.

Table 4. Resulting properties for models with the parameters of model A, but with different effective temperatures.

T_{eff} [K]	$\tau_{0.55}$	\dot{M}_d [$M_{\odot} \text{yr}^{-1}$]	r_1 [R_*]	τ_{10}	θ_* [mas]	f_b [Wm^{-2}]
1600	110	$2.61 \cdot 10^{-7}$	4.45	8.23	11.7	$3.1 \cdot 10^{-10}$
2000	100	$2.66 \cdot 10^{-7}$	7.80	7.49	7.5	$3.0 \cdot 10^{-10}$
2400	92	$2.73 \cdot 10^{-7}$	12.60	6.86	5.2	$2.9 \cdot 10^{-10}$

Table 5. Resulting properties for models with the parameters of model A, but with different grain radii.

a_{gr} [μm]	$\tau_{0.55}$	\dot{M}_d [$M_{\odot} \text{yr}^{-1}$]	r_1 [R_*]	τ_{10}	$\tau_{2.2}$
0.04	20.0	$2.60 \cdot 10^{-7}$	6.93	8.22	2.86
0.06	37.5	$2.69 \cdot 10^{-7}$	7.15	8.24	2.96
0.08	65.6	$2.66 \cdot 10^{-7}$	7.41	7.86	2.98
0.10	100	$2.66 \cdot 10^{-7}$	7.80	7.49	3.07
0.12	140	$2.63 \cdot 10^{-7}$	8.22	7.03	3.20
0.14	170	$2.60 \cdot 10^{-7}$	8.70	6.59	3.40
0.16	150	$2.65 \cdot 10^{-7}$	9.24	6.33	3.76

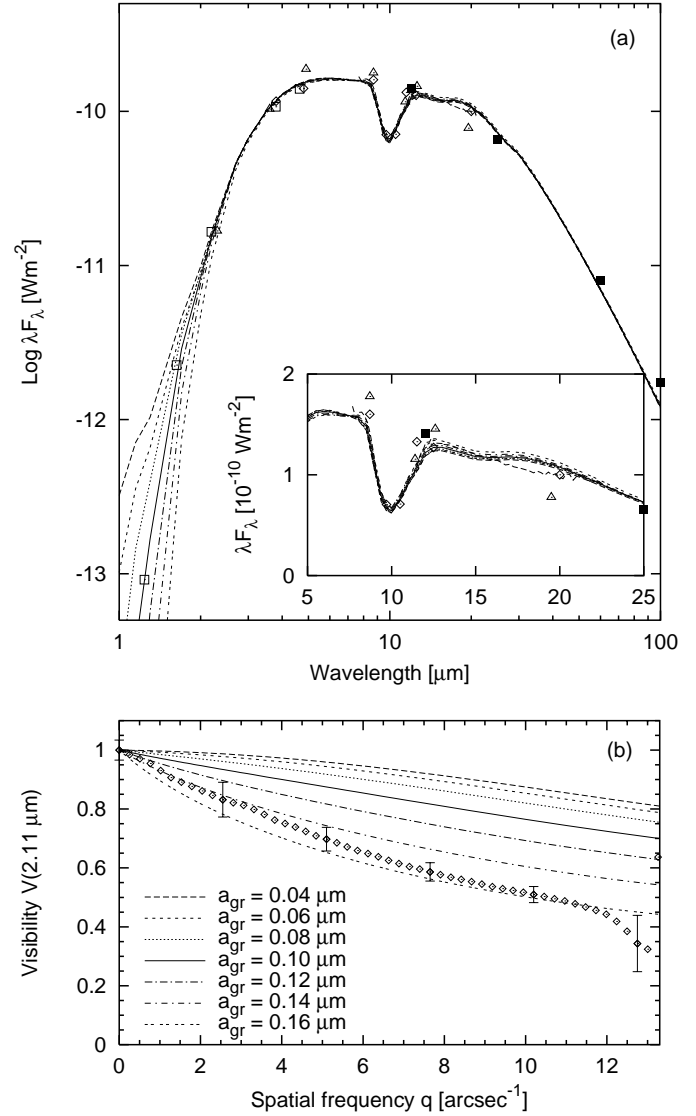
$$f_b = 3 \cdot 10^{-10} \text{ Wm}^{-2}, \theta_* = 7.5 \text{ mas.}$$

Since the changes of the optical depths are small, both the angular diameter of the inner boundary and the stellar contribution to the $2.11 \mu\text{m}$ flux only moderately increase with T_{eff} . Correspondingly, the visibility approaches a slightly higher constant value at a slightly smaller spatial frequency resulting in the minor differences for $V_{2.11}$ at spatial frequencies $q < 13.5 \text{ arcsec}^{-1}$. Thus, changing the T_{eff} within a reasonable range cannot produce a model, which matches the observed visibility.

4.2.3. Effects of different grain radii

The effects of different grain radii on the calculated SED and the $2.11 \mu\text{m}$ visibility are displayed in Fig. 11. The grain radius is varied between $a_{\text{gr}} = 0.04 \mu\text{m}$ and $a_{\text{gr}} = 0.12 \mu\text{m}$. The derived properties of the corresponding models are given in Table 5. Fig. 12 shows the extinction coefficient per unit volume of the grains $\kappa_{\text{ext}}/V_{\text{gr}}$ obtained from the optical data for ‘warm’ silicates from Ossenkopf et al. (1992).

The choice of the grain radius only affects the short wavelength tail of the SED below $\lambda \lesssim 3 \mu\text{m}$, because at these wavelengths $\kappa_{\text{ext}}/V_{\text{gr}}$ still depends on a_{gr} , but it becomes independent of a_{gr} at longer wavelengths (see Fig. 12). This behaviour is caused by two factors: the contribution of scattering to extinction and the dependence of the absorption efficiency on the grain size. The scattering efficiency per unit volume of the grains, which is $\propto a_{\text{gr}}^3$, steeply declines with increasing wavelength and can be neglected above a certain wavelength depending on a_{gr} . The absorption efficiency depends on the grain size only at short wavelengths and becomes independent of a_{gr} once the grains are sufficiently small compared to the wavelength. There-

**Fig. 11a and b.** SED **a** and visibilities **b** for models with the parameters of model A, but with different grain radii ranging from $a_{\text{gr}} = 0.04 \mu\text{m}$ to $a_{\text{gr}} = 0.16 \mu\text{m}$. The corresponding optical depths and derived model properties are given in Table 5. The symbols denote the observations (see Figs. 2 and 5).

fore, the grain radius is constrained by the observed fluxes at the shortest wavelengths $\lambda \lesssim 2 \mu\text{m}$. In our case the photometry at $\lambda = 1.65 \mu\text{m}$ excludes grain radii $a_{\text{gr}} \gtrsim 0.12 \mu\text{m}$ and $a_{\text{gr}} \lesssim 0.06 \mu\text{m}$ and the photometry at $\lambda = 1.25 \mu\text{m}$ restricts the grain radii to values close to $a_{\text{gr}} = 0.1 \mu\text{m}$. However, the values of the absorption and scattering efficiency depend on the adopted optical data. A different data set can result in vastly different grain radii (see Appendix A).

The variation of the grain radius has two effects on the $2.11 \mu\text{m}$ visibility. First, the slope of $V_{2.11}$ steepens with increasing values of a_{gr} , because models with larger grain radius require a higher optical depth at $2.11 \mu\text{m}$ in order to match the observed SED for $\lambda > 2 \mu\text{m}$. With increasing optical depth the intensity distribution becomes broader and the stellar con-

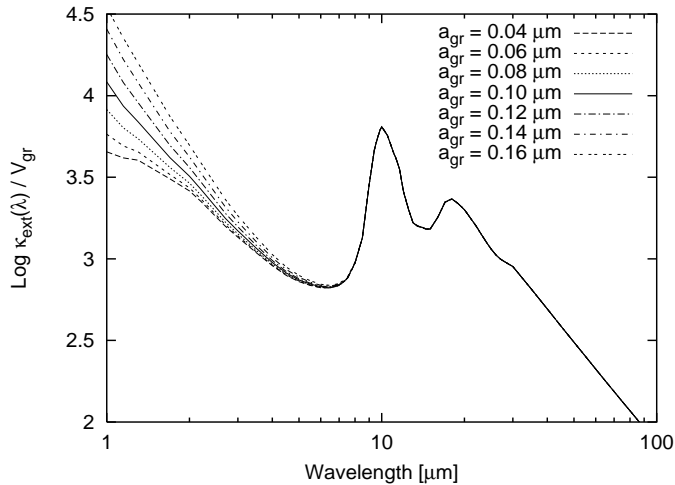


Fig. 12. Extinction coefficient per unit volume of the grains $\kappa_{\text{ext}}/V_{\text{gr}}$ for different grain radii ranging from $a_{\text{gr}} = 0.04 \mu\text{m}$ to $a_{\text{gr}} = 0.16 \mu\text{m}$ calculated with the optical data from Ossenkopf et al. (1992) for ‘warm’ silicates.

tribution to the monochromatic flux at $2.11 \mu\text{m}$ decreases. Correspondingly, the decline of visibility with spatial frequency becomes steeper (see Ivezić & Elitzur 1996). The second effect is the change of the curvature of $V_{2.11}$, which is noticeable at low spatial frequencies. The curvature changes its sign at about $a_{\text{gr}} < 0.1 \mu\text{m}$. This behaviour reflects the changes of the spatial intensity distribution. At large radial offsets b from the star the intensity decreases approximately as $I(b) \propto b^{-3}$, because the optical depth along the line of sight at b becomes small (see Jura & Jacoby 1976). For smaller offsets b , however, the decline of the intensity steepens and the slope of the visibility changes accordingly, i.e. the curvature of V indicates the changing slope of the spatial intensity distribution. Thus, the visibility constrains the grain radii not only via its slope, but also via its curvature.

The observed visibility V_{obs} declines in almost a straight line to values below ~ 0.40 at $q = 13.5 \text{arcsec}^{-1}$ with only a slight curvature. V_{obs} is fairly well matched by the model with $a_{\text{gr}} = 0.16 \mu\text{m}$, although the curvature of the model visibility is a little too strong. Since the visibilities for models with $a_{\text{gr}} = 0.15 \mu\text{m}$ and $a_{\text{gr}} = 0.17 \mu\text{m}$ already fall outside the error bars of the observation, at least for certain spatial frequencies, the grain radius is determined by V_{obs} with an uncertainty $< 0.01 \mu\text{m}$ (cf. Groenewegen 1997).

However, the SED for the model with $a_{\text{gr}} = 0.16 \mu\text{m}$, shows a deficit of flux below $\lambda = 3 \mu\text{m}$. This deficit cannot be removed by a change of T_1 or T_{eff} . Although lowering T_1 increases the flux at $\lambda \lesssim 3 \mu\text{m}$ it also decreases the flux at longer wavelengths. Furthermore, the inner boundary of the dust shell is moved outwards which deforms the resulting visibility in a way that destroys the fit. Increasing T_{eff} yields a similar behaviour.

The deficit of the short wavelength model flux could have several causes, but the clear evidence for a non-spherical dust distribution around AFGL 2290 from our speckle masking observations favors the explanation that the deficiency of flux in

the model is due to the assumption of a spherically symmetric circumstellar dust shell.

A more general assumption would be that the CDS has an axisymmetric, ‘disk-like’ structure. Theoretical investigations show that the variation of the effective optical depth with the inclination of a disk-like dust distribution affects the shape of the SED up to far infrared wavelengths, as well as the monochromatic intensity distributions and the corresponding visibilities (e.g. Efstathiou & Rowan–Robinson 1990; Collison & Fix 1991; Lopez et al. 1995; Men’shchikov & Henning 1997). If the disk-like dust distribution is viewed at an intermediate inclination one expects more flux at visual wavelengths than in the case of a spherically symmetric dust distribution, due to scattered light escaping from the optically thinner polar region located either above or below the equatorial plane. In other words, we expect a deficiency of the model flux at short wavelengths if we model the SED of an aspherical dust distribution assuming a spherically symmetric dust distribution.

5. Summary and conclusions

We have presented the first diffraction-limited $2.11 \mu\text{m}$ speckle masking observations of the circumstellar dust shell around the highly obscured type II OH/IR star AFGL 2290. The resolution achieved with the SAO 6 m telescope is 75 mas, which is sufficient to partially resolve the circumstellar dust shell at this wavelength. From a 2-dimensional Gaussian fit of the visibility function the diameter was determined to be $43 \text{mas} \times 51 \text{mas}$, which corresponds to a diameter of $42 \text{AU} \times 50 \text{AU}$ for a distance of 0.98 kpc. The reconstructed image shows deviations from a spherical structure with an elongation at position angle 130° .

Our new high resolution spatial measurements provide additional strong constraints for radiative transfer models for the dust shell of AFGL 2290, supplementing the information provided by the spectral energy distribution (SED). In order to investigate the structure and the properties of the circumstellar dust shell we have performed radiative transfer calculations assuming a spherically symmetric dust distribution. The spectral energy distribution at phase ~ 0.2 can be well fitted at all wavelengths by a model with an effective temperature of 2000 K, a dust temperature at the inner boundary of 800 K, an optical depth at $0.55 \mu\text{m}$ of 100, and a radius for the single-sized grains of $0.1 \mu\text{m}$, using the optical constants for ‘warm’ silicates from Ossenkopf et al. (1992). From this fit we derived e.g. a bolometric flux at earth of $3 \cdot 10^{-10} \text{Wm}^{-2}$, a radius of the inner boundary of the dust shell of $r_1 = 7.8 R_*$, and a dust mass loss rate of $2.7 \cdot 10^{-7} M_{\odot} \text{yr}^{-1}$, in agreement with the results of previous radiative transfer models for AFGL 2290. However, this model *does not* reproduce the observed $2.11 \mu\text{m}$ visibility function.

We have, therefore, investigated the changes of the calculated SED and the model visibility with the input parameters in search of an improved model. We found that the grain size is the key parameter in achieving a fit of the observed visibility, while retaining at least a partial match of the SED. Both the

slope and the curvature of the visibility react sensitively to the assumed grain radii. With the assumption of single-sized grains we obtain an uncertainty of less than $\pm 0.01 \mu\text{m}$ for a_{gr} . Another result was that the dust mass loss rate is well constrained by the shape of the SED at longer wavelengths and, especially, by the shape of the silicate absorption feature. For given optical constants the value of the dust mass loss rate, as derived from the match of the feature, is not very sensitive to changes of the input parameters. The uncertainty of \dot{M}_{d} is $\sim 3 \cdot 10^{-8} M_{\odot} \text{yr}^{-1}$. The effective temperature and the dust temperature at the inner boundary, however, are less well constrained. We roughly estimate a range of $\pm 300 \text{ K}$ for T_{eff} and $\pm 100 \text{ K}$ for T_1 .

The shape of the observed visibility and the strength of the silicate feature constrain the possible grain radii and optical depths of the model. The observed visibility can be reproduced by a model with a larger grain size of $0.16 \mu\text{m}$ and a higher $\tau_V = 150$, preserving the match of the SED at longer wavelengths. Nevertheless, the model shows a deficiency of flux at short wavelengths, which can be explained if the dust distribution is not spherically symmetric. If the CDS of AFGL 2290 has in fact a disk-like structure, the radial optical depths vary between the equatorial and polar direction. Due to the scattered radiation escaping from the optically thinner polar regions one expects more flux at shorter wavelengths than from a spherically symmetric system with equal optical depth towards the star.

Acknowledgements. This research made use of the SIMBAD database, operated by CDS in Strasbourg.

Appendix A: effects of different optical constants

In Sect. 4.2.3 the deficiency of short wavelength flux for the model which matches the observed $2.11 \mu\text{m}$ visibility of AFGL 2290 was explained by the assumption of a spherically symmetric dust distribution. However, the deficiency could be due to a different cause. For example, the optical constants of ‘astronomical’ silicates at wavelengths $\lesssim 7.5 \mu\text{m}$ are not well known (Ossenkopf et al. 1992) and it is possible that the optical properties of the grains around AFGL 2290 at short wavelengths differ from our assumption.

Therefore, we have investigated the effects of different dust optical properties on the SED and the visibility, as shown in Fig. A1. The models have been calculated with the parameters of model A (except for the value of $\tau_{0.55}$) using the optical data from Ossenkopf et al. (1992) for ‘cold’ silicates (sil–Oc), from Draine & Lee (1984) (sil–DL) and from David & Pégourié (1995) (sil–DP). The extinction coefficient per unit volume of the grains for $a_{\text{gr}} = 0.1 \mu\text{m}$ is shown in Fig. A2 and the derived properties of the models are given in Table A1.

The differences of the $\kappa_{\text{ext}}/V_{\text{gr}}$ resulting from the optical data sets are more or less directly translated into modifications of the SED, if the different values for $\tau_{0.55}$ are taken into account. Compared to the ‘warm’ silicates of Ossenkopf et al. (1992) (sil–Ow), the extinction of sil–Oc grains is higher between $\lambda \approx 1.3 \mu\text{m}$ and $8 \mu\text{m}$, resulting in a lower monochromatic flux of the corresponding model. For the sil–DL and sil–DP data the extinction is lower resulting in an excess of flux.

Table A1. Resulting properties for models with the parameters of model A, but with different dust optical properties.

Optical constants	$\tau_{0.55}$	\dot{M}_{d} [$M_{\odot} \text{yr}^{-1}$]	r_1 [R_{\odot}]	τ_{10}	f_{b} [Wm^{-2}]
Sil–Ow	100	$2.66 \cdot 10^{-7}$	7.80	7.49	$3.00 \cdot 10^{-10}$
Sil–Oc	85	$2.33 \cdot 10^{-7}$	7.63	7.81	$2.75 \cdot 10^{-10}$
Sil–DL	50	$1.57 \cdot 10^{-7}$	6.23	7.74	$3.75 \cdot 10^{-10}$
Sil–DP	50	$1.71 \cdot 10^{-7}$	5.94	9.29	$4.50 \cdot 10^{-10}$

Because the shape of the silicate features at around $10 \mu\text{m}$ and $18 \mu\text{m}$ is similar for the sil–Ow, sil–Oc, and sil–DP data, except for a slightly different ratio of the peak strengths, they yield comparably good fits to width and strength of the observed feature, which has its center at $10 \mu\text{m}$. In contrast, the silicate feature from the sil–DL data peaks at $9.7 \mu\text{m}$, and it is broader than the observed one.

Because the value of \dot{M}_{d} depends on the adopted optical properties of the grains (see Eq. 2), we obtain \dot{M}_{d} for the different models ranging from $1.6 \cdot 10^{-7} M_{\odot} \text{yr}^{-1}$ to $2.7 \cdot 10^{-7} M_{\odot} \text{yr}^{-1}$ (see Table A1). Nevertheless, if the dust mass loss rate is derived from the match of the silicate absorption feature, its value is not very sensitive to variations of the effective temperature, dust temperature at the inner boundary and the grain radius as long as the models are calculated with the same optical constants.

The changes of the $2.11 \mu\text{m}$ visibilities are again caused by the different optical depths of the models at this wavelength. For other fixed parameters a higher optical depth produces a more extended brightness distribution and, thereby, a steeper decline of the visibility. The optical depth at $2.11 \mu\text{m}$ has similar values for the sil–Ow and sil–Oc models and lower, but again similar values for the sil–DL and sil–DP models. Hence, the decline of visibilities from the latter models is shallower.

The optical properties from David & Pégourié (1995) yield a fit of the silicate feature, which is comparable to the fit obtained with the Ossenkopf et al. (1992) data, but they produce an excess of flux at smaller wavelengths for a grain radius of $0.1 \mu\text{m}$. From the investigation of the effects resulting from a variation of a_{gr} in Sect. 4.2.3, we know that the flux at short wavelengths decreases with increasing grain radius, and that the decline of the visibility becomes steeper. Therefore, we have calculated a series of models with the David & Pégourié (1995) data where we varied the grain radius from $a_{\text{gr}} = 0.1 \mu\text{m}$ to $0.5 \mu\text{m}$. Fig. A3 shows the calculated SED and the $2.11 \mu\text{m}$ visibilities. The derived properties of the corresponding models are given in Table A2. Fig. A4 shows the extinction coefficient per unit volume of the grains $\kappa_{\text{ext}}/V_{\text{gr}}$ for the different grain radii.

Compared to the models calculated with the sil–Ow constants, the sil–DP models show a flat flux distribution below $\lambda \lesssim 8 \mu\text{m}$ with a steep drop at a certain wavelength, which depends on the grain radius. Furthermore, much higher values of a_{gr} are needed to match the observation. The short wavelength photometry of AFGL 2290 constrains the grain radius to $a_{\text{gr}} \sim 0.5 \mu\text{m}$, although the slope of the observed SED at

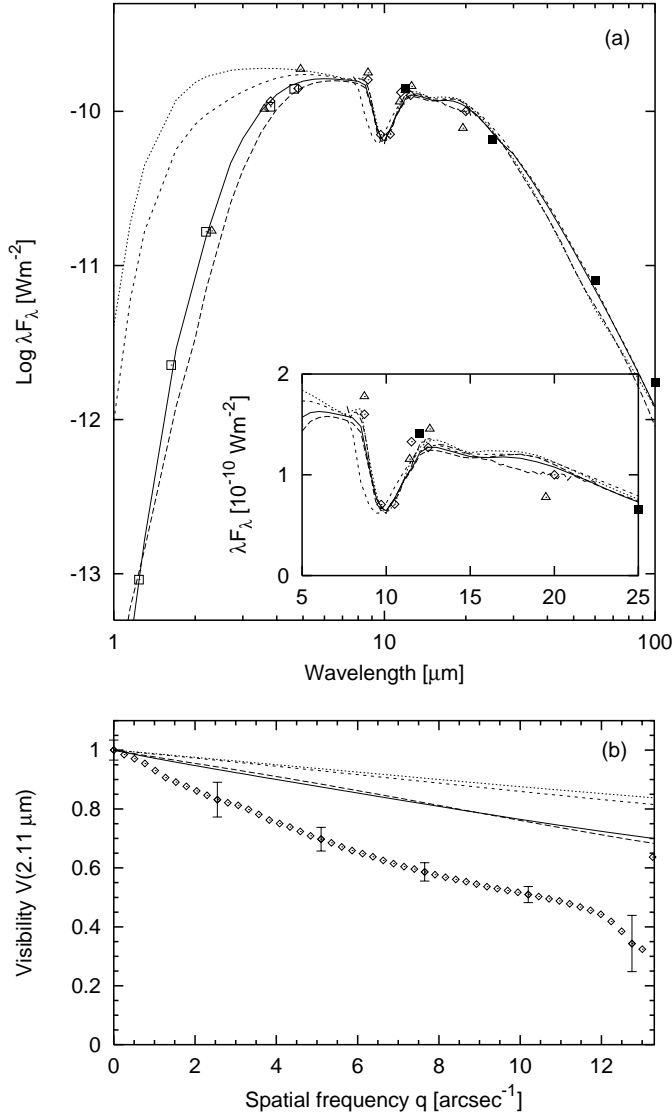


Fig. A1a and b. SED **a** and visibilities **b** for models with the parameters of model A, but with different dust optical properties: ‘warm’ silicates from Ossenkopf et al. (1992) (solid line), ‘cold’ silicates from Ossenkopf et al. (1992) (long dashed line), Draine & Lee (1984) (short dashed line), and David & Pégourié (1995) (dotted line). The corresponding optical depths and derived model properties are given in Table A1. The spectra have been scaled with different f_b to match the observations at $\lambda > 8 \mu\text{m}$.

wavelengths $\lesssim 2.2 \mu\text{m}$ is less well reproduced compared to the sil–Ow model with $a_{\text{gr}} = 0.1 \mu\text{m}$. The different behaviour below $\lambda = 8 \mu\text{m}$ is caused by the fact that the sil–DP constants yield smaller extinction efficiencies for grains of equal radius compared to the sil–Ow constants. Therefore, substantially larger grains are needed to produce comparable optical depths at shorter wavelengths. As a consequence, the contribution of scattering to the extinction is still important up to wavelengths, which are approximately 3–4 times larger.

Due to the stronger dependence of $\kappa_{\text{ext}}/V_{\text{gr}}$ on the grain radius (Fig. A4) and the resulting larger variation of the $2.11 \mu\text{m}$

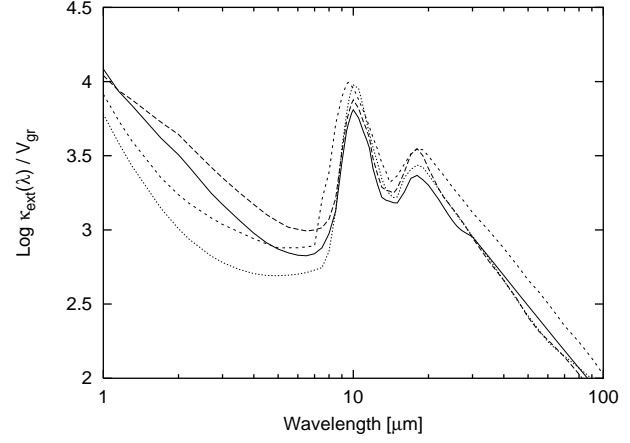


Fig. A2. Extinction coefficient per unit volume of the grains $\kappa_{\text{ext}}/V_{\text{gr}}$ for $a_{\text{gr}} = 0.1 \mu\text{m}$ obtained from different optical constants: ‘warm’ silicates from Ossenkopf et al. (1992) (solid line), ‘cold’ silicates from Ossenkopf et al. (1992) (long dashed line), Draine & Lee (1984) (short dashed line), David & Pégourié (1995) (dotted line).

Table A2. Derived properties for models with the optical constants from David & Pégourié (1995) and different grain radii. The other parameters are equal to model A, except for $\tau_{0.55}$ which has been adjusted to fit the observed SED.

a_{gr} [μm]	$\tau_{0.55}$	\dot{M}_{d} [$M_{\odot}\text{yr}^{-1}$]	r_1 [R_*]	τ_{10}	$\tau_{2.2}$	f_b [Wm^{-2}]
0.10	50	$1.71 \cdot 10^{-7}$	5.94	9.29	0.85	$3.00 \cdot 10^{-10}$
0.15	100	$1.76 \cdot 10^{-7}$	7.00	8.08	1.12	$3.25 \cdot 10^{-10}$
0.20	100	$1.89 \cdot 10^{-7}$	8.10	7.52	1.72	$3.50 \cdot 10^{-10}$
0.30	70	$1.94 \cdot 10^{-7}$	9.71	6.49	3.74	$4.00 \cdot 10^{-10}$
0.40	34	$1.92 \cdot 10^{-7}$	10.52	5.96	6.61	$4.25 \cdot 10^{-10}$
0.50	18.6	$2.00 \cdot 10^{-7}$	11.08	5.91	10.0	$4.50 \cdot 10^{-10}$

optical depth (see Table A2), the changes of the $2.11 \mu\text{m}$ visibility are much more pronounced. With increasing a_{gr} the curvature of the visibility increases, and $V_{2.11}$ falls off to smaller values at $q = 13.5 \text{ arcsec}^{-1}$ because the stellar contribution to the monochromatic flux is reduced. Up to $a_{\text{gr}} \approx 0.2 \mu\text{m}$ the change of the curvature is mainly caused by the changing slope of the spatial intensity distribution, as discussed in Sect. 4.2.3. At larger grain radii the increase of the radius of the inner boundary and the corresponding reduction of the spatial frequencies, where $V_{2.11}$ approaches a constant value (or zero) becomes more important.

The best match of the observed visibility V_{obs} is obtained for the model with $a_{\text{gr}} = 0.2 \mu\text{m}$ (dotted line in Fig. A3), which is somewhat larger than $a_{\text{gr}} = 0.16 \mu\text{m}$ for the best matching model with the sil–Ow optical constants. The resulting dust mass loss rate is about 30% smaller, and the radius of the inner boundary is about 12% smaller. Again the curvature of the model visibility is slightly too strong. But in contrast to the model with the sil–Ow optical constants, there is now an excess of flux at smaller wavelengths $\lambda \lesssim 5 \mu\text{m}$.

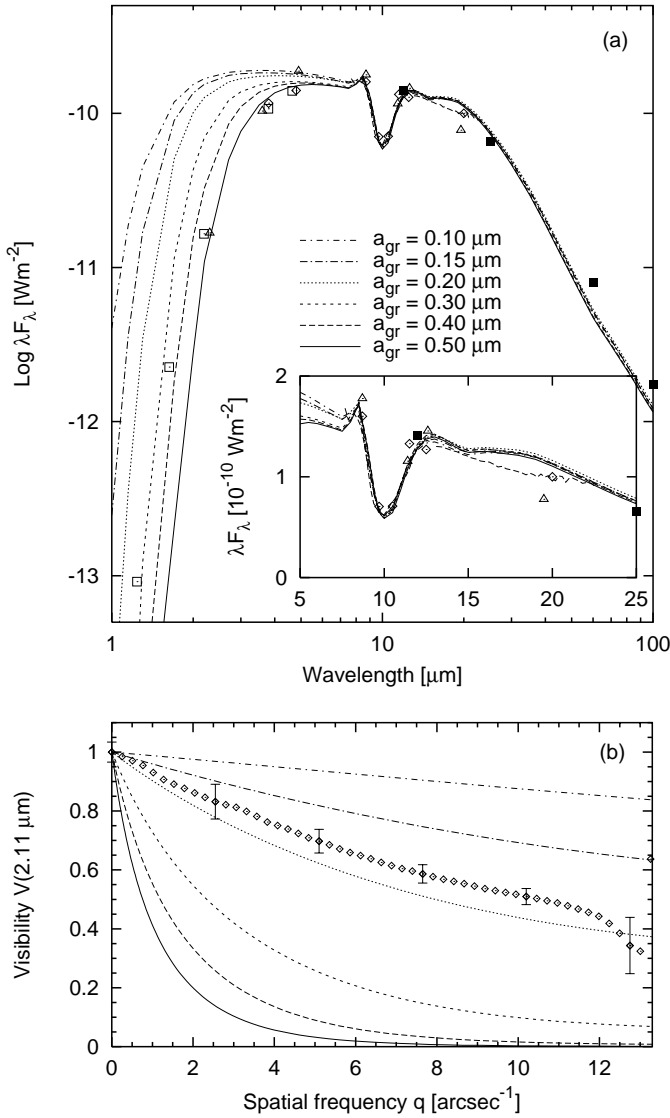


Fig. A3a and b. SED **a** and visibilities **b** for models with the optical constants from David & Pégourié (1995) and different grain radii ranging from $a_{gr} = 0.1 \mu\text{m}$ to $a_{gr} = 0.5 \mu\text{m}$. The other parameters are equal to model A. The corresponding optical depths and derived model properties are given in Table A2. The spectra have been scaled with different f_b to match the observations at $\lambda > 8 \mu\text{m}$.

As discussed at the end of Sect. 4.2.3, we would expect a deficiency of flux if the CDS of AFGL 2290 has a disk-like structure. This suggests that the optical constants from David & Pégourié (1995) underestimate the extinction of the grain material at short wavelengths. However, we also do not know, whether the optical constants from Ossenkopf et al. (1992) represent the intrinsic optical properties of the grains, because the shape of the SED at short wavelengths is affected to an unknown degree by the geometry of the non-spherical dust distribution around AFGL 2290. For the same reason we refrain from enforcing a match of the SED at short wavelengths by a suitable modification of the dust optical constants in this region.

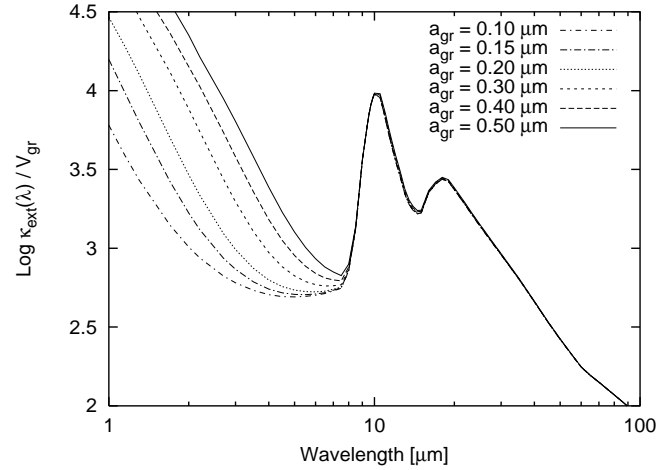


Fig. A4. Extinction coefficient per unit volume of the grains κ_{ext}/V_{gr} calculated with the optical constants from David & Pégourié (1995) for different grain radii ranging from $a_{gr} = 0.1 \mu\text{m}$ to $a_{gr} = 0.5 \mu\text{m}$.

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