Cirrus models for local and high z SCUBA galaxies

Andreas Efstathiou[1] and Michael Rowan-Robinson[2]

[1] *Department of Computer Science & Engineering, Cyprus College, 6 Diogenes Str, 1516 Nicosia, Cyprus.*
[2] *Astrophysics Group, Blackett Laboratory, Imperial College of Science Technology and Medicine, Prince Consort Road, London SW7 2BZ*

9 May 2007

ABSTRACT

We present a model for the UV to submillimeter emission from stars embedded in the general interstellar dust in galaxies (the 'infrared cirrus' component). Such emission is characterized by relatively low optical depths of dust and by cool (< 30 K) dust temperatures. The model incorporates the stellar population synthesis model of Bruzual & Charlot and the dust model of Siebenmorgen & Krügel which includes the effects of small grains/PAHs. We apply the model to fit the optical to submillimeter spectral energy distributions (SEDs) of nearby galaxies which are dominated by cirrus emission and find that our simple model is quite adequate to explain the observed SEDs.

We also, more controversially, apply this cirrus model to the SEDs of high redshift sources detected in blank field submillimeter surveys with SCUBA. Surprisingly, an excellent fit is found for many of these sources, with typical values for the optical depth A_V and the surface brightness of the stellar radiation field ψ being only a factor 2-3 higher than for nearby galaxies. This increase is not unreasonable given the expected evolution of dust optical depth in currently favoured star-formation history models.

We conclude that the tendency to interpret the high-z SCUBA galaxies as very highly obscured starbursts may be premature and that these galaxies may be more closely linked to optically selected high redshift galaxies than previously assumed.

Key words: infrared: galaxies - galaxies: evolution - star:formation - galaxies: starburst - cosmology: observations

1 INTRODUCTION

The need for several different components to understand the infrared and submillimetre spectral energy distributions (SEDs) of galaxies has been recognized for some time. Rowan-Robinson and Crawford (1989) modelled IRAS galaxy colour-colour diagrams in terms of three components, starburst, cirrus and AGN components. The cirrus component corresponded to the absorption of the general starlight of a galaxy by interstellar dust and reemission in the infrared, as identified in our Galaxy by Low et al (1984). Detailed models for the cirrus component were given by Rowan-Robinson (1992), but these did not include a treatment of the line emission from the PAH component. A model of the infrared emission of the solar neighbourhood that included the effect of small grains and PAHs was presented by Siebnmorgen & Krügel (1992). Efstathiou, Rowan-Robinson & Siebenmorgen (2000; hereafter ERS2000) have given the most detailed model to date of the evolution of the infrared emission from a starburst. In this paper we describe a tool which allows the cirrus emission to be modelled from 0.1-1000 μm and apply it both to local galaxies which have been mapped with SCUBA and to high redshift galaxies found in deep SCUBA surveys at 850 μm. Hitherto there has been a tendency to interpret these SCUBA galaxies as high redshift versions of Arp220, but Rowan-Robinson (2001) has pointed out that submillimetre counts and background radiation are much more naturally understood in terms of cirrus-like emission.

Silva et al (1998) and Granato et al (2000) have given models for infrared SEDs which include both starburst and cirrus components. These models take into account the distribution of dust and stars in the galaxy and incorporate a population synthesis model. The effect of changes in metallicity during the lifetime of a galaxy is also taken into account. The cirrus models we present here are simpler than those of Silva et al (1998) and Granato et al (2000) but appear to be just as good a representation of the observed SEDs of nearby normal galaxies. Starburst models that take into account the distribution of dust and stars were also presented by Krügel & Siebenmorgen (1994) and Siebenmorgen, Krügel & Laureijs (2001).

The layout of this paper is as follows: section 2 describes our cirrus model in detail, section 3 applies this model to nearby galaxies which have been mapped with SCUBA, section 4 discusses the application to high redshift SCUBA galaxies, and section 5 gives our discussion and conclusions.

2 THE CIRRUS MODEL

The ingredients of a cirrus model are (1) the input stellar radiation field, which has to be characterized both with regard to its spectrum and its intensity, (2) an interstellar dust model, with assumptions about its distribution and opacity, (3) a radiative transfer treatment of the interaction between the two to generate the output SED. Our goal is to provide a versatile tool which can be used for example in simulations of the galaxy formation history.

For specifying our input stellar radiation field we have used the Galaxy Isochrone Synthesis Spectral Evolution Library (GISSEL, Bruzual & Charlot 1993) that gives the ultraviolet to near infrared spectrum of radiation from a mass of stars as a function of time.

Stars form in dusty molecular clouds and spend a considerable amount of time inside them. During this phase, the stellar radiation is absorbed by molecular cloud dust and reprocessed to the infrared. We use the code of ERS2000 to compute the emission of the stellar population during this phase. The molecular cloud is assumed to disperse 7.2×10^7 years after the instantaneous formation of stars inside it. However, well before 7.2×10^7 years non-spherical evolution of the molecular cloud may allow a fraction f of the starlight to escape without any dust absorption. We assume that this occurs at time t_m after star formation. By further assuming that the radiation field in a galaxy is due to a large number of randomly oriented molecular clouds, their average emission (for stars in the age range t_m to 7.2×10^7 years) is approximately

$$(1-f)S_\nu^s + fS_\nu^*$$

where S_ν^s is the emission from a spherical GMC (as computed by ERS2000) and S_ν^* is the emission from the stellar population in the absence of any molecular cloud dust (Bruzual & Charlot). The emission of stars younger than t_m or older than 7.2×10^7 years is assumed to be S_ν^s or S_ν^* respectively. In fact for most of this paper we have simplified the model by assuming $f = 1$. The effect of allowing $f < 1$ is discussed in section 5.

Other parameters which have to be specified are the star formation history function $\dot{\phi}_*(t)$, the epoch at which this history begins, t_i, the epoch of observation, t, and the usual parameters for the stellar IMF. Since the quantity which determines the dust temperature is the intensity of the stellar radiation field, we have chosen to characterise this in terms of the ratio of the bolometric intensity of the radiation field to that in the stellar radiation field in the solar neighbourhood (Mathis et al 1983), ψ. The star-formation rate, $\dot{\phi}_*(t)$, is assumed to have an exponential form, with exponential time scale, τ, and a Salpeter IMF from 0.1-125 $M_\odot$ is assumed. The age of the galaxy, $t_* \equiv t - t_i$, can also be specified.

We use the dust grain model of Siebenmorgen and Krügel (1992), which incorporates a detailed treatment of small grains and PAHs, and then characterize the opacity of the interstellar dust by A_V. A_V determines how much of the uv to near-ir light is absorbed by dust and reemitted in the infrared and submillimetre bands, and therefore controls the ratio of luminosity in the far infrared to the luminosity in the uv to near-ir. If $A_V << 1$, we are in the optically thin regime and the dust temperature will then be determined by ψ and the shape of the input spectrum (determined by the star formation history). For $A_V \geq 1$ but not $>> 1$, the dust will modify the emergent optical and uv spectrum significantly, but will still not result in any significant change to the dust temperature along the line of sight to the central plane of the galaxy. We make a further simplifying assumption, that for the purposes of modelling the galaxy's emergent SED, we can characterize the galaxy by a single average value of ψ. Strictly speaking we should model the density distribution of both dust and stars and carry out a full radiative transfer calculation to compute the emergent spectrum. The emergent spectrum would essentially be a superposition of spectra corresponding to different values of ψ at different locations through the galaxy. In practice we find that a single value of ψ characterizes the emergent spectra very adequately.

To summarize, the parameters of the model that have to be set are ψ, τ, t_*, A_V, f and t_m. The parameters τ, t_*, f and t_m determine the shape of the optical SED, with A_V determining the reddening to be applied to this and also, in a self-consistent manner, the bolometric luminosity of the infrared emission. ψ determines the temperature of the different grain species in the model and hence the shape of the far infrared SED. There is also a slight dependence of grain temperature on the shape of the optical SED.
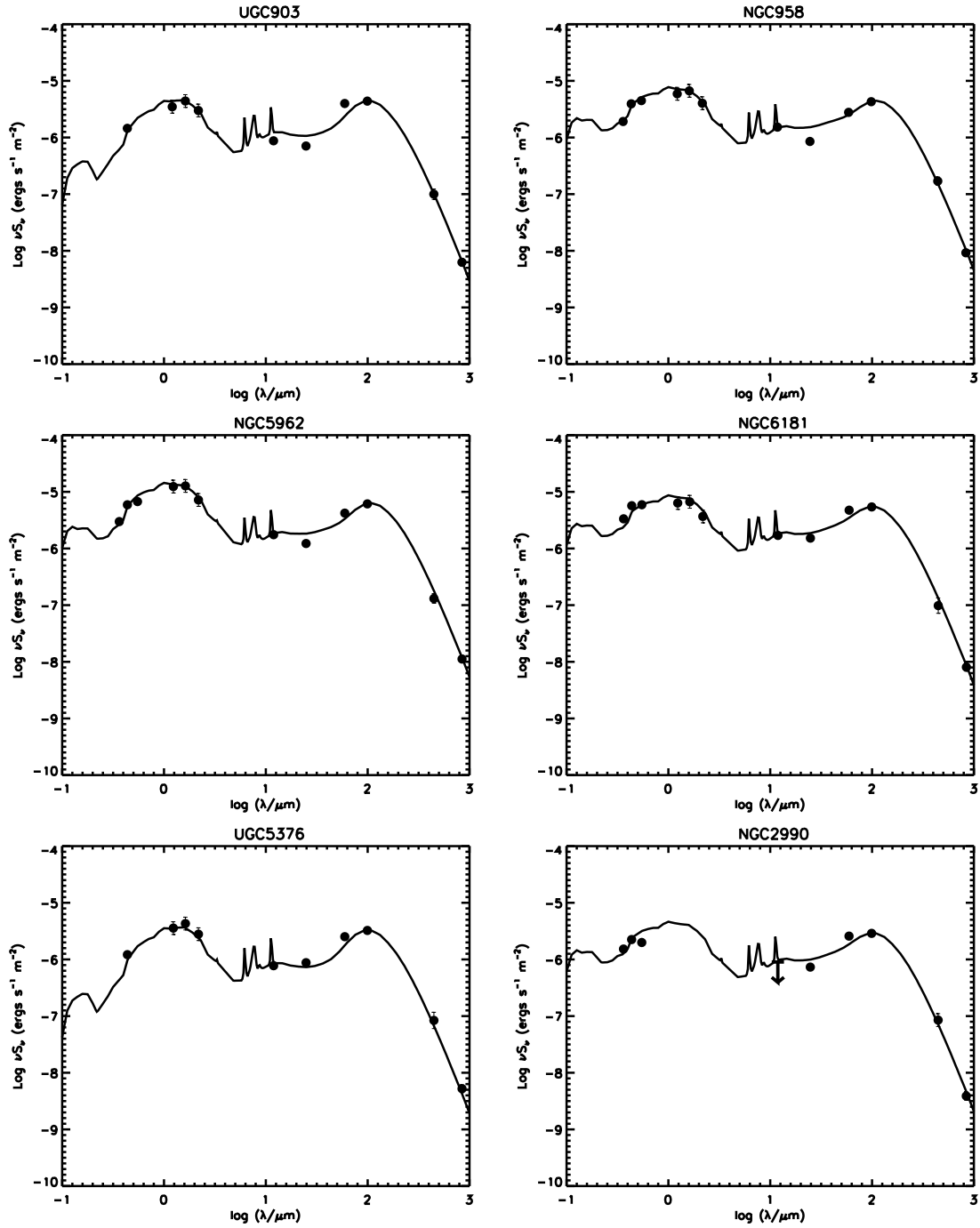
Figure 1. Spectral energy distributions of nearby cirrus galaxies. Data from IRAS, Dunne & Eales (2001) and the NASA/IPAC Extragalactic Database (NED). Model parameters given in Table 1.

For $t_* = 0.25$ Gyrs and $\tau = 6$ Gyrs the temperature of the large classical grains is in the range 17-24K for $\psi = 1$ and 28-41K for $\psi = 21$. Note that the far-infrared emission is dominated by the emission of the largest and coolest grains. For $t_* = 12.5$ Gyrs and $\tau = 6$ Gyrs the corresponding temperature ranges are 16-21K for $\psi = 1$ and 26-36K for $\psi = 21$.

Our code and a selection of models is available at http://astro.ic.ac.uk/~ane/cirrus-models.html

Name	A_V	τ/Gyrs	ψ	χ^2/ndf
UGC903	0.9	6	4	1.05
NGC958	0.4	9	2	0.56
NGC5962	0.4	5	3	0.56
NGC6181	0.4	11	3	0.97
UGC5376	0.9	5	5	0.35
NGC2990	0.4	11	3	1.33
NGC1667	0.5	11	8	1.42

Table 1. Fitted parameters for the nearby cirrus galaxies: dust optical depth, A_V; exponential time-scale for star formation, τ; intensity of interstellar radiation field relative to solar neighbourhood, ψ; goodness of fit, χ^2. All models assume a galaxy age t_* of 12.5Gyrs, $f = 1$ and $t_m = 3$Myrs.

3 APPLICATION TO NEARBY GALAXIES

Dunne & Eales (2001) have given the results of a SCUBA mapping program of 19 galaxies. The far infrared spectrum of four of these (N1614, I Zw 107, IR 1525+36, Arp 220) are obviously dominated by a starburst component. For a further 7 galaxies there is evidence from the 60/850 μm colours that a starburst component is present ($log_{10}\frac{S(60)}{S(850)} > 1.8$). We also excluded NGC7541 because of the large flux correction applied to the $450\mu m$ data by Dunne & Eales (2001). We have therefore modelled the SEDs of the remaining 7 galaxies, including optical and near infrared data from the literature, in terms of a cirrus component (Figure 1). The parameters for the models are given in Table 1. For NGC1667 we only give the fitted parameters in Table 1. The fits are extremely good and do not show evidence that a more elaborate cirrus model is required. The values of ψ range from 2 to 8, and the values of A_V range from 0.4 to 0.9. Such values are consistent with the local distribution function for the ratio $log_{10}(L_{fir}/L_{opt})$, which peaks at -0.7 and can be fitted with a Gaussian with $\sigma = 0.24$ about this (Rowan-Robinson et al 1987). As pointed out by Rowan-Robinson (1992), the parameter ψ is proportional to the mean surface brightness of the galaxy.

4 APPLICATION TO HIGH REDSHIFT SCUBA GALAXIES

The detection of a number of galaxies in blank field surveys with SCUBA et 850 μm (Hughes et al 1998, Eales et al 1999, Barger et al 1999, etc) and the realization that most of these are at redshift > 1, with some probably at z > 3, has had a big impact on ideas about galaxy formation and evolution. Most attempts to fit the SEDs of these galaxies (Hughes et al 1998, Downes et al 1999, Lutz et al 2001, etc) and most attempts to fit the 850 μm counts and background (Guiderdoni et al 1998, Dole et al 2001, Xu et al 2001, Franceschini et al 2001, Pearson 2001, Granato et al 2001) have assumed that we are looking at a very strongly evolving, deeply dust-embedded star-

burst population. However Rowan-Robinson (2001) argues that the natural interpretation of the submillimetre counts and background is in terms of a cirrus-type component. How can the latter picture be reconciled with the failure to identify many of the SCUBA galaxies with optical counterparts ? Obviously the dust optical depth must be higher than in local disk galaxies. However that is not an unreasonable expectation at z = 1-3. Calzetti and Heckman (1999) and Pei et al (1999) have predicted how the typical dust opacity in galaxies should evolve with epoch for star-formation histories typical of those derived from uv and infrared surveys. An increase of the average A_V in the interstellar medium in galaxies by a factor of 2 or 3 over present-day values at z =1-2 is to be expected, because the increased gas-density in galaxies far outweighs the slight decline in metallicity over the same look-back time.

Here we have selected two samples of SCUBA high-z galaxies from SCUBA blank-field surveys, confining attention to those with the most reliable optical identification: (a) submm galaxies which have been confirmed by submillimetre interferometry (e.g. Lutz et al 2001), (b) submm galaxies from the 8 mJy survey (Scott et al 2001, Fox et al 2001) which have been confirmed by association with radio sources (Ivison et al 2002). For both these samples the optical and near infrared associations should be reasonably secure. For sample (a) we have the added bonus that the reality of the submillimetre source is confirmed.

To make use of the radio data we have extended our model to the radio regime by utilizing the well known far-infrared-radio correlation (Helou et al 1985). For $\lambda > 60\mu m$ we add to the rest frame model SED S_ν^r where

$$S_\nu^r = 2.7\times10^{-3}(2.58 S_{60\mu m} + S_{100\mu m})\times(\frac{\nu}{1.4GHz})^{-0.8}$$

where $S_{60\mu m}$ and $S_{100\mu m}$ are the 60 and $100\mu m$ fluxes predicted by the model and ν is the frequency in Hz. The factor 2.7×10^{-3} is the maximum value allowed by the far-infrared-radio correlation (Blain 1999).

The model allows us to self-consistently estimate the star formation rate (SFR) of the objects studied. Assuming $t_* = 0.25$Gyrs the SFR is given by
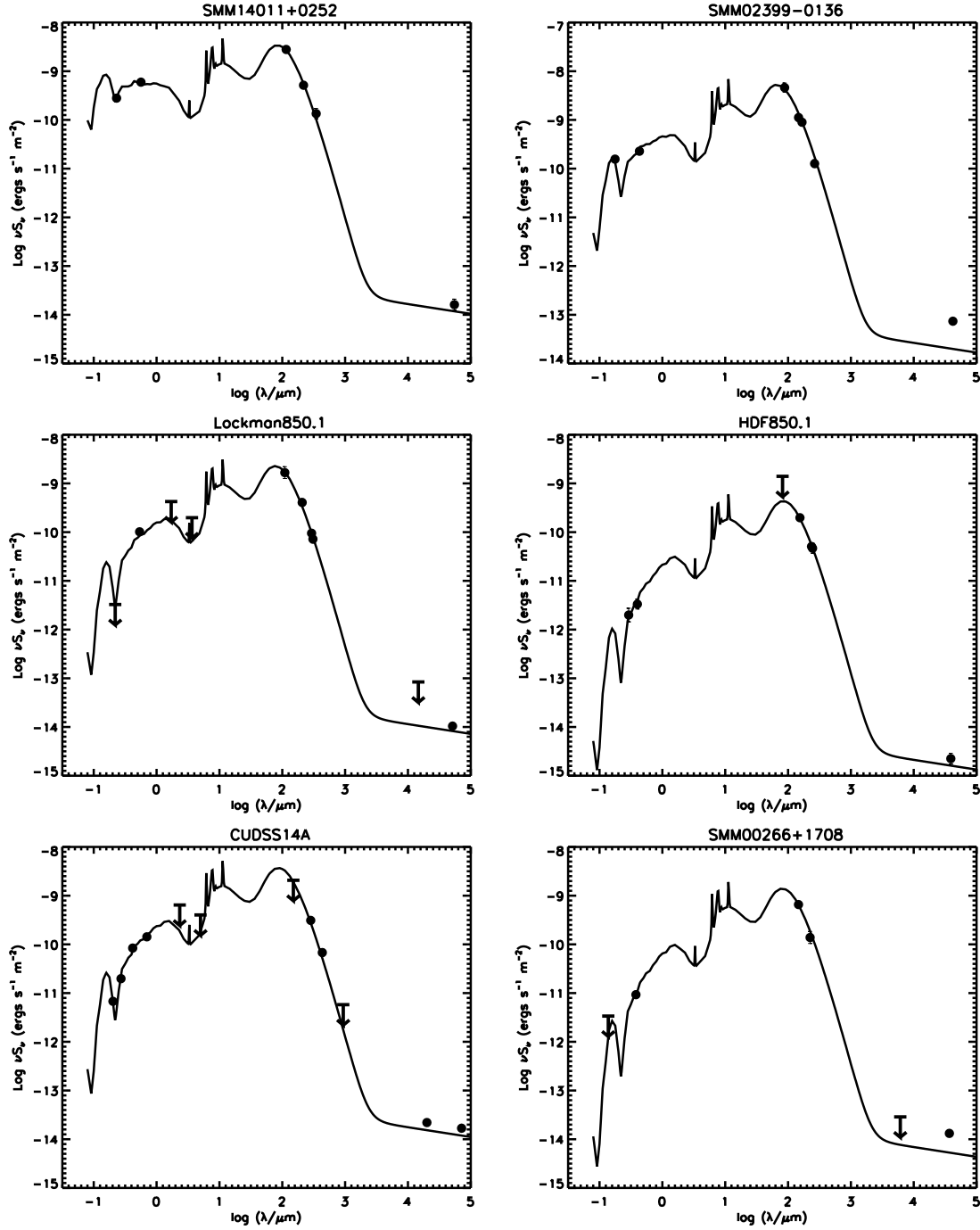
Figure 2. Spectral energy distributions of high redshift cirrus galaxies confirmed by millimetre interferometry. Data from Lutz et al (2001), Dunlop et al (2002), Ivison et al (1998, 2000, 2001), Frayer et al (2000) and Gear et al (2000). Model parameters given in Table 2. For HDF850.1 only the $z = 4.5$ fit is shown.

$$SFR = \frac{L_{bol}}{7.88 \times 10^9} M_\odot yr^{-1}$$

where L_{bol} is the bolometric luminosity of the object (in units of solar luminosity) which we obtain by integrating over the whole wavelength range covered by the models.

To test the predictions of our cirrus model we generated a grid of models in which we vary ψ (in the range 1-21 in steps of 1) and A_V (in the range 0 to 3 in steps of 0.1). For most of the sources in these
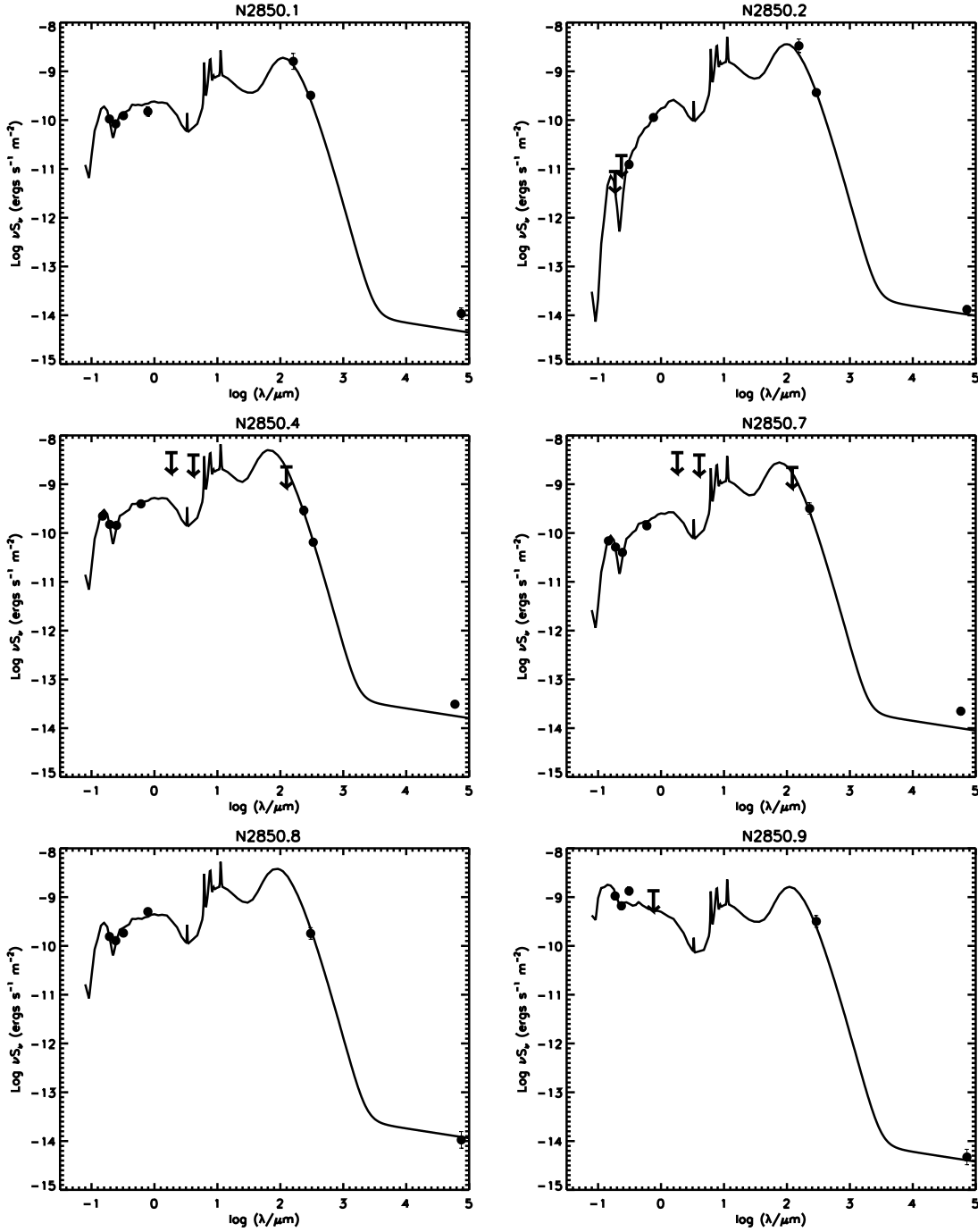
Figure 3. Spectral energy distributions of high redshift cirrus galaxies from the 8 mJy SCUBA survey in ELAIS-N2. Data from Fox et al(2001), Ivison et al (2002). Model parameters given in Table 2.

samples the redshift is unknown so we treat it as a free parameter varying between 0 and 10 in steps of 0.1. For objects with data in only four bands (all of the objects in Lockman East and SMM00266+170) we fix ψ to 6. For all the models we assume $t_* = 0.25 Gyrs$, $\tau = 6$ Gyrs, $f = 1$ and $t_m = 0$.

Minimum χ^2 fits of our cirrus model to the SEDs

of these two samples of high z SCUBA galaxies are shown in Figures 2-4, with the parameters of the models given in Table 2. In N2 we model all the objects with robust radio associations except N2850.5 which is a blank field in all optical and near-IR bands, and N2850.13 which is detected only in K. In LE we exclude LE850.12 and LE850.18 which are detected only
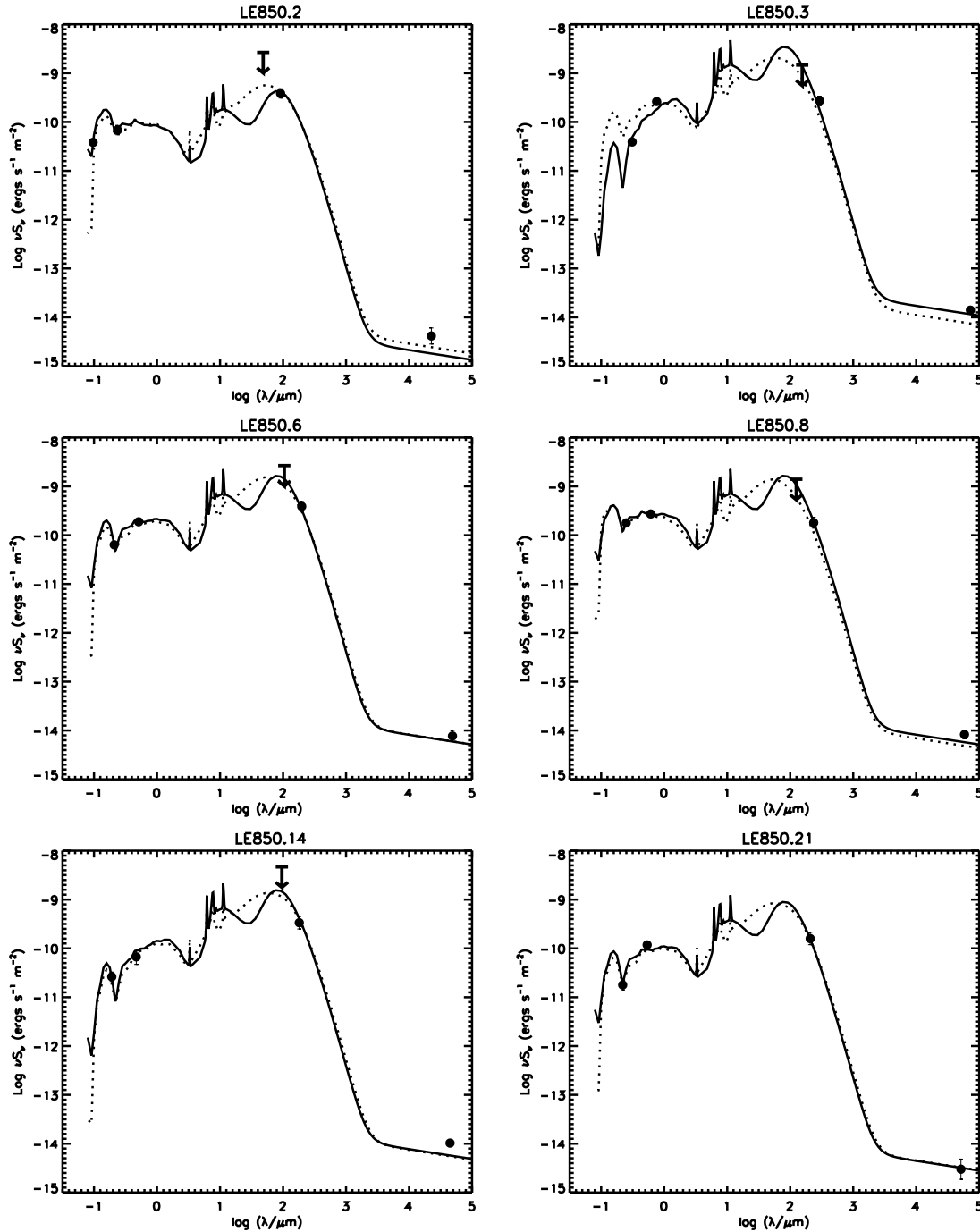
Figure 4. Spectral energy distributions of high redshift cirrus galaxies from the 8 mJy SCUBA survey in Lockman. Data from Fox et al(2001), Ivison et al (2002). Model parameters given in Table 2. Fits with a cirrus model that includes a dust enshrouded phase, discussed in section 5, are shown with the dotted lines.

in the I band. LE850.1 is included in the sample with millimetre interferometry. Fits that exceed the upper limits are rejected. The quoted errors in z indicate the spread in z for fits with χ^2 less than $\chi^2_{min} + 1$.

The fits we obtain are generally good. One notable exception is SMM02399-0136 where the high

reduced χ^2 is almost entirely due to the radio point. Ivison et al. (1998) find evidence for an AGN in this object. Also, the high fitted value of ψ in this object (the maximum value in our grid of models) is perhaps indicative of the presence of a circumnuclear starburst accompanying the AGN in this object. The

Name	χ^2/ndf	ψ	A_V	z	lensing magn.	$log_{10}\frac{L_{bol}}{L_\odot}$	SFR $M_\odot/\mathrm{yr}$
Objects with mm interferometry							
SMM14011+0252	0.824	5	0.9	$2.9^{+0.5}_{-0.5}$	3	12.76	731
SMM02399-0136	14.676	21	1.8	$4.1^{+0.1}_{-0.1}$	2.5	13.31	2577
Lockman850.1	3.329	8	2.3	$3.1^{+0.1}_{-0.1}$	-	13.05	1441
HDF850.1	0.638	5	3.0	$4.5^{+0.3}_{-0.2}$	3	12.23	219
	1.760	21	2.1	$7.1^{+0.2}_{-0.1}$	3	12.53	436
CUDSS14A	1.410	4	2.5	$2.0^{+0.1}_{-0.1}$	-	12.81	819
SMM00266+1708	7.840	(6)	3.1	$4.8^{+0.1}_{-0.2}$	2.4	12.91	1033
ELAIS-N2 objects							
N2850.1	3.923	1	1.3	$1.8^{+0.1}_{-0.1}$	-	12.45	360
N2850.2	3.041	2	3.1	$1.9^{+0.1}_{-0.1}$	-	12.75	705
N2850.4	2.007	20	1.5	$2.6^{+0.1}_{-0.1}$	-	13.22	2121
N2850.7	6.122	9	1.8	$2.7^{+0.1}_{-0.1}$	-	13.01	1295
N2850.8	8.378	4	1.4	$1.8^{+0.1}_{-0.1}$	-	12.74	700
N2850.9	7.789	1	0.4	$1.9^{+0.1}_{-0.1}$	-	12.63	542
LE objects							
LE850.2	0.936	(6)	0.7	$8.3^{+0.4}_{-4.3}$	-	13.46	3625
LE850.3	23.859	(6)	2.3	$1.9^{+1.1}_{-0.6}$	-	12.72	673
LE850.6	0.777	(6)	1.2	$3.3^{+0.2}_{-0.1}$	-	13.02	1343
LE850.8	0.275	(6)	0.9	$2.6^{+0.4}_{-0.2}$	-	12.81	815
LE850.14	2.507	(6)	1.8	$3.7^{+0.3}_{-0.1}$	-	13.09	1566
LE850.21	3.593	(6)	1.3	$3.1^{+0.1}_{-0.1}$	-	12.69	620
LE850.7	71.613	(6)	1.3	$3.0^{+0.1}_{-0.1}$	-	13.27	2366
LE objects cirrus model with starburst phase ($f = 0.5$, $t_m = 10^7$yrs)							
LE850.2	0.207	(6)	0.3	$7.9^{+0.2}_{-0.4}$	-	13.52	4222
LE850.3	10.838	(6)	0.8	$3.1^{+0.1}_{-0.1}$	-	13.11	1627
LE850.6	1.541	(6)	0.7	$3.4^{+0.3}_{-0.2}$	-	13.08	1522
LE850.8	0.086	(6)	0.2	$3.1^{+0.1}_{-0.5}$	-	12.95	1141
LE850.14	1.994	(6)	1.3	$3.9^{+0.3}_{-0.3}$	-	13.16	1822
LE850.21	5.278	(6)	0.8	$3.1^{+0.1}_{-0.1}$	-	12.72	662
LE850.7	78.395	(6)	0.8	$3.0^{+0.1}_{-0.1}$	-	13.30	2545

Table 2. Fitted parameters for the high redshift cirrus galaxies with fixed values given in brackets. The age of the starburst t_* is fixed at 0.25 Gyr and the star formation history is assumed to be exponentially decaying with time constant $\tau = 6$ Gyrs. Unless otherwise stated we assume $f = 1$ and $t_m = 0$. Luminosities are calculated by integrating over the whole wavelength range covered by the models. We assume a flat Universe with $H_o = 65$ Km/s/Mpc and $\Lambda = 0.7$. Where appropriate the luminosities (and the resulting SFR) have been corrected by the lensing magnification factor given in the table.

fits to LE850.3 and LE850.7 (not plotted) are also poor. The steep radio spectrum of these objects may also suggest the presence of an AGN (Ivison et al 2002).

The values of ψ are higher, typically, by a factor of 2-3 than the values for local galaxies, and the values of A_V are also higher by a factor of 2-3. Although the values of A_V are higher than in local galaxies, they are much lower (by one or two orders of magnitude) than would be expected in a typical molecular cloud under-

going a starburst. So these models are radically different from the typical dusty starburst model for these high-redshift submillimetre galaxies. Of course, because the bolometric luminosities correspond to high rates of star-formation, much of the optical and uv light which is illuminating the interstellar dust in our cirrus models is light that has escaped from a starburst region, for example by non-spherically symmetric evolution of the associated HII regions. It is also interesting to note that the A_V we infer are compa-

rable to those of molecular clouds in late stages of their evolution (about a few times 10^7 years) as predicted by the starburst evolution model of ERS2000. As pointed out by the latter authors the predicted IRAS colours of these clouds are similar to those of cirrus galaxies.

With a few exceptions we are able to put fairly strong constraints to the redshifts of the sources we model. For SMMS14011+0252 Ivison et al. (2000) report a spectroscopic redshift of 2.56 which is consistent with our model. Smail et al. (2003) give a spectroscopic redshift of 2.38 for N2850.4 which is close to the deduced photometric redshift. For HDF850.1 there are two distinct minima, one at $z = 4.5$ and one at around $z = 7.1$. In Table 2 we give the fitted parameters for both models. For LE850.2 there is a broad minimum between $z = 4$ and 9.

Of the 23 objects in our samples, our models successfully fit the SEDs of 16 of them (70 %). For 4 objects (17%) we have insufficient data (fewer than 4 bands) to be able to test our model. For these objects we may need a higher optical depth model of the M82 or Arp 220 starburst type or values of A_V (> 3) from our cirrus model which are not really consistent with the 'A_V not $>> 1$' requirement of our model. For 3 objects our fitted ψ is close to the maximum in the range considered (21). We assumed the age of the starburst $t_* = 0.25$ Gyr in each case. This will underestimate the contribution of older, low-mass stars in the rest-frame near infrared if present. In the case of N2850.8 we do see evidence for such a near-IR excess.

5 DISCUSSION AND CONCLUSIONS

Although the current state of observations of high-z SCUBA galaxies is insufficient to tell whether our models are better or worse than starburst models, the fits shown here demonstrate that it is premature to make an analogy between SCUBA galaxies and dusty ultraluminous starburst galaxies like Arp 220. Quite a modest dust optical depth ($A_V \sim 1 - 3$) combined with the redshifting of the optical and uv radiation is sufficient to explain why these galaxies are faint in the optical.

The inferred bolometric luminosities imply that enhanced star formation has taken place in these galaxies, so even if we are correct that the observed submillimetre emission arises mainly from cirrus emission, ie reemission from dust in the general interstellar medium of the galaxy, it is likely that some optical and ultraviolet light is intercepted by dust in the dense molecular gas from which the stars formed. Such emission would peak at ~ 50 (1+z) μm and could easily contribute bolometric luminosities comparable to the cirrus luminosities of table 2 without being detectable at present. Estimates of the fraction of optical-uv light which escapes from star-forming regions in the local universe range from 25-50 %. In Fig

4 we have also shown fits for a more elaborate model in which newly formed stars are completely shrouded in their molecular cloud for the first 10^7 yrs, 50% of the starlight escapes to illuminate the interstellar dust from $10^7 - 7.2 \times 10^8$ yrs (i.e. $f = 0.5$ and $t_m = 10^7$ years) and 100% escapes thereafter (cf the starburst evolution models of ERS2000). The starlight that escapes is reprocessed to the infrared in the same way as the pure cirrus model. We have generated a grid of models spanning the same parameter space in A_V, ψ and z as for the pure cirrus model. These models, when observed at 0.25 Gyr from the start of the starburst, are very similar to our pure cirrus models except for additional radiation peaking at 50 μm.

A critical test of our models would be to measure the angular extent of the millimetre or submillimetre sources in high-z galaxies. In our model these should be of order an arcsec, within range of current millimetre-wave interferometers, whereas the obscured nuclear starburst model would imply sizes an order of a magnitude smaller. Of course, this test would not be able to discriminate between our model and a model where star formation takes place in an extended highly obscured starburst.

There is a further factor at work which exaggerates the difference between the SCUBA galaxies and the high-redshift galaxies found in Lyman break surveys (Steidel et al 1999). Assuming that there is a spread in the typical optical depth of the interstellar medium, uv surveys will inevitably be biased towards galaxies with lower than average optical depth, while submm galaxies will be biased towards higher optical depth. According to this picture, if the Lyman break surveys could go a factor 10 deeper they would start to see the SCUBA galaxies, and if the SCUBA surveys could go a factor 10 deeper they would start to see the Lyman break galaxies. This is already hinted at by the analysis of Peacock et al (2000).

REFERENCES

Barger A.J., Cowie L.L, Sanders D.B., 1999, ApJ 518, L5

Blain, A.W., 1999, MNRAS, 309, 955.

Bruzual A.G., Charlot S., 1993, ApJ 405, 538

Calzetti D. & Heckman T.M., 1999, ApJ 519, 27

Dole, H., et al, 2001, AA, 372, 364.

Downes D. et al, 1999, AA 347, 809

Dunlop, J., et al, 2002, MNRAS, submitted, astro-ph/0205480

Dunne L., Eales S.A., 2001, MN, 327, 697.

Eales S.A. Lilly S.J., Gear W.K., Dunne L., Bond J.R., Hammer F., Le Fevre O., Crampton D., 1999, ApJ 515, 518

Efstathiou A., Rowan-Robinson M., Siebenmorgen R., 2000, MN 313, 734

Fox, M., et al, 2002, MNRAS, submitted, astro-ph/0107585.

Franceschini, A., Aussel, H., Cesarsky, C.J., Elbaz, D., Fadda, D., 2001, AA, 378, 1.

Frayer, D.Y., Smail, I., Ivison, R.J., Scoville, N.Z., AJ, 120, 1668.

Gear, W., et al., 2000, MNRAS, 316, L51.

Granato, G.L., Lacey, C.G., Silva, L., Bressan, A., Baugh, C.M., Cole, S., Frenk, C.S., 2000, ApJ, 542, 710.

Granato, G.L., Silva, L., Monaco, P., Panuzzo, P., Salucci, P., De Zotti G., Danese, L., 2001, MNRAS, 324, 757.

Guiderdoni, B., Hivon, E., Bouchet, F.R, & Maffei, B., 1998, MN, 295, 877.

Helou, G., Soifer, B.T., Rowan-Robinson, M., 1985, ApJ, 298, L7.

Hughes D.H. et al, 1998, Nature 394, 241.

Ivison, R.J., Smail, I., Le Borgne, J.-F., Blain, A.W., Kneib, J.-P., Bezecourt, Kerr, T.H., Davies, J.K., 1998, MNRAS, 298, 583.

Ivison, R.J., Smail, I., Barger, A., Kneib, J.-P., Blain, A.W., Owen, F.N., Kerr, T.H., Cowie, L.L., 2000, MNRAS, 315, 209.

Ivison, R.J., Smail, I., Frayer, D.T., Kneib, J.-P., Blain, A.W., 2001, ApJ, 561, L45.

Ivison, R.J., et al., 2002, MNRAS, in press, astro-ph/0206432.

Krügel E., Siebenmorgen R., 1994, AA 282, 407.

Low F.J. et al, 1984, ApJ 278, L19

Lutz D. et al, 2001, AA, 378, 70.

Mathis, J.S., Mezger, P.G., Panagia, N., 1983, AA, 128, 212.

Peacock J.A., Rowan-Robinson M., Blain A.W., Dunlop J.S., Efstathiou A., Hughes D.H., Jenness T., Lawrence A., Longair M.S., Mann R.G., Oliver S.J., Serjeant S., 2000, MN 318, 535

Pearson, C.P., 2001, MN, 325, 1511.

Pei Y.C., Fall M., Hauser M.G., 1999, ApJ 522, 604

Rowan-Robinson M., 1992, MN 258, 787

Rowan-Robinson M., 2001, ApJ 549, 745

Rowan-Robinson M., Helou G., Walker D., 1987, MN 227, 589

Rowan-Robinson M., Crawford J., 1989, MN 238, 523.

Serjeant, S., et al, 2002, MNRAS, submitted, astro-ph/0201502.

Siebenmorgen R., Krügel E., 1992, AA 259, 614

Siebenmorgen R., Krügel E., Laureijs, R.J., 2001, AA, 377, 735.

Silva, L., Granato, G.L., Bressan, A., Danese, L., 1998, ApJ, 509, 103.

Smail, I., Chapman, S.C., Ivison, R.J., Blain, A.W., Takata, T., Heckman, T.M., Dunlop, J.S., Sekiguchi, K., MNRAS, submitted, astro-ph/0303128

Steidel C.C., Adelberger K.L., Giavalisco M., Dickinson M., Pettini M., 1999, ApJ 519, 1

Xu, C., Lonsdale, C.J., Shupe, D.L., O'Linger, J., Masci, F., ApJ, 562, 179.