ABSTRACT
Observations in the submillimetre waveband have recently revealed a new population of luminous, sub-mm sources. These are proposed to lie at high redshift and to be optically faint due to their high intrinsic dust obscuration. The presence of dust has been previously invoked in optical galaxy count models which assume $\tau = 9$ Gyr Bruzual & Charlot evolution for spirals and these fit the count data well from U to K. We now show that by using either a $1/\lambda$ or Calzetti absorption law for the dust and re-distributing the evolved spiral galaxy UV radiation into the far infra-red (FIR), these models can account for all of the ‘faint’ ($\leq 1$mJy) 850$\mu$m galaxy counts, but fail to fit ‘bright’ ($\geq 2$mJy) sources, indicating that another explanation for the sub-mm counts may apply at brighter fluxes (e.g. QSOs, ULIRGs). We find that the main contribution to the faint, sub-mm number counts is in the redshift range $0.5 < z < 3$, peaking at $z \approx 1.8$. The above model, using either dust law, can also explain a significant proportion of the extra-galactic background at 850$\mu$m as well as producing a reasonable fit to the bright 60$\mu$m IRAS counts.

Key words: galaxies: spiral - evolution - infrared: galaxies - ultraviolet: galaxies

1 INTRODUCTION
The SCUBA camera (Holland et al. 1999) on the James Clerk Maxwell Telescope has transformed our knowledge of dusty galaxies in the distant Universe as a result of the discovery of a new population of luminous, dusty, infra-red galaxies (Smail et al. 1997; Ivison et al. 1998). It has been proposed that these galaxies may be similar to IRAS ULIRGs (ultra-luminous infra-red galaxies) which appear to be starbursting/AGN galaxies, containing large amounts of dust. The possibility that much star-formation is hidden by dust means that sub-mm observations can give an invaluable insight into the star-formation history of the Universe. This view is aided by the redshifting of the thermal dust emission peak in starbursting galaxies into the FIR, which results in a negative k-correction in the sub-mm. By this route, we can therefore study our Universe all the way back to very early times and gain unprecedented insight into the formation and evolution of galaxies.

The first sub-mm galaxy to be detected by SCUBA was SMM J02399-0136 (Ivison et al. 1998), which is a massive starburst/AGN at $z=2.8$ and the current situation is that the complete 850$\mu$m sample from all the various groups consists of well over 50 sources (Blain et al. 1999; Eales et al. 1999; Hughes et al. 1998; Holland et al. 1998; Barger et al. 1998; Smail et al. 1997). Optical and near infra-red (NIR) counterparts have been identified for about a third of the sources, although the reliability of these identifications varies greatly. This problem is due to the fact that the $\approx 15''$ FWHM of the SCUBA beam results in $\approx 3''$ positional errors on a sub-mm source, so there is a reasonable chance that several candidates could lie within these errors. Also, there is no guarantee that the true source will be detected down to the optical flux limit as, for example, many of the sources have been shown to be very red objects (Dey et al. 1999; Smail et al. 1999: Ivison et al. 2000) and therefore have not been found in optical searches for sub-mm sources.

What has proved extremely enlightening is that radio counterparts at 1.4GHz have now been identified for many of the sub-mm sources (Smail et al. 2000: Ivison et al. 2000) providing much more accurate angular positions ($< 1''$ in some cases) and reasonably accurate photometric redshifts. Various groups have obtained redshift distributions of sub-mm samples (Hughes et al. 1998; Barger et al. 1999a; Lilly et al. 1999; Smail et al. 2000) and they all derive results that are consistent with a mean redshift in the range $1 < z < 3$. The fact that almost all of the sources are associated with mergers or interactions seems to confirm that the population of sources contributing at the ‘bright’ ($> 2$mJy) sub-mm fluxes (since most of the sources so far discovered are ‘bright’) are similar to local IRAS ULIRG’s, ie massive, starbursting/AGN galaxies which are extremely luminous in the far-infra-red. This hypothesis is strengthened further by the fact that the only two sub-mm sources (SMM J02399-0136...
and SMM J14011+0252) with reliable redshifts have been followed up with millimeter wave observations (Frayer et al. 1998, 1999), resulting in CO emission being detected at the redshifts of both sources (z=2.8 and z=2.6), a characteristic indicator of large quantities of molecular gas present in IRAS galaxies.

The nature of the fainter (≤1mJy) sub-mm population is, however, the focus of this paper. It has been claimed by Peacock et al. (2000) and Adelberger et al. (2000) that the Lyman Break Galaxy (LBG) population could not only contribute significantly to the faint sub-mm number counts, but could also account for a substantial proportion of the background at 850µm. This may indicate that ULIRG’s cannot explain all of the sub-mm population and that the UV-selected galaxy population, which are predicted to be evolved spirals by the Bruzual & Charlot models, may in fact make a substantial contribution. It is exactly this hypothesis our paper addresses.

In this paper we will first review the situation regarding the optical galaxy counts, focusing in particular on the models of Metcalfe et al. (1996). These simple models which use a τ = 9Gyr SFR for spirals and include the effects of dust give good fits to galaxy counts and colours from U to K. The idea is then to see whether this combination of exponential SFR and relatively small amounts of dust in the first instance (A_B = 0.3 mag. for the 1/λ law), which would re-radiate the spiral ultra-violet (UV) radiation into the FIR, could cause a significant contribution to the sub-mm galaxy number counts and background at 850µm. Our modelling will be described in section 3 and then in section 4 our predicted contribution to the 850µm and 60µm galaxy counts and the extra-galactic background in the sub-mm will be shown. Also in this section we demonstrate how to get a fit to the background in the 100 – 300µm range by using warmer, optically-thicker dust in line with that typically seen in ULIRG’s. We will then discuss the implications of our predictions in section 5 and conclude in section 6.

2 THE OPTICAL COUNTS

It is well known that non-evolving galaxy count models, where number density and luminosity of galaxies remain constant with look-back time, do not fit the optical number counts e.g. (Shanks et al. 1984), as there is always a large excess of galaxies faintwards of B ~ 22″. One way to account for this excess of ‘faint blue galaxies’ is to investigate the way galaxy evolution will influence the optical number counts. Metcalfe et al (1996) showed that by assuming that the number density of galaxies remains constant, the Bruzual and Charlot (1993) evolutionary models of spiral galaxies with a τ = 9Gyr SFR give excellent fits to the optical counts. The galaxy number counts are normalised at B ~ 18″ so that the non-evolving models give good fits to the B band data and redshift distributions in the range 18″ < B < 22″.5. With this high normalisation, the models of the galaxy counts represent both spiral and early-type galaxies extremely well for 17″ < I < 22″. (Glazebrook et al. 1995a, Driver et al 1995) and also the less steep H/K counts out to K ~ 20″. The evolution model then produces a reasonable fit to the fainter counts to B ~ 27″, I ~ 26″, H ~ 28″.

Metcalfe et al (1996) included a 1/λ internal dust absorption law with A_B = 0.3 for spirals to prevent the τ = 9 Gyr SFR from over-predicting the numbers of high redshift galaxies detected in faint B< 24 redshift surveys (Cowie et al 1995). This 1/λ dust law differs from the Calzetti (1997) dust law derived for starburst galaxies, in that for a given A_B, more radiation is absorbed in the UV. The Calzetti dust law is used by Steidel et al (1999) to model their ‘Lyman Break’ galaxies; they find an average E(B-V)=0.15 which gives A_B = 0.87mag and A_I = 1.7mag. This compares to our A_I = 0.9mag with A_B = 0.3mag. Both models also fail to predict as red colours as observed for the U-B colours of spirals in the Herschel Deep Field (Metcalfe et al 1996). However, if we assumed E(B-V)=0.15 for our z=0 spirals, as compared to our E(B-V)=0.05, then the rest colours of spirals as predicted by the Bruzual & Charlot model might start to look too red as compared to what is observed. Otherwise, the main difference between these two dust laws is that the Calzetti law would produce more overall absorption and hence a higher FIR flux from the faint blue galaxies. Thus in some ways our first use of the 1/λ law appears conservative in terms of the predicting the faint blue galaxy FIR flux. Later, we shall experiment by replacing the 1/λ law with the Calzetti (1997) law in our model.

So this pure luminosity evolution (PLE) model with 1/λ dust and q_0 = 0.05 then slightly under-estimates the faintest optical counts but otherwise fits the data well, whereas for q_0 = 0.5 the underestimate (with or without dust) is far more striking. An extra population of galaxies has to be invoked at high redshift to attempt to explain this more serious discrepancy for the high q_0 model. This new population was postulated to have a constant SFR from their formation redshift until z ~ 1 and then the Bruzual & Charlot models predict a dimming of ~5″ in B to form a red dwarf elliptical (dE) by the present day and therefore has the form of a ‘disappearing dwarf’ model (Babul & Rees 1992). No dust was previously assumed in the dE population but this assumption is somewhat arbitrary.

The τ = 9Gyr SFR was inconsistent with the early observations at low redshift from Gallego et al (1996) and this is partly accounted for by the high normalisation of the optical number counts at B ~ 18″. There is still a problem with the UV estimates from the CFRS UV data of Lilly et al at z=0.2. More recent estimates of the global SFR at low redshift based on the [OII] line (Gronwall et al 1998; Tresse & Maddox 1998; Hammer and Flores 1998) indicates that the decline from z=1 to the present day may not be as sharp as first thought and that the τ = 9Gyr SFR in fact provides a better fit to this low redshift data. Metcalfe et al (2000) have further found that this model also agrees well with recent estimates of the luminosity function of the z=3 Lyman break galaxies detected by Steidel et al (1999).

The main question then that we will address in this paper is whether the small amount of internal spiral dust absorption assumed in these models which give an excellent fit to the optical galaxy counts, could cause a significant contribution to the sub-mm number counts and background at 850µm.

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The Contribution of Faint Blue Galaxies to the Sub-mm Counts and Background

3 MODELLING

Using the optical B band parameters for spiral galaxies, we attempt to predict the contribution to the sub-mm galaxy counts and background at 850µm by using a 1/λ absorption law for the dust and re-radiating the spiral UV radiation into the FIR. We use the Bruzual & Charlot(1993) galaxy evolution models with \( H_0 = 50\text{km}\text{s}^{-1}\text{Mpc}^{-1} \) and a \( \tau=9\text{Gyr} \) SFR - with a galaxy age of 16 Gyr in the low \( q_0 \) case, and 12.7 Gyr in the high \( q_0 \) case to produce our 1M\( _\odot \) galactic spectral energy distribution (SED) as a function of redshift. We then use the equation

\[
G_{abs}(z) = \int F_\lambda(z) (1 - 10^{-0.4A_B(\lambda/4500)}) d\lambda
\]

as used by Metcalfe et al(1996), which is used to calculate the radiation absorbed by the dust, \( G_{abs}(ergs^{-1}) \), for our 1M\( _\odot \) model spiral galaxy as a function of \( z \), using our 1/λ absorption law with \( A_B = 0.3 \). Since Bruzual & Charlot provides us with a 1M\( _\odot \) at each redshift increment, we need to calculate the factor required to scale this SED (after the effect of absorption from the dust) to obtain that of a galaxy with absolute magnitude \( M_B \) at zero redshift, and this factor will then remain constant for \( M_B \) galaxies at all other redshifts. This then provides a zero point from which to calculate scaling factors for all the other galaxies in our luminosity functions. We find the scaling factor for an \( M_B \) galaxy by making use of a relation from Allen(1995)

\[
m_B = -2.5\log \left( B_\lambda f_\lambda d\lambda \right) - 12.97
\]

where \( f_\lambda \) is the received flux \((ergs^{-1}A^{-1}cm^{-2})\) and \( B_\lambda \) is the B band filter function. By re-arranging, setting \( m_B=M_B \) and then multiplying by \( 4\pi(10pc)^2 \) we obtain the total emitted power, \( L_B(ergs^{-1}) \) in the B band from an \( M_B \) galaxy

\[
L_B = 4\pi(10pc)^2.10^{-0.4(M_B+12.97)}
\]

The intensity emitted in the B band, after absorption by the dust from our 1M\( _\odot \) galaxy, \( L_{BM_\odot} \), is then calculated by integrating the SED, assuming a flat B band filter, between 4000Å and 5000Å.

\[
L_{BM_\odot} = \int F_\lambda(z) 10^{-0.4A_B(\lambda/4500)} B_\lambda d\lambda
\]

The scaling factor to scale a Bruzual & Charlot 1M\( _\odot \) spectral energy distribution for a galaxy of absolute magnitude, \( M_B \), is then defined by the ratio \( L_B/L_{BM_\odot} \).

The way the dust will re-radiate this absorbed flux depends on its temperature, particle size and chemical composition. However the normalisation of the re-radiated flux from a galaxy with absolute magnitude \( M_B \), at redshift \( z \), is already determined (the quantity \( G_{abs}E_B/E_{BM_\odot} \)). We will adopt a simple model by assuming a mean interstellar dust temperature of 15K [Bianchi et al. 1999] and also a modest warmer component of 45K, (the actual luminosity ratio we use is \( L_{45K}/L_{15K} = 0.162 \)), which would come from circumstellar dust [Dominigue et al. 1999] and is needed in order to fit counts at shorter wavelengths eg. 60µm. The effect of varying the dust parameters is explored in section 4. We then simply scale the Planck function so that

\[
C(z,M_B) \int_{-\infty}^{\infty} \beta(\lambda,T) d\lambda = G_{abs}L_B/L_{BM_\odot}
\]

where \( C(z,M_B) \) is the scaling factor, which is a function of \( z \) and \( M_B \), \( \beta(\lambda,T) \) is the Planck function (in this case a sum of two Planck functions) and \( \kappa_\lambda(\lambda) \propto \lambda^{-\beta} \), where \( \kappa_\lambda(\lambda) \) is an opacity law (we use \( \beta = 2.0 \) for each Planck function to model optically thin dust).

We then calculate the received 850µm flux, \( S(z,M_B) \), from a galaxy with absolute magnitude \( M_B \) and redshift \( z \) using the equation

\[
S(z,M_B) = \frac{C(z,M_B) \lambda e^{-\beta} \beta(\lambda_e,T)}{4\pi(1+z)d_L^2}
\]

where \( C(z,M_B) \) is defined from (4) and \( \lambda_e \) is equal to 850µm/(1+z). We can then obtain the number count of galaxies with absolute magnitude between \( M_B \) and \( M_B + dM_B \) and redshift between \( z \) and \( z+dz \) for which we measure the same flux density \( S(z,M_B) \) at 850µm (see (4)).

\[
dN(z,M_B) = \phi(M_B) dV dz dM_B dz
\]

where \( \phi(M_B) \) is the optical Schechter function and \( dV/dz \) is the cosmological volume element. Then the integral source counts \( N(>S_{lim}) \) are obtained, for each value of \( S_{lim} \), by integrating (5) over the range of values of \( M_B \) and \( z \) such that \( S(z,M_B) > S_{lim} \), where \( S(z,M_B) \) is defined in (4).

\[
N(>S_{lim}) = \int_{M_B} dM_B \int_z \phi(M_B) dV dz dM_B dz
\]

It is straightforward to then obtain model predictions of the FIR background for a given wavelength. The intensity, \( dI \), at 850µm from galaxies with absolute magnitudes between \( M_B \) and \( M_B + dM_B \) and redshifts between \( z \) and \( z+dz \) is given by multiplying the number of galaxies with these \( z \)'s and \( M_B \)'s by the flux density which we would measure from each

\[
dI_{850} = S(z,M_B) \phi(M_B) dV dz dM_B dz
\]

and then we simply integrate over all absolute magnitudes and all redshifts (0 < \( z < 4 \) in this case)

\[
I_{850} = \int_{M_B} dM_B \int_z S(z,M_B) \phi(M_B) dV dz dM_B dz
\]

4 PREDICTIONS

Fig. 1 shows our model predictions for the 60µm differential number counts of IRAS galaxies (Saunders et al. 1990). This was an all sky local survey carried out with the IRAS satellite down to a flux limit of 0.6Jy. It therefore provides an important test of our model since spiral galaxies contribute significantly to IRAS counts (Neugebauer et al. 1984) and so if we are going to assume PLE out to redshifts of 4 then our local galaxy count predictions at 60µm need to be reasonably consistent with the data. The figure shows our evolution and no evolution model (the \( q_0 \) makes no difference) and because the IRAS survey was probing redshifts out to \( z=0.2 \) we can
see that there is very little difference between the two models and that they both fit the data reasonably well. The IRAS counts below 0.2Jy are slightly under-predicted using both dust laws, which could possibly be due to the fact our model doesn’t include any fast-evolving AGN/ULIRG population.

We use the Calzetti dust law with three dust temperature components of 15, 25, and 32K and this failure of the fainter IRAS counts is greater than when the 1/\lambda law is used because of the absence of the 45K dust component, which dominates the thermal emission at 60\mu m.

We then go on to show in Fig. 2 our sub-mm predictions using the Bruzual & Charlot evolution model with low and high q_0 (q_0 = 0.05, q = 0.5) and also for the corresponding no-evolution models where we use the Bruzual & Charlot SED at z = 0 for all redshifts. We have used a two-component dust temperature, as described in the previous section and a galaxy formation redshift, z_f = 4. The low q_0 model reproduces the faint counts well, but fails the very bright counts. This makes sense since these very luminous sources would require ULIRG’s, having SFR’s of order \approx 100-1000M_{\odot}yr^{-1}, and/or AGN, in order to produce these huge FIR luminosities. Indeed, the 850\mu m integral log N:\log S appears flat between 2-10mJy before rising again at fainter fluxes, suggesting that 2 populations may be contributing to the counts.

The high q_0 model contains a dwarf elliptical population in order to fit the optical counts, as already explained, but no dust was invoked in these galaxies in the optical models and so they do not contribute to our 850\mu m predictions. Contrary to the optical number counts, the high q_0 models predict more galaxies greater than a given flux limit than low q_0 models. The reason for this is illustrated in Fig. 3 which shows how the received flux density from a M_V = -22.5 galaxy would vary with redshift in the high and low q_0 case, with and without \tau = 9Gyr. Bruzual & Charlot evolution. In the no-evolution cases the two factors involved are the cosmological dimming and the effect of the negative k-correction, since we are effectively looking up the black body curve as we look out to higher redshift. The AGN model (the steeper of the curves) predicts that, at most, QSO’s could contribute 30 percent of the background at 850\mu m, and these models do much better in the number counts at brighter fluxes, but they fail to contribute at the 0.5mJy level where we predict that faint blue galaxies are dominant. Our Calzetti dust law uses three dust temperature components (see Fig. 1), and as with our 1/\lambda dust law, it can account for the faint number counts but then fails the much brighter sources.

Figure 1. The 60\mu m differential number counts. The graph shows the evolution and no-evolution models for a low q_0 Universe (the corresponding high q_0 models are indistinguishable) along with the observed 60\mu m counts of IRAS galaxies down to a flux limit of 0.6Jy, plotted in the format used by Oliver et al. (1992). The crosses are from Hacking & Houck (1987), the empty triangles from Rowan-Robinson et al. (1990), Saunders et al. (1990) are the filled triangles and the circles are Gregorich et al. (1995) and Bertin et al. (1997). We use a two-component dust temperature of 15K and 45K to model both interstellar and circumstellar dust respectively. Other parameters used are \beta = 2.0, H_0 = 50 and a redshift of formation of z = 4. The dot-dashed line shows the same evolution model using the Calzetti dust law with three dust temperature components of 15, 25, and 32K. This fits the IRAS counts less well at < 0.2mJy, and this is because of the lack of a 45K dust component meaning that there is much less thermal emission from the dust at 60\mu m.

Figure 2. The 850\mu m integral number counts. The filled circles show the results of the SCUBA Lens Survey (Blain et al. 1999); the open circles are as labelled: S97 - Small, Ivison & Blair (1997); B98 - Barger et al. (1998); B98 - Holland et al. (1998); E99 - Eales et al. (1999); HDF, P(D) - Hughes et al. (1998). Also shown are our predictions for q = 0.05 and q = 0.5 models with and without Bruzual & Charlot evolution, using the parameters from Fig. 1.

Both the high and low q_0 models, with evolution (dashed and solid curves), do very well with the faint counts but fail the most luminous sources. In the no evolution cases (dotted and dot-dashed) the high q_0 model again predicts more galaxies than the low q_0 model, but they both underpredict the faint 850\mu m counts by about an order of magnitude and then again fall away again at the higher flux densities. The graph also shows a predicted contribution from AGN (Gunn & Shanks 1999) and a model using the calzetti dust law (the two dot-dot-dot-dashed curves). The AGN model (the steeper of the curves) predicts that, at most, QSO’s could contribute 30 percent of the background at 850\mu m, and these models do much better in the number counts at brighter fluxes, but they fail to contribute at the 0.5mJy level where we predict that faint blue galaxies are dominant. Our Calzetti dust law uses three dust temperature components (see Fig. 1), and as with our 1/\lambda dust law, it can account for the faint number counts but then fails the much brighter sources.
Figure 3. If a galaxy has an absolute magnitude \( M_B = -22.5 \) at the present day then these graphs show how the received flux from such a galaxy would vary as a function of redshift using our model with the parameters described in the previous figure (Fig. 2). The solid line is for a \( q_0 = 0.05 \) Universe with Bruzual & Charlot evolution, the dashed line for \( q_0 = 0.5 \) with evolution, the dot-dashed line for \( q_0 = 0.05 \) without evolution and the dotted line for \( q_0 = 0.5 \) without evolution.

integral number counts are higher for a given flux density. When the Bruzual & Charlot evolution is invoked (solid and dashed lines), we predict more flux than in the corresponding no-evolution cases at high redshift, because a galaxy is significantly brighter than at the present day. The high \( q_0 \) model(with evolution) is virtually flat in the redshift range \( 0.5 < z < 2 \) and the low \( q_0 \) model again predicts slightly lower flux densities for a given redshift compared to high \( q_0 \). It may be noted that the no-evolution models in this plot differ slightly from that of Hughes et al.,(1998). This discrepancy is a result of the different assumed dust temperature and beta parameter. The colder temperature means that the peak of the thermal emission from the dust is probed at lower redshifts and so we lose the benefit of the negative k-correction at \( z \approx 2-3 \) instead of at \( z \approx 7-9 \) as in Hughes & Dunlop(1998).

Fig. 3 shows the effect of altering the interstellar dust temperature (where we have used the low \( q_0 \) evolving model). The interstellar dust temperature, \( T_{\text{int}} \), makes a big difference to our 850\( \mu m \) number count predictions and the variation is perhaps contrary to what one may expect in that the lower \( T_{\text{int}} \) means that we expect to see more galaxies above a given flux limit \( S_{\text{lim}} \). This is because, as we lower the dust temperature, although the integrated energy in the area under the Planck curve goes down, the flux density at 850\( \mu m \) goes up slightly because we are seeing the majority of radiation at much longer wavelengths. Now recall from the previous section that the normalisation of the Planck emission curve is already defined from the amount of flux absorbed by the dust and the Planck curve is simply scaled accordingly. So because the normalisation is fixed, when we lower the dust temperature, we have to scale the Planck curve up by a much larger factor and therefore find that we obtain much larger flux densities at 850\( \mu m \), explaining why our models are very sensitive to \( T_{\text{int}} \).

We have used a galaxy formation redshift, \( z_f = 4 \) which is reasonable since sub-mm sources seem to exist out to at least that, but we do in fact find that adopting \( z_f = 4 \) and \( z_f = 6 \) or indeed \( z_f = 10 \) does not make any difference to the number counts. Fig. 4 illustrates this, since at \( z > 4 \) we are observing radiation that was emitted beyond the peak of the black-body curve, and so cosmological dimming is no longer compensated for and all the curves begin to fall away very quickly explaining why increasing \( z_f \) beyond about \( z = 4 \) makes essentially no difference to the 850\( \mu m \) number counts. Of course, a higher assumed \( T_{\text{int}} \) would extend this redshift range to beyond \( z = 4 \).

Fig. 4 shows what sort of contribution we get to the extra-galactic background, simply by integrating over the number counts in each wavelength bin. The plot shows the low and high \( q_0 \) models with and without evolution, and with our standard parameters of \( T_{\text{int}} = 15K \), \( T_{\text{circ}} = 45K \), \( \beta = 2.0 \) and \( z_f = 4 \). All the models predict the same intensity at short wavelengths(\( \lambda = 60\mu m \)), as low redshift objects would dominate making the evolution and \( q_0 \) dependence less significant. The low \( q_0 \) model is able to account for all of the background at 850\( \mu m \), the high \( q_0 \) model in fact overpredicts it by about a factor of 2 and the no evolution models, although underpredicting it, are still well within an order of magnitude. Although we can fit the background at 850\( \mu m \), we noticeably fail the data between about 100 and 300\( \mu m \). We find that the only way to fit these observations
using our model is to use higher values of $A_B$ and higher dust temperatures, as this means dust is absorbing more energy from each galaxy and so the contribution to the background in the wavelength range where warmer dust emission dominates ($100 \mu m < \lambda < 500 \mu m$) is much greater. The solid curve in Fig. 5 shows a prediction where we have tried the Calzetti dust model which gives more overall absorption with similar amounts of reddenning; this model might also be expected to fit the B optical counts. We see that its larger amount of absorbed flux allows more flexibility in terms of using more dust components. By using three dust temperature components results we obtain a better (though still not perfect) fit to Fig. 3 in the $100 \mu m < \lambda < 300 \mu m$ range, while still giving fits to the IRAS $60 \mu m$ (Fig. 2) and faint $850 \mu m$ number counts (Fig. 3).

5 DISCUSSION

We have taken a different approach from the standard way in which sub-mm flux’s are estimated using UV luminosities (Meurer et al. 1997). Instead of assuming a relationship between the UV slope $\beta$ and the ratio $L_{FIR}/L_{UV}$, we proceed directly from the spiral galaxy UV luminosity functions and simply re-radiate into the FIR by assuming a simple dust law constrained from the optical counts. A direct result of this, as has already been illustrated in the previous section, is that decreasing the interstellar dust temperature actually increases the received flux density at $850 \mu m$, firstly because the peak in the Planck emission curve moves towards longer wavelengths and secondly because (as the absorbed flux from the dust is fixed) the normalisation scaling factor goes up. The fact then that we model the dust using a dominant interstellar component of 15K, which is signifi-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{The predicted number-redshift distribution of sub-mm selected faint blue galaxies down to flux limits, $S_{lim}$ of 4.0, 2.0, 1.0 and 0.5mJy. The graph shows the low-z0 model using the 1/\lambda dust law with the parameters described in Fig. 2. As the flux limit is increased, the peak in the n(z) distribution shifts from around z=1.8 at $S_{lim}=0.5$ mJy to much lower redshifts, reaching z=0.2 for $S_{lim}=4.0$ mJy.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{The predicted contribution to the FIR background from our models. The latest measurements of the extragalactic FIRB, compared with the COBE measurement of the cosmic microwave background (Mather et al. 1994). F98 - Fixsen et al.(1998)(upper solid line) and P96 - Puget et al.(1996)(lower solid line); H98 - Hauser et al.(1998); S98 - Schlegel et al.(1998). Both the Hauser and Schlegel data each have points at 240$\mu m$ and 130$\mu m$. Low and high q0 models are shown with and without evolution, where we have used our standard parameters of $T_{int}=15K$, $T_{circ}=45K$, $\beta=2.0$ and $z_f=4.0$. The evolution model, in the low q0 case can account for all of the FIR background at 850$\mu m$, whereas the high q0 one in fact overpredicts by about a factor of 2. The no evolution models both underpredict the sub-mm background but are consistent with it to within an order of magnitude. The solid curve shows a model where we have used the Calzetti dust law using $A_g=1.02$ (equivalent to E(B-V)=0.18 and close to the value 0.15 used by Steidel et al for their Lyman Break Galaxies) for the dust obscuration with a three-component dust temperature of 15K, 25K and 32K. It fits the background and faint number counts at 850$\mu m$, the IRAS 60$\mu m$ counts and also does much better in the wavelength range $100 \mu m < \lambda < 500 \mu m$.}
\end{figure}

cantly colder than that used in models of starburst galaxies (typically 30-50K), means that we are able to show that the evolution of normal spiral galaxies like our own Milky Way, using the Bruzual model with an exponential SFR of $\tau=9$Gy, could make a very significant contribution to the sub-mm number counts in the $S_{500}<2$ mJy range. Indeed this sort of temperature for spirals has been given recent support from observations of ISO at 200$\mu m$ (Alton et al. 1998a) where, for a sample of 7 spirals, a mean temperature of 20K was found, about 10K lower than previous estimates from IRAS at shorter wavelengths. They found that 90 percent of the FIR emission came from very cold dust at temperatures of 15K. Sub-mm observations of spirals (Alton et al. 1998b; Bianchi et al. 1998) and observations of dust in our own galaxy (Sodroski et al. 1994; Reach et al. 1995; Boulanger et al. 1996; Sodroski et al. 1997) also support the claims of these sorts of dust temperatures. Of course, at $z=4$ our assumed interstellar dust temperature of 15K is comparable to that of the microwave background.

Our models show that normal spiral galaxies (ie those...
that evolve into galaxies like our own Milky Way assuming the Bruzual model fail to provide the necessary FIR flux of the most luminous sources (> 2 mJy) and this is not surprising since the τ = 9 Gyr SFR at high redshift (z > 1), which is consistent with the UV data, is lower than that inferred by other models which fit the sub-mm counts by a factor of about 5 or so (Blain et al. 1998a). The LBG galaxies at high redshift are predicted to be evolved spirals by the Bruzual models and the dust we invoke (A9 = 0.3 implies an attenuation factor at 1500 Å of 2.3) is enough to make them low luminosity sub-mm sources at flux levels of around 0.5 mJy. This amount of dust, though, is not enough to account for the factor of 5 discrepancy and there are several possible reasons for this.

The first is the possible additional contribution to the sub-mm counts from AGN. Modelling of the obscured QSO population has shown that they could contribute, at most, about 30% of the background at 850 μm but they can get much closer to the bright end of the sub-mm number counts (Gunn & Shanks 1999). This is shown in Fig. 2 where we also show the q0 = 0.5 model of Gunn & Shanks. Although the slope of the QSO count at the faintest limits is too flat, at brighter fluxes the QSO model fits better than the faint blue galaxy model and the combination of the two gives a better fit overall.

It is also possible that the optical and sub-mm observations are sampling a completely different population of galaxies as the obscured galaxies sampled by the sub-mm observations may well just be too red or too faint to be detected in the UV at the current flux limits (Smail et al. 1999, 2000; Dey et al. 1999). That may mean that the most luminous sub-mm sources or ULIRG’s (≥ 1013 L⊙) are not the LBG galaxies (which the Bruzual model predicts as evolved spirals) and so then it would not be surprising if the current sub-mm and UV derived star-formation histories at high redshift were different. However, the evidence is growing that the faint blue galaxies are significant contributors to the faint sub-mm counts. Chapman et al. (1999) carried out sub-mm observations of 16 LBG’s and found, with one exception, null detections down to their flux limit of 0.5 mJy. But their one detection may suggest that with enough SCUBA integration time it might be possible to detect LBG’s that are particularly luminous in the FIR and indeed, while this paper was in preparation, work from Peacock et al. (1999) suggests that faint blue galaxies may be detected at 850 μm at around the 0.2 mJy level. This is below the SCUBA confusion limit of ∼ 2 mJy (Hughes et al. 1998; Blain et al. 1998b) and highlights the problem faced by Chapman et al. (1999) in performing targeted sub-mm observations of LBG’s. The conclusions of Peacock et al. (1999) suggest that the LBG population (the faint blue galaxies in our model) contribute at least 25 percent of the background at 850 μm and Adelberger et al. (2000) also come to similar conclusions, namely that the UV-selected galaxy population could account for all the 850 μm background and the shape of the number counts at 850 μm. However, the conclusions of Adelberger et al. (2000) are based on the fact that the SED of SMM J14011+0252 is representative of both the LBG and sub-mm population. At present, they are only assumptions, but nevertheless the conclusions of all these authors seem to suggest that ULIRG’s may not contribute to the faint sub-mm number counts and background as much as was first thought.

The spectral slope of the UV continuum and the strength of the Hβ emission line in Lyman Break Galaxies support the fact that interstellar dust is present (Chapman et al. 1999), but the physics of galactic dust and the way it obscures the optical radiation from a source is still very poorly understood. We started by adopting a very simplistic model for the dust, treating it as a spherical screen around our model spiral galaxy. The dust might, in reality, be concentrated in the plane of the disk for spiral galaxies and may also tend to clump around massive stars. This would make the extinction law effectively grayer as suggested by observations of local starburst galaxies (Calzetti, 1997). Indeed, we have investigated the effect of the grayer Calzetti extinction law and found that it would produce a larger sub-mm count contribution due to the higher overall absorption it would imply. Metcalfe et al. (2000) have also suggested that there may be evidence for evolution of the extinction law from the U-B,B-R diagram of faint blue galaxies in the Herschel Deep Field.

We have assumed pure luminosity evolution (PLE) throughout this paper. The assumption that the number density of spiral galaxies remains constant might certainly not be the case if dynamical galaxy merging is important for galaxy formation. However, as we have seen it is relatively easy to fit the sub-mm number counts with PLE models whereas it is in fact impossible to fit the counts using pure density evolution models without hugely overpredicting the background by 50 or 100 times (Blain et al. 1998a). So, if existing sub-mm observations are correct then although density evolution may also occur, luminosity evolution may be dominant. It is also striking how well the PLE models do in the optical number counts and colour-magnitude diagrams and together with the fact that we observe highly luminous objects in the sub-mm out to at least z = 3, this could indicate that the biggest galaxies could have formed relatively quickly, on timescales of about 1 Gyr or so. If this were true, then the PLE models may be a fair approximation to the galaxy number density and evolution in the Universe out to z ≈ 3 in both the optical/near-IR and FIR.

We have not taken into account early-type galaxies as no dust was invoked in these in the optical galaxy count models. In particular, we have not included any contribution from dust in the dE population which is invoked to fit the faint optical counts in the q0 = 0.5 model (Metcalfe et al. 1996). If we were to include their possible contribution this would increase our 850 μm counts predictions at the faint end since in our models both early-type and dE star formation occurs at high redshift which is the region of greatest sensitivity for the sub-mm counts. At brighter fluxes though, where, in our models, low redshift galaxies are the only possible influence, the inclusion of early-type galaxies would be negligible.

6 CONCLUSIONS

The aim of this paper was to investigate whether, by re-radiating the absorbed spiral galaxy UV flux into the FIR, the dust invoked in the faint blue spirals at high z from the optical galaxy count models of Metcalfe et al. (1996) could
have a significant contribution to the sub-mm galaxy counts and also the FIR background at 850µm. We have found that, using a interstellar dust temperature of 15K, a modest circumstellar component of 45K, a beta parameter of 2.0 and a galaxy formation redshift of $z_f \approx 4$ we can account for a very significant fraction of the faint 850µm source counts, both in the low and high $q_0$ cases when we invoke Bruzual & Charlot evolution (see Fig. 3). These evolutionary models give 5-10 times more contribution to the faint sub-mm counts than the corresponding no-evolution models. At brighter fluxes, we find that the SFR and dust assumed in our normal spiral model are too low to produce the FIR fluxes of the most luminous sources. In the no-evolution cases, we underpredict the number counts, even at the faint end. Our predicted redshift distribution of sub-mm selected faint blue galaxies suggests that the main contribution to the faint counts is in the range $0.5 < z < 3$, peaking at $z \approx 1.8$. We have shown that our model fits the 60µm data by nearly an order of magnitude in the 100-150µm range. We have shown that the only way to fit these observations using this optically based model is to use assume more dust obscuration ($A_B = 0.6$) and much warmer dust ($T=30$K). Effectively gray extinction laws such as that of Calzetti et al (1997) may also provide more overall absorption and hence allow more dust temperature components to allow the flexibility to fit the FIR background from 60-850µm. However, the bright sub-mm counts will still require a further contribution from QSO’s or ULIRGs to complement the contribution of the faint blue galaxies at fainter fluxes.

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