

# The past and present infrared spectrum of BD+30°3639

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**Summary.** We present a radiative-transfer calculation which reproduces the infrared spectrum of the planetary nebula BD+30°3639, fitting both the spectral energy distribution and the spatial extent at infrared wavelengths. We obtain an acceptable fit to most of the spectrum, including the infrared bands. The fit requires a distance of  $\geq 2$  kpc, which implies that BD+30°3639 has evolved from a massive progenitor of several solar masses. Two surprising results are (1) a very low dust-to-gas ratio, (2) an absence of the smallest PAH molecules. Extrapolating back in time, we calculate the previous infrared evolution of BD+30°3639.

## 1. Introduction

BD+30°3639 is one of the best studied planetary nebulae (PN) in the infrared. We have used a recently developed dust model, which incorporates all the important dust components in the interstellar medium, to fit its infrared spectrum. Such calculations allow us to study the dust composition in PN, which significantly differs from that in the interstellar medium. Also, we can extrapolate the model back in time to study how the infrared spectrum may have evolved after the end of the mass loss. We have to solve two basic problems: i) The objects are highly embedded in an optically thick dusty envelope and the equation of radiative transfer has to be properly handled. ii) A more or less realistic description of the nature of interstellar dust particles is required as well.

In this paper we will first present the dust model. We then fit the spectral energy distribution of the carbon-rich PN BD+30°3639. The calculated spectra at several stages of the preceding post-AGB evolution are presented in Section 4.

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## 2. The dust model

The dust model used in the present calculations is that of Siebenmorgen & Krügel (1992, henceforth SK). The dust model is governed by a grain size distribution ( $n(a) \propto a^{-q}$ ) with radii between approximately  $2500\text{\AA}$  down to molecular sizes of about  $5\text{\AA}$  ( $\sim 25$  atoms) in which we distinguish three different populations of dust particles:

i) Large particles with sizes  $a \geq 100\text{\AA}$ ,  $q = 3.5$ , causing the far-infrared and sub-millimetre emission. These particles have sufficient large heat capacities that we can neglect the quantum-statistical behaviour of photon-grain interactions. We have used the optical constants for amorphous carbon.

ii) Small graphite grains with sizes  $10\text{\AA} \leq a < 100\text{\AA}$ ,  $q = 4$ , emitting predominately in the mid-infrared. These particles show temperature fluctuations after individual energy absorption events (e.g. with photons, electrons); to calculate their emission spectrum one has to consider multi-photon events.

iii) Small PAHs ( $\sim 25$  atoms) and larger PAH clusters ( $\sim 250$  atoms), which are the probable carriers of the family of emission features between  $3-14\mu\text{m}$  (e.g. Allamandola et al. 1989a). The ratios of the various bands is determined by the hydrogen-to-carbon atom ratio and by the size distribution of these molecules.

The solution of the radiative transfer problem including scattering for spherically symmetric dusty objects containing quantum-heated particles is described in Siebenmorgen et al. (1992). The heating source is described as a blackbody with an adopted stellar temperature  $T_*$  and bolometric luminosity. The density distribution is defined here by means of power laws  $n(r) \propto r^\beta$ .

## 3. The infrared spectrum of BD +30°3639

Our fit is shown in Figure 1. The data points are a literature compilation; the lower panel shows new data of Schutte and Tielens (1993). We have used a distance of 2 kpc, which is the smallest distance for which we were able to obtain a satisfactory fit of the infrared spectrum. Hajian and Terzian (1993), from a measurement of the radio expansion, find a distance of  $2.68 \pm 0.81$  kpc. The density structure is modelled as an inner region of uniform density around a central cavity, surrounded by a larger region where the density falls as  $r^{-2}$ . We assume that the dust composition does not depend on position in the nebula.

The fit is accurate over most of the spectrum to within  $\leq 20\%$ , although one should take in consideration the simple density model used and the uncertainties in the optical constants of the dust properties. The observations become noisier near  $5\mu\text{m}$ , which presents a problem in where to define the continuum level. The PAH features at  $7.7$  and  $8.6\mu\text{m}$  are not well fitted. For the latter, the SK model consistently predict values too low by about a factor  $\leq 3$  and it is likely that the cross section used for this feature is too low. The feature at  $7.0\mu\text{m}$ , which is not fitted, is due to an [ArII] line. The last two data points have a large contribution from free-free emission. The measured stellar flux at K ( $0.09\text{Jy}$ ) agrees very well with the model prediction ( $0.1\text{Jy}$ ).

Radial profiles at several wavelengths have been published by Hora et al. (1993). Our calculations reproduce these well. However, we find that the predicted radial flux

distribution is almost constant between 3 and  $15\mu\text{m}$ , whereas Hora et al. find that the PAH features are slightly more extended than the  $10\mu\text{m}$  continuum. This could be due to the destruction of PAHs in the ionized region by  $\text{Ly}\alpha$  emission.

We find a dust-to-gas ratio of  $3.5 \times 10^{-3}$ , confirming earlier findings, e.g. Hoare et al. (1993). This is a surprisingly low ratio, well below the generic value for the interstellar medium. PN such as BD+30°3639 do not appear to enrich the ISM with dust.

The PAH emission is completely dominated by the largest PAH component, the cluster molecules. The contribution from the small PAHs is almost negligible. The band ratios of BD+30°3639 yield a low H/C ratio of the PAH clusters. The  $11.3\mu\text{m}$  feature can also be identified with SiC (e.g. Hoare et al. 1992). We failed to reproduce the spectrum assuming that the  $11.3\mu\text{m}$  feature is completely due to SiC, and conclude that the SiC contribution is likely  $< 50\%$ .

We predict a significant extinction towards the central star, caused by the dust inside the nebula:  $A_V = 0.43$ . The assumption that the extinction towards the star and the nebula are equal does not appear to be validated for BD+30°3639.

The model predicts a stellar luminosity of  $1.3 \times 10^4 L_\odot$ . We have used the lowest acceptable distance, and therefore this should be taken as a lower limit. The luminosity–core mass relation (e.g. Boothroyd and Sackman 1988) implies a corresponding core mass of 0.7–0.75  $M_\odot$ . Of the well-known galactic PN, only NGC 7027 and NGC 6369 are known to have such high luminosities (Gathier and Pottasch 1989), where it should be noted that NGC 7027 appears to have entered the cooling track in the HR diagram, and therefore will have had a higher luminosity in the past. The total nebular mass in our fit is about 2.5  $M_\odot$ . This value is poorly determined, however it clearly also implies a massive progenitor of several solar masses, which has shed a large amount of mass. From the inner radius of the nebula, and using the known expansion velocity, we derive an age of the nebula of around 600 yr, measured from the end of the mass-loss phase. This short transition time also implies a high-mass star.

#### 4. The infrared evolution of BD+30°3639

The density distribution used in the final fit allows one to calculate the preceding infrared evolution of BD +30°3639. In calculating the progenitor evolution we have made a number of simplifying assumptions. First, the entire nebula was represented only by the  $1/r^{-2}$  dust density component. We extended the wind-like component of the fit inward, keeping the total nebular mass constant. Second, we calculated the age of BD+30°3639 from the adjusted inner radius and the observed expansion velocity of  $22 \text{ km s}^{-1}$ . Third, we assumed that the mass loss terminated at a stellar temperature of 5000 K, and that the stellar temperature has increased linearly during the post-AGB evolution. The first step of the evolutionary sequence is calculated when the inner radius reaches  $10^{15} \text{ cm}$ , approximately ten years after the mass loss ends. In this way we avoid the problem at what distance from the star the dust particles form.

Figure 2 shows six evolutionary steps. The first step exhibits a steep cut-off around  $2.5\mu\text{m}$ , caused by the high optical depth in the circumstellar envelope. At this phase

the visual extinction will drop quickly, and the star will become visible at near-infrared wavelengths within 25 yr. Optical visibility follows after  $\sim 100$  yr. The submillimetre continuum slowly increases with time, caused by the fact that the dust temperature in the outer regions of the cloud increases as the optical depth towards the star goes down. The PAH features develop quickly when the star is still relatively cool, and reach full strength around 15000 K.

Figure 3 presents the evolution of the IRAS colours in the post-mass-loss phase. The colours evolve significantly during the first 500yr, after which the evolution slows down. At that stage the colours are already close to the colours exhibited by planetary nebulae. Thus, this implies that slowly-evolving transition objects will have colours close to those of PN. Surveys which concentrated on objects with colours more similar to AGB stars will have been biased in favour of young post-AGB objects.

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## Figure Captions

**Figure 1:** a) The spectral energy distribution of BD+30°3639. Observations are shown by squares, the model with amorphous carbon grains for the large-grain component is depicted by a solid line. b) High-resolution spectrum between 3 and 14 $\mu$ m. Observations shown are from Schutte and Tielens (1993).

**Figure 2:** The infrared time evolution between 0.1 and 1000 $\mu$ m of BD +30°3639. The first evolutionary sequence is calculated 13 years after the mass loss ends.

**Figure 3:** The calculated evolution of the IRAS colours. The open circles are IRAS data of planetary nebulae.

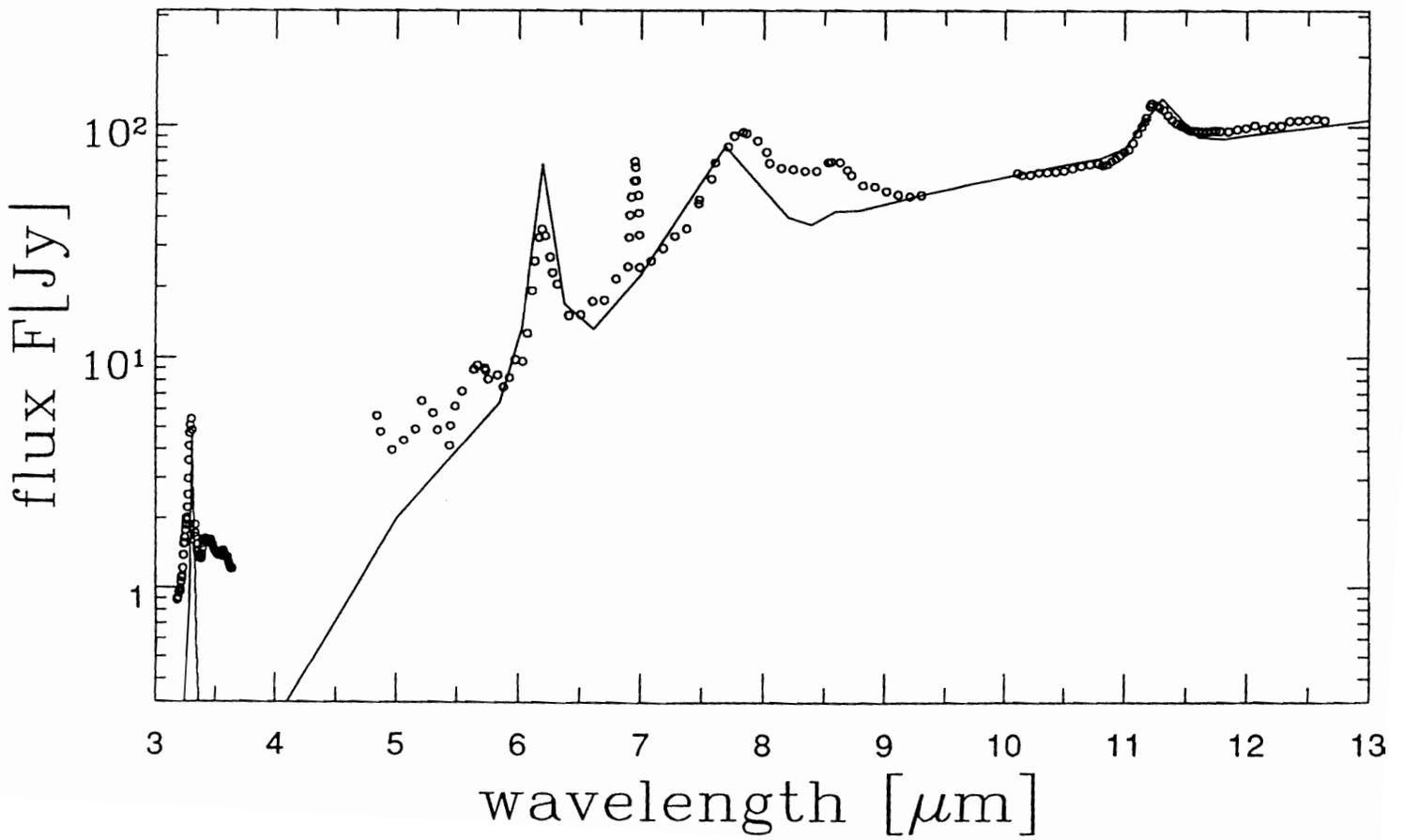
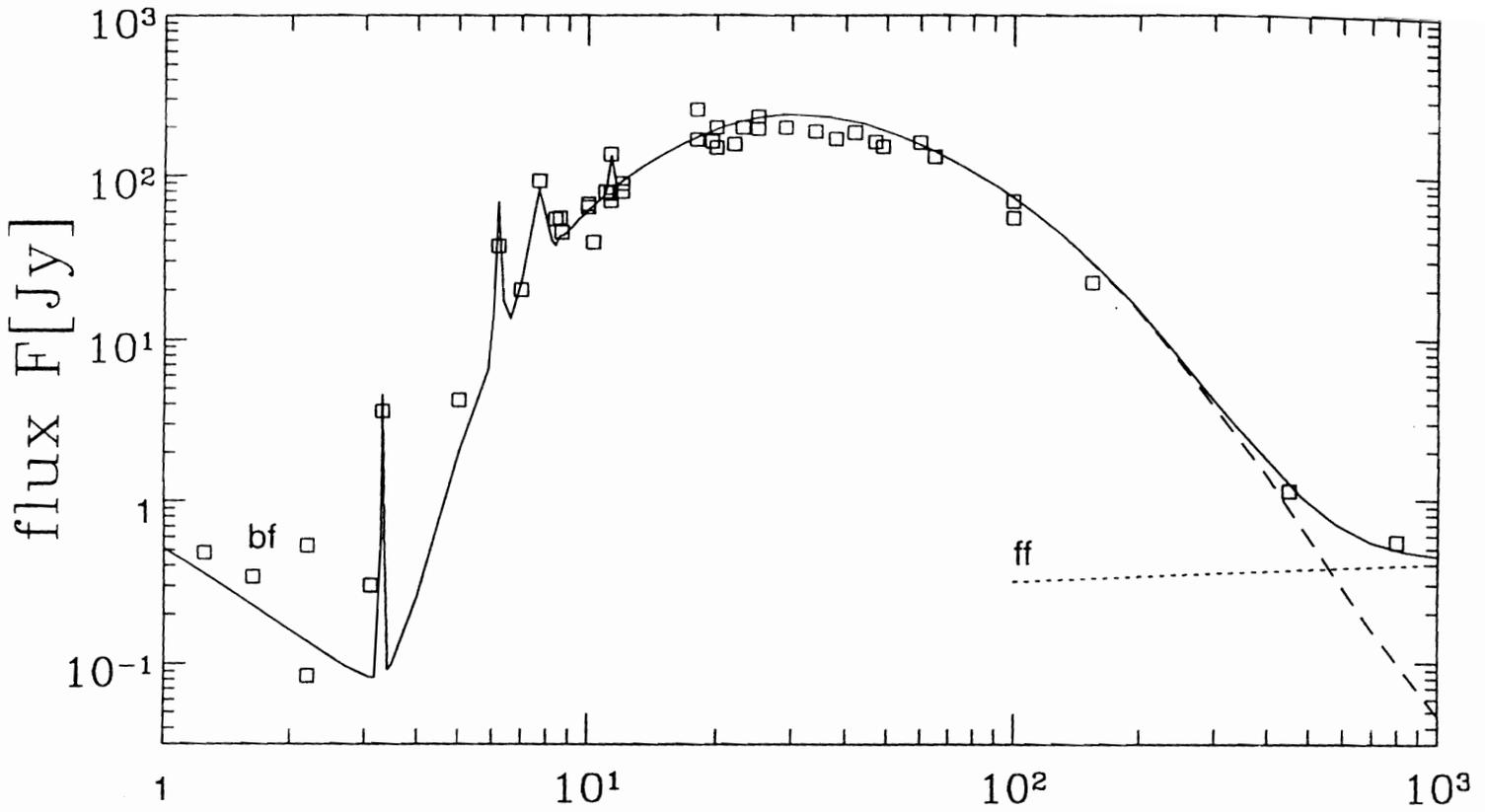


fig. 2

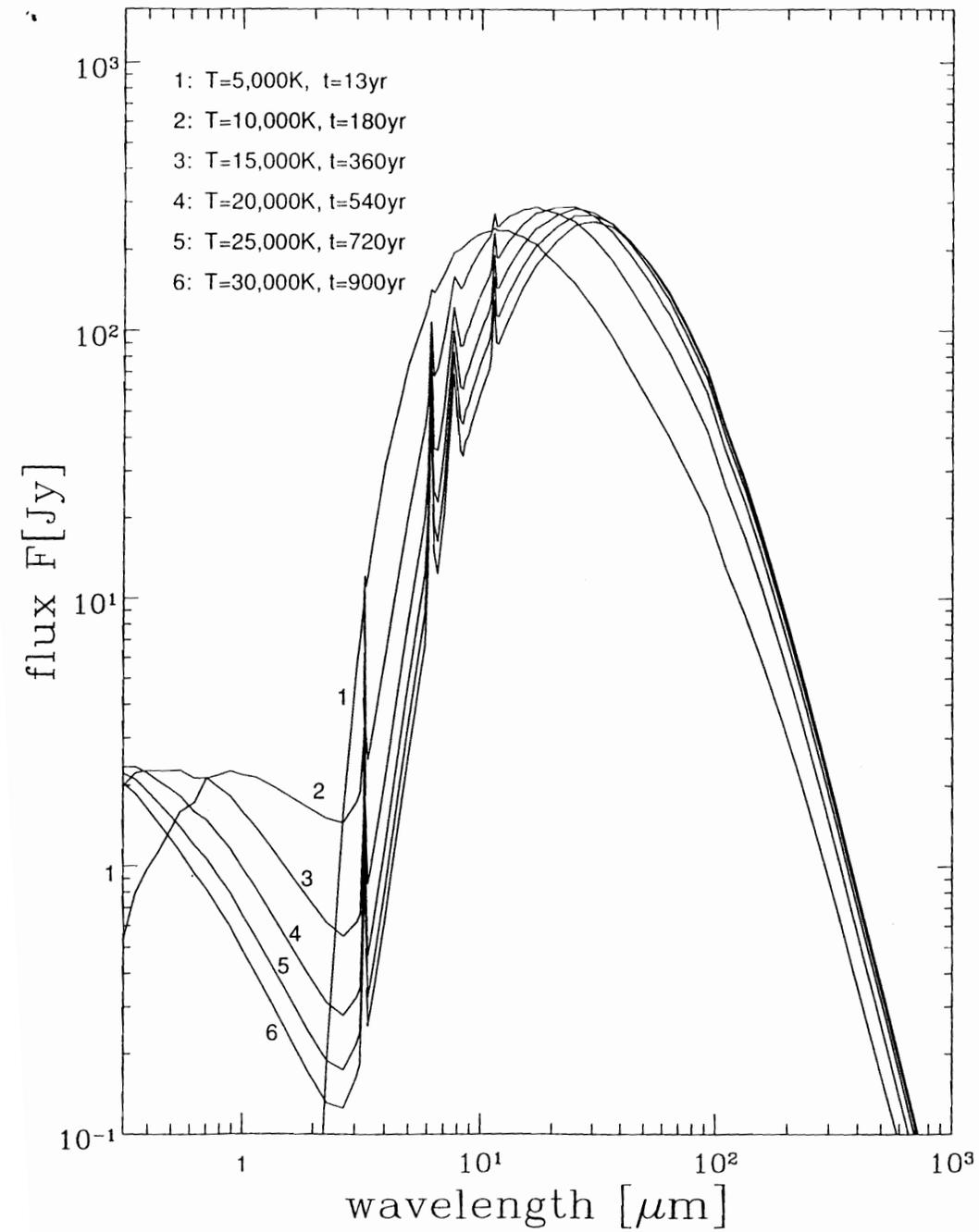


fig. 3

