MODELING THE COSMIC INFRARED BACKGROUND

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ABSTRACT

The contribution to the cosmic far-infrared and submillimeter background (CIBR) from extragalactic sources, including normal and active galaxies and protogalaxies, is not well constrained by direct observational number counts of galaxies, which are currently limited to the relatively local universe at these wavelengths. Therefore our estimates of their contribution to the background are based on model extrapolations. I review the principle modeling techniques currently in use, including Backward Evolution in time of a locally-observed luminosity function, and Forward Evolution in time of a high redshift galaxy population. The most modestly and passively evolving model extrapolations lie below the current FIRAS and DIRBE limits on the CIBR; however some of the more strongly evolving models are now in conflict with the best COBE limits, even though the DIRBE limits still notably contain some foreground zodiacal and galactic emission. The most important unknown parameters which govern the model predicted far-infrared and submillimeter emission of the integrated light of galaxies are the galaxy formation redshift; the dust temperature at high redshifts; the star formation history; and the variation of the dust optical depth with time, ~(t), which governs the fraction of the galaxy light that is reprocessed into the far-infrared. The next generation of spacecraft (ISO, WIRE, SIRTF), and of instruments on the new 10m class telescopes, will go a long way towards answering these questions, providing much insight into key aspects of galaxy formation and evolution.

1. INTRODUCTION

Why should we expect galaxies to produce enough infrared emission at early epochs that their integrated emission in this wavelength range will be both detectable and informative? The nucleosynthesis argument (eg. Peebles, these proceedings) indicates that we expect to find an integrated background light due to the formation of the metals we see in the local universe of about $10^{-8} Wm^{-2}sr^{-1}$, of order a decade wide, somewhere in the electromagnetic spectrum. Such a background has yet to be detected in the UV-optical-NIR range. There are several lines of evidence which point to the conclusion that there was significant early metal and dust enrichment, at least in proto-elliptical galaxies, and that much of the early radiative output of galaxies emerged longward of $1\mu m$ and was subsequently reradiated to longer wavelengths. One piece of direct observational evidence for early dust and metal enrichment comes from the detection of both dust and molecular CO emission in IRAS F10214+4724 (Rowan-Robinson *et al.* 1991, Brown and Vanden Bout 1992, Solomon, Dowries and Radford 1992) and the Cloverleaf quasar (Barvainis, Antonucci and Coleman 1992, Barvainis *et al.* 1994), at redshifts of $z = 2.36$ and 2.56, respectively.

Although both of these objects are likely gravitationally lensed, the implied dust and CO masses are still large, indicating that in these objects at least, a very significant metal and dust enrichment has occurred. Not only do these objects illustrate enrichment, they also demonstrate high dust optical depth to optical/UV radiation since the far-infrared luminosities are high ($\gtrsim 10^{13} L_\odot$, after correction for lensing). Elbaz *et al.* (1992) and Mazzei and De Zotti (1994) have modeled IRAS F10214+4724 successfully as a very massive proto-elliptical galaxy of age about 1 Gyr; taking into account the probable lensing, their models will scale down to a match a more typical giant elliptical galaxy. (Alternatively, the very high infrared luminosity of these objects could arise in a dust torus around a luminous AGN (for which there is strong evidence in both cases), in which case their relevance to galaxy evolution in general is less obvious.)

We can also find some quite general evidence for a high far-infrared integrated background light from conditions in the local universe, where about 1/3 of the volume emissivity of all galaxies emerges in the far-infrared; this emission is dominated by ongoing massive star formation in disk galaxies. If the star formation rates in disk galaxies have undergone a relatively slow rate of change with time, as expected for isolated dissipatively-evolving systems and supported by direct measurements of current and recent star formation tracers in some nearby disks, it follows that their integrated far-infrared emission over the age of the universe is likely to be at least several percent of the Cosmic Microwave Background (Partridge and Peebles 1967). As emphasized by Mazzei and de Zotti (1994) and Franceschini *et al.* (1994) the integrated far-infrared emission of elliptical galaxies could be even higher than that of disks if ellipticals formed rapidly with a large initial star formation rate and a high optical depth, as in the models Elbaz *et al.* and Mazzei and de Zotti (1994) for F10214+4724. Support for the possibility of a high dust optical depth in protogalaxies comes from the fact that despite years of painstaking effort, protogalaxies have remained elusive in the optical and UV.

Another line of evidence argues that the integrated background in the far-infrared and submillimeter could be even higher than predicted by a model of slow dissipative evolution of isolated disk galaxies; the possibility that merging and starbursting may have been an important feature of galaxy evolution at intermediate times. A significant fraction of the local luminous galaxy energy density is generated in the far-infrared by starburst and/or AGN episodes associated with interacting and merging galaxies. The steeply rising IRAS 60μm number counts may imply an increase of this activity backwards in time, a scenario consistent with results deduced from submJy radio source counts and the optical and near-infrared color distributions of faint galaxy samples. Thus we might expect a very significant integrated light at far-infrared wavelengths from this phenomenon, in excess of that predicted under the assumption that disk galaxies have evolved quite passively as isolated systems.

2. MODELING THE INTEGRATED EMISSION OF GALAXIES

There are two basic types of model in use for understanding the evolution of galaxies with time and predicting the integrated backgrounds in the far-infrared (FIR) and submillimeter range. Both have their advantages and disadvantages but taken together they are strongly complementary.

The first modeling method I call Backward Evolution (BE) of the Luminosity Function (LF). In this class of model, a locally- derived luminosity funcion of galaxies is extrapolated backwards in time according to a simply parameterized evolutionary function, to match the observed number-magnitude, number-redshift, color- magnitude, etc., distributions, as available. Since the IRAS-selected observational distributions are generally restricted to redshifts lower than about 0,3, large extrapolations of the evolutionary function backwards in time are required to make predictions about the integrated light of galaxies.

This class of model was orginally developed for application to radio source counts, and has also been extensively used in the interpretation of the evolution of QSOs. The method has the advantage of being empirical with a minimum of input and assumed parameters: the local luminosity function, the form of the evolution law, the spectral energy distribution(s) of galaxies (required in order to perform k-corrections as a function of z for the model galaxy population(s)) and a maximum redshift, z_{max}, at which the model integration is terminated. Such models provide an excellent context for a broad phenomenological overview of far-infrared galaxy evolution, but they can give limited physical insight into detailed galaxy evolution processes.

The second class of model, Forward Evolution, works the opposite way in time: a theoretical galaxy formation paradigm and evolutionary framework are first adopted, and then a population of galaxies is evolved forwards in time from the formation epoch to match the local $N(S)$, $N(z)$, and color distributions, *etc.* This class of model is more physical than backward LF evolution, since it can incorporate the detailed modeling of numerous physical parameters and processes. It also has the advantage that it can be highly multi-wavelength, drawing on data at many wavelengths to constrain the input parameters. Its advantages, of course, also highlight its disadvantages: the large number of assumptions and free parameters typically involved mean the models are often severely under-constrained.

2.1 Backward LF Evolution Models

In the simplest Backward LF Evolution models, the entire luminosity function is fixed in shape with time, and it translates en *masse* in luminosity and/or density at the rate specified by the adopted evolutionary law. The evolutionary law usually is either a single power law or exponential in z. Such models are called translational models, and they were originaly pioneered for the evolution of radio sources and quasars. The physical interpret.ation of such evolution involved an increasing luminosity of AGNs with lookback time for luminosity evolution, or an increasing fraction of galaxies possessing an AGN at earlier times for density evolution. In the context of far-infrared bright galaxies, power law translational evolution would be ideal for describing an increasing luminosity of starbursts and/or AGN with lookback time, or an increasing fraction of galaxies undergoing starburst episodes and/or AGN events with lookback time, as long as the rate of mergers is low. However, this kind of I. F- invariant evolution is not well suited for describing true merging scenarios, in which smaller galaxies merge to form larger ones -- such scenarios implicitly involve evolution of the shape of the luminosity function. It is also questionable for describing continuous passive evolution of stellar populations, which also involves an implicit evolution of the shape of the LF at some level (because galaxies of different shape and mass can be expected to brighten and fade with time at different rates), regardless of the merging process,

A sample of the parametric models of the far-infrared background that have been published based on translational evolution are shown in Figures 1 and 2. In these figures, α denotes pure power luminosity evolution, given by $L(t) = L(t_0)(1 + z)^\alpha$; β denotes pure power law density evolution described as $\rho_{co}(t) = . \rho_{co}(t_0)(1 + z)^\beta$, where ρ_{co} is the co-moving density; and Q denotes the exponential luminosity evolution relation used by Oliver *et* al. (1992): $L(t) = L(t_0)\exp\{2/3Q[1-(1+z)^{-3/2}]\}$ (appropriate for $\Omega=1$). Other published models include the power law models of Hacking and Soifer (1991), Weedman (1990), Franceschini et *al.* (1991) and Treyer and Silk (1993), which give similar results to those illustrated in Figures 1 and 2.

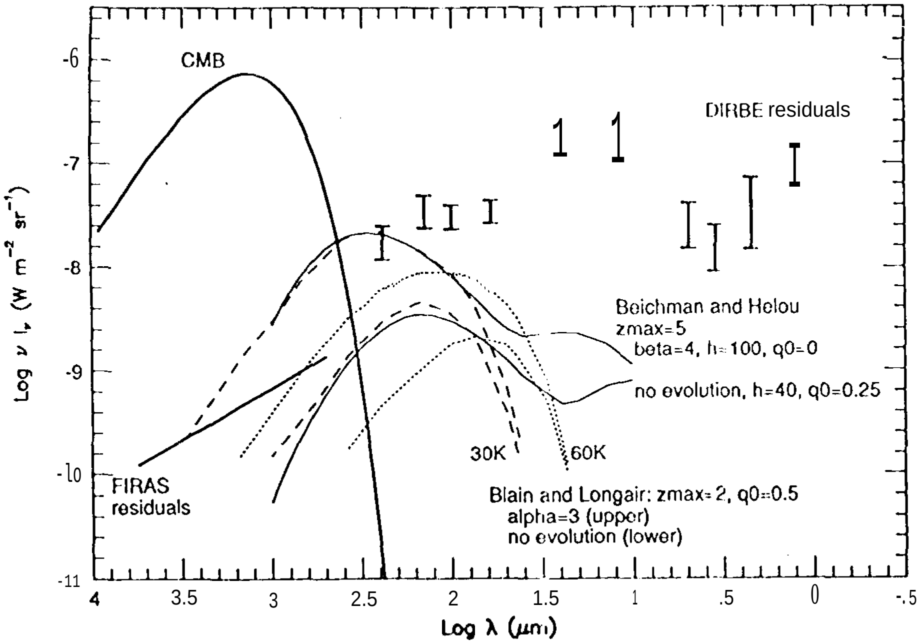

Figure 1: Comparison of the integrated CIBR predicted by representative Backward Evolution models of Beichman and Helou (199) and Blain and Longair (1993) to the most recent FIRAS and DIRBE residual measurements, as summarized by Hauser (these proceedings).

For most of the BE models all galaxies comprising the LF are allowed evolve at the same rate. In the model of Franceschini *et al.* (1991), the three galaxies types evolve at different rates. The model of Treyer and Silk is different in nature from the others in that they do not allow the luminosity function of "normal" galaxies to evolve with time, but add a new population of dwarf galaxies whose characteristic space density, ϕ^* (Mpc^{-3}), is the parameter that evolves: $\phi^*_{dw} = 6.0\times10^{-2}((0.7/z) + 1)^{-1}$ h^3, where h=H$_0$ in units of 100 km/s/Mpc. This model is designed to explain the steepness of the observed blue number counts of galaxies with a population of dwarf galaxies which is present at z = 0.7 but has faded or merged to invisibility by the current epoch.

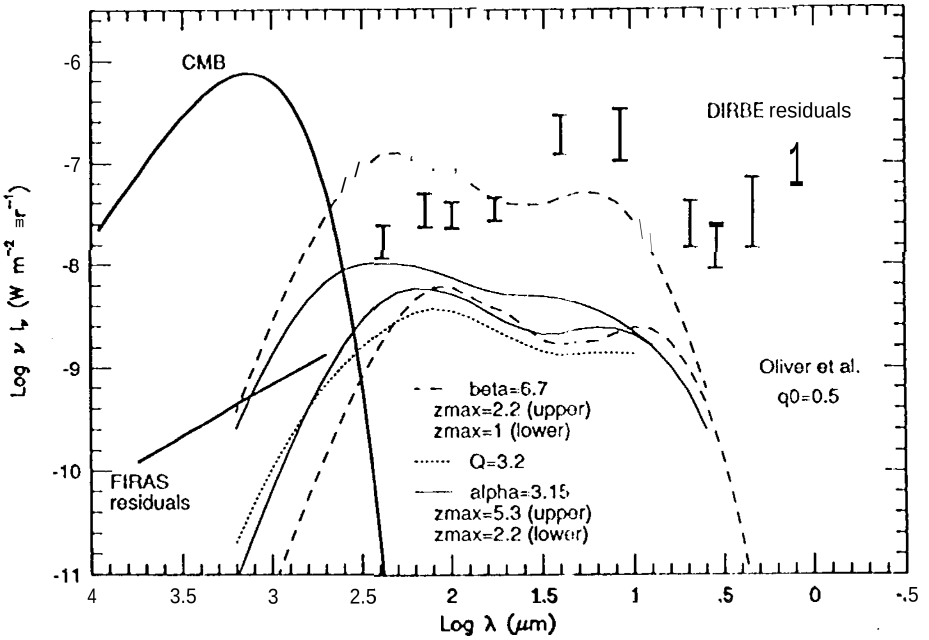

Figure 2: Comparison of the integrated CIBR predicted by the models of Oliver *et al.* (1992) to the most recent FIRAS and DIRBE residual measurements.

For all the models shown in Figures 1 and 2, except those labeled "no evolution", the evolutionary parameters (α, β or Q) have been selected by their authors to fit the slope of the locally-observed IRAS $60\mu m$ source counts. This is a very important aspect of the interpretation of these models which I will return to in Section 3.1.

2.2 *Evolutionary Synthesis Models*

The model of Franceschini *et al. (1994)* is based on the closed box chemical evolutionary population synthesis models of Mazzei, Xu and De Zotti (1992) and Mazzei, de Zotti and Xu (1994). Starting at a selected formation epoch, a population of model galaxies is given a range of masses and initial star formation rates and allowed to evolve forwards in time according to the adopted prescriptions for chemical and stellar evolutionary theory and a Salpeter IMF. The star formation rate, ψ, of each galaxy evolves with time as a power, n, of the fractional gas mass f_g, $\psi(t) = \psi_0 f_g^n M_\odot yr^{-1}$ where $f_g =$ kf~$_0$s/^{1}149^{0}1 evolves as the changing stellar populations use up interstellar material and re-process some of it back for use by future generations. The far- infrared and submillimeter emission is modeled as the sum of a warm component heated by the massive stars and a cooler component heated by the older stars, depending on the evolving dust-to-gas ratio and dust optical depth. The galaxies with the highest initial star formation rates are elliptical galaxies, which use Up most of their ISM very rapidly with an early, very far-infrared-luminous phase (a "protogalaxy" phase), and then settle down to a long passively evolving history of low far-infrared emissivity. Disk galaxies evolve more slowly, reaching an epoch of peak far-infrared emissivity at much later times. The latest galaxy types are still increasing in optical depth after a Hubble time.

As noted above, a young elliptical galaxy model can match the luminous $z=2.3$ IRAS galaxy F10214+4724 quite well, while the same model at 15 Gyr matches the UV-far-infrared energy distribution of local elliptical well; see Mazzei and de Zotti (1994). Two integrated light models of Franceschini *et al.* (1994), differing in the value adopted for n, are shown in Figure 3; if their picture of galaxy evolution is correct then the integrated background light expected from galaxies in the wavelength range is clearly within close reach of being detected by COBE.

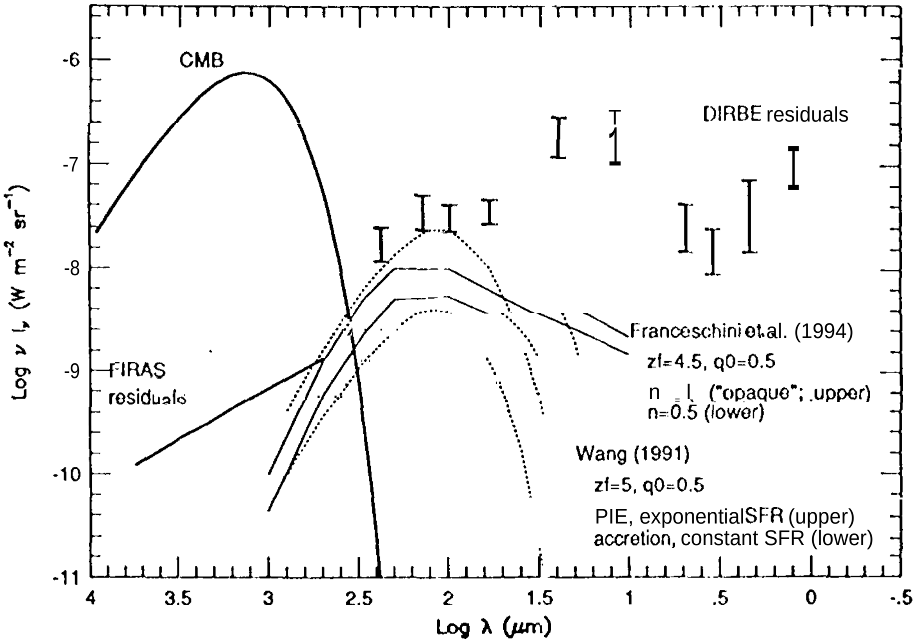

Figure 3: Comparison of the integrated CIBR predicted by the models of Franceschini *et al.* (1994) and Wang (1991) to the most recent FIRAS and DIRBE residual measurements.

Wang (1991a,b) takes a simpler approach to the evolving stellar energy output of his model galaxy population than Franceschini *et al.* (1994), and focuses on the chemical enrichment and evolution of the dust in molecular clouds in more detail. He investigates two enrichment/star formation rate scenarios: prompt initial enrichment with either a constant or exponentially declining SFR, and a model allowing continued accretion of material from intergalactic space coupled with constant star formation. Wang fixes the dust temperature at 30K, based on observations of local disks, rather than attempting a derivation of expected dust temperatures, and his galaxies are formed at a range of redshifts given by a Gaussian distribution with variable z_f and σ_z.

Wang finds that the dust content of young disk galaxies at early times can be up to 4 times larger than today, and the far-infrared luminosity can be two orders of magnitude greater. The PIE model predicts much stronger backgrounds than the accretion model because it shows strong evolution of the dust mass.

Wang's results are compared to those of Franceschini *et al.* (1993) in Figure 3, where it may be seen that for similar cosmology and z_f the "opaque" ($n=1$) model of Franceschini *et al.* (1994) is very similar to the PIE model of Wang with exponentially declining star formation, at least at $\lambda > 200$ μm. At shorter wavelengths the models are expected to diverge because Wing, focusing only on the far-infrared emission, considers only a single temperature dust component.

Both the Franceschini *et al. (1994)* and the Wang models assume conservation of galaxy number density. Blain and Longair (1993) derive the integrated background for a hierarchical clustering model with merging based on the Press-Schecter formalism for the growth of structure. In their model the far-infrared and submillimeter emissivity of galaxies is proportional to the SFR, which varies as a gaussian with time during each galaxy merger event. They ran models adopting two different assumed dust temperatures, 30 and 60K, and constrained the models to generate the correct heavy element abundance and to fit local 60pm source counts. Their models are shown in Figure 4.

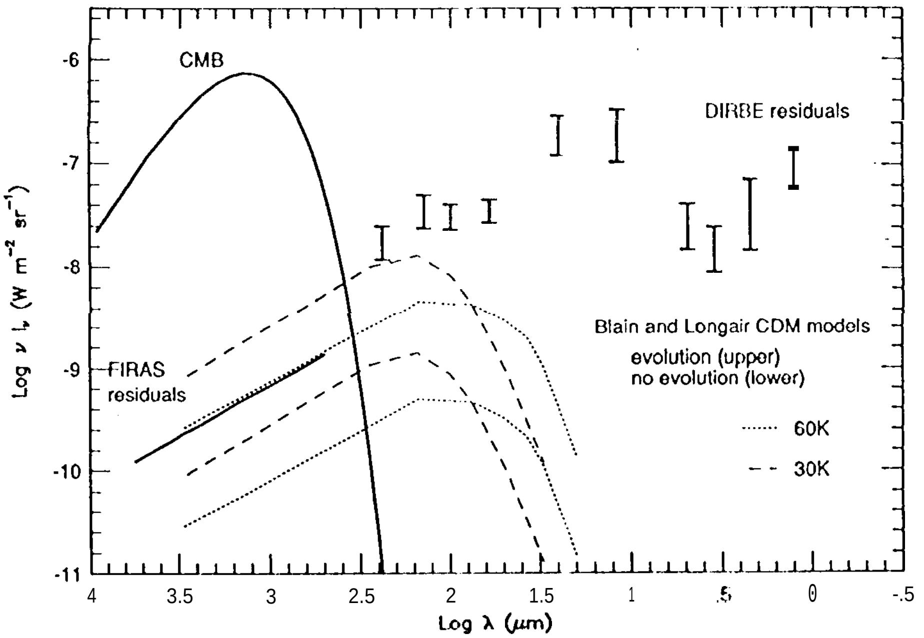

Figure 4: Comparison of the integrated CIBR predicted by the CDM models of Blain and Longair (1993) to the most recent FIRAS and DIRBE residual measurements

3. MODEL RESULTS AND CONCLUSIONS

Several of the models shown in Figures 1-4 are in conflict with the FIRAS residuals, and even with some of the current DIRBE limits, in spite of the fact that the DIRBE limits clearly still contain significant levels of foreground zodiacal and galactic emission. This confluence between theory and data means that we can begin to learn something about galaxy formation and evolution from the details of the modeling processes. In particular, it is very exciting to note that the COBE limits are getting down to the level predicted by the general nucleosynthesis argument of $\sim 10^{-8}$ $W\ m^{-2} sr^{-1}$, *the* level we expect if a large percentage of the tots] stellar energy density of the universe emerged in the FIR, therefore a detection at close to these levels may show that it actually did do so. The Desert *et* al. tentative detection (these proceedings) is therefore tantalizing.

3.1 Backward Evolution Models: Redshift Cutoff or Lower Evolutionary Rates?

The first conclusion that can be made from a consideration of the various models of Figs 1-4 is that for similar assumptions (cosmology, the galaxy formation epoch and the spectral energy distribution of the model galaxies), the strongly evolving power law Backward Evolution models tend to predict higher integrated backgrounds than the Forward Evolution models. Compare, for example, the α=3.15, z_f=5.3, Ω= 1 BE luminosity evolution model of Oliver *et al.* with the z_f=5, Ω= 1 models of Wang, which assume similar galaxy spectral energy distributions.

In general, all of power law the translational BE models that can fit the slope of the IRAS local 60μm number counts are in serious conflict with the COBE limits, unless a low redshift cutoff is imposed on them (the more complex model of Treyer and Silk is an exception and is discussed further below). The translational density evolution models, in particular, require an especially low redshift cutoff because higher evolutionary rates are nominally required to fit the local 60μm counts using density evolution rather than luminosity evolution (Hacking, Condon and Houck 1987; Saunders *et al.* 1990; Lonsdale *et al.* 1 990). For luminosity evolution (and Ω= 1) z_{max} is about 2 — 3, and for density evolution it is about 1 – 2, depending on the details of the adopted spectral energy distributions (see Rowan-Robinson, these proceedings, an update to the models of Oliver *et al.*). Of course, a traditional translational power law evolution model will always require a redshift cutoff at some point because such a model otherwise diverges at high redshift. Power law density evolution models in particular become meaningless at high redshifts, because at some point the mass of the total number of galaxies involved in the backward extrapolated series of mergers will exceed the total galactic mass of the universe. On the other hand, the exponential luminosity evolution model of Oliver *et al.* dots not suffer from this problem because it converges at high redshift; indeed this model is not in conflict with the COBE limits.

How physically plausible is a redshift cutoff at $z \sim 2$ for the strongly evolving BE translational evolution models? Recall that this class of translational evolution model was developed as an aid to understanding the evolution with redshift of radio source counts and QSOs. As such they have been quite successful, and have a reasonably simple and physic all y plausible interpretation in terms of an increase with lookback time of the luminosity and/or frequency and/or duration of AGN events in galaxies. The character of the A GN events themselves are not expected to change much with lookback time, thus a redshift-invariant LF is not unreasonable. A turnover in redshift is also seen for QSOs, and is interpreted in terms of the formation epoch of QSOs. For the FIR number counts and integrated background an analogous scenario could be considered, since it is very possible that a significant fraction of the far-infrared luminosity of galaxies ultimately derives from dust-enshrouded A Gil, especially in the most luminous galaxies (e.g.. Lonsdale, Smith and Lonsdale 1995), and from starbursts caused by interaction and merger events, and is therefore reasonably modeled to first order by translational LF evolution. But there remains a large fraction of the far-infrared emissivity of galaxies which derives from passive stellar evolutionary processes, in galaxy disks, which *are* expected to change continuously with cosmological epoch, and which *are not* well modeled by translational evolution of a fixed LF.

An alternative solution to the strongly evolving models with a redshift cut-off is to question whether the rate of evolution assumed in these models is simply too high. In fact there is good reason to question this, and the argument is very similar to that which has arisen around the '(faint blue galaxy question". The focus of research in optical and near-infrared observational cosmology has recently revolved around the fact that redshift distributions of faint field galaxy samples routinely fail to find enough galaxies at high redshifts to agree with evolving models for the number-magnitude relations (see e.g., Koo and Kron 1992). Several explanations for this failure have been put forward; the most popular invoke some sort of population of low luminosity galaxies that were present at moderate redshifts, and therefore contributed to steepening the number-magnitude relation, which have either faded to invisibility or merged with other galaxies by the present time (*eg.* Broadhurst, Ellis and Shanks 1998). A simpler explanation is that we have simply got either the shape of the local luminosity function (in particular, the slope of the faint end) or the normalization of the local number-magnitude relations wrong (*eg.* Lonsdale and Chokshi 1993; Gardner, these proceedings).

It now seems that there is a similar conflict between the steepness of the number-magnitude relation and redshift distributions at 60μm; Ashby, Houck and Hacking (1992) fail to find the high redshift galaxies expected for a translational evolution model that can fit the count slope. Therefore we should likewise question both the adopted shape of the 60μm LF and the normalization of the models to the number-magnitude relation, and we should consider more complex evolutionary forms. The far-infrared integrated background model of Treyer and Silk (1993) is based on a fading/merging dwarf scenario, such as those put forward to explain the faint blue galaxy problem, and indeed it has no conflict with the CIBR limits (it predicts a CIBR similar in intensity and distribution to the lower of the two models of Beichman and Helou illustrated in Figure 1). Alternatively, if we suspend the requirement that the BE models in general must match the 60μm $N(S)$ slope, then the more slowly evolving models of for example, Beichman and Helou, come into consideration.

3.2 The FE Models

To gain more physical insight into galaxy evolution than possible from the BE models, we can turn to the more detailed FE modeling approaches. The "opaque" (n= 1) stellar population synthesis model of Franceschini *et al. (1994)* can be considered an illustration of a classical non- CDM galaxy formation model in which a large fraction of all the light of the forming elliptical protogalaxies emerges in the FIR, Indeed, a large fraction of all galaxy light emerges in the FIR in this model, leaving little of the approximately $10^{-8} Wm^{-2}sr^{-1}$ expected on general grounds from the nucleosynthesis prediction to emerge at other wavelengths. The PIE model with exponential star formation of Wang is likewise a good illustration of a non-CDM universe in which most of the energy density of galaxies emerges in the FIR, as it also accounts for essentially all of the nucleosynthesis energy. The Blain and Longair evolving models illustrate an alternative CDM merging scenario, some of them also accounting for much of all nucleosynthesis energy. The fact that these models are so closely constrained by the new CIBR data means that they are clearly worthy of more detailed refinement, in anticipation of further observational progress in both the CIBR limits and in number count, redshift and color distributions at intermediate redshifts. It is worth emphasising, however, that there is room for uncertainty in those models which have been designed to fit the steep $60\mu m$ source counts. This is because, following the arguments in the previous section, such models may give a biased picture of far-infrared evolution rates in the local universe. Therefore further modeling should take care to fit the available FIR redshift distributions and take full account of the current uncertainties in the shape of the local LF and the absolute normalization of the N(S) relation.

The long wavelength shape of the integrated model spectra is the most critical aspect for comparison to the FIRA S limits (and the tentative FIRAS detection of Desert *et* al.). It's shape is principally governed by the convolution of the dust temperatures and the redshifts of the dominant contributing galaxies to the integrated background. At one extreme, a dominant contribution from very cool dust in very high redshift galaxies will cause the integrated background to greatly exceed the FIRAS limits, as in the 30K evolving CDM model of Blain and Longair, while at the other extreme a dominant contribution from relatively low redshift and/or relatively warm galaxies, such as the accretion model with low z_f of Wang, will predict an integrated emissivity at FIRAS wavelengths that is much lower.

4. FUTURE DIRECTIONS

Where do we go from here? The prospects for progress in understanding galaxy evolution via modeling of the Cosmic Infrared Background are obviously very exciting at present, since several different modeling approaches result in CIBR predictions that lie within reach of detection, and some plausible scenarios are already ruled out. Therefore more refined modeling approaches would clearly be very timely and important.

By itself, a detection of the CIBR will not distinguish between the variety of galaxy formation and evolution paradigms represented by the models discussed in this paper, but will tell us only in general terms what fraction of the total energy generated over the history of the universe was r-c-radiated into the FIR by dust; *ie.* it will give us an integral of the stellar energy and dust optical depth over time. The spectral shape of the CIBR will give us information about the integral of the temperature of that dust, and the redshift range at which it was emitted, over the history of the universe.

Therefore, of equal important to the refinement of the various models to agree with the CIBR measurements will be model predictions and detailed observations of galaxy populations at a variety of wavelengths and a range of redshifts which can be used to critically test these different model approaches. Redshift surveys of large samples of the faintest IRAS galaxies will help to solve the dichotomy between the steep slope of the 60μm number counts and the shallow redshift distribution (*eg.* Smith *et al.* 1996), while deep ISO and WIRE (Wide Field Infrared Explorer) surveys and their subsequent follow-up with redshift determinations will push these studies to redshifts of unity or above. High resolution HST or Keck imaging of the intermediate and high redshift ISO galaxies will shed much light on the overall role of mergers and starbursts in galaxy evolution. The new submillimeter SCUBA instrument promises to be extremely valuable because submillimeter number counts at intermediate redshifts are expected to be especially sensitive diagnostics of galaxy evolution models as the k-correction redshifts the strong FIR peak into the submillimeter band (see Blain and Longair 1993; also Guiderdoni, these proceedings).

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