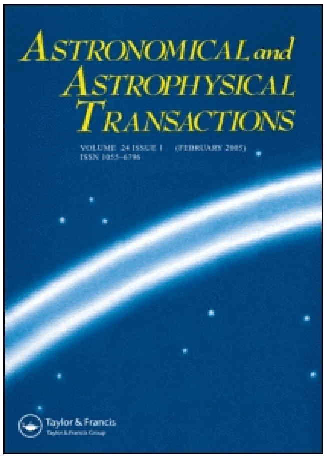

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 July 1995
To cite this Article: Bogdanov, M. B. (1995) 'Brightness distributions for models of circumstellar dust shells of cool carbon stars', Astronomical & Astrophysical Transactions, 8:1, 23 - 29
To link to this article: DOI: 10.1080/10556799508203293
URL: http://dx.doi.org/10.1080/10556799508203293

Astronomical and Astrophysical Transactions, 1995,
Vol. 8, pp. 23–29
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BRIGHTNESS DISTRIBUTIONS FOR MODELS OF CIRCUMSTELLAR DUST SHELLS OF COOL CARBON STARS

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(Received April 20, 1994)

Emergent intensity profiles and strip brightness distributions in near infrared are calculated for a grid of models of a cool carbon star, surrounded by an envelope containing amorphous carbon dust particles. It is shown that an optically thin dust shell of a carbon star can be observed as a bright annulus with a sharp maximum of intensity. Radius of this annulus is equal to the inner shell radius and determines a boundary of the dust condensation region. Such a hot dust shell can be detected using modern high spatial resolution methods if its optical thickness in near infrared exceeds approximately 0.05 and resolution limit is below the stellar radius.

KEY WORDS **Carbon stars, dust shells, brightness distributions**

1 INTRODUCTION

Many cool carbon stars emit more radiation in the infrared than would be expected from a simple extrapolation of the observed optical flux. These infrared excesses have generally been attributed to thermal emission from hot dust particles in circumstellar shells (Bergeat *et al.*, 1976a, 1976b). Observational knowledge and analysis of physical parameters of the circumstellar dust shells of cool carbon stars is of prime importance for the understanding of their evolution and basic processes such as dust formation, wind origin and mass loss.

The most commonly available observational data are photometric measurements in the visible and infrared. However a unique determination of the structure of a dust shell from spectrophotometric data alone is very difficult. The observed flux from a circumstellar dust shell depends on many unknown parameters: the nature of the grain material, particle size, dust density distribution, effective temperature of a central star and equilibrium grain temperature.

One approach to study these shells is to compare observational spectrophotometric data with spectra for a grid of computed models in which input parameters are systematically varied. Several models of dust shells of carbon stars were discussed by many authors using various assumptions on the shell parameters and different methods in solving the radiative transfer problem. These models addressed mainly spectral properties of the emergent radiation. They range from simple models (Bergeat *et al.*, 1976b) to more elaborate ones based on a self-consistent solution of radiative transfer equations in spherical geometry for the general nongray case (e.g. Jones and Merrill, 1976; Lefevre *et al.*, 1982). Graphite was been regarded as a grain material for all these models.

The exact form of carbon in circumstellar dust shells of carbon stars is still unclear. The evidence is against graphite, however (Draine, 1984; Martin and Rogers, 1987). Conditions in which grains form in the atmosphere of red giants, along with the extensive damage to which grains are subjected during their growth, appears to point to amorphous carbon as the favored form. The first attempt to consider amorphous carbon as the grain material was undertaken by Rowan-Robinson and Harris (1983).

An alternative approach to investigation of the dust shells of carbon stars is observations with high spatial resolution in the infrared including the speckle interferometric techniques, modern versions of the Michelson interferometer and lunar occultation method. Such an approach was used by many authors for IRC+10216 and some other objects (e.g. Ridgway and Keady, 1988; Bloemhof *et al.*, 1988). The presence of an optically thin circumstellar shell has been recently discovered for the carbon star T Cnc from an analysis of lunar occultation data (Bogdanov and Cherepashchuk, 1993). The high spatial resolution observations complete the spectrophotometric data very well and their application to study of circumstellar shells allow to reduce the number of the unknown parameters.

The purpose of the present paper is calculation of brightness distributions for models of optically thin dust shells of cool carbon stars using the new optical constants for amorphous carbon. These brightness distributions can be compared with results of high spatial resolution observations.

2 MODELS OF OPTICALLY THIN DUST SHELLS

We consider a grid of models of dust shells of cool carbon stars. These models consist of a central star emitting like a black body with effective temperature $T_e = 2800$ K and a uniform brightness distribution across the disk, surrounded by an envelope containing amorphous carbon dust particles. For amorphous carbon we used the new optical constants of Rouleau and Martin (1991) which represent a homogeneous data set ranging from far ultraviolet to 300 μm. The circumstellar dust shell was assumed to be optically thin for its thermal emission but not for the radiation of the central star. For dust particles considered the contribution of scattering in the infrared to the total extinction of radiation is negligible as compared to absorption.

The following model assumption were adopted:

The dust shell and the central star are both spherically symmetric. The stellar radius is r_0 and the shell has a sharp inner boundary at a radius r_1.

The dust is assumed to condense instantaneously at r_1 and all the dust grains are assumed to have the same radius $a = 0.05\ \mu$m. Thus $a \ll \lambda_e$, where λ_e is the effective wavelength of stellar radiation.

The flow is steady, thus the number density of the dust grains $n(r)$ is given by $n(r) = n_0(r_1/r)^2$, where n_0 is the number density at the inner boundary of the shell and r is the distance from the center of the system. For $r < r_1$, we put $n(r) = 0$.

Our numerical experiments show that results of the modeling are essentially independent of the outer shell radius r_2 provided $r_2/r_1 > 50$ and this value has been chosen for the outer boundary of the shell. It is evident that the shell optical thickness at each wavelength is proportional to $n_0 r_1$. Therefore, we can characterize the dust shell by the value of this product or of the shell optical thickness τ_0 at any wavelength. This reference wavelength was chosen as 2.20 μm.

Given a certain grain material, particle size and the number density of the dust, the equilibrium grain temperature is determined by the ratio of the inner shell radius to the stellar radius $\eta = r_1/r_0$. The conditions for the amorphous carbon condensation are not known very well and they depend on the radiation energy density at the inner boundary of the shell which is determined by value of η. Thus, free parameters of our grid of dust shell models are τ_0 and η.

When optical thickness of the dust shell is small enough, a self-consistent solution of radiative equilibrium and radiative transfer equations in spherical geometry can be obtained relatively easily for our nongray case (Shulman, 1975). The distribution of equilibrium grain temperature $T(r)$ inside the dust shell is obtained from solution of the thermal balance nonlinear integral equation.

$$\begin{aligned} 2\int_0^\infty \sigma_a(\lambda) B_\lambda(T)\,d\lambda &= \int_0^\infty \sigma_a(\lambda) B_\lambda(T_e)\,d\lambda \\ &\times \int_{f(r,r_0)}^{1} \exp\left[-\int_{r_1}^{r} \alpha_\lambda(x) f(x, r\sqrt{1-y^2})\,dx\right] dy, \end{aligned} \tag{1}$$

where $f(r, r_0) = r/\sqrt{r^2 - r_0^2}$, $B_\lambda(T)$ is Planck's function, $\alpha_\lambda(r) = (\sigma_s + \sigma_a)n(r)$, σ_s and σ_a are cross-section of scattering and the absorption for amorphous carbon dust particles. In our case Rayleigh's approximation is valid for these cross section. The solution of integral equation (1) is obtained iteratively using Newton's method.

The intensity of radiation from the stellar disk $I^\circ_\lambda(p)$ is given by

$$I^\circ_\lambda(p) = B_\lambda(T_e) \exp\left[-\int_{r_1}^{\infty} \alpha_\lambda(r)\, f(r,p)\,dr\right] \tag{2}$$

for the values of impact parameter $0 \le p \le r_0$ and $I^\circ_\lambda(p) = 0$ otherwise. For amorphous carbon dust particles, $\sigma_a \gg \sigma_s$ in infrared. Therefore, the source function practically coincides with the Planck function inside the dust shell of a carbon star.

In this case intensity $I_\lambda(p)$ emerging from the dust shell at impact parameter p for the given value of wavelength λ is

$$I_\lambda(p) = \int_{r_1}^{\infty} \alpha_\lambda(r)\, f(r,p)\, B_\lambda(T)\, dr \quad \text{for} \quad 0 \le p \le r_0, \tag{3}$$

$$I_\lambda(p) = \int_{r_1}^{\infty} 2\alpha_\lambda(r)\, f(r,p)\, B_\lambda(T)\, dr \quad \text{for} \quad r_0 \le p \le r_1, \tag{4}$$

$$I_\lambda(p) = \int_{p}^{\infty} 2\alpha_\lambda(r)\, f(r,p)\, B_\lambda(T)\, dr \quad \text{for} \quad p \ge r_1. \tag{5}$$

The total intensity $I_\lambda^W(p)$ is a sum of intensities emerging from the stellar disk and from the dust shell:

$$I_\lambda^W(p) = I_\lambda^\circ(p) + I_\lambda(p). \tag{6}$$

Equations (2) and (3)–(5) were solved numerically for the temperature distribution $T(r)$ obtained. The accuracy of intensity calculation was 0.1 percent.

A more complete description of numerical methods, computer programs and results on the spectral dependence of the emergent radiation flux will be published elsewhere. Here we consider only brightness distribution for the dust shell models and the possibility of observations of these shells with high spatial resolution.

3 BRIGHTNESS DISTRIBUTIONS

It is obvious that intensity $I_\lambda(p)$, emerging from the circumstellar shell gives the observed shell brightness at impact parameter p. Twelve models of dust shells were calculated for the values of free parameters $\tau_0 = 0.01$, 0.1, 0.3, 0.5 and $\eta = 2$, 3, 6. In this case, dust particles are hot enough near the inner boundary of the shell. For the values of η considered the temperature of grains at the inner boundary of the shell is accordingly 1654, 1402 and 1066 K.

The calculated intensity profiles $I_\lambda(p)$ for wavelength 2.20 μm and $\tau_0 = 0.1$, 0.3, 0.5 are shown in Figure 1. For the sake of simplicity, stellar intensity profiles are omitted in Figure 1. It is evident that an optically thin dust shell of a cool carbon star can be observed in near infrared as a bright annulus which is found exactly at the inner boundary of the shell corresponding to very sharp maximum of intensity for small values of η. The observed brightness of the stellar disk depends only on τ_0 but not on η. The ratio of the brightness at center of the stellar disk to the maximum value of shell intensity for $\eta = 2$ and $\tau_0 = 0.01$, 0.1, 0.3, 0.5 is 340.0, 32.2, 9.5 and 5.0 respectively. Thus, the contrast of the shell relative to the stellar disk rapidly increases when its optical thickness decreases.

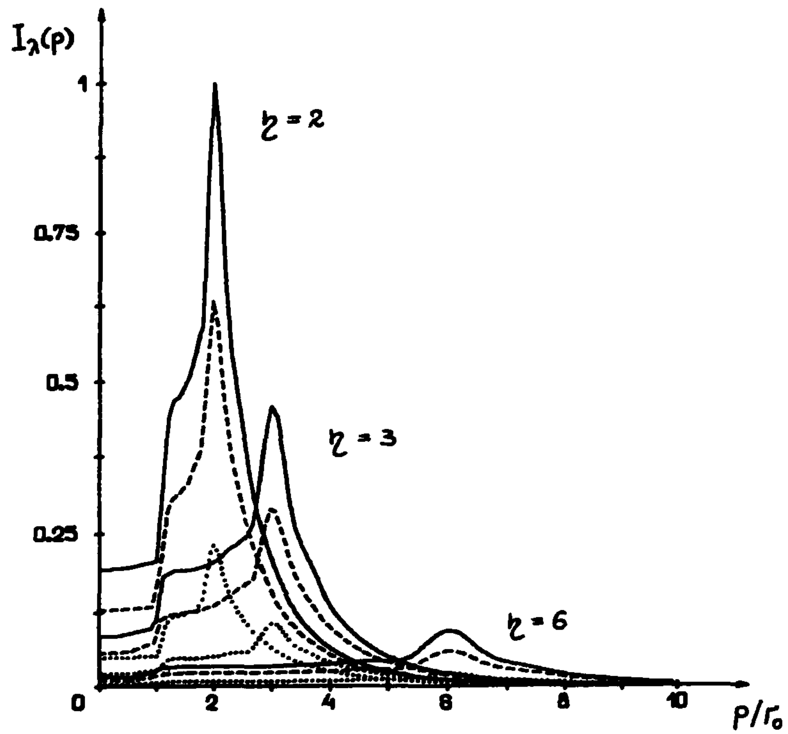

Figure 1

The majority of high spatial resolution methods give information only on the strip brightness distribution, $B_\lambda(x)$, across an observed object. This distribution can be obtained when the object is scanned with an infinitely narrow split in direction of some given axis x. Under axial symmetry, $B_\lambda(x)$ is independent of the direction of the x-axis and is connected with intensity $I_\lambda(p)$ via Abel's integral equation:

$$B_\lambda(x) = \int_x^\infty 2f(p,x) I_\lambda(p)\, dp. \tag{7}$$

In particular, for a star with uniform brightness distribution across the disk, $I_\lambda(p) = I_\lambda^\circ$, equation (7) implies

$$B_\lambda(x) = 2I_\lambda^\circ \sqrt{r^2 - x^2}, \tag{8}$$

where r is the angular radius of the star and x is the angular distance from the center of the stellar disk.

Strip brightness distributions $B_\lambda(x)$ were calculated for our intensity profiles $I_\lambda(p)$ from Figure 1 in order to compare them with observational data. These

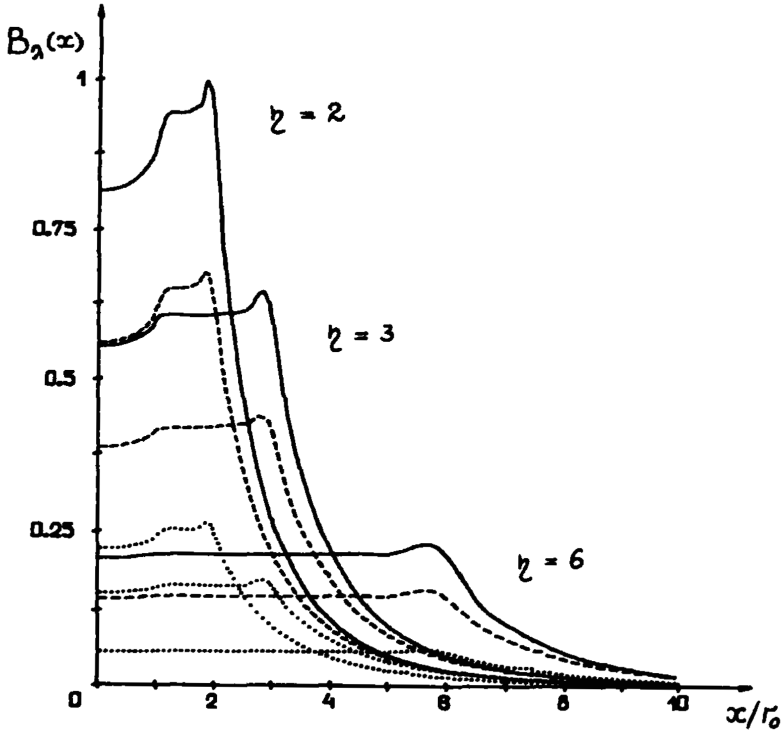

Figure 2

results are given in Figure 2 where strip brightness distributions across the disk of the central star are also omitted. It is clear from Figure 2 that the maximum of $B_\lambda(x)$ is also found exactly at the inner boundary of the shell. However the shape of the maximum is noticeably smoother. In the case of large η the strip brightness distribution in the central region has the form of plateau and the position of a maximum of $B_\lambda(x)$ cannot be determined with confidence.

Dynamical range of modern high spatial resolution methods is within a few tens. Therefore, detection limit for a hot dust shell of a cool carbon star in near infrared is approximately equal to 0.05 in terms of the optical thickness. Spatial resolution must then be better than the stellar radius.

4 CONCLUSION

We have calculated brightness distributions for models of compact optically thin shells containing amorphous carbon dust particles. The following conclusions can be drawn.

An optically thin dust shell of a carbon star can be observed in near infrared as a bright annulus with a sharp maximum of intensity.

Observations of cool carbon stars using high spatial resolution methods allow to determine important parameters of their dust shells, including the inner radius of the shell, which determines the boundary of the dust condensation region and can be found easy from analysis of intensity profiles $I_\lambda(p)$ or the strip brightness distributions $B_\lambda(x)$. Using modern high spatial resolution methods, a hot dust shell can be detected in near infrared if its optical thickness exceeds 0.05 and resolution is better than the stellar radius.

The derived brightness distributions can be also used for the comparison with observational data for cool carbon stars.

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