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HOT DUST IN GALAXIES

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Abstract. We present an approximate method for calculating the infrared emission from a galactic nucleus that has recently undergone a starburst and is powered mainly by massive stars of spectral type O and B. Such nuclei are usually heavily obscured by dust and we outline the radiative transfer in a dusty medium with scattered sources. We include in the model transiently heated small dust particles and illustrate their dominating influcence on the near and mid infrared spectrum.

1. Galactic nuclei

Galactic nuclei are a most interesting class of objects as they are the site of diverse kinds of activity often accompanied by large infrared luminosities. The origin of the activity may be either rapid star formation or accretion onto a massive black hole. In both cases, the hard primary radiation, from the star or the black hole, is converted into infrared photons by dust. We here consider stars as the source of energy. As galactic nuclei, like the center of the Milky Way, usually possess a fair degree of spherical symmetry, one may try to model their infrared spectral energy distribution.

2. Hot spots in a spherical stellar cluster

To model the infrared emission of a dusty galactic nucleus, one has to specify the properties and space density of the stars, the distribution of the dust grains and then solve in some approximate way the radiative transfer in the dusty medium. The radiative transfer in a star cluster is, however, complicated by the fact that the geometrical configuration is intrinsically three–dimensional because the dust temperature varies not only on a large scale with galactic radius r, which is the distance to the center of the stellar cluster, but also locally with the separation to the nearest star. This circumstance must be taken into account [Krü78]. Loosely speaking, the temperature of a grain located in the immediate vicinity of a star is determined by the distance to and the properties of that star, whereas a grain at the same galactic distance, but not very close to any star, absorbs only the mean interstellar radiation field $J_\nu^{\mathrm{isrf}}(r)$ and will thus be cooler. The spherical symmetry is broken on a small scale because the surroundings of a star constitute a hot spot (abbreviated HS) in the interstellar medium. Their presence significantly changes the spectral appearance of a galactic nucleus.

Let us assume that the hot spots are homogeneous dusty spheres, each with a star of monochromatic luminosity L_ν at the center. It will turn out that their total volume fraction is small, so they are distributed over the galactic nucleus like raisins in a cake. The radius R^{HS} of a hot spot is determined by the condition that outside, a dust grain is mainly heated by the interstellar radiation field, whereas inside, heating by the star dominates. If τ_ν is the optical depth from the star to the boundary of the hot spot and Q_ν the absorption efficiency of a dust grain, R^{HS} follows from

$$\int Q_\nu J_\nu^{\mathrm{isrf}}\, d\nu \;=\; \frac{1}{(4\pi R^{\mathrm{HS}})^2} \int Q_\nu L_\nu\, e^{-\tau_\nu}\, d\nu \;. \tag{1}$$

R^{HS} is a function of r. Furthermore, R^{HS} depends on the strength and spectral shape of the interstellar radiation field, the monochromatic stellar luminosity L_ν, the dust distribution or density within the hot spot, and on the grain properties via the absorption efficiency Q_ν. Equation (1) can readily be formulated for a dust mixture. Then all hot spots at any given galactic distance r have the same radius $R^{\mathrm{HS}}(r)$.

3. Low and high luminosity stars

It is useful to divide the stars in a galactic nucleus into two categories, each containg identical objects. Stars of the first class have small or moderate luminosity, a space density $n^*(r)$ and a monochromatic and bolometric luminosity L_ν^* and L^*, respectively, where

$$L^* \;=\; \int L_\nu^*\, d\nu \;.$$

They represent the population of old stars. The second class consists of young and luminous OB stars that were formed in a starburst; the corresponding values are denoted $n^{\mathrm{OB}}(r)$, L_ν^{OB} and L^{OB}.

- The low luminosity stars are very numerous, altogether there are typically 10^9 in a nulceus, and the contribution of their hot spots to the overall spectrum may be neglected. To see why consider a nucleus of integrated luminosiy L_{nuc} containing N identical stars of luminosity L^*. When we fix $L_{\mathrm{nuc}} = NL^*$, but increase N and thus lower L^*, the intensity of the interstellar radiation field in the galactic nucleus is to first order independent of N. In view of the definition for R^{HS} in (1), one finds

  $$R^{\mathrm{HS}} \;\propto\; \sqrt{L^*} \;\propto\; N^{-1/2} \;.$$

  Therefore, the total volume $N \cdot (R^{\mathrm{HS}})^3$ of all hot spots decreases as $N^{-1/2}$. A large population of low luminosity stars may be smeared out smoothly over the galactic nucleus and the structure of their hot spots need not be evaluated. To account for the radiation of these stars, one only has to introduce in the numerator of the source function (see equation (2)) the volume emission coefficient

  $$\Gamma_\nu^*(r) \;=\; n^*(r) \cdot L_\nu^* \;.$$

If the stellar atmospheres are black bodies of temperature T^*, one may put $L^*_\nu \propto B_\nu(T^*)$. Note that L^*_ν need not be specified, only the product $\Gamma^*_\nu(r) = n^*(r) \cdot L^*_\nu$.

- The OB stars, on the other hand, are very bright and not so numerous. There are rarely more than 10^6 in a galactic nucleus and their space density $n^{\rm OB}(r)$ is moderate, typically one star per pc^3 or less in the starburst region. The emission of their hot spots is not negligible and has to be evaluated explicitly. Before solving the radiative transfer on a large scale in the galactic nucleus, one has to determine the luminosity $L^{\rm HS}_\nu(r)$ emerging from a hot spot. The frequency integral $\int L^{\rm HS}_\nu d\nu$ is, of course, equal to the luminosity $L^{\rm OB} = \int L^{\rm OB}_\nu d\nu$ of a single OB star, but $L^{\rm OB}_\nu$ and $L^{\rm HS}_\nu$ are different because much of the hard stellar UV flux is converted by dust into infrared radiation.

To obtain $L^{\rm HS}_\nu(r)$, we calculate for each galactic radial grid point the radiative transfer of a spherical cloud centrally heated by an OB star. This is a standard task of radiative transfer. The cloud radius $R^{\rm HS}$ is determined from (1). The hot spot is illuminated at its edge by an interstellar radiation field (isrf), which fixes the outer boundary condition for the intensity. Because the volume emission coefficient due to the hot spots is

$$\Gamma^{\rm HS}_\nu(r) = n^{\rm OB}(r) \cdot L^{\rm HS}_\nu ,$$

the source function in a spherical galactic nucleus becomes

$$S_\nu = \frac{\Gamma^{\rm HS}_\nu(r) + \Gamma^*_\nu(r) + K^{\rm abs}_\nu B_\nu(T_{\rm d}) + K^{\rm sca}_\nu J^{\rm isrf}_\nu}{K^{\rm ext}_\nu} . \tag{2}$$

$K^{\rm abs}_\nu$ and $K^{\rm sca}_\nu$ are the absorption and scattering coefficient of a grain, $K^{\rm abs}_\nu B_\nu(T_{\rm d})$ is the emissivity of dust at temperature $T_{\rm d}$, and the expression $K^{\rm sca}_\nu J^{\rm isrf}_\nu$ is due to isotropic scattering. With this source function, one then solves the integral equation (we now drop the frequency index ν)

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

for the intensity in positive and negative direction, I^+ and I^-, along lines of constant impact parameter. From I^+ and I^- one can readily deduce the mean intensity $J_\nu(r)$. As the galactic nucleus in this model consists of two phases, a dusty medium interspersed with hot spots, equation (3) is not strictly correct. It gives, however, a good approximation as long as the volume fraction γ of the hot spots,

$$\gamma(r) = \frac{4\pi}{3} \cdot n^{\rm OB}(r) \cdot \left[R^{\rm HS}(r)\right]^3$$

is small; $\gamma(r)$ shrinks when $n^{\rm OB}(r)$ becomes large. For typical space densities of OB stars in starburst nuclei, γ is of order 10^{-3}.

4. Small grains with temperature fluctuations

Because of the copious UV radiation field in a galactic nucleus, we also consider in our model the presence of small grains (radii $a \sim 10$Å) and polycyclic aromatic hydrocarbons (PAHs). Such particles have heat capacity of the same order as the energy of an UV photon and therefore undergo temperature fluctuations which strongly influence the near and mid IR part of the spectrum. Such fluctuations require a special numerical treatment ([Guh89], [Li01]).

The top panel of Fig. 1 displays for illustration the temperature variation $T(t)$ of a silicate grain as a function of time over an interval of 1400 s. The grain has a radius of 10Å and is at a distance $r = 10^{17}$ cm from a B1V star ($L = 10^4\, L_\odot$, $T_* = 2 \cdot 10^4$). The probability density $P(T)$ in the lower left panel of Fig. 1 gives the chance $P(T)$ of finding the grain within a temperature interval of 1 K width centered on T; the area under the curves equals one.

When looking at the temperature evolution $T(t)$, one hesitates to assign an average temperature to the grain at all, although mathematically this can, of course, be done. There are two disparate regimes: Most of the time the grain has a temperature of about 40 K, but occasionally the grain is excited to a high temperature from which it rapidly cools radiatively. The probability density $P(T)$ is asymmetric and has its maximum is at $T_{\rm max} = 51.9$ K, so this is the most likely temperature. On the other hand, the equilibrium temperature $T_{\rm eq}$, which one would obtain if one disregards the stochastic character of photon absorption, is 116.2 K and thus much larger. $T_{\rm eq}$ follows from the energy balance between heating and cooling,

$$\int Q_\nu J_\nu \, d\nu \;=\; \int Q_\nu B_\nu(T_{\rm eq}) \, d\nu \;,$$

where J_ν is the mean intensity of the radiation field. By comparing the dotted and solid line in the lower left box of Fig. 1, we see that to evaluate the grain emission without taking into account its hot excursions would underestimate the near and mid infrared flux by orders of magnitude; this explains the immense influence which small particles have on the spectral energy distribution in this wavelength range. Nevertheless, the frequency integrated emission for both curves is the same and equal to the absorbed flux. Note also the strong 10μm silicate feature.

As a further illustration, we show in Fig. 2 the (optically thin) emission from a dust mixture in a reflection nebula. The dust includes the standard three major components:

- big grains with a size range between 300Å and 3000Å consisting either of silicate material or amorphous carbon. Their temperatures are not time–variable.
- Very small grains (vsg) with temperature fluctuations consisting of silicate material or graphite (a form of crystalline carbon).
- polycyclic aromatic hydrocarbons (PAHs). These are planar molecules, made of a number of benzene rings, usually with hydrogen atoms bound to the edges. The smallest consist of barely more than a dozen atoms, so they are intermediate between molecules and grains. They account for a number of well studied near and mid infrared resonances. Their temperatures strongly fluctuate.

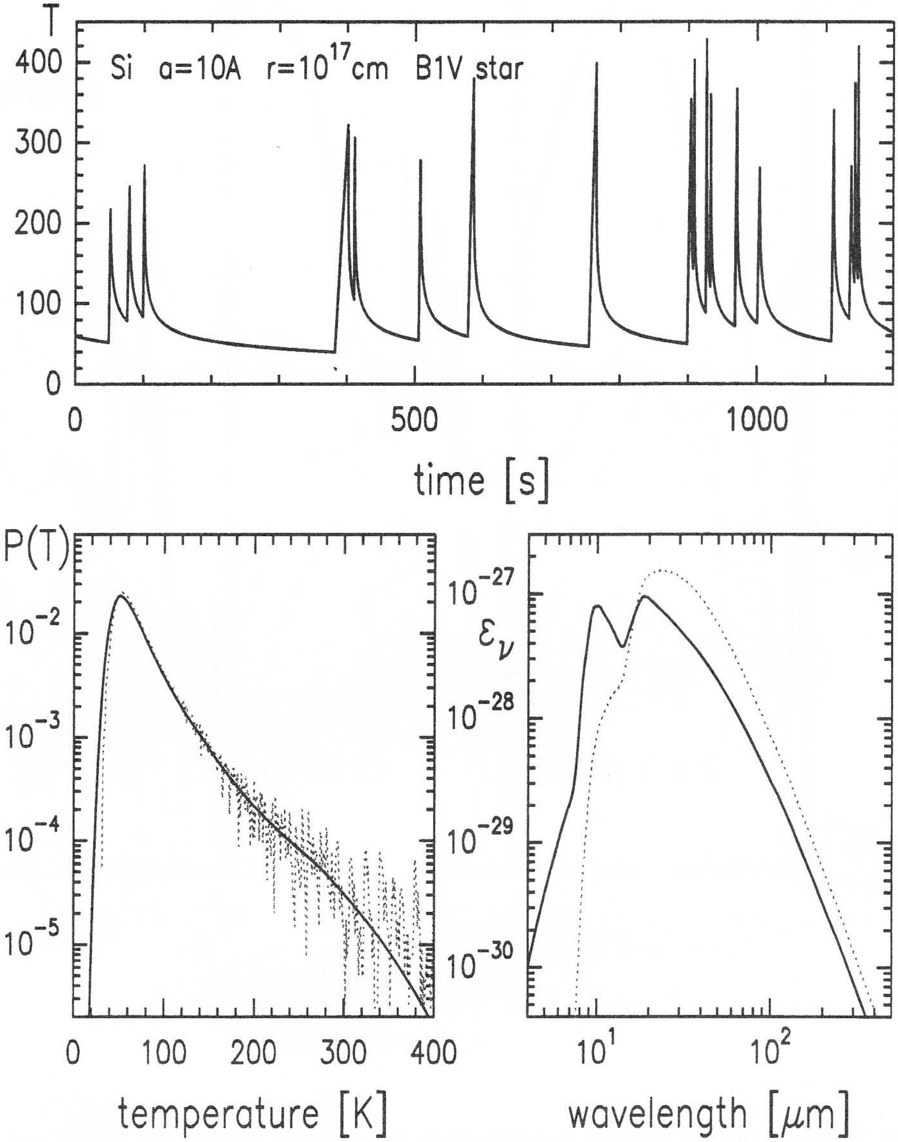

Fig. 1: Temperature fluctuations of a small silicate grain (radius a = 10Å) at a distance of 10^{17} cm from a B1V star. *Top:* Stochastic temporal evolution of the temperature. *Lower left:* The solid line shows the probability density $P(T)$ of the temperature; the jittery dotted curve is ignored. *Lower right:* Emissivity ϵ_ν of the grain in erg/s Hz ster. Dots show the emission under the wrong assumption that the temperature is constant; the solid line correctly includes temperature fluctuations.

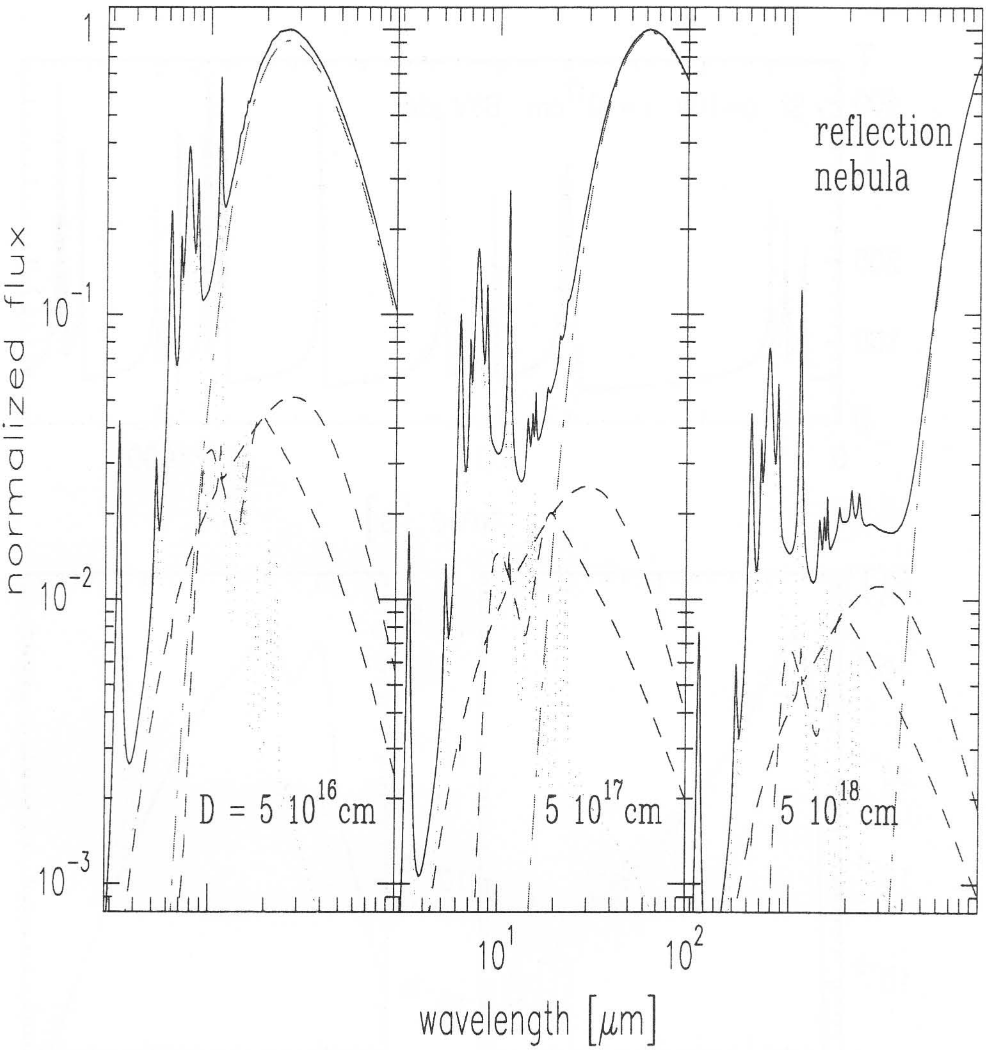

Fig. 2: The emission by dust in a reflection nebula near a B3V star with $L = 10^3\,\mathrm{L}_\odot$ and $T_{\text{eff}} = 18000\,\mathrm{K}$ at various distances D to the star. The spectra are normalized at their maxima. The maximum occurs at $\sim 25\mu$m in the left box where the dust is at a distance $D = 5 \cdot 10^{16}$ cm, and is shifted beyond 100μm for $D = 5 \cdot 10^{18}$ cm. *Solid:* total spectrum of all three dust components. *dash–dot:* big grains only. *dashed:* very small graphite and silicate grains (vsg) of 10Å radius; the silicates have a hump at 10μm. *dots:* PAHs.

5. The influence of hot spots and PAHs on the spectrum

The nucleus of a galaxy is usually deeply embedded in dust and can therefore only be probed by infrared observations. One way to derive the structure of the nucleus, to find out how dust and stars are geometrically arranged, what the total extinction and the gas mass are, or to which spectral type the stars belong, is to model the dust emission spectrum.

Following the procedure discussed above (for details, see [Krü94]), we compute the radiative transfer and the resulting emission spectrum from a dusty starburst nucleus. First, we convince ourselves that it is indeed necessary to properly include the surroundings of the OB stars (we call them hot spots). If one does not separately treat the emission from the hot spots, where the dust is much warmer than elsewhere, but takes averages of the dust emission over larger volumes, one grossly underrates the mid–infrared flux. This can be seen from Fig. 3, where spectra are displayed that have been calculated with and without hot spots. Their presence also reduces the depth of the 10μm silicate absorption feature (except for the highest hot spot density of $n(\mathrm{H}) = 10^5$ H atoms per cm^3).

None of the spectra in Fig. 3 includes PAHs or very small grains (except for the point source model, see below). An improved model that is closer to reality has, of course, to incorporate these dust components. Their importance arises mainly from the fact that they undergo temperature fluctuations. In this way, their emission becomes prominent at much shorther wavelengths than if they were at an equilibrium temperature. We see from Fig. 4 that PAHs and very small grains appreciably further enhance the mid infrared flux compared to the models of Fig. 3 and radically change its spectral appearance. As a consequence, it is now not obvious at all how to derive from the 10μm silicate feature, which lies between PAH bands, an absorption optical depth. We add that in view of the strong and hard radiation field prevalent in a galactic nucleus, the radiative transfer code must allow for the possibility of photo–destruction of PAHs.

Of interest is also a point source model of the same luminosity and spectral appearance as the exciting stars, but where the stars are squeezed into a tiny volume at the center of the galactic nucleus. It is shown by the upper dotted curve in Fig. 4. It too yields a very strong mid–infrared flux, but differs from the models with extended emission out of a stellar cluster by its small angular size. Mid–infrared cross cuts of high spatial resolution over the galactic nucleus allow to discriminate between the two alternatives.

A massive black hole with an accretion disk appears to an observer also as a point source, but it is one with a considerably harder emission spectrum than OB stars. Usually one assumes for the black hole a power law $S_\nu \propto \nu^\alpha$ with $\alpha \simeq -0.5$. If the dust is exposed to the flux from such an object, PAHs will evaporate in its vicinity (they can only survive farther out) and the ratio of mid infrared over total luminosity is reduced. This can be checked observationally. However, spectral lines from multiply ionized atoms, which require for their excitation more energetic photons than are found in HII regions, are generally a better diagnostic for the presence of a powerful non–thermal source.

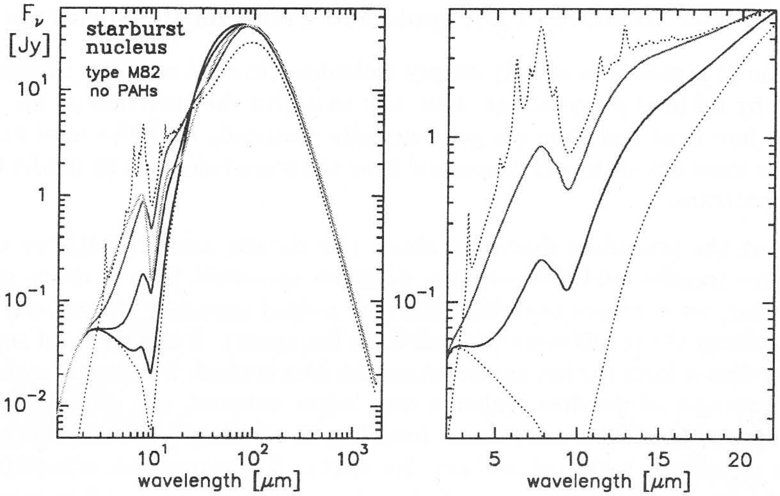

Fig. 3: Radiative transfer models of a starburst nucleus similar to M82. Source distance $D = 20\,\mathrm{Mpc}$, further parameters in Table 1. *Left:* The two dotted curves are benchmarks for comparison with the right box and with Fig. 4. The lower dotted curve shows the case without hot spots. The upper one depicts a point source model, and this is the only curve in the figure where PAHs and very small grains are included. The remaining solid lines are computed with hot spots. The density in the hot spots ranges from $n(\mathrm{H}) = 10^2\,\mathrm{cm}^{-3}$ to $n(\mathrm{H}) = 10^5\,\mathrm{cm}^{-3}$ in steps of a factor 10. *Right:* Enlargement of left box showing only the intermediate and probably more realistic hot spot densities 10^3 (lower solid line) and $10^4\,\mathrm{cm}^{-3}$ (upper solid line).

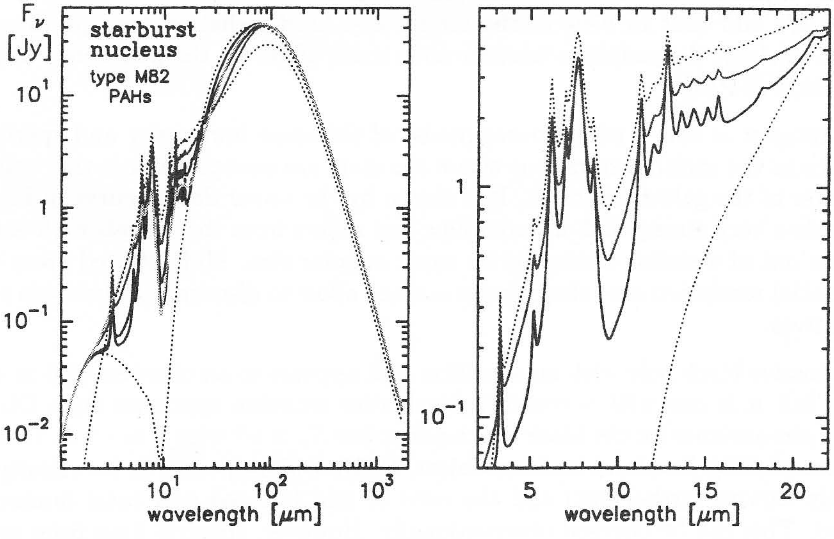

Fig. 4: *Left:* As Fig. 3 and with the same benchmark models (upper and lower dotted curves), but now with hots spots *and* PAHs and very small grains. *Right:* Enlargement of left box, but only for hot spot densities 10^3 and $10^4\,\mathrm{cm}^{-3}$.

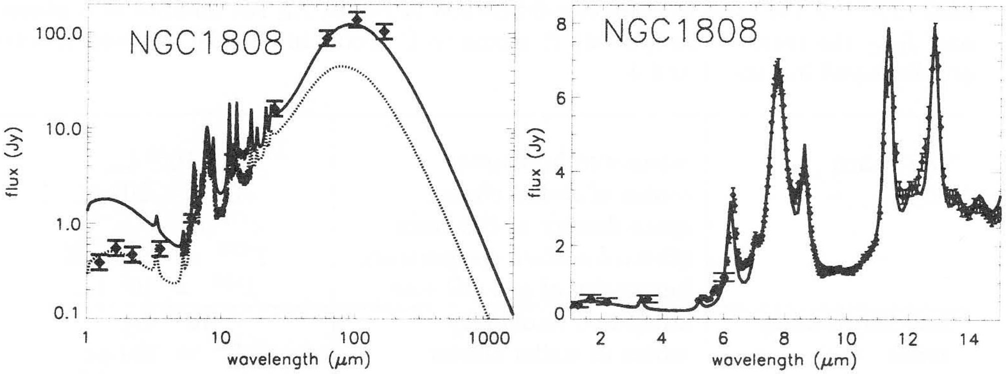

Fig. 5: *Left:* Dust emission from the nucleus of the galaxy NGC 1808. The dotted (solid) line shows the model flux received in a 25″ (100″) aperture. The galaxy is at a distance of 11 Mpc where 1″ corresponds to 53 pc. Circles represent observational data [Sie00]. *Right:* Blowup of the near and mid infrared data and of the 25″ aperture model. The model fit is very good.

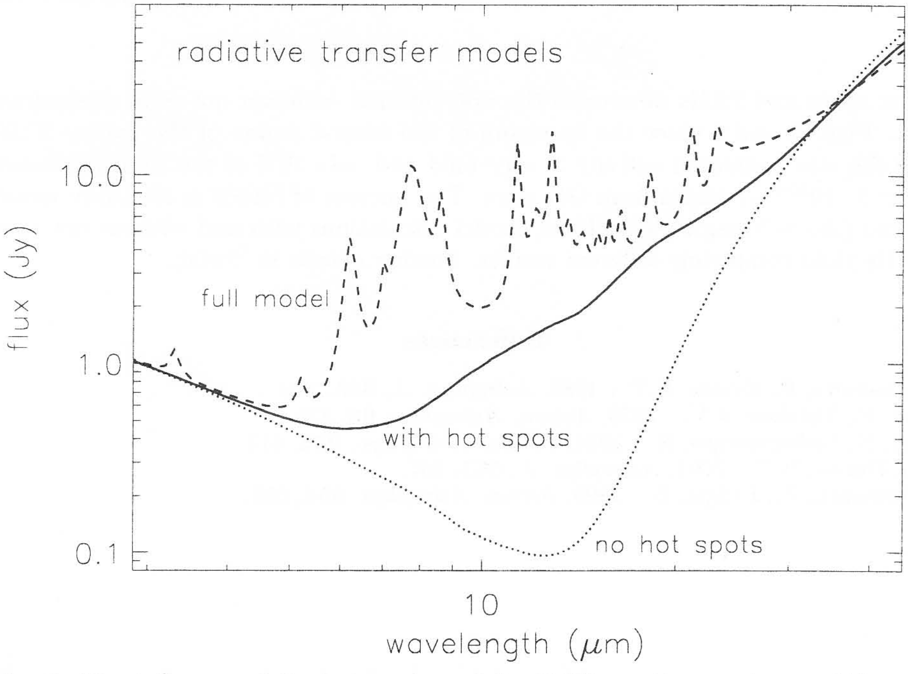

Fig. 6: The influence of the hot spots and the PAHs on the spectrum of the galaxy N1808. The line labeled full model includes PAHs and hot spots.

Table 1: Typical parameters for a galactic nucleus with a starburst, like the archetype M82. $Y_C^{\rm PAH}$ is the mass fraction of solid carbon in PAHs, N_C the number or C atoms, and $f_{H/C}$ the ratio of (peripheral) H atoms to C atoms in a PAH. Infrared spectra are displayed in Figs. 3 and 4.

OB stars	integrated luminosity	$3 \cdot 10^{10}$ $L_\odot$
	radius of stellar cluster	$R^{\rm OB} = 200$ pc
	space density of OB stars	$n^{\rm OB}(r) \propto r^{-1/2}$
	effective surface temperature	$T^{\rm OB} = 25\,000$ K
	luminosity of one OB star	$L^{\rm OB} = 10^5$ $L_\odot$
low luminosity stars	integrated luminosity	10^{10} $L_\odot$
	radius of stellar cluster	$R^* = 700$ pc
	space density	$n^*(r) \propto r^{-1.8}$
	effective surface temperature	$T^* = 4000$ K
dust	radius of dust cloud	$R_{\rm dust} = 800$ pc
	density $\rho_{\rm dust}(r)$	$=$ const for $r \leq 230$ pc
	$\propto r^{-1/2}$ for $r > 230$ pc	
	A_V from cloud edge to center	29 mag
	A_V from $r = 0$ to $r = 230$ pc	10 mag
PAHs	small ones ($N_C = 50$)	$Y_C^{\rm PAH} = 0.05$, $f_{H/C} = 0.4$
	big ones ($N_C = 300$)	$Y_C^{\rm PAH} = 0.05$, $f_{H/C} = 0.16$
very small grains	radius $a = 10$Å	graphites: $Y_C^{\rm vsg} = 0.05$

Hot spots and PAHs determine the mid infrared emission not only of starburst nuclei. Figs. 5 and 6 show the spectrum of the central region of the galaxy N1808 where the star formation activity is very mild and only 10% of the total luminosity ($L_{\rm tot} \simeq 5 \cdot 10^{10}$ $L_\odot$) comes from OB stars. The nucleus of N1808 is also only weakly obscured ($A_V \sim 5$ mag). Neverthless, model calculations with and without hot spots or PAHs yield completely different results. Further details in [Sie00].

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