

Multigrain dust cloud models of starburst and Seyfert galaxies

Michael Rowan-Robinson and Andreas Efstathiou

School of Mathematical Sciences, Queen Mary and Westfield College, Mile End Road, London E1 4NS

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ABSTRACT

We present improved, spherically symmetric, multigrain dust models for the far-infrared emission from starburst galaxies, based on an exact radiative transfer code. The parameters of the models are similar to those of the starburst model of Rowan-Robinson & Crawford, with a total optical depth at 1000 \AA of $\tau_{UV} = 200$ ($A_V = 40$). We also extend these models to the class of ultraluminous compact starburst galaxies, and find that similar models with higher optical depths, up to $\tau_{UV} = 500$, explain the far-infrared spectra of these galaxies. Spherically symmetric models are also presented for the infrared emission from Seyfert galaxies.

Key words: radiative transfer – dust, extinction – galaxies: ISM – galaxies: Seyfert – galaxies: starburst – infrared: galaxies.

1 INTRODUCTION

This is one of a series of papers which develop the models for the infrared emission of galaxies given by Rowan-Robinson & Crawford (1989, hereafter RRC). RRC modelled the 12–100 μm emission of *IRAS* galaxies in terms of three components: a starburst component peaking at 60 μm , a ‘Seyfert’ component peaking at 25 μm and a cirrus/disc component peaking at 100 μm . Rowan-Robinson (1992) described a new multigrain model for interstellar grains, and provided a family of models for the emission from interstellar dust in galaxies. These models were fitted to selected nearby galaxies of size > 8 arcmin from the Large Galaxy Catalog (Rice et al. 1988). The present paper applies the same multigrain dust model to starbursts, using an approach based on the models for massive star-forming/H II regions by Efstathiou & Rowan-Robinson (1993, Paper I). We also present spherically symmetric multigrain ‘Seyfert’ models analogous to that of RRC. A variety of arguments have been given in favour of a disc geometry for dust in active galactic nuclei (AGN) (e.g. Lawrence 1991). Efstathiou & Rowan-Robinson (in preparation) have therefore developed axially symmetric, flared disc models for Seyferts and quasars, and these will be presented in a future work.

The concept of a single characteristic starburst spectrum works well for most *IRAS* galaxies (RRC). However, two galaxies studied by RRC, Arp 220 and NGC 4418, were anomalous and required additional dust extinction to fit their far-infrared spectra. Arp 220 was modelled either by a standard starburst model with an additional $A_V = 78$ mag of extinction, which could arise because the system is seen edge-on (RRC), or by a quasar in a uniform dust cloud with

$A_V = 40$ mag. NGC 4418 was modelled as a starburst with an additional 39 mag of extinction.

Condon et al. (1991) have shown that there are a number of ultraluminous galaxies which have similar infrared spectra to Arp 220. Condon et al. showed that the resolved radio structure of the sources corresponds to a compact starburst with high optical depth. In this paper we show that such galaxies form a natural extension of the starburst model of RRC.

2 DESCRIPTION OF THE STARBURST MODELS

The method of solution of the radiative transfer problem for multigrain models is a generalization of the method of Efstathiou & Rowan-Robinson (1990), and was described in Paper I. Each grain species is in radiative equilibrium with the total radiation field. The grain mixture adopted for the calculations in this paper is that of Rowan-Robinson (1992), which is in very good agreement with the interstellar extinction curve and with *COBE* observations of the spectrum of emission from interstellar dust. The mixture invokes the minimum number of grain types consistent with all the available observational evidence. It includes (i) 0.1- μm amorphous carbon grains with optical properties derived from models of circumstellar dust shells around carbon stars, (ii) 0.1- μm amorphous silicate grains with properties derived from circumstellar dust shells around M stars, (iii) 0.03- μm graphite grains, (iv) 0.03- μm silicate grains, (v) 0.01- μm graphite grains, (vi) 0.01- μm silicate grains, and (vii) 30- μm amorphous grains. The optical properties of the 0.03- and 0.01- μm grains are as calculated by Draine & Lee (1984).

The 30- μm grains are required to explain excess submillimetre and millimetre radiation from interstellar dust, as observed by *COBE* and balloon-borne experiments.

The model of Rowan-Robinson (1992) also includes two species of very small grain, of radii 0.002 and 0.0005 μm . In the high optical depth models considered in this paper, these very small grains will have a negligible effect on the continuum spectrum (Rowan-Robinson 1986). We have not included them in the present calculations; their mass is included in that of the 0.01- μm graphite particles. Results from the multigrain calculation were compared with those obtained from a composite-grain model derived from this mixture in Paper I. For models with high optical depth, the results were remarkably similar for the multigrain and composite-grain models.

The total amount of dust in the cloud is parametrized by the ultraviolet (1000 \AA) optical depth to the centre of the cloud, τ_{UV} , given by

$$\tau_{\text{UV}} = \int_{r_1}^{r_2} \sum_{i=1}^N C_{n,\text{ext}}^i n^i dr, \quad (1)$$

where $C_{n,\text{ext}}^i$ is the cross-section and n^i the density of the i th grain species (N in all). The source function of the central source is assumed to be either a blackbody at temperature T_s and radius r_s or a power law with index α ($F_\nu \propto \nu^{-\alpha}$). The dust cloud is assumed to be spherically symmetric and to have a density distribution given by $n(r) \propto r^{-\beta}$, for $r_1 \leq r \leq r_2$, and the dust temperature at the inner edge of the dust cloud is taken to be T_1 (1000 K unless specified otherwise). Other assumptions about the source function or the density distribution could easily be incorporated into the calculation.

The assumption of a single illuminating source is clearly an oversimplification of the situation in a starburst, where a large number of massive stars are expected to have formed. The calculation is valid if the stars form a cluster of radius $\ll r_1$. However, even if the stars are distributed throughout the inner part of the dust cloud, the models will probably give a reasonably accurate prediction of the far-infrared spectrum. The starburst model spectrum presented here can also be thought of as a superposition of many H II region spectra of the type modelled in Paper I. In that case, the derived values of r_1 and r_2 would be $n^{1/2}$ times the values for the individual clouds, where n is the number of clouds.

The optical depths required in these models are so large ($\tau_{\text{UV}} \geq 100$, $A_V \geq 20$) that for a spherically symmetric dust cloud no optical emission lines would be seen, in contrast to observations of starburst galaxies, for which H α is a very prominent line and is well correlated with the infrared luminosity (Persson & Helou 1987; Leech et al. 1988). Some portion of the ultraviolet continuum in the starburst must therefore escape capture by the dust (Leech et al. 1989; Rowan-Robinson 1990). On the other hand, the high optical depths assumed are supported both by the observed depths of the 10- μm silicate feature (Phillips, Aitken & Roche 1984; Aitken & Roche 1984, 1985; Roche et al. 1991) and by the ratios of Br α to Br γ (Kawara, Nishida & Phillips 1989). In general, we must therefore suppose that the geometry is not spherically symmetric. In the case of the nearby starburst in NGC 1068 the illuminating stars form a ring at the inner edge of the dust cloud, and it may be that a disc geometry is appropriate in most cases. However, the covering factor of the dust must be high because of the high ratio of far-infrared

to H α luminosity seen in starburst galaxies (≈ 40 , even after correction for the dust extinction seen to the H α and H β emission lines). The spherically symmetric, centrally illuminated models presented here should therefore provide a good model for the far-infrared emission. Our models will not, however, be adequate for the case in which the illuminating stars are spread uniformly throughout the dust cloud (e.g. Puxley et al. 1990, model C). It is not clear that the latter geometry is capable of accounting for all of the phenomena discussed above. Detailed mapping in the 2–10 μm region of the spectrum will be needed to unravel the geometry.

Finally, the simple power-law dust density distributions used here are bound to be an oversimplification. It is perhaps surprising how well the uniform-density models fit the spectra, both of individual H II regions in our Galaxy and of starbursts in other galaxies.

3 A NEW MODEL FOR THE FAR-INFRARED EMISSION FROM STARBURST GALAXIES

The infrared spectra of galaxies can be modelled in terms of a small number of distinct components (Helou 1986; Rowan-Robinson & Crawford 1986, 1989; Edelson & Malkan 1986; Désert, Boulanger & Puget 1990; Lawrence et al. 1991). RRC, in particular, have demonstrated that the far-infrared spectra of most *IRAS* galaxies can be modelled by the superposition of three components that are independently known to exist: a cool ‘disc’ or ‘cirrus’ component arising from re-emission by interstellar dust of the general galactic starlight; a ‘Seyfert’ component peaking at 12–25 μm arising from emission from dust in the narrow-line regions of AGN, and a ‘starburst’ component peaking at around 60 μm . The concept of three simple components is supported by the distinct locations of normal galaxies, starbursts and Seyferts/AGN in the *IRAS* colour–colour diagrams (Edelson & Malkan 1986; RRC). Rowan-Robinson (1992) has produced a family of ‘disc’ models corresponding to different levels of the mean intensity of the interstellar radiation field, parametrized by the quantity χ which is defined as the ratio of the interstellar radiation field to the corresponding value in the solar neighbourhood. Such models account for the far-infrared emission from interstellar dust in our Galaxy and in other nearby galaxies.

We naturally seek a model for the starburst component within the framework of the models of Paper I, which provide a satisfactory explanation of the far-infrared spectra of compact H II regions and regions of massive star formation in our Galaxy. As in Paper I, we assume that $T_s = 40\,000$ K [Rowan-Robinson (1980) showed that this is not a very critical parameter], and that the density distribution index $\beta = 0$, i.e. that we have a uniform dust cloud. Fig. 1(a) shows a fit to the prototype starburst spectrum of RRC, and to the spectrum of the starburst component of NGC 1068, with a multigrain model in which $\tau_{\text{UV}} = 200$ and $r_1/r_2 = 0.002$. The model provides a good overall fit to the observed spectrum, including the recent millimetre and submillimetre measurements by Rowan-Robinson et al. (in preparation). The model spectrum lies slightly below that observed in the wavelength range 150–300 μm . At long wavelengths ($\lambda > 300$ μm), the 30- μm grain component postulated by Rowan-Robinson (1992) provides the bulk of the emission. Fig. 1(b) shows the corresponding fit to the

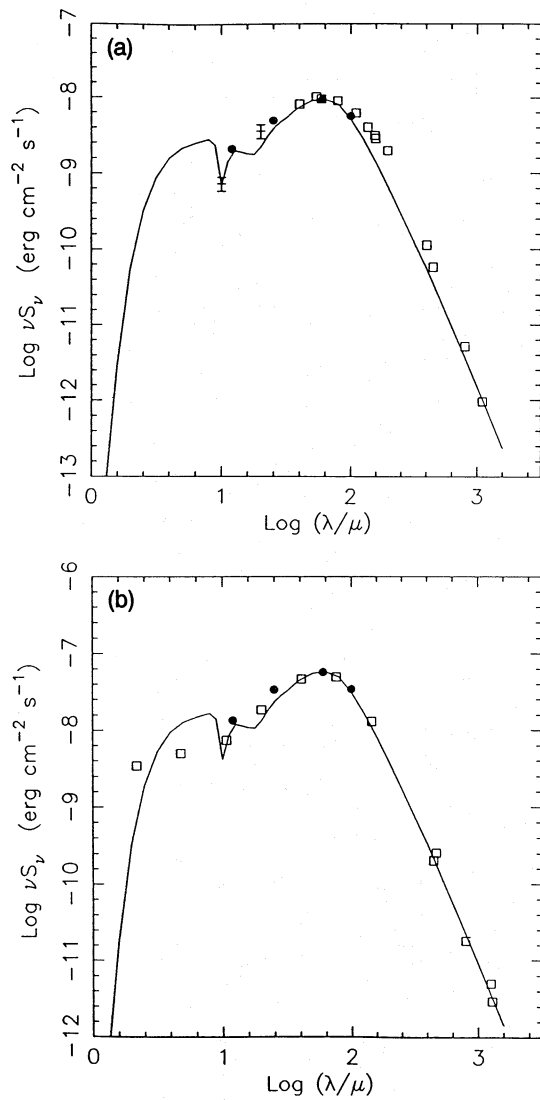


Figure 1. (a) A simultaneous fit to the spectrum of the 'starburst' component of RRC (crosses) and to the starburst ring of NGC 1068 with the starburst model of the present paper ($\beta=0$, $T_s=40\,000$ K, $r_1/r_2=0.002$, $\tau_{UV}=200$). Filled circles are *IRAS* data; other data from Telesco, Becklin & Wynn-Williams (1984) and Rowan-Robinson et al. (in preparation). (b) A similar fit for M82 (data from Hughes, Gear & Robson 1990).

integrated spectrum of another nearby starburst galaxy, M82. Again, the fit is excellent at wavelengths $\geq 10\ \mu\text{m}$. At shorter wavelengths, the predicted spectrum is very sensitive to the details of the density distribution near the illuminating stars, and to any departures from spherical symmetry. The use of the new multigrain dust model of Rowan-Robinson (1992), which was developed to fit the interstellar extinction curve and cirrus spectrum of our Galaxy, has also significantly improved the fit to the spectra of starburst galaxies. Table 1 tabulates the model spectrum.

4 NEW MODELS FOR THE INFRARED EMISSION FROM SEYFERT GALAXIES AND AGN

The infrared emission from Seyfert galaxies and AGN is more difficult to model, for a number of reasons. The spectra

Table 1. Starburst model ($4\nu H_\nu \equiv \nu S_\nu / \Omega$ in $\text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$).

$\log \lambda\ (\mu\text{m})$	$\log(4\nu H_\nu)$
3.200	-3.759
3.100	-3.357
3.000	-2.957
2.900	-2.557
2.800	-2.160
2.700	-1.767
2.600	-1.378
2.500	-1.034
2.400	-0.681
2.300	-0.330
2.200	0.009
2.100	0.319
2.000	0.585
1.900	0.789
1.800	0.851
1.700	0.838
1.600	0.750
1.550	0.684
1.500	0.608
1.450	0.545
1.400	0.461
1.350	0.351
1.300	0.213
1.250	0.120
1.200	0.126
1.150	0.149
1.100	0.164
1.050	0.030
1.000	-0.286
0.950	0.235
0.900	0.312
0.800	0.261
0.700	0.196
0.600	0.067
0.500	-0.188
0.400	-0.629
0.300	-1.391
0.200	-2.640
0.100	-4.484
0.000	-6.235

of AGN show a considerable range in the ratio of the energy emitted in the optical-UV and infrared bands. The origin of the difference between type 1 and type 2 Seyfert line spectra is still controversial, and the mechanism that makes some AGN radio-loud and others radio-quiet remains unclear. Some properties of AGN can be understood in terms of an axisymmetric geometry for the dust cloud surrounding the nucleus, for example, a disc or torus geometry (Lawrence 1991, and references therein). The line spectrum and the ratio of optical-UV to infrared luminosity would then depend on viewing angle. Although the presence of at least some dust in AGN is widely acknowledged, it is not clear whether the infrared emission from Seyferts is due to an underlying power law extending all the way from the ultraviolet to the far-infrared on which a small amount of dust emission is superposed, or to emission from a thicker cloud which reprocesses a significant fraction of the central source

radiation and re-emits it in the infrared. RRC modelled the far-infrared ‘Seyfert’ component using the former of these two pictures. The inconsistency in the source sizes inferred from synchrotron models for a sample of radio-quiet AGN, for which millimetre data had been obtained, prompted Lawrence et al. (1991) to consider models consisting of a thermal source (a blackbody at $T_s = 30\,000$ K) embedded in an optically thick cloud.

Axially symmetric disc models for AGN will be discussed in a later paper in this series (Efstathiou & Rowan-Robinson, in preparation). Here we present spherically symmetric multigrain models, analogous to those of RRC and Lawrence et al. (1991) which employed composite grains. Fig. 2 shows two spherically symmetric models that are in reasonable agreement with the spectrum of the standard ‘Seyfert’ component of RRC. The first is a low optical depth ($\tau_{UV} = 1$) cloud with $r_1/r_2 = 0.001$ surrounding a power-law continuum source with $\alpha = 0.7$. The second model is analogous to that of Lawrence et al. (1991): a blackbody source with $T_s = 30\,000$ K surrounded by a dust cloud with $\tau_{UV} = 90$ and $r_1/r_2 = 0.004$. In both cases the density distribution is taken to be $n(r) \propto r^{-1}$. This is largely determined by the requirement that the spectrum must peak in the mid-infrared. It has been pointed out by Lawrence et al. (1991) that one of the challenges faced by such models is that they tend to predict prominent emission features at 10 and 20 μm , which seem to be absent from the spectra of the small number of AGN for which mid-infrared spectrophotometry is available (Aitken & Roche 1985; Roche et al. 1991). It is interesting to note

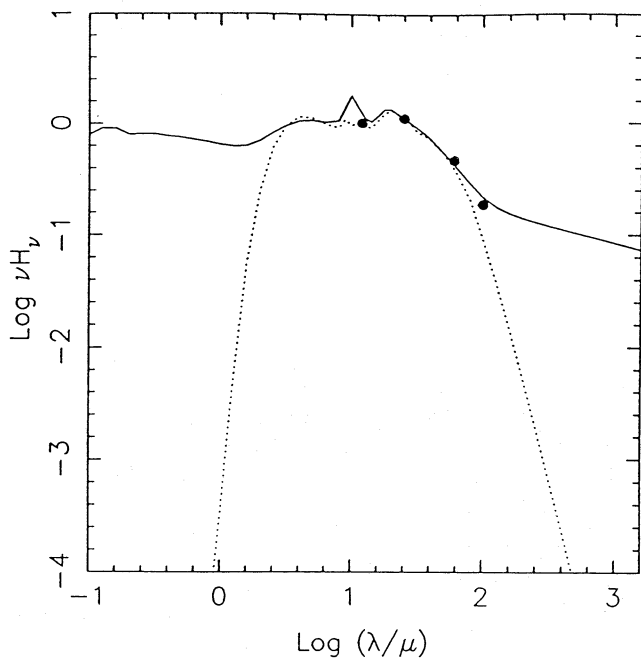


Figure 2. Fit to the spectrum of the ‘Seyfert’ component of RRC with two physically different models. The solid line represents a power-law source ($\alpha = 0.7$) surrounded by a cloud of low optical depth ($\beta = 1$, $\tau_{UV} = 1$, $r_1/r_2 = 0.001$). The dotted line represents a blackbody source ($T_s = 30\,000$ K) surrounded by an optically thick cloud ($\beta = 1$, $\tau_{UV} = 90$, $r_1/r_2 = 0.004$).

that, in the high- τ_{UV} model, the parameters needed to fit the ‘Seyfert’ component colours are also the ones that minimize the silicate features.

Preliminary results from axisymmetric models for AGN (Efstathiou & Rowan-Robinson, in preparation) show that models with flat mid-infrared spectra and a range of optical-to-infrared luminosity ratios can be obtained when dusty discs are viewed from different orientations. The infrared spectra of AGN therefore suggest that the dust responsible for the infrared emission must be concentrated in axisymmetric clouds with high equatorial optical depth and a density distribution of the form $n(r) \propto r^{-1}$. However, such models invariably predict a 10- μm emission feature when viewed from a face-on direction, and no such feature is observed in Seyfert 1 galaxies.

5 MODELS FOR COMPACT ULTRALUMINOUS STARBURSTS

One of the greatest challenges of infrared astronomy today is the quest for the energy source that powers the most luminous *IRAS* galaxies, those with infrared luminosities greater than, say, $10^{12} L_{\odot}$. Three possible powering mechanisms have been suggested: starburst activity, accretion in a dust-embedded AGN or the kinetic energy of colliding galaxies (Harwit et al. 1987).

The presence of about $10^{10} M_{\odot}$ of molecular gas in some of these galaxies, indicated by their CO line strengths (Sanders et al. 1988), argues in favour of the starburst interpretation. Their optical spectra, on the other hand, often show evidence of Seyfert or LINER activity [Sanders et al. (1988) claim that all galaxies with $L_{FIR} > 10^{12} L_{\odot}$ show such activity; but see Rowan-Robinson (1991) and Leech, Rowan-Robinson & Lawrence (1993)]. Their radio structure may be the only way in which we can distinguish between different mechanisms. Radio sources produced by AGN usually have very compact components (≤ 1 kpc), whereas starbursts are more extended, with diffuse structures.

The 40 most luminous galaxies in the Bright Galaxy Sample (Soifer et al. 1984) are dominated by compact (≤ 1 arcsec) radio sources. Recent mapping of these galaxies with 0.25-arcsec resolution at 8.44 GHz (Condon et al. 1991) has shown that, while galaxies with $L_{FIR} < 10^{11.7} L_{\odot}$ exhibit radio properties similar to those of known starburst galaxies, the more luminous ones often contain resolved radio components that are significantly smaller than the lower limit of their far-infrared sizes (the latter being estimated from their *IRAS* spectra). Condon et al. (1991) attributed the unusual properties of the more luminous galaxies to the fact that the infrared and radio emissions originate in compact starbursts that are dense enough to be optically thick for $\lambda \leq 25 \mu\text{m}$. A similar conclusion has been reached by Sopp & Alexander (1991).

In the light of the above evidence, it is natural to investigate whether optically thicker versions of our starburst model could explain the spectra of these galaxies. To test this hypothesis, we plot in Fig. 3 the $S(100)/S(60)$ versus $S(60)/S(25)$ colour-colour distributions of both the compact sources and the more extended ones. The two classes of object occupy fairly distinct regions in the colour-colour diagram. While the colours of the extended sources lie more or less along the mixture line joining the ‘starburst’ and

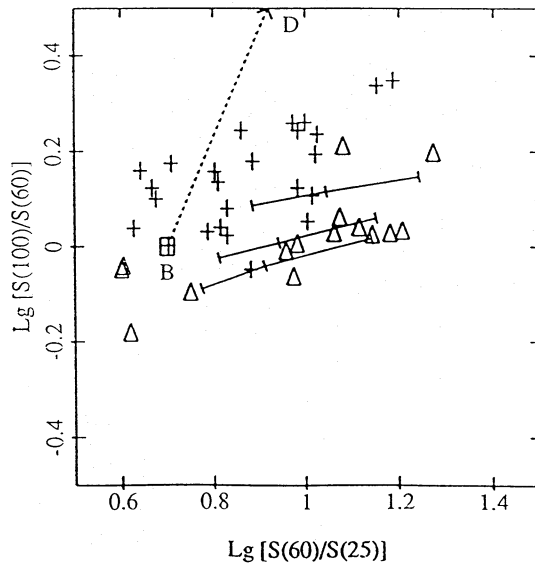


Figure 3. The *IRAS* $S(100)/S(60)$ versus $S(60)/S(25)$ colour-colour diagram for the 40 most luminous galaxies in the Bright Galaxy Sample. Triangles represent the compact radio sources and crosses represent the more extended ones (see text). Superposed are theoretically predicted colours plotted along lines of constant r_1/r_2 (0.001, top; 0.0015, middle; 0.002, bottom). Tick marks denote models with $\tau_{UV} = 200, 300$ and 500 (left to right). All models assume $\beta = 0$ and $T_s = 40\,000$ K. Also shown (dashed line) is the line joining the 'starburst' (B) and 'disc' (not shown) components of the RRC model.

'cirrus' components of RRC (as do less luminous *IRAS* galaxies), the compact sources generally have a higher $S(60)/S(25)$ ratio than that of the 'starburst' component (labelled B in Fig. 3). Also plotted in Fig. 3 are the colours predicted by theoretical models with $\tau_{UV} = 200$ – 500 and $r_1/r_2 = 0.001, 0.0015$ and 0.002 . These models straddle the region occupied by the compact ultraluminous starbursts remarkably effectively. The corresponding $25\text{-}\mu\text{m}$ optical depths lie in the range 0.84 – 2.1 , supporting the conjecture of Condon et al. (1991).

Even more impressive is the agreement of one of the computed models with the infrared spectrum of the prototypical ultraluminous galaxy Arp 220, shown in Fig. 4. The model has $\tau_{UV} = 500$ ($A_V = 100$), and the inner and outer angular radii of the dust cloud are 0.0055 and 3.64 arcsec. For an assumed distance of 78 Mpc, these correspond to inner and outer linear radii of 2.1 pc and 1.4 kpc. The total mass of dust required is $1.1 \times 10^8 M_\odot$.

6 CONCLUSIONS

We have applied the multigrain radiative transfer code described in Paper I to spherically symmetric dust cloud models for starburst and Seyfert galaxies, and have obtained good fits to the infrared spectra of these galaxies. A subsequent paper (Efstathiou & Rowan-Robinson, in preparation) will discuss axisymmetric disc models for infrared emission from Seyferts and AGN.

We have also presented models for compact ultraluminous starbursts, which are simply higher optical depth variants of our standard starburst model. The excellent fit of these

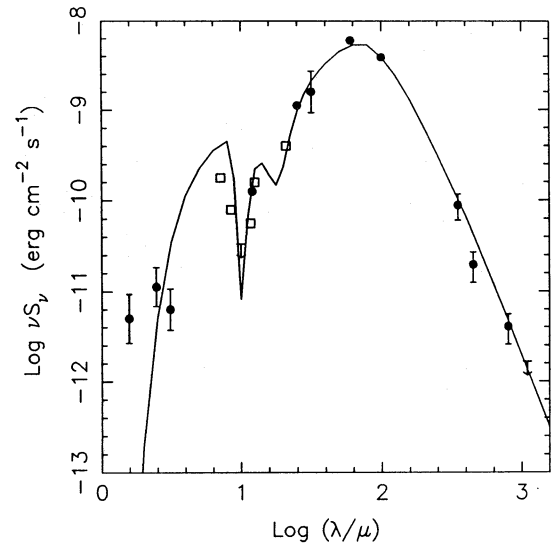


Figure 4. Model fit to the spectrum of the prototypical ultraluminous galaxy Arp 220. The model assumes $\beta = 0$, $r_1/r_2 = 0.0015$, $\tau_{UV} = 500$ and $T_s = 40\,000$ K. Filled circles at $12, 25, 60$ and 100 μm are *IRAS* data; other data are from Emerson et al. (1984), Becklin & Wynn-Williams (1987) and Eales, Wynn-Williams & Duncan (1989).

models to the far-infrared spectra of such galaxies supports the idea of compact starbursts as the energy sources in most ultraluminous galaxies.

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