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The 60-μm extragalactic background radiation intensity, dust-enshrouded active galactic nuclei and the assembly of groups and clusters of galaxies

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ABSTRACT

Submillimetre- (submm-) wave observations have revealed a cosmologically significant population of high-redshift dust-enshrouded galaxies. The form of evolution inferred for this population can be reconciled easily with *COBE* FIRAS and DIRBE measurements of the cosmic background radiation (CBR) intensity at wavelengths longer than $\sim 100\,\mu$m. At shorter wavelengths, however, the 60-μm CBR intensity reported by Finkbeiner, Davis & Schlegel is less easily accounted for. Lagache et al. have proposed that this excess CBR emission is a warm Galactic component, and the detection of the highest-energy γ-rays from blazars limits the CBR intensity at these wavelengths, but here we investigate possible sources of this excess CBR emission, assuming that it has a genuine extragalactic origin. We propose and test three explanations, each involving additional populations of luminous, evolving galaxies not readily detected in existing submm-wave surveys. First, an additional population of dust-enshrouded galaxies with hot dust temperatures, perhaps dust-enshrouded, Compton-thick active galactic nuclei (AGN) as suggested by recent deep *Chandra* surveys. Secondly, a population of dusty galaxies with temperatures more typical of the existing submm-selected galaxies, but at relatively low redshifts. These could plausibly be associated with the assembly of groups and clusters of galaxies. Thirdly, a population of low-luminosity, cool, quiescent spiral galaxies. Hot AGN sources and the assembly of galaxy groups can account for the excess 60-μm background. There are significant problems with the cluster assembly scenario, in which too many bright 60-μm *IRAS* sources are predicted. Spiral galaxies have the wrong spectral energy distributions to account for the excess. Future wide-field far-infrared (IR) surveys at wavelengths of 70 and 250 μm using the *SIRTF* and *Herschel* space missions will sample representative volumes of the distant Universe, allowing any hot population of dusty AGNs and forming groups to be detected.

Key words: galaxies: evolution – galaxies: formation – cosmology: observations – cosmology: theory – diffuse radiation – infrared: galaxies.

1 INTRODUCTION

Surveys using the Submillimetre (Submm) Common-User Bolometer Array (SCUBA; Holland et al. 1999) camera at the James Clerk Maxwell Telescope (JCMT) have revealed a new and important population of dust-enshrouded high-redshift galaxies (see Smail et al. 2002 and references therein). Two very well-studied examples of this population with redshifts are described by Ivison et al. (1998, 2000a, 2001). Distant dust-enshrouded galaxies have also been detected using the millimetre-wave MAMBO bolometer array at 1.2 mm (Bertoldi et al. 2000), and the *Infrared Space Observatory* (*ISO*), both at 175 μm using the ISOPHOT instrument (Kawara et al. 1998; Puget et al. 1999; Matsuhara et al. 2000; Linden-Vornle et al. 2000; Dole et al. 2001) and at 15 μm using the ISOCAM instrument (Altieri et al. 1999; Elbaz et al. 2000).

The counts of these galaxies, and the spectrum of submm-wave cosmic background radiation (CBR) at wavelengths greater than 100 μm (Puget et al. 1996; Fixsen et al. 1998; Hauser et al. 1998; Schlegel, Finkbeiner & Davis 1998) can be readily accounted for using well-constrained models of the evolution of dusty galaxies at temperatures of the order of 40 K (Blain et al. 1999c,d; Trentham,

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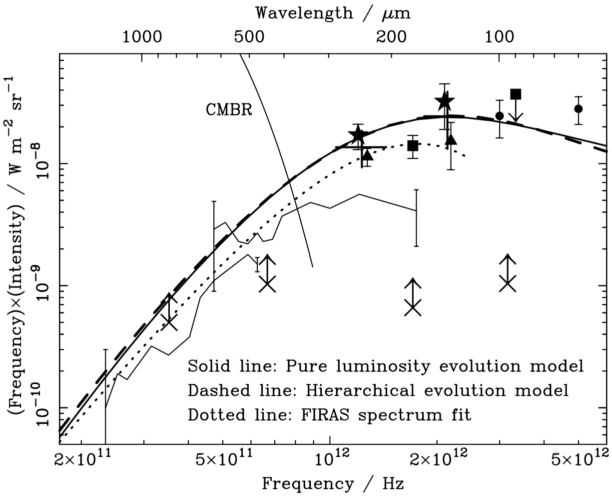

Figure 1. The CBR intensity in the mm, submm and far-IR wavebands, as deduced by: Puget et al. (1996) – thin solid lines with error bars at the ends; Fixsen et al. (1998) – dotted line; Schlegel et al. (1998) – stars; Hauser et al. (1998) – thick solid crosses; Lagache et al. (1999) – solid triangles; Kiss et al. (2001) – solid squares; Finkbeiner et al. (2000) – solid circles. Lagache et al. (1999, 2000) claim that a warm diffuse Galactic dust component accounts for ~50 per cent of the isotropic DIRBE signal attributed to the extragalactic CBR intensity by Hauser et al. (1998), Schlegel et al. (1998) and Finkbeiner et al. (2000). The diagonal crosses represent lower limits to the CBR intensity inferred from source counts. From left to right: the 850- and 450-μm counts (Blain et al. 1999b; Smail et al. 2002), and the 175- and 95-μm counts of Kawara et al. (1998) and Puget et al. (1999). The CBR spectrum in the 40-K hierarchical clustering model from Blain et al. (1999d) is represented by the solid line, while the CBR spectrum in a model of pure luminosity evolution (Blain et al. 1999c) is shown by the dashed line. Both curves have been updated in the light of more observational data and a world model with a non-zero cosmological constant (see Blain 2001).

Blain & Goldader 1999). However, the far-infrared (IR) CBR intensity inferred at wavelengths of 140 μm from *COBE*-DIRBE observations by Schlegel et al. (1998) and Hauser et al. (1998), and more recently at shorter wavelengths of 100 and 60 μm by Finkbeiner, Davis & Schlegel (2000), is significantly greater, by a factor of ~2, than that predicted by the models from 1999. In updated models (Blain 2001), based on larger data sets and with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$, the difference between the models and the CBR measurements of Finkbeiner et al. are only significant at 60 μm, as shown by the solid and dashed lines in Fig. 1. Lower estimates of the CMB intensity at wavelengths close to the peak of the CBR spectrum are provided by Lagache et al. (1999) and Kiss et al. (2001).

If this is a true extragalactic signal, rather than being associated with either a warm component of the interstellar medium (ISM) in the Milky Way (Lagache et al. 1999, 2000) or emission from a distant component of zodiacal dust (Finkbeiner, private communication), then this CBR data appears to require an additional source of far-IR, but not submm-wave, luminosity in the models.

Renault et al. (2001) describe constraints on the CBR intensity from recent observations of TeV γ-ray emission from blazars. γ-rays are destroyed by pair production in interactions with far-IR photons that have the same numerical value of wavelength in micrometres as the γ-ray photon energy in TeV. For reasonable CBR spectra, the mean free path to pair production decreases strongly with increasing γ-ray energy. Hence, the highest-energy γ-ray photons can have a mean-free path through the Universe that is shorter than the distance to low-redshift blazars (Aharonian 2002). If the blazar is not to have an energetically forbidden increasing power-law spectrum at high energies (> 10 TeV), after correcting for the intergalactic attenuation, then the 100-μm CBR intensity must be less than ~20 nW m^{-2} sr^{-1}. However, note that the number of photons detected from blazars at the highest energy is small, and the intrinsic curvature of the blazar spectrum is unknown. A variety of exotic physics has also been invoked to reduce the inferred optical depth (see Aharonian 2002 and papers cited therein). Future TeV observations should allow the CBR spectrum to be mapped in detail at wavelengths shorter than ~100 μm. At present it is worth considering models that are in mild conflict with existing results. If the results remain once more robust TeV γ-ray data are available, then the need for additional components of the CBR could be removed. Of course, if the 60-μm background excess is of Galactic origin, then the attenuation would be negligible.

An additional CBR component must not make a significant contribution to the CBR intensity at wavelengths longer than ~100 μm. The discrete sources associated with this excess far-IR CBR contribution also do not dominate the counts of galaxies detected at either 1300, 850 or 450 μm (Bertoldi et al. 2000; Carilli et al. 2002; Blain et al. 1999b; Smail et al. 2002), as these results can be accounted for in full by the existing models. However, an additional population may contribute to both the deep 15-μm (Altieri et al. 1999; Elbaz et al. 2000) and 175-μm counts (Kawara et al. 1998; Puget et al. 1999).

Note that the observed counts of galaxies from both *IRAS* at 60 μm and *ISO* at 175 μm can be reproduced accurately by a population of galaxies that evolves in luminosity as $(1+z)^{\simeq 4}$ with a dust temperature of ~40 K (see fig. 4 in Blain et al. 1999c). It is not possible to vary the dust temperature and form of evolution of a single population of galaxies to account for an excess 60-μm CBR while remaining consistent with these counts. An additional population of galaxies or other sources of CBR intensity could be included, with a different temperature or form of evolution, but they must be too distant to be detected by *IRAS* in order to accord with the existing low-redshift 60-μm count data.

Because of the thermal spectral energy distribution (SED) of dust-enshrouded galaxies, these conditions imply that in order to contribute to the CBR intensity spectrum only at the higher frequencies, either the new population has a lower mean redshift or a greater mean dust temperature compared with the standard population of 40-K dusty galaxies.

Here we discuss the potential sources of this possible excess radiation. First, we consider a population of galaxies hotter than the SCUBA sources (see also Wilman, Fabian & Ghandi 2000; Trentham & Blain 2001). These probably correspond to optically faint or invisible, probably dust-enshrouded, active galactic nuclei (AGN) detected in the hard X-ray band by *Chandra* (Fabian et al. 2000; Hornschemeier et al. 2000; Mushotzky et al. 2000). The *Chandra* sources in the background of the rich cluster A2390 are known to be hotter than the 40-K SCUBA galaxies because their Rayleigh–Jeans thermal dust emission is not detected at 850 μm using SCUBA (Fabian et al. 2000), but their 15-μm emission on the short-wavelength side of their spectral peak is detected using *ISO* (Altieri et al. 1999): see Wilman et al. (2000). Dust-enshrouded AGN are likely to comprise at least a significant minority of the faint 15-μm *ISO* galaxies (Franceschini et al. 2002). Two counterexamples, cooler dusty galaxies with *Chandra* hard X-ray detections, exist at present (Bautz et al. 2000). These galaxies were detected by both SCUBA and *ISO* in the field of the cluster A370, with dust temperatures close to the typical value of 40 K (Ivison et al. 1998; Smail et al. 2002).

Secondly, we consider a population of star-forming galaxies with 40-K dust SEDs similar to those of many high-redshift galaxies and quasi-stellar objects (QSOs) (Benford et al. 1999; Blain et al. 1999c,d; Trentham et al. 1999; Scott et al. 2000), but which lies at a lower mean redshift. This population thus contributes to the CBR spectrum at relatively short wavelengths. A potential source of low-redshift activity is the conversion of the remaining cold gas in cluster member galaxies into stars, triggered by shocks and tidal forces induced when the galaxies are incorporated into the common dark matter halo of a forming group or cluster. Being relatively rare and short-lived events, any such less massive groups and more massive clusters that are forming are unlikely to have been observed in significant numbers in the sub-0.1-deg^2 fields that have been surveyed so far with SCUBA, with the exception of the central cD galaxies (Edge et al. 1999). Note that the foreground clusters in the SCUBA Lens Survey of Smail et al. (1997, 2002) do not produce any significant far-IR emission, consistent with them being observed long after their assembly.

Finally, we consider the CBR expected from a population of potentially evolving low-redshift spiral galaxies with lower 20-K dust temperatures (Reach et al. 1995; Alton et al. 1998).

We discuss the consequences of each population for the spectrum of submm and far-IR CBR, and then consider existing and future observations that could discriminate between plausible models. In particular, we consider the detection of hot dusty galaxies using the future wide-field far-IR and submm-wave surveys using the *SIRTF*[1] and *Herschel* (Pilbratt 1997) satellites. Throughout the paper we assume that $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with $h = 0.65$, $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$.

2 BACKGROUNDS FROM ADDITIONAL POPULATIONS

2.1 Luminous infrared galaxies with warmer dust temperatures

The population of luminous dust-enshrouded galaxies at moderate and high redshifts discussed in the context of modelling the SCUBA source counts and the submm-wave CBR are usually assumed to have dust temperatures of $\sim$40 K. At this temperature the observed low-redshift *IRAS* 60-μm luminosity function (Saunders et al. 1990) and the $z \lesssim 1$ 175-μm *ISO* counts can both be explained, requiring only a single SED and a simple form of pure luminosity evolution (Blain et al. 1999c). In an alternative hierarchical model described in Blain et al. (1999d) a temperature of $\sim$40 K is also required to generate a plausible redshift distribution for the SCUBA galaxies (Smail et al. 2002). A mean dust temperature of $\sim$40 K is also consistent with both the SEDs of high-redshift galaxies and QSOs detected using the SCUBA, SHARC and MAMBO mm/submm-wave cameras (Ivison et al. 1998, 2000a; Benford et al. 1999; McMahon et al. 1999; Carilli et al. 2001), the sample of low-redshift *IRAS*-selected galaxies observed by Dunne et al. (2000), Lisenfeld, Isaak & Hills (2000) and Dunne & Eales (2001) using SCUBA, and faint radio galaxies observed by Chapman et al. (2002a).

However, an additional high-redshift subpopulation with a different dust temperature is not ruled out by the data. In fact, there is a significant observational bias against detecting galaxies with higher dust temperatures using SCUBA (Eales et al. 1999; Blain et al. 2002). There is so far very little information concerning the existence or properties of any hotter population. A fraction of the galaxies detected by ISOPHOT at a wavelength of 175 μm (Puget et al. 1999) have been observed using SCUBA (Scott et al. 2000), but as their redshifts are uncertain, it was difficult to assign a reliable temperature; a value of $T/(1+z) \simeq 30$ K is favoured at present. These ISOPHOT galaxies are unlikely to be at redshifts greater than unity. More recently, Chapman et al. (2002b) have detected two of these galaxies at $z = 0.45$ and 0.91 with dust temperatures of only $T \simeq 30$ K. One of the most interesting possibilities is that at least a subset of dust-enshrouded galaxies containing an AGN have dust temperatures hotter than the standard 40 K, probably reflecting a very intense radiation field. The high-redshift lensed QSOs H1413+117 (Kneib et al. 1998), IRAS F10214+4724 (Lacy, Rawlings & Serjeant 1998) and APM 08279+5255 (Lewis et al. 1998) have SEDs observed at wavelengths longer than 60 μm that can be fitted accurately by single-temperature dust clouds at $\sim$75, 80 and 110 K, respectively (Blain 1999a), all considerably greater than 40 K. Note, however, that their apparent temperatures may be increased by a factor of the order of 20 per cent because of the effects of gravitational lensing: dust clouds on different spatial scales in different areas of the source can be magnified by different amounts.

The lower-redshift *IRAS* galaxies P09104+4109 and F15307+3252 are also extremely hot, with dust temperatures greater than 100 K (Deane & Trentham 2001). At wavelengths shorter than 60 μm, hotter dust components are detectable in almost all galaxy SEDs, but do not typically dominate the luminosity of the galaxy. The handful of optically faint, hard X-ray sources selected using *Chandra*, for which 850-μm SCUBA data are available in the same field (Bautz et al. 2000; Fabian et al. 2000;

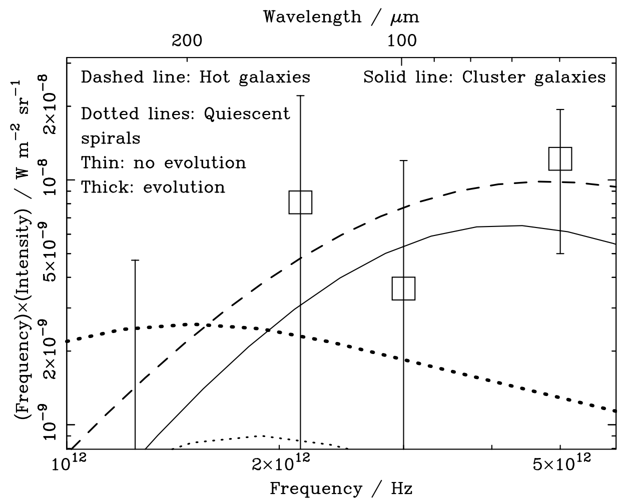

Figure 2. CBR intensity predictions for a model of cluster assembly (solid line), a hot population of dusty galaxies (dashed line), non-evolving quiescent disc galaxies (thin dotted line) and strongly evolving quiescent disc galaxies (thick dotted line). The form of evolution of the quiescent galaxies is identical to that of the standard 40-K SCUBA galaxies. The data points are the CBR intensities reported by Finkbeiner et al. (2000), with the predicted contribution from 40-K SCUBA galaxies shown in Fig. 1 subtracted. The hot galaxies are assumed to have a dust temperature of 80 K, and a luminosity density evolving in the same way as, but 50 per cent less intense than that of the standard SCUBA galaxy models. The cluster galaxies are assumed to have a temperature of 50 K and $\Omega_\infty f_g = 0.02$. The full listing of parameters in this model is given in Section 2.2.

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Hornschemeier 2000; Mushotzky et al. 2000; Almaini et al. 2002) have submm–X-ray spectral indices consistent with dust temperatures of ~ 50 K or greater if their redshifts are in the range $z \simeq 1$–2. This is all consistent with the ability to detect some of these X-ray-selected AGN in 15 μm surveys using ISOCAM (Wilman et al. 2000; Risaliti, Elvis & Gilli 2002).

We now consider the effects of adding a population of galaxies that are considerably hotter than 40 K to the standard model (Blain et al. 1999d). In the simplest case, if we add a population of hotter (80-K) dust-enshrouded hierarchically merging galaxies with an identical form of much better fit to the latest far-IR CBR intensities (Finkbeiner et al. 2000) can be obtained; see Fig. 2. It is also quite plausible that a population of galaxies with a more complex distribution of dust temperatures that peaks at ~ 80 K could account for the observations.

The population of galaxies detected by *IRAS* at 60 μm extend only to a redshift of $z \simeq 0.2$, and so the addition of a hot distant population of galaxies would not conflict with the faint 60-μm data. Surveys at wavelengths of 450 and 850 μm are more sensitive to cooler galaxies, and so the addition of the hotter 80-K population is not expected to conflict with the observed counts; however, the strength of evolution of dusty galaxies at $z \lesssim 1$ required to account for the 175-μm counts may be reduced slightly.

If the hotter dust-enshrouded galaxies are assumed to be predominantly powered by AGN accretion, and the cooler 40-K SCUBA galaxies are assumed to be powered by star formation, then in order to account for the 60-μm CBR intensity shown in Fig. 2, approximately half as much energy is generated over the history of the Universe by accretion as by high-mass star formation. As a result, assuming an accretion efficiency of ϵ, the ratio of the amount of energy released by star formation and by accretion should be approximately $2 \simeq 0.007\epsilon_* M_*/\epsilon M_{\rm BH}$, where $\epsilon_* \simeq 0.4$ is the fraction of the material incorporated in high-mass stars that is involved in nuclear burning, $M_{\rm BH}$ is the black hole mass and M_* is the stellar mass. If a value of $M_{\rm BH}/M_* \simeq 0.006$ (Magorrian et al. 1998) is universal, then this implies that $\epsilon \simeq 0.23$, which is a very plausible value. If $M_{\rm BH}/M_*$ is several times less (Ferrarese & Merritt 2000; Gebhardt et al. 2000), then ϵ is greater by the same fraction: see also Trentham & Blain (2001).

A population of hotter dusty galaxies, perhaps dust-enshrouded AGN that are undergoing relatively efficient accretion, could thus account for a greater intensity of 60-μm CBR, without breaching other observational constraints. At wavelengths of 850, 450, 175 and 60 μm the increase in the CBR intensity generated by including the additional population of hot dusty galaxies described above is 3.3, 5.3, 17 and 85 per cent, respectively, as compared with the conventional 40-K dusty galaxy models (Fig. 1).

2.2 Luminous star-forming galaxies triggered by the assembly of groups and clusters

An alternative explanation of the excess far-IR CBR intensity is an additional population of low-redshift galaxies with SEDs more similar to those of luminous *IRAS* galaxies and high-redshift SCUBA galaxies. This population would boost the far-IR CBR intensity without exceeding the measured intensity of the submm-wave CBR.

In hierarchical models of structure formation, the assembly of groups and clusters of galaxies is the most significant process that takes place at redshifts less than those at which galaxy formation takes place. The formation of clusters involves the merger of overdense regions, which already contain galaxies, into a common dark matter halo. This assembly of a new halo is likely to involve strong dynamical interactions of the enclosed galaxies, which are likely to trigger bursts of star formation activity, and perhaps consume any remaining cold gas in the pre-existing galaxies. The conditions in these member galaxies are likely to be similar to those in pairs of merging field galaxies, and so it is reasonable to assume dust temperatures similar to those in the 40-K SCUBA galaxies for tidally or shock-induced starbursts in forming clusters.

Using a simple model of the process of cluster assembly, it is possible to predict the CBR spectrum expected to arise from this star formation activity. Using the Press–Schechter (Press & Schechter 1974) formalism for the evolution of bound structures and the resulting merger rate (see Blain & Longair 1993a,b; Blain et al. 1999d), the number of bound haloes that form at a given mass between M and $M + \mathrm{d}M$, $\dot{N}_{\rm form}$ can be predicted as a function of redshift.

$$\dot{N}_{\rm form} = \dot{N}_{\rm PS} + \phi \frac{\dot{M}^*}{M^*} N_{\rm PS} \exp\left[(1-\alpha)\left(\frac{M}{M^*}\right)^{\gamma}\right], \tag{1}$$

where

$$\dot{N}_{\rm PS} = \gamma \frac{\dot{M}^*}{M^*}\left[\left(\frac{M}{M^*}\right)^{\gamma} - \frac{1}{2}\right] N_{\rm PS}, \tag{2}$$

and

$$N_{\rm PS}(M,z) = \frac{\bar{\rho}}{\sqrt{\pi}} \frac{\gamma}{M^2} \left(\frac{M}{M^*}\right)^{\gamma/2} \exp\left[-\left(\frac{M}{M^*}\right)^{\gamma}\right], \tag{3}$$

in which $\bar{\rho}$ is the mean density of dark matter, γ, ϕ and α are numerical constants, and $M^*(z)$ is the evolving mass of the typical bound halo at redshift z. $M^* \propto \delta(z)^{2/\gamma}$, where $\delta(z)$ is the amplitude of a growing density fluctuation as a function of redshift.

If we assume that a bound object forming at a mass between $M_{\rm cl}$ and $A_{\rm cl}M_{\rm cl}$ will be recognized as a cluster for the first time, then the total rate of processing mass, in the form of dark and baryonic matter, during the formation of clusters as a function of redshift

$$\dot{\rho}_{\rm cl}(z) = \int_{M_{\rm cl}}^{A_{\rm cl}M_{\rm cl}} \dot{N}_{\rm form}(M,z) M \,\mathrm{d}M. \tag{4}$$

The process of assembly of the cluster is likely to trigger large-scale star formation activity in the cluster member galaxies, depleting their cold gas content. As a result the gas depletion is likely to prevent any constituent galaxies of a cluster more massive than $A_{\rm cl}M_{\rm cl}$ from being involved in large-scale star formation activity at later times. $A_{\rm cl}$ is expected to be of the order of a few, and so the integral in equation (4) can be approximated as

$$\dot{\rho}_{\rm cl} \simeq \frac{A_{\rm cl}^2 - 1}{2} M_{\rm cl}^2 \dot{N}_{\rm form}\left(\frac{A_{\rm cl}+1}{2} M_{\rm cl}, z\right). \tag{5}$$

If we substitute

$$U = \left(\frac{A_{\rm cl}+1}{2}\frac{M_{\rm cl}}{M^*}\right)^{\gamma}, \tag{6}$$

then

$$\dot{\rho}_{\rm cl} \simeq 4\bar{\rho}\gamma \frac{A_{\rm cl}-1}{A_{\rm cl}+1} \frac{\dot{\delta}}{\delta} \frac{U^{1/2}}{\sqrt{\pi}} \left[\left(U - \frac{1}{2}\right) \mathrm{e}^{-U} + \frac{\phi}{\gamma} \mathrm{e}^{-\alpha U}\right]. \tag{7}$$

This expression includes the ratio of $M_{\rm cl}$ and M^* through U. The ratio of these masses can be normalized, at the present epoch, by assuming a value for the fraction of all mass that is bound to

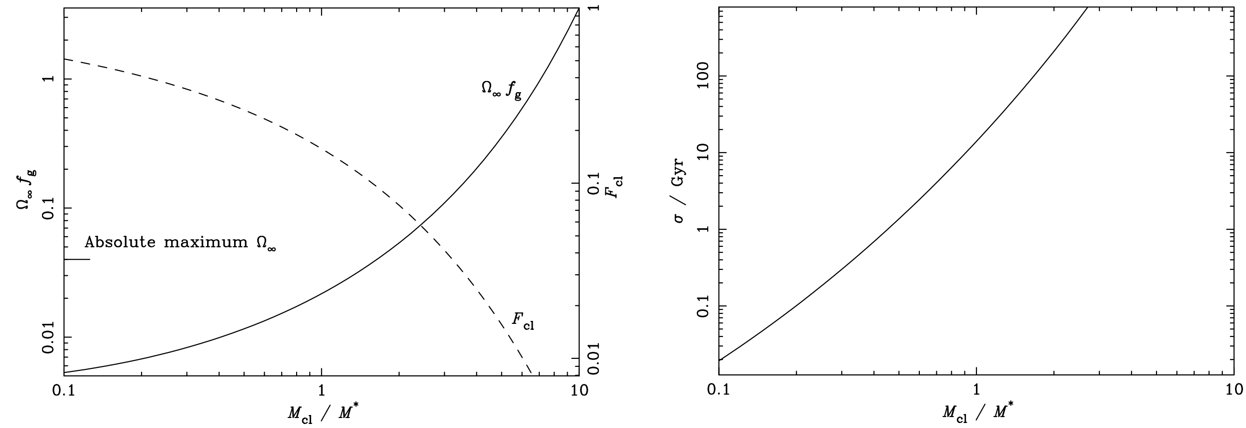

Figure 3. (a – left-hand panel) Solid line: the value of the parameter $\Omega_\infty f_g$ (equation 11; left-hand ordinate axis) in the cluster/group assembly model that is required to produce an excess 60-μm CBR intensity equal to that shown by the data point in Fig. 2. The value of $\Omega_\infty = \Omega_b$ for $f_g = 1$ is shown as an absolute maximum value of this parameter. The value of the parameter F_{cl} (equation 8; right-hand ordinate axis) is also shown. As F_{cl} declines, $\Omega_\infty f_g$ must increase in order to generate the same CBR intensity. (b – right-hand panel) The value of the parameter σ (equation 16) that is required for a model of cluster formation that reproduces the excess 60-μm CBR intensity to equal the bright 60-μm *IRAS* count. Values of σ below the line are inconsistent with the count observations. Realistic models must have values of σ much less than the Hubble time.

clusters of galaxies at the present epoch,

$$F_{cl} = \frac{\int_{M_{cl}}^{\infty} M N_{PS}\, dM}{\int_0^{\infty} M N_{PS}\, dM}. \tag{8}$$

Assuming $\gamma \simeq 2/3$ (Blain et al. 1999d), if $F_{cl} = 0.1$, which is reasonable for clusters, then $M_{cl}/M^*(0) \simeq 1.6$; if $F_{cl} = 0.5$, which is reasonable for groups, then $M_{cl}/M^*(0) \simeq 0.1$ (see Fig. 3a). Fixing F_{cl} thus allows one parameter in the calculation to be removed. Note that the absolute value of $M^*(0)$ does not affect the result.

If the fraction of cold gas in the constituent galaxies is assumed to be representative of the Universe as a whole at z, $\Omega_g(z)$, and a fraction f_g of this gas is assumed to be converted into stars during the formation of the cluster, then the comoving luminosity density generated in forming clusters is

$$\epsilon_{cl}(z) \simeq 0.007 c^2 f_g \Omega_g(z) \dot{\rho}_{cl}(z), \tag{9}$$

as a function of epoch. The global form of evolution of the density of gas $\Omega_g(z)$ can be determined by using the simple formalism discussed by Jameson (2000) and Longair (2000). In this case,

$$\Omega_g(z) = \frac{1}{2}\Omega_\infty \{1 + \tanh[B \ln(1+z) - C]. \tag{10}$$

The values of the two dimensionless parameters B and C can be determined by fitting the submm-wave CBR spectrum and the bright counts of *IRAS* galaxies: see Blain et al. (1999d) and Blain (2001). The function is an exact solution for an Einstein–de Sitter model, but is also an accurate representation of the behaviour of Ω_g in the cosmological model assumed here if $B = 1.95$ and $C = 1.60$.

If all the energy released in star formation induced by the formation of a cluster is assumed to appear in the far-IR waveband, and f_ν represents the SED of the dusty galaxies involved, then the CBR intensity generated,

$$I_\nu = \frac{1}{4\pi} 0.007 c^2 f_g \int \frac{\Omega_g(z)\dot{\rho}_{cl}(z)}{1+z} \frac{f_{\nu(1+z)}}{\int f_{\nu'}\, d\nu'} \frac{dr}{dz} dz, \tag{11}$$

where dr is the radial comoving distance element. Note that the values of the parameters f_g and Ω_∞ only affect the scaling of the predicted intensity. A_{cl} introduces a more subtle shift in the CBR spectrum. The values of ϕ, α and γ have only weak effects on the result.

Making the simplest assumption of a common SED with the 40-K SCUBA galaxies, then the CBR spectrum predicted using equation (11) peaks at slightly too low a frequency to describe the observations shown in Fig. 2; however, if the dust temperature is increased to 50 K, reasonable agreement can be obtained. The results shown in Fig. 2 are derived for values of $F_{cl} = 0.1$, $A_{cl} = 2$, $\gamma = 2/3$, $\phi = 1.53$, $\alpha = 1.17$, $\Omega_\infty = 0.02$ and $f_g = 1$.

In the context of the standard nucleosynthesis value of $\Omega_b h^2 = 0.019$ (Burles & Tytler 1998) and if $h = 0.65$, then a value of $\Omega_\infty = 0.02$ corresponds to 44 per cent of all the baryons being available to form stars in the form of cold gas, which is not an unreasonable assumption.[2] If the value of Ω_∞ is more closely linked to the mass of stars at the present epoch ($\Omega \simeq 0.004$–9 per cent of baryon density; Fukugita, Hogan & Peebles 1998), then no plausible value of A_{cl} can account for the excess CBR if $F_{cl} = 0.1$.

The values of the parameter $\Omega_\infty f_g$ (equation 11) that is required to equal the 60-μm CBR data point in Fig. 2 are shown in Fig. 3(a) as a function of the mass threshold for cluster or group formation, M_{cl}. As the fraction of mass bound to structures more massive than the hypothetical forming groups and clusters F_{cl} falls with increasing mass, the efficiency of star formation activity, parametrized by $\Omega_\infty f_g$, must increase in order to generate the same CBR intensity. If the cosmic density of stars formed to generate the excess CBR is not to exceed the baryon density, then M_{cl}/M^* must be less than ~ 1.7. Hence, it is possible that the assembly of groups and small clusters (with $F_{cl} \simeq 0.5$) could explain the far-IR CBR excess. The formation of rarer massive clusters cannot account for the excess, because too great a baryon mass would have to be involved.

In the 'standard' model of dusty galaxy evolution, the density of stars generated exceeds the value of Fukugita et al. (1998) by a factor 2–3 (see fig. 6 in Blain et al. 1999d). This discrepancy can be corrected relatively easily by requiring the initial mass function

[2] A higher value of Ω_b was suggested by an analysis of microwave background anisotropy from the BOOMERANG experiment (de Bernadis et al. 2000); however, subsequent analysis supports a value of Ω_b close to the value of Burles & Tytler (de Bernadis et al. 2002).

(IMF) to have a lower limit of 1–3 $M_\odot$. In the case of clusters with $F_{cl} = 0.1$ ($M_{cl}/M^* \simeq 1.6$), however, the discrepancy between the mass processed into stars in order to produce the observed CBR intensity exceeds the measurement of Fukugita et al. by a factor of ~ 10. No changes in the form of the IMF can reconcile these values.

Any excess star formation activity induced by group and cluster assembly is likely to be rather short lived, and so not to introduce any significant variation in the colours of the ensemble of cluster member galaxies. It is thus unlikely that observations of cluster and group member galaxies made several Gyr after their formation epoch would be able to detect any clear signs of this final burst of activity (Verdes-Montenegro et al. 1998). Observations that might probe the evolution of cluster member galaxies at moderate redshifts include searches for signs of ongoing star formation activity, via either unobscured starlight (Poggianti et al. 1999), radio emission from supernova remnants (Dwarakanath & Owen 1999) or mid-IR emission from heated dust (Fadda et al. 2000).

2.3 Low-redshift quiescent disc galaxies

The population of low-redshift disc galaxies similar to the Milky Way, with dust temperatures of ~ 20 K (Reach et al. 1995; Alton et al. 1998), can be associated with either the low-luminosity end of the empirical 60-μm *IRAS* galaxy luminosity function (Saunders et al. 1990; Soifer & Neugebauer 1991), or with the mass function of non-merging galaxies derived in a hierarchical clustering model of galaxy evolution, assuming a certain mass-to-light ratio (see fig. 11a of Blain et al. 1999d). The observational constraints on such a population are discussed further by Barnard & Blain (2002); note that its properties are constrained by the counts of *IRAS* galaxies at 60 μm (Bertin, Dennefeld & Moshir 1998), and the bright counts at 175-μm reported by Stickel et al. (1998).

In Fig. 2 we show the CBR intensity predicted by a suitably constrained population of quiescent galaxies, drawn from a Press–Schechter mass function of galaxies, assuming a dust temperature of 20 K and a mass-to-light ratio during ongoing quiescent star formation activity that is 1 per cent of the rate during a merger – values that are consistent with counts of bright *IRAS* and *ISO* galaxies. Regardless of whether the population of quiescent galaxies undergoes either no evolution or strong evolution of a form that matches the evolution of the luminosity density of merging galaxies, the CBR spectrum attributable to this quiescent population is quite different to the observed excess (Finkbeiner et al. 2000), both in terms of its SED and its absolute intensity. Hence, no plausible form of evolution of a population of dusty spiral galaxies can account for the excess far-IR CBR intensity.

If the properties of the population of quiescent, non-merging galaxies were modified to generate a CBR spectrum similar to that observed, then evolution of the same form as that of the merging galaxies, hotter dust temperatures of ~ 40 K, and an increase in the intensity of star formation activity by a factor of ~ 5, are all required. In this case, the properties of the 'quiescent' galaxies become indistinguishable from those of the merging dusty galaxies included in existing models, and so they cease to make up a distinct, additional population. A population of disc galaxies with enhanced star formation rates caused by their infall into clusters could produce a suitable CBR spectrum, but the number of galaxies falling into clusters (Meusinger, Brunzendorf & Krieg 2000) would be far too small to account for the factor of 2 increase in the CBR intensity required to account for the 60-μm observations of Finkbeiner et al.

2.4 Permitted models

A co-ordinated burst of star formation activity induced by the assembly of small clusters and groups of galaxies, and a hot population of dust-enshrouded merging galaxies both appear to be able to reproduce the possible excess in the measured spectrum of the far-IR CBR.

No current observations rule out the hot galaxies model. The CBR intensity in this model is generated at $z \simeq 1$ by galaxies with luminosities typically of several $10^{12}\,L_\odot$, and so these galaxies will not be found in either 60-μm *IRAS* counts (Bertin et al. 1997) or bright 175-μm *ISO* counts (Stickel et al. 1998). However, they would contribute to the faint 15-μm *ISO* counts and the counts of faint hard X-ray *Chandra* galaxies: the majority of both these populations appear to galaxies at $z \simeq 1$. The acquisition of much larger samples of these objects, using *Chandra*, *XMM–Newton* and *SIRTF* will be very valuable for testing this hypothesis.

Conversely, a ready test is available for the idea that co-ordinated star formation activity that takes place at $z < 1$ in assembling groups and clusters generates the CBR excess. The amount of activity required to reproduce the far-IR CBR can be determined, and by assuming a time-scale for the duration of the activity, a count of far-IR luminous clusters in the process of formation can be derived. The measured bright counts of galaxies at 60 and 175 μm can be predicted. As these counts are already explained by the evolving field galaxy models, the group/cluster assembly scenario must not lead to a large additional contribution.

2.5 Far-IR counts of assembling clusters

From equation (1), we know the formation rate of clusters. The comoving space density of clusters forming at masses between M_{cl} and $A_{cl}M_{cl}$ is

$$n(z) = \sigma \int_{M_{cl}}^{A_{cl}M_{cl}} \dot{N}_{form}(M, z)\,dM, \tag{12}$$

where σ is assumed to be a constant duration of the luminous phase. As A_{cl} cannot be too large, this integral can be approximated by

$$n(z) \simeq \frac{8\sigma\bar{\rho}\gamma}{\sqrt{\pi}} \frac{\dot{\delta}}{\delta} \frac{A_{cl} - 1}{(A_{cl}+1)^2} \left[\left(U - \frac{1}{2} \right) e^{-U} + \frac{\phi}{\gamma} e^{-\alpha U} \right] \frac{U^{1/2}}{M_{cl}}, \tag{13}$$

where U was defined in equation (6). This expression can be integrated over a comoving volume to yield the count of such objects on the sky brighter than a flux density S_ν at frequency ν per unit solid angle,

$$N(> S_\nu) = \int_0^{r_{max}(S_\nu)} n[z(r)] r^2\,dr, \tag{14}$$

where

$$r_{max} \simeq \left[\frac{0.007c^2}{\sigma} f_g \frac{A_{cl}+1}{4\pi S_\nu} \frac{M_{cl}}{2} \Omega_g(0) \frac{f_\nu}{\int f'_\nu\,d\nu'} \right]^{1/2}, \tag{15}$$

the maximum distance to which a star-forming group or cluster can be seen. By evaluating equation (14) at $z \simeq 0$, which is a reasonable redshift to assume for the brightest counts,

$$N(>S_\nu) = \frac{\bar{\rho}\gamma c^3}{12\sqrt{2}\pi^2}\frac{A_{\rm cl}-1}{\sqrt{A_{\rm cl}+1}}\frac{\dot{\delta}}{\delta}\left[\frac{M_{\rm cl}U}{\sigma}\right]^{1/2} S_\nu^{-3/2} \times \left[\frac{0.007 f_{\rm g}\Omega_{\rm g}(0) f_\nu}{\int f_{\nu'}\,{\rm d}\nu'}\right]^{3/2}\left[\left(U-\frac{1}{2}\right){\rm e}^{-U} + \frac{\phi}{\gamma}{\rm e}^{-\alpha U}\right]. \tag{16}$$

The only parameter not constrained explicitly from the fit to the excess CBR spectrum shown in Fig. 2 is $M_{\rm cl}$, for any assumed dust temperature and thus SED. The effect of changing the value of $M_{\rm cl}$ on the predicted count is very great: the value of σ required to generate both the excess 60-μm CBR shown in Fig. 2 and the observed 60-μm count $N(>S_\nu)$ at the bright flux density $S_\nu = 5$ Jy is shown in Fig. 3(b). Note that the value of $M_{\rm cl} \simeq 3.6\times10^{12}\,{\rm M}_\odot$ based on the Tully–Fisher normalized value of M^* on galactic scales (Blain, Möller & Maller 1999a).

The observed 175-μm count, $N_{175} \simeq 1800\,{\rm sr}^{-1}$ brighter than $S_{175} = 2.2$ Jy (Stickel et al. 1998), and the 60-μm count, $N_{60} \simeq 60\,{\rm sr}^{-1}$ brighter than $S_{60} = 5$ Jy (Bertin et al. 1999), can be compared with the predicted ratio from equation (16),

$$\frac{N_{175}(S_{175})}{N_{60}(S_{60})} = \left(\frac{f_{60}}{f_{175}}\right)^{-3/2}\left(\frac{S_{60}}{S_{175}}\right)^{3/2}. \tag{17}$$

Taking a reasonable ratio of the SED values f_{60} and f_{175} ($f_{60}/f_{175} \simeq 4.3$ for 50-K dust), at the flux limits S_{175} and S_{60} listed above, the predicted count ratio $N_{175}/N_{60} = 0.38$. Hence, the most significant constraint is imposed by the requirement to agree with the 60-μm count.

In order not to exceed the 60-μm count, while generating the excess 60-μm CBR value shown in Fig. 2, a value of $\sigma = 80$ Gyr is required for $M_{\rm cl}/M^* = 1.6$ ($F_{\rm cl} = 0.1$), while for $M_{\rm cl}/M^* = 0.1$ ($F_{\rm cl} = 0.5$), $\sigma \simeq 19$ Myr is required. Note that the count depends on $\sigma^{-1/2}$, and so relatively large changes in the value of σ are required to modify the count significantly. Unless σ is significantly greater than the value shown in Fig. 3(b), the fraction of bright 60-μm *IRAS* counts caused by assembling groups and clusters will be unacceptably large. Hence, only for groups with values of $M_{\rm cl}/M^* \lesssim 0.2$ is it possible to generate excess 60-μm CBR without violating the 60-μm count constraint. The large value of σ required in the cluster model renders it capable of accounting for only a very small fraction of the CBR excess.

The constraint on σ can be relaxed slightly if the individual galaxies in the cluster or group undergo star formation activity that is not coincident in time. The count slope is -3/2 at bright flux densities, and so splitting the activity into N components should lead to a reduction in the count by a factor of $\sqrt{N}$, and thus to a reduction in the limiting value of σ by a factor of N. However, even if $N \simeq 100$, σ remains at 0.8 Gyr for clusters with $F_{\rm cl} \simeq 0.1$. When the requirement for non-simultaneous bursts in each galaxy is multiplied in, the total duration of star formation activity in the cluster remains comparable to or greater than the Hubble time, and so unlike the assembly of groups, the assembly of clusters is not a plausible mechanism for explaining the 60-μm CBR spectrum. The amount of dust-enshrouded star formation activity required to generate the additional 60-μm CBR spectrum would lead to a large number of mid-IR-luminous clusters on the sky in this model, which were not observed by *IRAS*.

3 OBSERVATIONAL CONFIRMATION OF A POPULATION OF HOT DUSTY GALAXIES OR FORMING GROUPS

From the discussions above, we suspect that a population of dust-enshrouded galaxies at cosmological distances with dust temperatures that are considerably higher than inferred for most nearby *IRAS* galaxies and high-redshift SCUBA galaxies could be responsible for the excess far-IR CBR intensity reported by Finkbeiner et al. (2000). A population of assembling galaxy groups with masses a few times less than M^* could also be a plausible source of the excess far-IR CBR, if star formation were induced in the gas-rich member galaxies during the interactions associated with the assembly of the group. Any contribution from our alternative proposals – cooler evolving dusty galaxies with SEDs such as spiral galaxies, or star formation induced in the assembly of rich clusters – are unlikely to be significant.

In order to confirm the presence of a significant population of hot dusty galaxies, sensitive large-area surveys are required at short submm and far-IR wavelengths. Deep images are required in order for distant galaxies to be detected, and images of the survey fields in several wavebands spanning the mm to mid-IR wavebands are required in order to place constraints on the redshifts and temperatures of the detected objects (see Blain 1999c; Blain et al. 2002). A data set that might be sufficiently deep for conducting this research has been obtained using *ISO* (Oliver et al. 2000). However, much larger images, with much better photometric accuracy, resolution and spectral coverage, will be produced by the *SIRTF* telescope in 2002/3, the SOFIA airborne observatory after 2004/5 and ultimately by the 3.5-m aperture *Herschel* telescope at the end of the decade.

Note that the thermal nature of the emission from these objects means that even the most accurately calibrated multiwavelength observations across the submm, far- and mid-IR wavebands can only provide information concerning the redshifted dust temperature $T/(1+z)$, and not the temperature directly. A dust temperature can only be derived once either a photometric redshift, determined from accurate multicolour photometry in the optical/near-IR wavebands, or a spectroscopic redshift is obtained. This temperature–redshift degeneracy is also expected to affect the radio–far-IR flux ratio in the detected galaxies (Carilli & Yun 1999; Blain 1999b) if $T < 60$ K.

In order to test the idea of forming groups being responsible for excess 60-μm CBR intensity, the spatial distribution of luminous dusty galaxies within a representative cosmological volume must be determined. This can be derived once areas in excess of the order of $1\,{\rm deg}^2$ have been surveyed out to a redshift $z \gtrsim 1$. Observations of fields of similar size at longer wavelengths using future wide-field mm and submm-wave instruments, including the 1.1/1.4/2.1-mm BOLOCAM (Glenn et al. 1998), 450/850-μm SCUBA-II (Holland et al. 2000) and 350-μm SHARC-II (Moseley, Dowell & Phillips 2000) cameras will provide high-resolution images of these fields at longer wavelengths, and thus accurate SEDs for the detected sources. The analysis of clustering in, and the determination of optical counterparts to and redshifts for, galaxies detected in unbiased deep far-IR surveys covering several square degrees using *SIRTF* and *Herschel* will be crucial for testing whether a significant fraction of faint 60-μm sources are associated with forming groups, and so this explanation for an excess CBR could be correct.

At present the clustering properties of submm and far-IR selected galaxies have not been investigated using large statistical samples, owing to the small number of detected objects, although a start has been made using analyses of the amplitude of background fluctuations and correlation functions in observations using SCUBA (Peacock et al. 2000; Almaini et al. 2002; Scott et al. 2002) and fluctuations using *ISO* (Lagache & Puget 2000; Kiss et al. 2001). No region containing highly clustered sources, as might correspond to groups or clusters in the process of formation has been detected in an unbiased survey in these wavebands, as the surface density of such objects is expected to be small, and an insufficient area of sky has so far been surveyed to the appropriate depths to detect one. Note that there are signs from observations in the fields of powerful high-redshift radio galaxies, which may be tracers of high peaks in the density field of the early Universe (Ivison et al. 2000b), that very significant overdensities of dust-enshrouded galaxies do exist at high redshifts.

4 CONCLUSIONS

If recent reports of additional extragalactic background radiation at an observed wavelength of 60 μm are correct, then an extra population of dust-enshrouded galaxies could be required in models of galaxy formation in order to account for them. This is in addition to the relatively cool 40-K dusty galaxies that can account for the measured submm and far-IR counts and the mm- and submm-wave CBR intensity. The most plausible sources of the excess emission are likely to be either a population of hotter dust-enshrouded galaxies, heated predominantly by AGN, or a population of star-forming galaxies associated with the assembly of galaxy groups. It is very unlikely that dust emission from either moderate redshift spiral galaxies or dust-enshrouded star formation in assembling rich clusters of galaxies can account for the excess CBR intensity. Follow-up observations of faint X-ray sources detected by *Chandra* and *XMM-Newton* using mid-/far-IR sensitive telescopes, such as *SIRTF* and *Herschel*, and deep wide-area surveys of representative cosmological volumes using the same telescopes, should allow these suggestions to be confirmed or refuted.

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