DUST EMISSION FROM IRC +10216

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Abstract. Infrared emission from the dust shell around IRC +10216 is analysed in detail, employing a self-consistent model for radiatively driven winds around late-type stars that couples the equations of motion and radiative transfer in the dust. The resulting model provides agreement with the wealth of available data, including the spectral energy distribution in the range 0.5–1000 μm, and visibility and array observations. Previous conclusions about two dust shells, derived from modelling the data with a few single-temperature components of different radii, are not supported by our results. The IR properties vary with the stellar phase, reflecting changes in both the dust condensation radius r_1 and the overall optical depth τ — as the luminosity increases from minimum to maximum, r_1 increases while τ decreases. We find that the angular size of the dust condensation zone varies from $0\rlap{.}''3$ at minimum light to $0\rlap{.}''5$ at maximum. The shortage of flux at short wavelengths encountered in previous studies is resolved by employing a grain size distribution that includes grains larger than $\sim$ 0.1 μm, required also for the visibility fits. This distribution is in agreement with the one recently proposed by Jura in a study that probed the outer regions of the envelope. Since our constraints on the size distribution mostly reflect the envelope's inner regions, the agreement of these independent studies is evidence against significant changes in grain sizes through effects like sputtering or grain growth after the initial formation at the dust condensation zone.

1. Introduction

The purpose of this work is to perform a self-consistent case study of the bright infrared source IRC +10216 that employs a dust density distribution determined from the solution of the coupled system of radiative transfer and hydrodynamics equations for the wind. The equations are described elsewhere (Netzer & Elitzur 1993; Ivezić & Elitzur 1995, hereafter IE95).

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As shown by Elitzur & Ivezić (2000, this Symposium), the solution of this system is essentially determined by a single quantity – the flux-averaged optical depth τ_F. Once τ_F is determined, scaling relations listed in IE95 and in Ivezić & Elitzur (1996a, 1996b) can be used to constrain all other relevant quantities.

2. Spectral Energy Distribution

Our best-fitting model for the spectral shape is shown in Figure 1 together with the observations. The model is primarily determined by the overall optical depth and the dust composition. From previous work (e.g. Blanco et al. 1994), the dust grains around IRC +10216 are primarily composed of amorphous carbon with a minor inclusion of SiC to account for the 11.3 μm feature. With optical properties for amorphous carbon taken from Hanner (1988) and for SiC from Pégourié (1988), we find that the best fit to the 11.3 μm feature is obtained with a mixture of 95% amorphous carbon and 5% SiC (by mass), although varying the percentage of SiC in the range 3–8% still produces satisfactory agreement. In addition to the chemical composition, the distribution of grain radii a also affects the optical properties. We employed two types of size distributions $n(a)$. Most often used is

$$n_{\rm MRN}(a) \propto a^{-3.5}, \qquad a \le a_{\rm max} \tag{1}$$

proposed by Mathis, Rumpl & Nordsieck (1977). Recently Jura (1994) proposed a similar form

$$n_{\rm J}(a) \propto a^{-3.5} {\rm e}^{-a/a_0}, \tag{2}$$

replacing the sharp cutoff with an exponential one. Both distributions can produce satisfactory fits: the MRN distribution requires $a_{\rm max} \approx$ 0.2–0.3 μm, the Jura distribution $a_0 \approx$ 0.15–0.2 μm. With these grain properties, the best-fit values for the visual optical depth are 20 at maximum luminosity and 24 at minimum.

We have thus determined the two major ingredients that affect the spectral shape, the grain optical properties and overall optical depth. In addition, the stellar temperature T_* and dust condensation temperature T_1 have a discernible effect on the spectral shape, but only at short wavelengths. Our best fit gives $T_* = 2200 \pm 150$ K, $T_1 = 750 \pm 50$ K.

3. Spatially Resolved Observations

As the stellar luminosity varies from minimum to maximum, the dust condensation radius increases, and the overall optical depth decreases. Therefore in interpreting the spatially resolved observations, the source variability must be taken into account. From our best-fitting model for the SED, and

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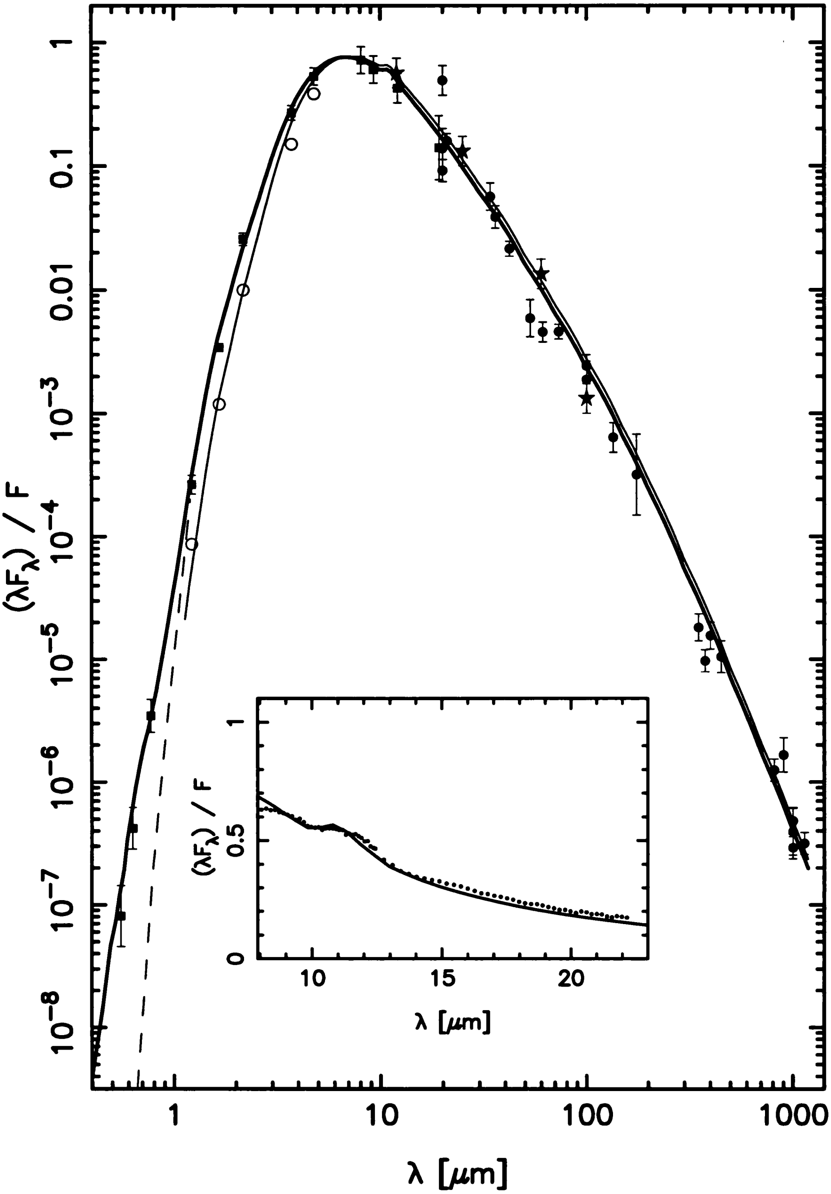

Figure 1. Spectral energy distribution for IRC +10216; lines represent model results, symbols the observations. Data are from the following sources: (■) Le Bertre (1987); (○) Le Bertre (1988); (●) Rengarajan et al. (1985); and (⋆) IRAS Point Source Catalogue. All observations are at maximum light except for those denoted by open circles, which were at minimum light. The thick solid line is the model result for maximum light, the thin solid line the result for minimum. The dashed line is the model result for maximum light and single-size (0.05 μm) grains. The inset shows an expanded view of the IRAS LRS spectral region: the dots are the data, taken close to maximum light, the solid line the model. From Ivezić & Elitzur (1996b).

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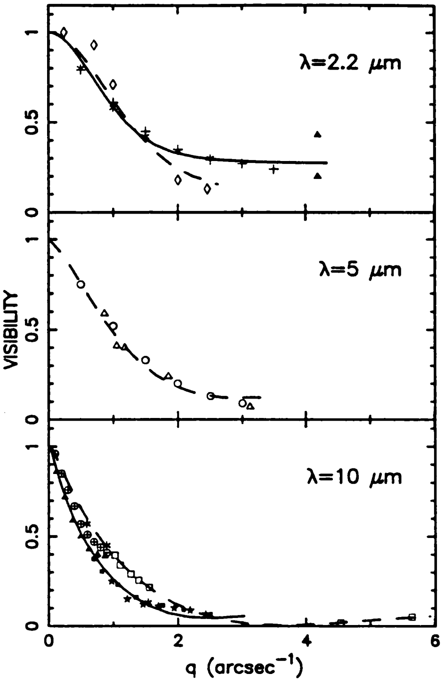

Figure 2. Visibility functions for IRC +10216. Lines represent model results, symbols the observations. Solid lines and full symbols (including + and ∗) correspond to phases close to maximum light, open symbols and dashed lines to phases close to minimum. Data are from the following sources: (⋆) Sutton, Betz & Storey (1979); (◇) Selby, Wade & Sanchez Magro (1979); (△) McCarthy, Howell & Low (1980); (o) Mariotti et al. (1983); (+) Dyck et al. (1984); (∗) Dyck et al. (1987); (⊕) Benson, Turner & Dyck (1989); and (□) Danchi et al. (1990, 1994). From Ivezić & Elitzur (1996b).

an expected bolometric amplitude of 1 mag, we find that the angular size of the dust condensation zone, θ_1, varies from 0.″35 at minimum light to 0.″56 at maximum. These estimates for the angular scale must agree with high-resolution observations. We find this to be the case to within 15–20% for the visibility observations shown in Figure 2.

Bloemhof et al. (1988) obtained a single-scan image of IRC +10216 at 10 μm close to minimum light (phase $\simeq$ 0.4). We computed the profile expected in those observations from the model surface brightness determined for this phase from the spectral shape. Figure 3 shows the comparison between the observed profile (thick dashed line) and our convolved model result (outermost thin solid line, overlapping the observations). The innermost thin solid line is the model surface brightness distribution, the central peak corresponds to the stellar contribution, and the features at relative RA $\pm\theta_1/2$ correspond to the dust formation zone.

The close agreement between our models and the spatially resolved

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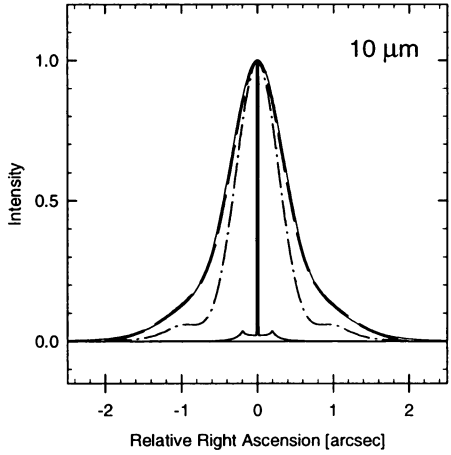

Figure 3. Single-scan (E–W) imaging of IRC +10216 at 10 μm. The thick dashed line represents the observations of Bloemhof et al. (1988). Superimposed on it is our model result drawn as a thin solid line, hardly distinguishable from the observations. It was obtained by a two-dimensional convolution of the surface brightness for $\theta_1 = 0.''35$ (innermost thin solid line) with the point-spread function (PSF, dot-dashed line; all profiles are normalized to unity at the peak).

observations shows that previous conclusions about two dust shells, derived from modeling the data with a few single-temperature components of different radii, are not supported by our results. The extended, continuous temperature and density distributions derived from our model obviate the need for such discrete shells.

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Discussion

Wagenhuber: Do you get information about the mass-loss rate out of your model, or is it an input parameter?

Ivezić: IR emission constrains optical depth and not $\dot{M}$. However, optical depth does depend on $\dot{M}$ and various other parameters. If there are independent estimates for these other parameters, then one can constrain $\dot{M}$, too.

Bagnulo: The value of 5 % for the SiC/AC ratio derived from your analysis is actually dependent on the assumption that both AC and SiC grains form at the same distance from the star.

Ivezić: Certainly. However, varying the difference in the condensation temperatures of amorphous carbon and SiC will have only a minor effect on the inferred SiC/AC ratio. Such differences in the SiC/AC ratio are on the order of the uncertainty in its determination, and I would say that it is probably in the range 3–10 %.

Steffen: What, in the context of your steady-state models, is the explanation for the existence of detached dust shells?

Ivezić: As discussed in our paper (*ApJ* 445, 415, 1995), one possibility is interaction between the wind and the interstellar medium. However, as recently shown by Schönberner and co-workers, the evolutionary scenario provides an equivalent, if not better, explanation.

Kandemir: There seems to be some uncertainty about the use of the term "envelope", e.g. where it starts — do some astronomers avoid using the term "envelope" and prefer "shell"?

Ivezić: We find that r_2/r_1 must be at least 700. Whether to call this an "envelope" or a "shell" seems to be more semantics than a real physical problem.

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