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The transfer of radiation in galactic nuclei. Dusty hot spots in the starburst galaxy M 82

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Abstract. We compute the equations of radiative transfer for the nucleus of a galaxy assuming that the dust is heated by stars. The stars are distributed over a wide volume of the nucleus. It is an important aspect of our model that dust temperatures vary not only on a galactic scale, but change also locally in the hot spots around luminous OB stars. Because of the often copious UV radiation field in a galactic nucleus and observational evidence in starburst galaxies we also consider in our model the presence of small grains and polycyclic aromatic hydrocarbons (PAHs) which both undergo temperature fluctuations and therefore strongly influence the near and mid IR part of the spectrum. We demonstrate the deficiency of those approximations which neglect either the hot spots or the emission by small grains or treat the stars as a point source located in the center of the galactic nucleus. Our method is applied to the starburst galaxy M 82. The overall spectrum, including PAH feautres is fitted as well as the observed source sizes between near IR to millimetre wavelengths.

Key words: galaxies: individual: M 82 – ISM: dust – radioactive transfer – galaxies: ISM – galaxies: nuclei – infrared: galaxies

1. Introduction

Galactic nuclei, including the center of the Milky Way, are a most interesting class of objects as they are the site of diverse kinds of activity generally accompanied by large IR luminosities. The source of the activity may be rapid star formation or an accreting black hole (Harwitt & Pacini 1975; Harwitt et al. 1987; Cameron et al. 1993). In either case, the primary emission is hard and it is converted into infrared (IR) wavelengths by dust. In this paper we consider stars as the source of energy. Because of the obscuration, optical and ultraviolet (UV) observations are often prohibited and where they can be performed they usually refer only to a small fraction of the luminosity that leaks out through a clumpy medium.

A quantitative understanding of the activity and infrared spectrum of galactic nuclei requires therefore a model for the IR radiation: One must describe the properties and space density of the stars, specify the parameters of the grains and their distribution and solve in some approximation the radiative transfer in a dusty medium. All this is done in the same spirit as the analysis of IR spectra from star forming regions (e.g. Leung 1976; Finn & Simon 1977: Haisch 1979; Flannery et al. 1980; Chini et al. 1986; Wolfire & Churchwell 1987; Aannestad & Emery 1989; Churchwell et al. 1990; Hoare et al. 1991; Efstathiou & Rowan-Robinson 1990; Spagna et al. 1991; Collison & Fix 1991; Lis & Leung 1991; Pier & Krolik 1992). However, the radiative transfer is complicated by the fact that the stars are not a central point source, are distributed over the volume of the nucleus. The problem is thus intrinsically three–dimensional.

As the more luminous stars of type OB have a hard spectrum they will lead to temperature fluctuations in very small grains, whose heat capacity is of the same order as the energy of the photons. Such fluctuations require a special treatment (e.g. Duley 1973; Greenberg & Hong 1974; Purcell 1976; Aannestad & Kenyon 1979; Draine& Anderson 1985; Désert et al. 1986; Dwek 1986; Guharthakurta & Draine 1989; Siebenmorgen et al. 1992). How grains with temperature fluctuations can dominate the near and mid IR part of the spectrum is well known for galactic as well as extra galactic sources (Aitken 1981; Sellgren et al. 1985; Boulanger 1988; Désert et al. 1990; Siebenmorgen & Krügel 1992; henceforth SK). Therefore their presence should be included in any model that aims at a more than qualitative fit to the observations. Of particular interest are the PAHs (polycyclic aromatic hydrocarbons; Léger & Puget 1984; Allamondola et al. 1989; Puget & Léger 1989) which account for a number of well studied resonances between 3 to $14\mu m$.

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2. Radiative transfer in a galactic nucleus

2.1. Hot spots

Dust temperatures in a spherical galactic nucleus do not only vary on a large scale with galactic radius r, but change also locally with the distance to the nearest star. A grain located between the stars, but not in the immediate vicinity of any of them, attains a temperature $T(r)$ determined by the mean interstellar radiation field $J_\nu^{\rm ISRF}(r)$. Another grain at the same galactic distance, but closer to a star, will be hotter. Therefore the configuration is on a small scale not spherically symmetric. The surroundings of a star constitute a dusty hot spot (HS) in the interstellar medium and the presence of such hot spots may significantly change the emission of the galactic nucleus. It should therefore be taken into account in some approximate way.

One such way was presented in an attempt to model the emission from the Galactic Center (Krügel & Tutukov 1978). The hot spots, which were then called "zones of influence", were assumed to be of spherical shape and their volume was defined by the condition that outside the dust is mainly heated by the ISRF, whereas inside heating by the nearest star dominates. This definition leads for grains of various diameter and chemistry to different sizes of the hot spot. To simplify matters, we apply in the following the size definition of the hot spot to the whole mixture of grains so that at any given galactic distance all hot spots have the same radius. There are two basic situations:

2.1.1. Population II stars

The galactic nucleus contains very many stars. For example, the Galactic Center has about 10^9 population II stars. The contribution of the hot spots to the overall spectrum is then small. To see this consider a galactic nucleus with fixed integrated luminosiy containing N stars each of luminosity L and uniform spectral type so that $N \cdot L$ = const. Because the mean intensity of the radiation field $J^{\rm ISRF}$ in the galactic nucleus is to first order independent of N we find, in view of the definition for the radius of the hot spot R^{HS} that $R^{HS} \propto L^{1/2} \propto N^{-1/2}$ and so the combined volume of all hot spots $(N \cdot (R^{\rm HS})^3)$ decreases as $N^{-1/2}$. Therefore a population of very numerous stars may be smeared out smoothly over the galactic nucleus and the structure of the hot spots need not be evaluated. One only has to introduce into the source function a smoothly varying term for the stellar emission:

$$\Gamma_\nu^{\rm G}(r) = n^{\rm G}(r) \cdot L_\nu^{\rm G} \tag{1}$$

where $\Gamma_\nu(r)$ is in units erg $\cdot$ s^{-1}cm^{-3}Hz^{-1}ster^{-1}. The luminosity of a single star at frequency ν is denoted by $L_\nu^{\rm G}$ and the stellar volume density within the nucleus by $n^{\rm G}(r)$. Let the stars be black bodies of temperature $T_*^{\rm G}$ so that $L_\nu^{\rm G} \propto B_\nu(T_*^{\rm G})$. As the luminosity of the very numerous stars comes mainly from giants we put $T_*^{\rm G}$ = 3000K. The luminosity $L_\nu^{\rm G}$ itself need not be specified, but only the product $\Gamma_\nu^{\rm G}(r) = n^{\rm G}(r) \cdot L_\nu^{\rm G}$ (Eq. 1).

2.1.2. Very luminous stars

The stars are not so numerous as, for instance, OB stars, of which there are rarely more than 10^6 in a galactic nucleus; their space density $n^{\rm OB}(r)$ is, compared to low mass stars, moderate, say 1 star per pc^3 or less. The total volume of the hot spots is now not neglegible and their emission must be evaluated explicitly, especially if the optical depth for stellar radiation within the hot spot is not very small. This is quite likely since OB stars are usually associated with some dust shell. Apart from solving the radiative transfer on a large scale in the galactic nucleus one must now also determine the emergent flux $L_\nu^{\rm HS}$ from the hot spots. This requires calculating for each galactic radial grid point the radiative transfer for a centrally heated spherical cloud.

The integral $\int L_\nu^{\rm HS} d\nu$ is, of course, equal to the luminosity $L^{\rm OB}$ of the embedded OB star. We assume $L^{\rm OB} = 10^4 {\rm L}_\odot$ and a stellar temperature $T_*^{\rm OB}$ = 20000K. Each hot spot is at its outer boundary illuminated by the ISRF. The radius $R^{\rm HS}$ of the hot spots is determined iteratively as it depends on the strength and spectral shape of the ISRF. The ISRF is governed by the space density of the giants and the OB stars and by the emission from the hot spots. The radius $R^{\rm HS}$ depends furthermore on $L^{\rm OB}$ and $T_*^{\rm OB}$ and the dust density distribution within the hot spot. For the latter we assume a constant value corresponding to a molecular hydrogen density $n^{\rm HS}({\rm H}_2) = 10^4{\rm cm}^{-3}$. This may or may not be typical for molecular clouds into which the OB stars are embedded and we vary this value in the calculations to determine its influence on the spectrum.

In the hot spots some of the stellar UV flux is converted by the dust into IR radiation. We thus replace the OB stars, having only hard radiation, by the hot spots which may have plenty of IR emission, depending on the optical depth within them, and introduce into the source function the term

$$\Gamma_\nu^{\rm HS}(r) = n^{\rm OB}(r) \cdot L_\nu^{\rm HS} \tag{2}$$

again in units ergs^{-1}cm^{-3}Hz^{-1}ster^{-1}

2.2. Mathematical formulation

We consider a spherical galactic nucleus with radial coordinate r and calculate the radiative transfer with a ray tracing method (Hummer & Rybicki 1971). Along lines of sight with different impact parameter we solve the equation

$$I(\tau) = I(0) \cdot e^{-\tau} + \int_0^\tau S(x) \cdot e^{-(\tau - x)} dx \tag{3}$$

for the intensity in positive and negative direction, I^+ and I^-. From I^+ and I^- one can readily deduce the mean intensity $J_\nu(r)$ and flux $H_\nu(r)$. As a boundary condition we assume that there is no outer radiation field. Equation (3) requires knowledge of the source function which is obtained iteratively. Details are given in Siebenmorgen et al. (1992) and Siebenmorgen (1993). There the radiative transfer was solved from a differential equation, but otherwise the formalism, especially the treatment of the emission of very small grains with temperature fluctuations, remains unchanged.

Because the galactic nucleus in our model consists of two phases, a medium interspersed with hot spots, Eq. (3) is not strictly correct. It gives, however, a good approximation if the volume fraction $\gamma(r)$ of the hot spots

$$\gamma(r) = \frac{4\pi}{3} \cdot n^{\mathrm{OB}}(r) \cdot (R^{\mathrm{HS}}(r))^3 \tag{4}$$

is small. The volume fration $\gamma(r)$ shrinks when $n^{\mathrm{OB}}(r)$ becomes large. For the space densities $n^{\mathrm{OB}}(r)$ of OB stars in our models $\gamma(r)$ is small, of order 10^{-3}, and so we may use Eq. (3). In a previous paper (Krügel & Tutukov 1978) we had introduced into the equation of radiative transfer a correction term: For the emission of the dust we had written $(1-\gamma(r)) \cdot \kappa^{\mathrm{abs}} \cdot B_\nu(T_d)$ (the absorption cross section is denoted by κ^{abs} and the dust temperature by T_d), instead of $\kappa^{\mathrm{abs}} \cdot B_\nu(T_d)$, to indicate that the emission comes only from the volume outside the hot spots. But this correction is small and irrelevant for our purposes.

In view of the presence of the stars and hot spots the source function S_ν is written as

$$S_\nu(r) = \frac{\Gamma_\nu^{\mathrm{HS}}(r) + \Gamma_\nu^{\mathrm{G}}(r) + \epsilon_\nu + J_\nu^{\mathrm{ISRF}}(r) \cdot \kappa_\nu^{\mathrm{sca}}}{\kappa_\nu^{\mathrm{ext}}} \tag{5}$$

where $\kappa_\nu^{\mathrm{sca}}$ and $\kappa_\nu^{\mathrm{ext}}$ are the scattering and extinction coefficient of the dust and ϵ_ν its emission given by

$$\epsilon_\nu = \kappa_\nu^{\mathrm{abs}} \int B_\nu(T) P(T) dT \tag{6}$$

The temperature distribution function is denoted by $P(T)$ and may for large grains be replaced by a δ – function at the equilibrium temperature T_{eq} of the grain: $P(T) = \delta(T_{\mathrm{eq}})$. Computational details are given in Siebenmorgen et al. (1992).

The emission $\Gamma_\nu^{HS}(r)$ from the hot spots is evaluated by solving the radiative transfer for a cloud centrally heated by an OB star. The relevant equation is the same as that for the galactic nucleus (Eq. 3) only the boundary conditions are different. At the center there is now the star and at its outer radius $R^{\mathrm{HS}}(r)$ the cloud is illuminated by the ISRF. We recall that $\Gamma_\nu^{HS}(r)$ is a function of the galactic radius r and it must therefore be computed at each corresponding grid point. Particular attention has to be given to grain destruction in the innermost part of the hot spots. The small grains are destroyed if they absorb several energetic photons within their cooling time (Désert & Dennefeld 1988). This process is incorporated in our code as outlined in Siebenmorgen (1993). For the large particles we adopt an inner boundary of 10^{15}cm, which amounts to a melting temperature of these grains between 1500 and 2000 K.

2.3. Computational aspects

To cover all IR resonances we use 115 frequency points. For the galactic nucleus we adopt 200 radial grid points, for the hot spots 50 to 80. The iteration procedure goes as follows: In the first cycle we disregard scattering, neglect all small grains with temperature fluctuations and smear out the OB stars in the same way as the giants, i.e. in the first cycle we do not calculate the hot spots explicitly. After having made an educated guess for the temperature distribution of the dust we solve Eq. (3) for the galactic nucleus and obtain a first determination of $J_\nu^{\mathrm{ISRF}}(r)$. This allows us to calculate the radii of the hot spots $R^{\mathrm{HS}}(r)$ and to improve the estimates for the temperature of the dust outside the hot spots. We start the second and all following cycles by calculating the emission from the hot spots ($\Gamma_\nu^{HS}(r)$) and include now in the source function also scattering and the emission of small grains. Each cycle gives updated values for the source function (Eq. 5). We need typpically 9 iterations.

A fine grid is required for the radiative transfer in the galactic nucleus, at least, in the volume where the OB stars are located. The increase in optical depth $\tau_{\mathrm{i,i-1}}(\lambda_{\mathrm{eff}})$ from one grid point i to the next $i-1$ at the effective wavelength (λ_{eff}), i.e. where most of the energy is carried, should be

$$\tau_{\mathrm{i,i-1}}(\lambda_{\mathrm{eff}}) \lesssim 0.2. \tag{7}$$

As the effective wavelength for OB stars lies in the UV, where the extinction curve is rising, one needs for an A_V of only 20 mag more than 100 grid points. Therefore at present it is difficult to treat large optical depths (say $A_V > 50$mag). This is also the reason why we took for the temperature of the OB stars a rather low value of 20000 K, instead of a more likely 35000 K (Duffy et al. 1987), which would have shifted the effective wavelength further into the UV.

3. Comparison of different methods

To demonstrate the importance of including in the calculations the hot spots as well as the small grains we present theoretical spectra for the emission from a dusty, spherical galactic nucleus in three ways of approximation:

a) The stars form a central point source.
b) The extension of the stellar cluster is taken into account. The emission of the stars is smeared out after Eq. (1), but the hot spots are not evaluated.
c) The hot spots are explicitly evaluated.

Models of type *a)* for whole galaxies are presented by Rowan-Robinson & Crawford (1989): At the basis is a starburst core, the emission of which is calculated via the formalism described by Rowan-Robinson (1980) for a cloud with a central point source. Rowan-Robinson & Crawford (1989) superimpose onto the flux from the starburst core a disk component and a Seyfert component of predefined spectral shape. A model of type *b)* is found in Siebenmorgen (1991). Type *c)* models with hot spots are introduced in Krügel & Tutokov (1978).

3.1. The influence of the hot spots on the spectrum

We ignore for the moment in all three cases the very small grains and the population II stars of which we know that they can be smeared out because of their high space density; instead we consider a nucleus filled only with OB stars. We pick parameters for the model in very rough agreement with the values for M 82. The cloud is at a distance $D = 3$Mpc and has a radius $R = 300$pc.

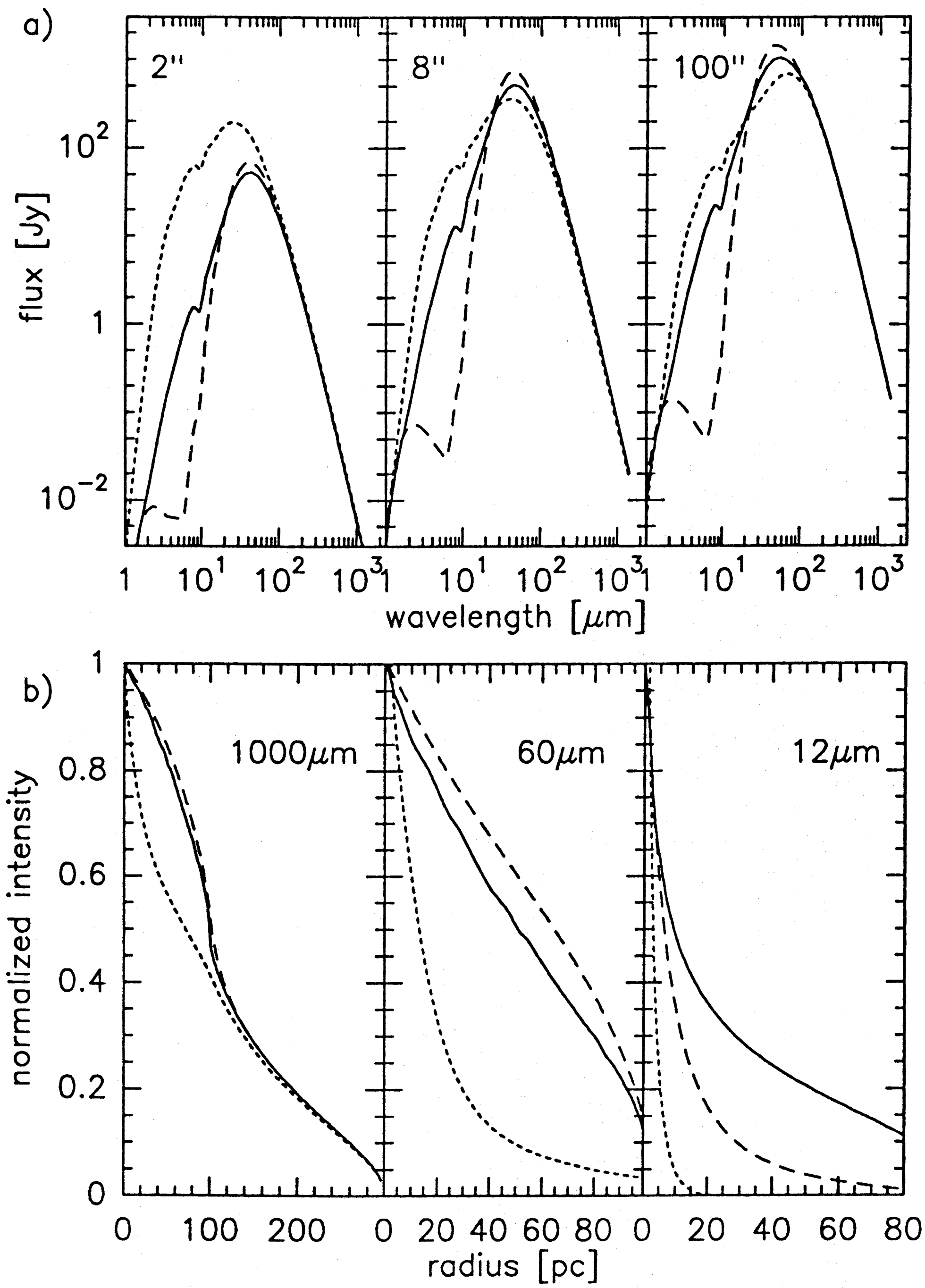

Fig. 1. a and b. Comparison between three methods to compute IR spectra in a galactic nucleus: stars form a central point source (dotted; case a) in Sect. 3), stars form an extended stellar cluster (dashed; case b)) and full treatment of hot spots (solid line;case c)). **a** The spectral energy distribution observed with three different apertures. The 2″ beam represents the peak position, the 8″ beam shows the emission within the stellar cluster and the 100″ beam gives the spectrum of the whole nucleus. **b** Scans across the source. Normalized intensities at 1000, 60, 12 μm observed with a pencil beam as a function of distance to the center. Note that the point source model is never applicable for fitting high spatial resolution data

The OB stars extend only to r = 100pc, i.e. the stellar cluster is enshrouded by a dust shell. The stars have a space density $n^{\rm OB}(r) \propto r^{-1}$ so that for $r <$ 100pc the integrated flux through a sphere of radius r increases with r^2. The total luminosity of all OB stars is $3 \cdot 10^{10}{\rm L}_\odot$. The dust density $\rho(r)$ is constant for $r \leq$ 100pc, i.e. within the stellar cluster, and falls off smoothly with r^{-1} for $r >$ 100pc. The total visual extinction from the edge of the cloud to its center equals A_V = 22.1mag and to the outer boundary of the stellar cluster 11.6mag.

Figure 1a shows the IR spectra for three different diaphragms Θ always directed towards the cloud center: 2″ represents just the peak position, 8″ shows the inner part of the stellar cluster and 100″ comprises the whole cloud. We note, first, that differences in the spectra show up only at wavelengths below 100μm. This is understandable because the submillimetre emission is determined by the mass of the dust in the beam and its temperature; the latter is more or less fixed by the total luminosity. Comparing the point source (case a) with the hot spots (case c), we see that for a large beam (Θ = 100″) the fluxes are not dramatically different, although at 8μm they may disagree by up to a factor of 3. However, with higher spatial resolution the

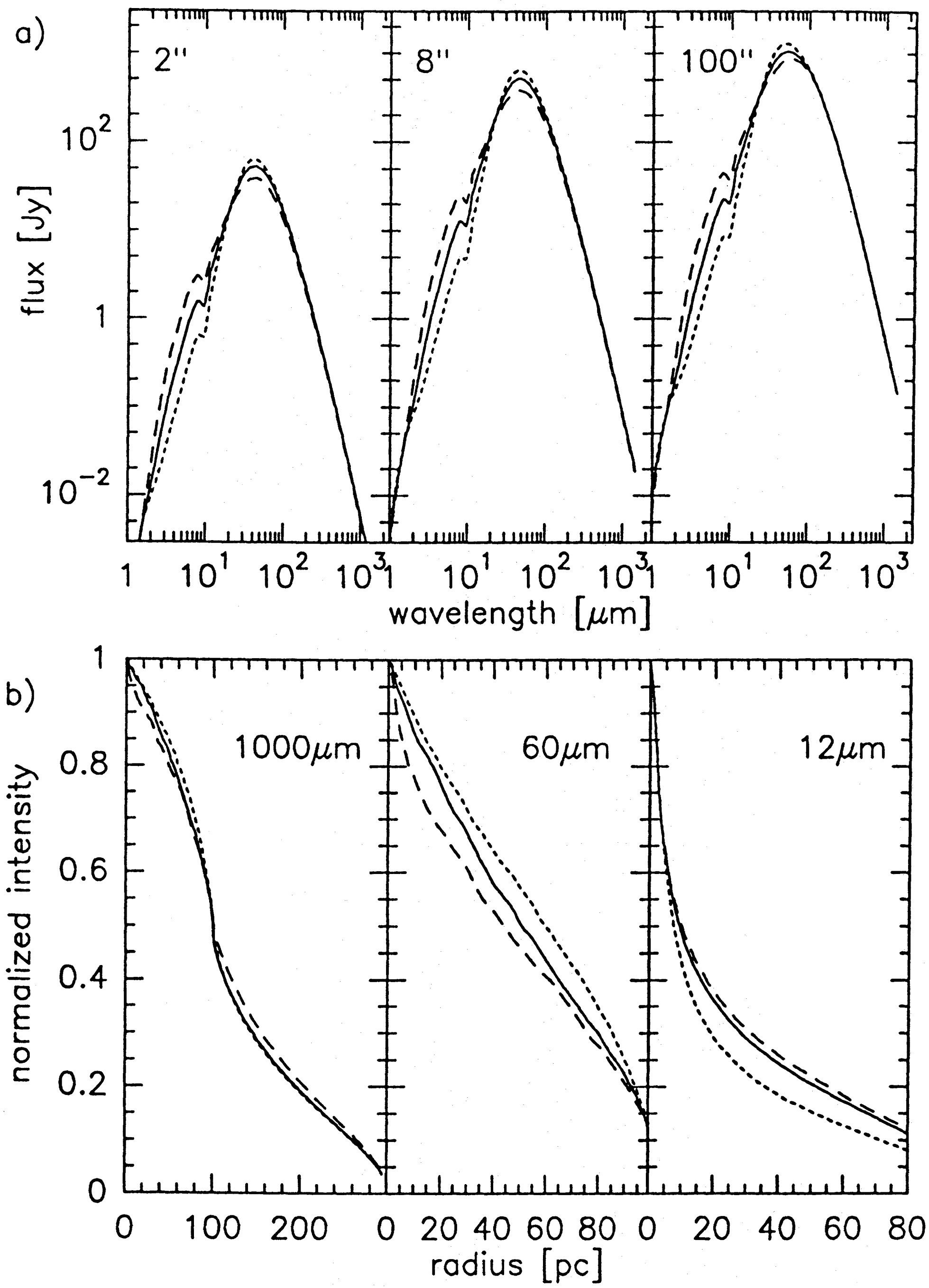

Fig. 2. Influence of the density in the hot spots on the spectrum and on cross scans ($n^{\rm HS}(H_2) = 3 \cdot 10^3 \rm cm^{-3}$, dotted; $10^4 \rm cm^{-3}$, full line and $3 \cdot 10^4 \rm cm^{-3}$, dashed). Higher dust densities in the hot spots lead to stronger mid IR emission. **a** The effect of beam size on the IR spectrum. **b** Normalized scans across the source with a pencil beam

discrepancy widens and may reach orders of magnitude: There is too much luminosity in a small beam in case of a point source.

Comparing next distributed stars without hot spots (case b) with the hot spot model (case c) we always find a large disparity for $\lambda \leq 20\mu m$. This is also easy to understand: As the hot spots are generally compact their emission is particularly strong in the mid IR. Ignoring them and smearing the OB stars out (case b) neglects this emission. For case b) the bump with the peak at $\approx 2\mu m$ represents the stellar cluster which shows up separetly from the dust emission through a dip in the spectrum at $6\mu m$. The bump is absent for the point source because extinction to the stars is now larger; nor is the bump seen in the model with the hot spots. In the latter two cases the dip at $10\mu m$ reflects the silicate feature.

Figure 1b shows for the same three models normalized scans across the source with a pencil beam at three wavelengths. Finite resolution would make the decline towards the cloud's edge less steep. As expected, in a point source model the size of the cloud at $12\mu m$, but also at $60\mu m$, is heavily underestimated because this model neglects the presence of hot stars out to radial diatances of 100pc. At $1000\mu m$ the point source model still gives somewhat weak fluxes towards the central region ($r <$

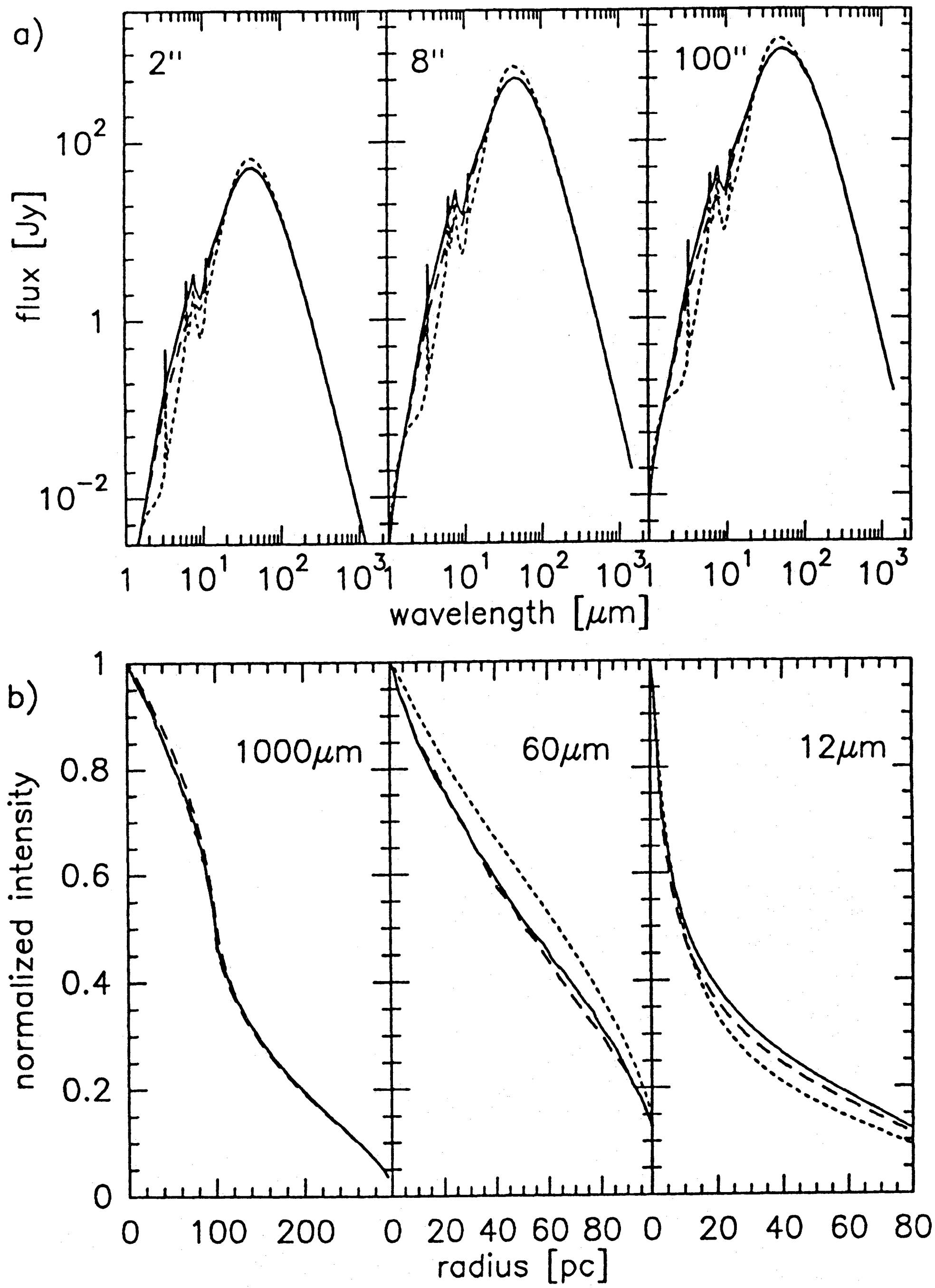

Fig. 3. a and b. Computation of the spectral energy distribution from a galactic nucleus in three approximations: First, with evaluation of hot spots, but without emission from small grains with temperature fluctuations (dashed); second, without hot spots (the stars are smeared out) but with small grains (dotted); third, with hot spots and with small grains (solid). The small grains (see also Section 4.2) consist of graphites of 10 Åradius and an abundance $Y_C^{sg} = 0.1$, the PAHs have $N_C^{PAH} = 80$ C-atoms, an abundance $Y_C^{PAH} = 0.1$ and a H/C ratio of 0.1. **a** The IR spectrum of the models with different diaphragms and **b** scans with a pencil beam at different wavelengths

100pc). The discrepancy seems now enhanced with respect to Fig. 1a because of the linear scale used in Fig. 1b. Comparing the hot spots with case b) we notice that the agreement is very good at 1000 μm, reasonable at 60 μm, but poor at 12 μm. At the latter wavelength the decline in surface brightness in the model with the hot spots is much weaker.

As far as the rather uncertain, although not arbitrary choice for the density in the hot spots is concerned its influence on the total spectrum is fortunately not dramatic, as Fig. 2 demonstrates. Nevertheless, it cannot be neglected. We varied the molecular hydrogen density in the range from $n^{HS}(H_2) = 3 \cdot 10^3$ to $3 \cdot 10^4 cm^{-3}$ and, as expected, higher densities lead to stronger mid IR emission.

From the arguments outlined in Sect. 2.1 one expects that the calculation of the hot spots (case c) is the best approximation to reality; unfortunartely, it is the numerically most laborious. We conclude from Fig. 1 that approximating a galactic nucleus by a point source (case a) or a smoothed stellar distribution without hot spots (case b) gives usually bad results. They are marginally acceptable only under special conditions: A point source model when one is dealing with the galactic nucleus as a whole (low spatial resolution); the model with distributed stars and without zones of influence when scanning the source at FIR and sub-

Table 1. IR continuum observations of M 82

$\lambda(\mu m)$	S_ν(Jy)	Reference
1300	2.1 ± 0.2	Krügel et al.(1990, in total map)
	0.7 ± 0.3	" (in 11″)
1300	1.3 ± 0.3	Thronson et al.(1988)
1100	1.9 ± 0.4	Hughes et al. (1990)
1000	2.7 ± 0.7	Elias et al.(1978)
800	1.9 ± 0.4	Hughes et al. (1990)
450	49 ± 21	Smith et al. (1990)
400	30 ± 10	Jaffee et al. (1984)
141	630 ± 24	Telesco & Harper (1980)
100	1145± 170	IRAS PSC
78	1255± 34	Telesco & Harper (1980)
60	1168± 175	IRAS PSC
41	625 ± 51	Telesco & Harper (1980)
30	363 ± 40	Houk et al. (1984)
25	274 ± 40	IRAS PSC
21	120 ± 8	Rieke & Low (1972)
12.4	36 ± 51	Telesco & Gezari (1992)
12	53 ± 8	IRAS PSC
11	27 ± 2	Rieke & Low (1972)
10.6	6.4 ± 0.64	Rieke et al. (1980, in 5.8″)
	3.9 ± 0.39	" (in 3.9″)
5	8.4 ± 1.5	Rieke & Low (1972)
2.2	2.5 ± 0.1	Rieke & Low (1972)
	0.475 ± 0.05	Rieke et al. (1980, in 7.8″)
	0.35 ± 0.04	" (in 5.8″)
1.60	0.35 ± 0.04	" (in 7.8″)
	0.252 ± 0.04	" (in 5.8″)
1.25	0.161 ± 0.02	" (in 7.8″)
8 – 22		IRAS ST (1986)
8 – 13		Gillett et al. (1975)
		Jones & Rodriguez (1984, in 2.5″, 3″)
2 – 8		Willner et al. (1977)

millimetre wavelengths. For modeling the mid IR flux, which is of particular value as it indicates nuclear activity (e.g. Rieke et al. 1980; Jones & Rodriguez–Espinosa 1984; Wynn–Williams & Becklin 1993), we found that case a) is never applicable nor is case b), at least, if one neglects the emission of small grains.

3.2. The influence of the small grains on the spectrum

PAH features in external galaxies are discussed by e.g. Gillett et al. (1975), Willner et al. (1977), Aitken et al. (1981, 1982), Philips et al. (1984), Roche et al. (1983, 1984), Aitken & Roche (1985), Moorwood (1986), Désert & Dennefeld (1988), Mouri et al. (1990), Roche et al. (1991). From 10 μm excess emission Wynn-Williams & Becklin (1985), Helou (1986), Telesco et al. (1989), Ho et al. (1989) and others propose a population of small grains. We demonstrate in Fig. 3 how they affect the emission by comparing the spectra of three models for a galactic nucleus: one without hot spots but containing small grains, another with hot spots but without small grains, and a third one with hot spots and small grains. We see that hot spots and small grains have qualitatively a similar effect of enhancing the near and mid IR emission. The PAHs produce in addition the specific resonances. Remembering how strongly the hot spots change the emission from a galctic nucleus (Fig. 1) it now becomes evident from Fig. 3 that including small grains is equally important and both hot spots and small grains must be taken into account in an advanced model.

Analysing Fig. 3, we see that the model with hot spots but without small grains is not drastically different from the one without hot spots but with small grains. This holds, at least, for this particular choice of parameters (especially for the small grains and the density in the hot spots). Nevertheless, the discrepancy can at some wavelengths be larger than a factor of three. If we include in the hot spot model also the small grains (solid line in Fig. 3) the subsequent changes are now moderate because the two effects are of the same order and add up linearly.

4. The starburst galaxy M 82

4.1. The data base

We now apply the numerical approach for calculating the spectrum from a galactic nucleus including hot spots and small grains to a specific source. We choose the core of the starburst galaxy M 82. It is quite close (D = 3.25 Mpc) so apparent fluxes are strong and many IR data have accumulated over the years. Because of its proximity there is also reasonable spatial resolution (1 ″ corresponds to 15pc). The IR luminosity of M 82 equals $L = 3 \cdot 10^{10} L_\odot$. It is known that the bulk of the energy cames from young and massive stars ($\approx$ 80%) and approximately one–fifth of the total infrared luminosity is due to late K and early M giant stars (Willner et al. 1977). The inclination angle of M 82 is 79° so we look towards the nucleus partly through the disk. Although the nucleus has an elongated shape, we will probably not make a big error by assuming spherical symmetry and using averages of the values along the major and minor axis. We summarize the relevant maps and cross cuts, by citing the wavelength of the measurements and the spatial resolution: 2.2 μm (2″) Dietz et al. (1986); Brγ line at 2.17 μm (4″) Lester et al. (1990); J (1.24 μm), H (1.65μm), K (2.16 μm) (1.35″) and 10.8 μm (4″) Telesco et al. (1991); 10.6 μm (2.5″) Rieke et al. (1980); 12.4 μm (1″) Telesco & Gezari (1992); profiles at 19.2 μm, 30 μm (4″) Telesco et al. (1989); 40 μm (14″), 100 μm (40″) Joy et al. (1987); 60 μm (60″) Telesco & Harper (1980); maps at 450 μm (13″) Smith et al. (1990) and Hughes (1993); 800 μm (14″), 1100 μm (22″) Hughes et al. (1990); 1.3mm (33″) Thronson et al. (1989); 1.3mm (11″) Krügel et al. (1990); 3.3mm continuum (6″) Carlstrom & Kronberg (1991); 9mm (26.5″) Klein et al. (1988). Table 1 contains the photometric data displayed in Fig. 4, unless stated otherwise refering to a diaphragm of $\geq$ 30″.

Table 2. Parameters of the radiative transfer model for M 82

Distance	$D = 3.25\text{Mpc}$	
Total luminosity of OB stars with $T_*^{OB} = 20000\text{K}$	$L^{HS} = 2.4 \cdot 10^{10} L_\odot$	
Total luminosity of population II stars with $T_*^G = 3000\text{K}$	$L^G = 0.6 \cdot 10^{10} L_\odot$	
Radius		
OB stellar cluster	$R^{OB} = 150\text{pc}$	
Nucleus	$R^{out} = 700$ pc	
Volume density		
OB stars	$n^{OB}(r) \propto r^{-0.5}$	
Giants	$n^G(r) \propto const$	
Dust density distribution	$\rho(r) \propto \begin{cases} \text{const} \\ r^{-1} \end{cases}$	for $72\text{pc} \leq r$ for $72\text{pc} < r \leq R^{out} = 700\text{pc}$
Visual extinction to cloud center	$A_V = 41 mag$	

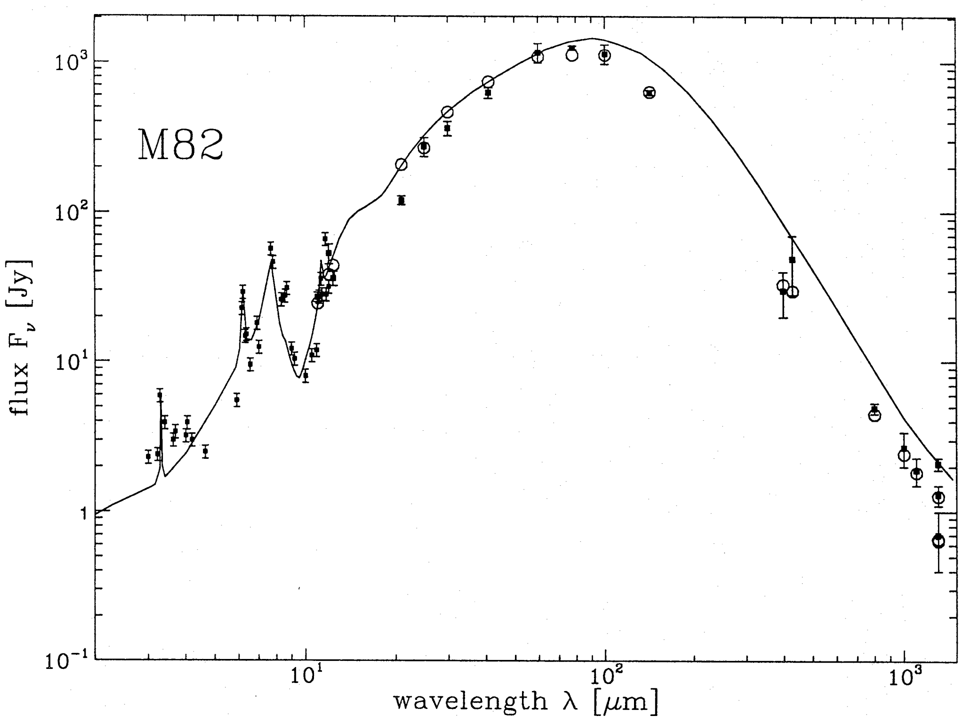

Fig. 4. The IR spectrum of the starburst galaxy M 82. The total flux from the hot spot model is shown by the full line. Observations (filled squares with error bars) were often made with beams smaller than the source and should be compared with beam matched model values (circles). At millimeter wavelengths we have added the contribution of the free – free emission as extrapolated from the 3.3mm flux densities by Carlstrom & Kronberg (1991)

4.2. Fit parameters

The dust density distribution is a major parameter in radiative transfer calculations. It can be constrained from millimetre maps because these fluxes are directly proportional to the dust column density. From a 1.3mm map with 11″ resolution Krügel et al. (1990) found a total mass $M_{\text{tot}} = 8.7 \cdot 10^8 M_\odot$. Cross cuts in this map along the major and minor axis can be used to roughly derive the density distribution in the nucleus, $\rho \propto r^{-1}$. For the innermost region ($r < 72$pc) the spatial resolution of the map is not adequate to determine $\rho(r)$. Our best fit model has $\rho = const$ for $r < 72$pc and $\rho \propto r^{-1}$ for $72\text{pc} \leq r < R^{out} = 700$pc. In our choice for the outer boundary radius R^{out} we are guided by an extrapolation of the $1.3mm$ map to its rms noise of 32mJy and the mid IR maps of Telesco et al. (1991) and Telesco & Gezari (1992), which show extended emission out to at least 1.3kpc.

The proportionality factor in the dust density distribution $\rho(r)$ can be fixed by the amount of visual extinction to the center ($r = 0$) of M 82. Telesco et al. (1991) determine from the near IR colors $A_V \leq 8$mag. Our best fit, which is mainly gauged on the 9.7 μm silicate absorption feature, requires $A_V = 41$mag. This is somewhat higher than estimates based on the Brα / Brγ line ratio of hydrogen (Gillet et al. 1975; Willner et al. 1977), which indicates $A_V = 25$mag.

The size of the starburst region can be estimated from mid IR maps to be $R^{OB} \approx 150$ pc (Rieke et al. 1980; Joy et al. 1987; Telesco et al. 1991; Telesco & Gezari 1992). The spatial density

Table 3. Parameters of dust components for M 82 (the notation refers to SK)

Large grains	
(carbon and silicates)	
Lower size	a_{-} = 300 Å
Upper size	a_{+} = 1200 Å
Exponent of size distribution	q = 3.5
Small graphites	
Size	a_{-}^{sg} = 10 Å
Abundance	Y_{C}^{sg} = 0.15
Small PAHs	
Number of C-atoms	N_{C}^{PAH} = 25
Abundance	Y_{C}^{PAH} = 0.1
H / C atom ratio	$\alpha_{H/C}^{PAH}$ = 0.1
PAH cluster	
Number of C-atoms	N_{C}^{Clu} = 250
Abundance	Y_{C}^{Clu} = 0.1
H / C atom ratio	$\alpha_{H/C}^{Clu}$ = 0.1

distribution of the giants is constant, whereas the massive stars vary as $n^{\rm OB}(r) \propto r^{-0.5}$. This is different from the stellar density in the center of the Milky Way ($r^{-1.8}$, Becklin & Neugebauer, 1968), but was necessary to fit the change of the near and mid IR emission with diaphragm. OB stars extent only to a radius $R^{\rm OB}$ and giants are distributed over the whole nucleus up to R^{out}. All parameters of the radiative transfer model for M 82 are listed in Table 2.

M 82 is also of special interest because PAH resonances are observed towards its nucleus. Our dust model is described in in Table 3, it is based on typical parameters for the Milky Way listed in SK. For the large grains we have used optical constants for amorphous carbon (Edoh 1983) and astronomical silicate (Draine & Lee 1984, 1987). For fitting the spectral data in the 3 – 14 μm region (Willner et al. 1977) we use as free parameters only the ratio of hydrogen to carbon atoms of the PAHs, $\alpha_{\rm H/C}$, to adjust the strength of the spectral features associated with C-H bonds with respect to those associated with C=C bonds, and the abundance of the small PAHs $Y_{\rm C}^{\rm PAH}$. Abundances are taken to be constant throughout the model cloud.

4.3. The spectral energy distribution

Figure 4 shows the model fit to the spectral energy distribution of M 82. Model fluxes at $12, 25, 60, 100\mu$m are obtained after convolving the model spectrum with the IRAS transmission functions. We have not used the IRAS low resolution spectrum (IRAS Science Team 1986) because it contains significiant amount of dust emission outside the nucleus of M 82 (LeVan & Price 1987). One should only compare beam matched model values with the observations. At millimeter wavelengths there is some contribution from thermal radio emission. Extrapolating the 3.3mm flux densities by Carlstrom & Kronberg (1991) with with $S_{\nu}^{th} \propto \nu^{-0.1}$, the free – free emission is 540 at 1300, 520 at 1100 and 480mJy at 800 μm, respectively. These fluxes are added to the dust emission. Our hot spot model fits most of the observations very well. Mild deviations occur at 1300μm, where the emission comes from a more compact region than the model predicts and at 21μm (Rieke & Low 1972). The fit at L (3.6μm) could probably be improved by including the weaker PAH bands in this region (Tokunga et al. 1991). The model does not account for gas emission (e.g. lines of Brα, Brγ, NeII, OIII, NIII). As mentioned in Siebenmorgen et al. (1993) the model emission for the PAH band at 8.6μm is notoriously weak (factor of 2.5) compared to observations. The 3.3μm broad band feature is a discriminator of the activity type of the nucleus (Moorwood 1986) and mapping it could serve as a check to our simple treatment of the photo–destruction of PAHs.

4.4. Source size at various wavelengths

As demonstrated in Section 3, the model is strongly restricted by requiring besides a fit to the spectral energy distribution additionally a fit to cross scans over the source. We therefore compute scans across the source, convolved with the spatial resolution of the relevant observations, and compare FWHM sizes of the model with observed FWHM sizes averaged over the major and minor axis. The results of such a comparison is given in Table 4. At near (2.2μm) and mid (10.8μm) IR wavelengths the agreement is better than a factor of 2. This is remarkable considering the spherical symmetry of our model, whereas Efstathiou & Rowan-Robinson 1990, Piere & Krolik 1992, Efstathiou & Siebenmorgen 1993 argue that non–sphericity can have strong influence to the near IR. We also note, that X - ray heating of grains as discussed by Voit (1991) seems to be of minor importance for M 82. At longer wavelengths geometrical effects become less important and the model sizes are in good agreement with the extent of the emission at far IR wavelengths. The fit to the observed 1300 μm size is nearly perfect, which is not supprising as we have read out one of the major model parameter ($\rho(r)$) from this map.

5. Summary

We present a method to model the transfer of radiation in a dusty galactic nucleus. Stars are distributed over the whole nucleus and we evaluate in an approximate way the emission of very warm dust in the immediate vicinity of OB stars; their surroundings are called hot spots. We also take into account the presence of very small grains. Their emission is known to be dominated by temperature fluctuations.

For comparison, we discuss simpler alternatives for the radiative transfer in galactic nuclei which arise when all stars are approximated by one central point source or when the explicit treatment of the hot spots or the emission from very small grains is neglected. When analyzing the resulting IR spectra and cross

Table 4. Comparison of (FWHM) sizes of M 82 between observations and the hot spot model

			Observations		Model
λ (μm)	Beam (″)	Minor axis (″)	Major axis (″)	References	Mean size (″)
2.2	3.3	7	17	Dietz et al. (1987)	8.4
10.8	4	7	26	Telesco et al. (1991)	7.7
40	14	8	25	Joy et al. (1987)	17.5
58	30	–	–	Telesco & Harper (1980)	35
100	24	14	35	Joy et al. (1987)	20
450	9	13	37	Hughes (1993)	26
800	14	16	42	Hughes (1993)	36.5
1100	22	20	43	Hughes (1993)	45
1300	11	18	40	Krügel et al. (1990)	31

scans at various wavelengths it turns out that these simpler methods are inadequate.

We model in detail the starburst galaxy M 82. Under the assumption of spherical symmetry most of the fit parameters are well constrained observationally. Our hot spot model gives a good fit to the spectral energy distribution, including the PAH resonances, and can explain the FWHM sizes from near IR to millimetre wavelengths.

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