MODELS FOR EVOLUTION OF DUSTY AND E/S0 GALAXIES SEEN IN MULTIBAND SURVEYS
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ABSTRACT

Phenomenological models for evolution of dusty and E/S0 galaxies, respectively, are developed to address two major questions concerning galaxy populations in deep infrared (IR) surveys: (1) Do normal late-type galaxies or starburst galaxies (including galaxies with obscured active galactic nuclei) dominate among sources in deep IR surveys? (2) How much do E/S0 galaxies contribute to the counts in deep mid-infrared (MIR: 3–20 μm) surveys? Among three new models for evolution of dusty galaxies, it is assumed in model S1 that starburst galaxies are the dominant population and in model S2 that normal galaxies dominate. Model S3 is an intermediate model. Comparing the model predictions with a wide range of observational data collected from the literature, we find that none of these models can be ruled out, given the uncertainties of the data. We show that the most direct method to distinguish these models is to compare the predicted color distributions of IR galaxies with observations, which will soon be available from the SIRTF Wide-Area Infrared Extragalactic (SWIRE) survey. The models for E/S0 galaxies follow a simple passive evolution approach. Among the three E/S0 models (E1, E2, and E3) investigated in this paper, model E2, which is specified by a peak formation redshift $z_{\text{peak}} = 2$ and an e-folding formation timescale $\omega = 2$ Gyr, fits the data best. This suggests a synchronization between the evolution of E/S0 galaxies and that of starburst galaxies, in the sense that the peak of the formation function of E/S0 galaxies ($z_{\text{peak}} = 2$) is close to the peak of the evolution functions of starburst galaxies ($z_{\text{peak}} = 1.4$). We find that E/S0 galaxies contribute about 10%–30% of the counts in the MIR bands of less than 10 μm and up to 30%–50% of the optical/near-IR counts in the bright end. Their contributions to counts in the UV (2000 Å) and in the longer wavelength IR (≥12 μm) bands are negligible. Taking into account this contribution, new predictions for counts and confusion limits in the SIRTF bands are presented.

Subject headings: galaxies: luminosity function, mass function — galaxies: Seyfert — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

Many new windows have recently been opened in various wave bands for observations of high-redshift galaxies. Particularly, deep Infrared Space Observatory (ISO) surveys (e.g., Rowan-Robinson et al. 1997; Franceschini et al. 1997; Kawara et al. 1998; Elbaz et al. 1999; Aussel et al. 1999; Flores et al. 1999b; Puget et al. 1999; Dole et al. 2001; Clements et al. 1999; Serjeant et al. 2000) in the infrared and SCUBA surveys (Hughes et al. 1998; Barger et al. 1998; Blain et al. 1999) in the submillimeter wave bands have shed light on the dark side of galaxy formation and evolution. This stimulated a surging wave of empirical models (Rowan-Robinson et al. 1997; Franceschini et al. 1997; Lonsdale 1999) may have provided biased information (Madau et al. 1996) by neglecting the dust extinction (Rowan-Robinson et al. 1997; Lonsdale 1999). This will certainly have impact on the theoretical simulations of galaxy formation and evolution, which (e.g., Somerville, Primack, & Faber 2001) have just started facing the fact that most of the early star formation may be hidden behind a thick veil of dust, making the incorporation of effects of dust extinction and emission in the framework essential (Granato et al. 2000).

Some of the most recent empirical models (Rowan-Robinson et al. 2001; Xu et al. 2001; Franceschini et al. 2001; Pearson 2001; Chary & Elbaz 2001) have the feature that they can be constrained by counts and the cosmic background radiation in various IR and submillimeter bands simultaneously. This is achieved by using spectral energy distribution (SED) templates to link sources in different bands. The SED library of Xu et al. (2001) contains realistic SEDs of a complete sample of 837 IRAS 25 μm–selected galaxies, enabling prediction of counts as well as color distributions, which provide additional constraints to the model. Templates in Rowan-Robinson (2001), Xu et al. (2001), and Chary & Elbaz (2001) extend from the results such as the Hubble Deep Field survey (Williams et al. 1996) may have provided biased information (Madau et al. 1996) by neglecting the dust extinction (Rowan-Robinson et al. 1997; Lonsdale 1999). This will certainly have impact on the theoretical simulations of galaxy formation and evolution, which (e.g., Somerville, Primack, & Faber 2001) have just started facing the fact that most of the early star formation may be hidden behind a thick veil of dust, making the incorporation of effects of dust extinction and emission in the framework essential (Granato et al. 2000).

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IR-submillimeter to optical and UV wave bands; hence, these models can predict also the contributions from IR sources to optical and UV counts, relating the evolution of IR sources to that of galaxies seen in earlier optical and UV surveys. All of these works found strong evolution among IR sources in the redshift range of $0 < z < 1.5$. Assuming that the narrow submillijansky bump on the Euclidian normalized differential counts of ISOCAM 15 $\mu$m surveys (Elbaz et al. 1999) is due to the $K$-corrections caused by the strong unidentified broadband (UIB) emission features at 6–8 $\mu$m, which are shifted into the ISOCAM 15 $\mu$m band filter (LW3) when $z \sim 1$, Xu (2000) concluded that typical IR galaxies at $z \sim 1$ have $L_{15,\mu m} / L_{\odot} \sim 10^{11}$, namely, about 20 times more luminous than their local counterparts, while their comoving density is about the same as their local counterparts. As argued by Xu et al. (2001), the location of the 15 $\mu$m bump ($f_{15,\mu m} \sim 0.4$ mJy) provides a strong constraint on the luminosities of IR sources at $z \sim 1$. This has been confirmed by the detailed study of ISOCAM sources in the Hubble Deep Field–North (HDF-N) by Elbaz et al. (2002), who obtained redshifts for nearly all of these sources (40 out of total of 41). The strong evolution has also been supported by surveys in other ISOCAM bands. For example, Clements, Desert, & Franceschini (2001) found that the luminosity functions (LFs) of their ISO 12 $\mu$m sources are consistent with a pure luminosity evolution rate of $\sim (1 + z)^{3.5}$, as derived by Xu (2000) from the ISOCAM 15 $\mu$m counts.

On the other hand, different authors identified different populations of galaxies as the major carriers of the evolution of IR sources. It was found in early IRAS studies (Franceschini et al. 1988; Rowan-Robinson & Crawford 1989) that IR sources can be divided into three different populations: normal late-type galaxies (“circus galaxies”), starburst galaxies, and galaxies with active galactic nuclei (AGNs). Assuming that all IR sources undergo pure luminosity evolution with the same evolution rate, Rowan-Robinson (2001) found that cirrus galaxies dominate the ISOCAM 15 $\mu$m counts, the SCUBA 850 $\mu$m counts, and the cosmic IR background radiation. Xu et al. (2001), motivated by results of optical identifications of ISO galaxies by Flores et al. (1999b) and Aussel et al. (1999) that show that a larger percentage of these sources are in interacting systems, assumed that most of the evolution of the IR sources is due to starburst galaxies (defined by warm far-infrared [FIR] colors: $f_{60,\mu m} / f_{100,\mu m} \geq 0.5$). Obscured AGNs with relatively low $f_{25,\mu m} / f_{60,\mu m}$ ratios (due to the very high extinction affecting even the mid-infrared [MIR] fluxes) may be misclassified as starbursts in Xu et al. (2001), who classified galaxies with AGNs using the criterion $f_{25,\mu m} / f_{60,\mu m} \geq 0.2$. Franceschini et al. (2001) also assumed that the strong evolution is confined to the starburst population. Their starburst galaxies include all “active” galaxies not classified as Seyfert 1, i.e., including the Seyfert 2 galaxies and the LINERs, in Rush, Malkan, & Spinoglio (1993). Pearson (2001) found that a separate population of ultraluminous galaxies (ULIRGs) with $L \sim 10^{12} L_{\odot}$ confined in a very narrow range of redshift centered at $z \sim 1$, is mostly responsible for the strong evolution seen in the ISOCAM 15 $\mu$m counts. Since all these models can fit the IR-submillimeter counts and the cosmic infrared background (CIB) within uncertainty limits, there is apparently a degeneracy concerning the population of galaxies that carry most of the evolution of IR sources. The degeneracy still remains even when the new, detailed information of the 15 $\mu$m universe (source counts, redshift distributions, LFs at different redshifts, etc.; Elbaz et al. 2002; Franceschini et al. 2001) is considered (see § 2).

One of the central issues in the current agenda of hierarchical galaxy formation simulation studies concerns the roles played by two different star formation modes (e.g., Somerville et al. 2001; Kauffmann, Charlot, & Balogh 2001), namely, the quiescent star formation mode and the interaction-induced star formation mode. There are apparent links between the normal quiescent galaxies and the quiescent star formation (as in the Milky Way and M31) and between starburst galaxies and the interaction-induced star formation (as in the Antennae galaxies and in M82). Therefore, the answer to the question of whether the normal galaxies or starburst galaxies dominate the faint IR counts will have important impact on galaxy evolution theories.

Another deficiency of the current models for IR sources is the neglect of early-type galaxies. Although these galaxies have little dust emission and therefore do not contribute significantly to IR counts at wavelengths longer than $\sim 10 \mu$m, they are found as an important population in ISO 6.7 $\mu$m counts (Flores et al. 1999b; Aussel et al. 1999; Serjeant et al. 2000). Future mid-IR surveys such as those planned for SIRTF Infrared Array Cameras (IRACs) (four bands centered at 3.6, 4.5, 5.8, and 8 $\mu$m, respectively) will certainly detect many of these galaxies.

In this paper we shall address the above two issues, namely, (1) developing new models to investigate how to break the degeneracy concerning the major evolution population in IR counts (using SIRTF data in particular), and (2) modeling the evolution of E/S0 galaxies and predicting their contributions to the MIR counts. The plan of the paper is as follows: In § 2 a set of new models for evolution of dusty galaxies is presented, while in § 3 models for evolution of E/S0 galaxies are developed and compared to the observations. Predictions for the UV, optical, and near-infrared (NIR) counts by a set of composite models, each consisting of a dusty galaxy evolution model and an E/S0 evolution model, are presented and compared with data in § 4. The predictions for counts and confusion limits in SIRTF bands by the same models are presented in § 5. In § 6 we show how to use color distributions of ISO sources and future SIRTF sources to answer the question of whether starburst galaxies or normal late-type galaxies are dominant in the IR sources. Section 7 is devoted to discussion. A summary is given in § 8.1 The cosmology ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$) is assumed throughout the paper.

2. NEW MODELS FOR EVOLUTION OF DUSTY GALAXIES

2.1. Previous Models

In all the multiband models for the evolution of dusty galaxies in the literature, the different populations of galaxies are separated by their characteristic SEDs: the normal galaxies have relatively low $f_{60,\mu m} / f_{100,\mu m}$ and $f_{25,\mu m} / f_{12,\mu m}$ ratios and very prominent UIB features, the starburst

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1 More detailed results on predictions of models presented in this paper are available on request to C. K. X.
galaxies have relatively high $f_{60\mu m}/f_{100\mu m}$ and $f_{25\mu m}/f_{12\mu m}$ ratios and less prominent UIB features over a steep rising MIR continuum, and galaxies with AGNs have relatively high $f_{25\mu m}/f_{60\mu m}$ ratios and very weak UIB features (contributed by interstellar medium [ISM] dust not associated with the AGN). Models by Xu et al. (2001) have also considered the luminosity dependence of the SED in each population, while some other models (Rowan-Robinson 2001; Franceschini et al. 2001; Pearson 2001; Chary & Elbaz 2001) separate high-luminosity starbursts (Arp 220 type) from moderate-luminosity starbursts (M82 type). Because of their different SEDs, these different populations of galaxies give different relative contributions to counts at different wavelengths. However, it appears that the counts are rather loose constraints to these relative contributions. At least two factors are responsible for this degeneracy: (1) there are many parameters in the evolution functions (both the luminosity evolution and the density evolution) when different populations are allowed to evolve differently, and (2) there are still significant uncertainties in the current ISO counts (e.g., counts of the same European Large-Area ISO Survey [ELAIS] 15 $\mu m$ sources reported by Serjeant et al. 2000 and Gruppioni et al. 2002 differ with each other by as much as a factor of 3), as a result of both calibration errors and the field-to-field variation. In principle, the degeneracy can be broken by comparing model predictions on redshift distributions of deep FIR-selected ($\lambda \geq 60 \mu m$) samples with observations: models assuming warmer IR SEDs (starbursts dominant) usually predict larger mean redshifts than models assuming cooler IR SEDs (normal galaxies dominant). However, similar to the SCUBA galaxies, the large beams of FIR detectors (such as the ISOPHOT cameras) make it rather difficult to pin down the optical counterparts (usually quite faint) of faint FIR sources.

A more direct method to constrain the relative contributions of different populations to the IR counts is to compare the predicted and observed color distributions of IR sources. Among the multiband models for evolution of dusty galaxies in the literature, those of Xu et al. (2001) have the most sophisticated algorithm in dealing with the SEDs and are the only ones that can predict both the mean colors and their dispersions. Therefore, we choose to build our new models using the same algorithm as Xu et al. (2001).

### 2.2. New Models

In the new models, the simulation code of Xu et al. (2001) is modified in the following aspects:

1. The luminosity and density evolution functions for the starburst galaxies and normal late-type galaxies, respectively, have the following new form:

\[
F_i(z) = (1 + z)^{u_i} \frac{1 + (1 + z)/(1 + z)}{1 + 1/(1 + z)} \times \frac{1 + 1/(1 + z)}{1 + (1 + z)/(1 + z)}^{v_i + w_i} (z \leq 7), (1)
\]

\[
G_i(z) = (1 + z)^{q_i} \frac{1 + (1 + z)/(1 + z)}{1 + 1/(1 + z)}^{q_i + w_i} \times \frac{1 + 1/(1 + z)}{1 + (1 + z)/(1 + z)} (z \leq 7). (2)
\]

These smoothly joined three-piece power laws, in contrast with the sharply joined two-piece power laws used in Xu et al. (2001), will allow softening in the low-redshift end ($z < 0.5$) of the evolution functions to improve the fit to the redshift distribution of IRAS 60 $\mu m$ sources.

2. The 25 $\mu m$ local LFs (LLFs) of three populations used in Xu et al. (2001) did not themselves take into account the evolutionary effects. In the new models, new 25 $\mu m$ LLFs corrected for these effects are used (see Appendix A for the details of the new LLFs). It is found that these new LLFs are only marginally different from the old ones.

3. The UV portion ($\lambda < 3000$ A) of the SEDs in the SED library, which is an important part of the code, is better constrained in this work (Appendix B).

Given the large number of parameters, it is out of the scope of this paper to explore the entire parameter space for models allowed by available data. Instead, we concentrate on three models that predict very different relative contributions by starburst galaxies and normal late-type galaxies to the counts in the IR surveys. For each of them, parameters have been fine-tuned so that the model can fit all available data as well as possible. These models for dusty galaxies are presented in Table 1 and Figure 1.

Model S1 is similar to the models in Xu et al. (2001) and Franceschini et al. (2001) in the sense that the starburst galaxies are assumed to dominate the evolution of the IR sources. In model S2, similar to Rowan-Robinson (2001), all three populations of dusty galaxies are assumed to have pure luminosity evolution with the same evolution rate. This is actually the same evolutionary scenario adopted by Xu (2000), who assumed that the entire body of IR sources evolve as a single population. Note that Rowan-Robinson (2001) assumes that there is no SED evolution, while in model S2 we assume SEDs evolving with luminosity. In model S3, it is assumed that the normal and starburst galaxies give equal contributions to the ISO CAM 15 $\mu m$ counts, as hinted at by the optical identifications of ISO sources (Flores et al. 1999b; Aussel et al. 1999). For models

### Table 1

| Models  | $z_1$ | $z_2$ | $u_1$ | $v_1$ | $w_1$ | $u_2$ | $v_2$ | $w_2$ | $p_2$ | $q_2$ | $r_2$ | $u_3$ | $v_3$ | $w_3$ |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| S1     | 0.5  | 0.85 | 1.5  | 1.5  | 2    | 2    | 11.5 | 1.2  | 1    | 9.8  | 1.2  | 1.36z – 0.27z² | 1.36z – 0.27z² | 1.36z – 0.27z² |
| S2     | 0.5  | 1.2  | 3.2  | 5.7  | 2.5  | 3.2  | 5.7  | 2.5  | 0    | 0    | 0    | 3.2  | 5.7  | 2.5  |
| S3     | 0.5  | 1    | 2    | 8    | 2    | 2    | 10.2 | 1.5  | 2    | 3    | 1.5  | 1.36z – 0.27z² | 1.36z – 0.27z² | 1.36z – 0.27z² |
S1 and S3, the luminosity evolution function of galaxies with AGNs is adopted from the optical QSO luminosity evolution function of Boyle et al. (2000):

$$F_{\text{AGN}}(z) = 10^{1.36 - 0.27z^2} \quad (z \leq 7).$$

This is slightly different from the power-law function used in Xu et al. (2001).

2.3. Predictions for Counts and Redshift Distributions

In Figures 2, 3, and 4, predictions by these three models for the 15, 60, 90, 170, and 850 μm counts and for the CIB are compared with the data, respectively. The data points are taken from a large pool of measurements found in the literature, which is still evolving rapidly. This is particularly true for the measurements involving ISO data because more and more new data reduction tools are becoming available for these rather complex data.

Model S1, which is otherwise the same as the “peak model” in Xu et al. (2001) except for the modifications listed in § 2.2, predicts that the contribution from the starburst population dominates almost everywhere in these plots. The model predictions are in reasonably good agreement with data in all plots, given the large dispersions in the data sets. Particularly, the new results of Gruppioni et al. (2002) on the 15 μm counts of ELAIS sources (filled four-point stars) are about a factor of 3 lower than the counts from the same survey reported by Serjeant et al. (2000; open four-point stars) and are also significantly lower than other ISO CAM measurements in the flux range of 1 mJy < f_{15} < 10 mJy. Model S1 predicts a less prominent submillijansky peak in the 15 μm counts than the peak model of Xu et al. (2001) because the sharp peak at z = 1.5 in the evolution functions of the old model is replaced by a smooth peak in the new model (at z ≈ 1.3; see Fig. 1). It is worth noting that, in the bright end of the SCUBA counts (f_{850} < 5 mJy), the model predicts that the contribution from galaxies with AGNs exceeds that from starbursts. This result seems to be consistent with the limited knowledge we have about the bright SCUBA sources: out of the seven SCUBA sources of f_{850} > 8 mJy in the sample of Smail et al. (2002), four show signs of AGNs. On the other hand, the model predictions on the SCUBA 850 μm counts are close to the lower boundary of the data.

In contrast to model S1, model S2 predicts that for 15 μm counts, 850 μm counts, and the CIB, the population of normal galaxies dominate (Fig. 3). This is in agreement with the results of Rowan-Robinson (2001). The same model predicts that normal and starburst galaxies give about equal contributions to the 170 μm counts and starbursts dominate the 90 and 60 μm counts. This model can also fit the data in all these plots well (Fig. 3).

By design, the contributions from normal and starburst galaxies are indeed nearly equal in the predictions of model S3 for 15 μm counts (Fig. 4). The same model predicts that the 60, 90, and 170 μm counts are dominated by starbursts. For the SCUBA 850 μm band, the model predicts comparable contributions from the normal and starburst galaxies to the counts in a wide flux range, and the contribution from AGNs dominates the counts at a few times 10 s of millijansky level while being negligible at submillijansky level. The
Fig. 2.—Comparisons of predictions of model S1 with observed IR counts and CIB. Data points in the plot of 15 μm counts: the ELAIS counts reported by Serjeant et al. (2000) are plotted with open four-point stars, and the ELAIS counts reported by Gruppioni et al. (2002) are plotted with filled four-point stars. Other data points have the same symbols as in Elbaz et al. (1999): A2390 (six-point stars); ISOHDF-North (open circles); ISOHDF-South (filled circles); Marano FIRBACK Ultra-Deep (open squares); Marano Ultra-Deep (crosses); Marano FIRBACK Deep (asterisks); Lockman Deep (open triangles); Lockman Shallow (filled triangles). Filled squares with error bars are counts taken from Xu (2000). Note that the high points in the bright end ($f_{15 \mu m} \geq 0.5$ Jy) are due to the Local Supercluster (Lonsdale et al. 1990). The shaded area marks the range of counts estimated by Mazzei et al (2001). Data points in the IRAS 60 μm plot: Mazzei et al. (2001; large filled circles); Hacking, Condon, & Houck (1987; crosses); Gregorich et al. (1995; open stars); Bertin, Dennefeld, & Moshir (1997; open circles); counts in the south Galactic cap ($b < -50^\circ$) by Lonsdale et al. (1990; small filled squares); Saunders et al. (1990; open triangles); Rowan-Robinson et al. (1990; open squares). Data points in the 90 μm plot: Efstathiou et al. (2000; filled circles); Linden-Voornle et al. (2000; crosses); Matsuhara et al. (2000; open square); total counts of Juvela, Mattila, & Lemke (2000; open diamonds); counts of multiple detections of Juvela et al. (2000; open triangles). Data points in the 170 μm plot: Dole et al. (2001; filled circles); Matsuhara et al. (2000; open square); total counts of Juvela et al. (2000; open diamonds); counts of multiple detections of Juvela et al. (2000; open triangles). The SCUBA 850 μm counts: Blain et al. (1999; crosses); Hughes et al. (1998; open circles); Eales et al. (2000; open diamonds); Barger, Cowie, & Sanders (1999; open squares); Scott et al. (2002; filled diamonds). The cosmic IR background: Lagache et al. (1998; filled circles); Finkbeiner, Davis, & Schlegel (2000; open squares); Gorjian, Wright, & Chary (2000; open stars); Dwek & Arendt (1998; filled star); SCUBA source count results (Blain et al. 1999; large crosses); the range of COBE/FIRAS results (Fixsen et al. 1998; shadowed area); upper limits from TeV gamma-ray radiation of Mrk 403 and Mrk 501 (Dwek & Slavin 1994; Staney & Franceschini 1998; diamonds and crosses with upper limits).
CIB predicted by this model is dominated by the contribution from the starburts in the wavelength range $20 \mu m \leq \lambda \leq 300 \mu m$ and by that from normal galaxies at other wavelengths.

In Figures 5, 6, and 7, predictions by the three models for the redshift distributions for the IRAS $60 \mu m$, ISOAM $15 \mu m$, ELAIS $90 \mu m$, FIRBACK $170 \mu m$, SCUBA $850 \mu m$, and future SIRTF Wide-Area Infrared Extragalactic (SWIRE) $24 \mu m$ surveys are plotted. The model predictions for the IRAS $60 \mu m$ and ISOAM $15 \mu m$ surveys are compared to the data. All three models give more satisfactory fits to redshift distribution of the

Fig. 3.—Comparisons of predictions of model S2 with observed IR counts and CIB. The sources of data points are the same as in Fig. 2.
IRAS 60 μm sources than the peak model (favorite model) of Xu et al. (2001), although model S1 still overpredicts the number of IRAS 60 μm sources with $z > 0.2$ by about a factor of 3. For the redshift distribution of ISOCAM 15 μm sources in the HDF-N, the predictions of model S1 give the best fit among the three models although, given the large error bars of the data, the difference among model predictions is subtle.

All three models predict bimodal redshift distributions for ELAIS 90 μm and FIRBACK 170 μm sources, with normal galaxies dominating the first peak and starburst galaxies dominating the second peak. Model S1 predicts that
most of ELAIS 90 μm and FIRBACK 170 μm sources have \( z \geq 0.5 \). In contrast, model S2 predicts that most of these sources have \( z \leq 0.5 \), being in the first peak of the redshift distributions. This difference is due to the so-called temperature-redshift degeneracy for IR galaxies (Blain 1999): in the long-wavelength bands such as the 90 and 170 μm bands, the sources in model S1 tend to have larger redshifts than those in model S2 in order to compensate their warmer IR SEDs. Interestingly, this indicates that we can break the degeneracy over these models by comparing the predicted and observed redshift distributions of the ISOPHOT sources in these bands. Serjeant et al. (2001) obtained high-confidence

![Graphs showing redshift distributions for various IR surveys.](image)

Fig. 5.—Predictions of model S1 for redshift distributions of various IR surveys. The observed redshift distributions (histograms in corresponding plots) of IRAS 60 μm sources and ISO 15 μm sources are taken from Rowan-Robinson (2001) and Franceschini et al. (2001), respectively.
redshifts for 16 (out of 37) sources of $f_{90 \mu m} \geq 0.1$ Jy in the ELAIS S1 field (3.96 deg$^2$); none of them have redshift larger than 0.5. This sets a lower limit of $43\% \pm 11\%$ for the percentage of the 90 $\mu$m sources in this field to have $z < 0.5$. Taken at face value, only the prediction of S2 (53%) is comfortably above this lower limit, while the prediction of S3 (37%) is marginally consistent with it, and the prediction of S1 (30%) is marginally below the limit. The above comparisons seem to favor model S2. However, given the fact that this data set was taken from a small region and can be seriously affected by any clustering effect, more observations are needed for any definitive conclusions.

Model S1 predicts a broad redshift distribution, peaking between $2 < z < 3$, for bright SCUBA sources ($f_{850 \mu m} > 8$
mJy), broadly consistent with observational constraints (Smail et al. 2002; Ivison et al. 2002; Fox et al. 2002). For the same sources, model S2 predicts a prominent peak around \( z = 1.5 \) and less than 25% of sources at redshifts greater than 2, not favored by observations that in general suggest a mean redshift larger than 2 (see, e.g., Ivison et al. 2002). Model S3 also predicts a peak around \( z = 1.5 \) for the \( f_{850 \mu m} > 8 \) mJy sources, although with a much wider high-redshift wing (44% of sources have \( z \geq 2 \)).

2.4. Predictions for ISO Luminosity Functions and Star Formation History

The ISOCAM 15 μm sources in HDF-N have been thoroughly studied in the literature (Rowan-Robinson et al.
1997; Aussel et al. 1999; Elbaz et al. 1999, 2002; Cohen et al. 2000; Franceschini et al. 2001). All but one of a total of 41 sources with $f_{15\mu m} \geq 0.1$ mJy have spectroscopic redshifts (Franceschini et al. 2001; Elbaz et al. 2002). Exploiting these redshifts, we derived the $15\mu m$ LFs in three redshift intervals, $0 < z < 0.7$, $0.7 < z < 1$, and $1 < z < 1.3$, using the classical $V_{\text{max}}$ method. These results are compared to the predictions of the three models in Figure 8.

Given the small size of the data set (40 galaxies), it is understandable that the derived LFs have substantial uncertainties. Particularly, significant fluctuations can be found in the redshift distributions (Figs. 5–7), presumably as a result of clustering effects. Compared to these uncertainties, the difference in the predictions by the three different models is again subtle. They all lie near the lower ends of the error bars (Poisson error) of the two data points in the panel of $0 < z < 0.7$. This is likely to be due to a bias in the data caused by the overdensity in the $0.4 < z < 0.6$ bin (Figs. 5–7). In the panels of $0.7 < z < 1$ and $1 < z < 1.3$, the predictions of model S1 are slightly higher and fit the data slightly better than those of the other two models.

In Figure 9a, the star formation history (SFH) predicted by the three models is compared to observations. The red lower limits are derived from the ISOCAM $15\mu m$ LFs (Fig. 8). The lower limit of $15\mu m$ luminosity density is derived by summing up the contributions in the bins where the LF is actually measured (i.e., no extrapolations are applied to measured LFs), then converted to total IR luminosity using the formula $L_{\text{IR}} = 11.1L_{15\mu m}$ (Elbaz et al. 2002). The SFR is then estimated from the IR luminosity density using the formula of Kennicutt (1998): $\text{SFR}(M_\odot \text{ yr}^{-1}) = L_{\text{IR}} / (1.7 \times 10^{-10}) L_\odot$. The predictions of the three models are very close to each other (within 50%).

In Figures 9b, 9c, and 9d, these predictions are broken into contributions by different populations. Indeed, model S1 predicts that, except for in the low-$z$ end ($z \lesssim 0.2$), the starburst galaxies overwhelmingly dominate the star formation in the universe. Model S2 predicts just the opposite: the star formation in the universe has always been dominated by normal late-type galaxies, while in model S3 the contributions of these two populations are more comparable. All three models predict minor contributions from galaxies with AGNs. Note that since some of the IR emission from

![Figure 8](image-url)
galaxies with AGNs is powered by the gravitational energy released in the AGN, not by star formation, the model predictions plotted here should be treated as upper limits. In the literature, the steep decline of the SFR since $z_C > 1$ has been well established since early works of Lilly et al. (1996) and Madau et al. (1996). However, it is still controversial what happened to the SFR in the earlier universe, particularly before $z = 2$. Most information on this issue is obtained from observations of Lyman break galaxies (LBGs; Steidel et al. 1999). However, the extinction correction for these rest-frame UV-selected galaxies is very uncertain. In addition, many high-redshift star-forming galaxies may be completely missed in the surveys of LBGs because of heavy extinction, causing systematic underestimation when using LBGs to determine the SFR in the high-$z$ universe (see, e.g., Rowan-Robinson et al. 1997). In this respect, the predictions of our models follow closely the data points determined from LBG surveys after the extinction correction (Steidel et al. 1999). As discussed in Xu et al. (2001), the evolution of IR galaxies at redshifts greater than 2 is mainly constrained by the submillimeter data in the SCUBA surveys and in the CIB observations, as a result of the negative $K$-correction. Too much star formation in those large redshifts will result in too many submillimeter counts and too high submillimeter background radiation. In the literature, other models (e.g., Gispert, Lagache, & Puget 2000; Rowan-Robinson 2001; Chary & Elbaz 2001) that also invoked submillimeter data to constrain the evolution of $z > 2$ IR galaxies found the similar trend (a peak at $z \sim 1$ and a shallow/flat slope in $z \geq 2$) in the SFR evolution. The claim that the universal SFR increases monotonically with redshift to very high $z$ ($\gtrsim 7$) by Lanzetta et al. (2002) is not supported by our and other studies on evolution of IR galaxies.

3. PASSIVE EVOLUTION MODELS FOR E/S0 GALAXIES

The models follow a simple, passive evolution approach (Pozzetti, Bruzual, & Zamorani 1996). The basic assumption is that there has been no star formation in an E/S0 galaxy since its initial formation. Consequently, its radiation in different bands (i.e., the SED and the $L/M$ ratio) evolves passively with the ever aging stellar population. Instead of assuming that all E/S0 galaxies formed at once together (as in the classical monolithic galaxy formation scenario), the
E/S0 galaxies are assumed to form in a broad redshift range (Franceschini et al. 1998), specified by a truncated Gaussian function. The SEDs of different ages are calculated using the GRASIL code of Silva et al. (1998). No dust emission is considered in these models.

3.1. Evolution Function

The evolution function \( \Psi(M, t) \), specifying how many E/S0 galaxies are formed in a unit volume, in a unit time interval, and in a unit mass interval, is assumed to have the following form:

\[
\Psi(M, t) = \psi(M) T(t),
\]

where the time dependence function \( T(t) \) is a truncated Gaussian:

\[
T(t) = \begin{cases} 
\exp \left\{ -\frac{[t - t(z_{\text{peak}})]^2}{\omega^2} \right\}, & t \geq t(z_0), \\
0, & t < t(z_0) .
\end{cases}
\]

In this prescription, for the sake of simplicity, the time dependence is assumed to be independent of the mass. The mass dependence function \( \psi(M) \) can be derived:

\[
\psi(M) = \frac{\Phi(M, z = 0)}{\int_{t(z_0)}^{t(z)} T(t') dt'},
\]

where \( t(z = 0) \) is the current age of the universe.

In this work, the local mass function is constrained using the local K-band LF of Kochanek et al. (2001) and the \( L_K/M \) ratio predicted by the GRASIL code (Silva et al. 1998).

3.2. Galaxy Age Distribution and SED Assignment

Equation (6) predicts galaxy number for a given redshift in a unit mass interval and a unit volume. These galaxies have different ages spanning between \( \tau = 0 \) and \( \tau = t(z) - t(z_0) \). The age distribution function, \( G(z, \tau) \), is also a truncated Gaussian:

\[
G(z, \tau) = \begin{cases} 
G_0 \exp \left\{ -\frac{[t(z) - \tau - t(z_{\text{peak}})]^2}{\omega^2} \right\}, & 0 \leq \tau \leq [t(z) - t(z_0)], \\
0, & \text{otherwise}.
\end{cases}
\]

For every galaxy simulated, an age is assigned to it according to the above distribution (i.e., probability) function. According to the passive evolution model, galaxies of different ages have different SEDs and different \( L/M \) ratios. The SEDs of different ages are calculated using GRASIL (Silva et al. 1998). Again, for the sake of simplicity, we assume a simple “single-burst” scenario, in analogy to the merger scenario of E/S0 formation as hinted at in the studies of ULIRGs (Kormendy & Sanders 1992), to model the formation of E/S0 galaxies. Namely, we assume that all the stars in an E/S0 galaxy were formed in a short burst (lasting \( 10^8 \) yr), after which all the ISM was blown out. Accordingly, the following parameters are adopted for the input of GRASIL: \( t_{\text{bin}} = 0.1 \) (Gyr), \( k_{\text{sch}} = 1.0, \nu_{\text{sch}} = 20.0, \) and \( t_{\text{inf}} = 0.01 \). Then, in the simulation of E/S0 galaxies, we include only sources older than 1 Gyr. Here we implicitly assume that merger remnants younger than 1 Gyr do not look like E/S0 galaxies because these systems may not have fully relaxed, namely, they should be classified as poststarbursts or E+A galaxies, not E/S0 galaxies. Optical follow-up observations of ISOCAM sources (Flores et al. 1999b; Aussel et al. 1999; Cohen et al. 2000; Elbaz et al. 2002) have shown that E+A galaxies are IR-bright and have similar IR properties as active starburst galaxies.

3.3. Three Models for E/S0 Evolution

We consider three different E/S0 models in this paper, specified by different \( z_{\text{peak}} \) and \( \omega \) (Table 2; Fig. 10).

**TABLE 2**

| Models | \( z_{\text{peak}} \) | \( \omega \) | \( z_0 \) |
|--------|-----------------|--------|---------|
| E1     | 5               | 0.5    | 7       |
| E2     | 2               | 2      | 7       |
| E3     | 1               | 3      | 7       |

* In units of Gyr.

Model E1 (\( z_{\text{peak}} = 5, \omega = 0.5 \) Gyr) mimics the classical monolithic scenario (Eggen, Lynden-Bell, & Sandage 1962). Model E2 assumes a later and broader E/S0 formation epoch (\( z_{\text{peak}} = 2, \omega = 2 \) Gyr). Model E3 (\( z_{\text{peak}} = 1, \omega = 2 \) Gyr) simulates an E/S0 galaxy.
3 Gyr) assumes that most E/S0 galaxies are formed at $z > 1$, as hierarchical galaxy formation workers have advocated (Kauffmann, White, & Guiderdoni 1993; Kauffmann & Charlot 1998).

In Figure 11 we compare the model predictions on the redshift dependence of optical/NIR colors with the data from Franceschini et al. (1998). Predictions of all three models can fit the overall trend of the data well. On the other hand, model E1 predicts very little scattering, which is not confirmed by the data. The other two models predict significantly larger dispersion, in better agreement with the data.

In Figure 12 the redshift distribution of early-type galaxies of $K_{AB} \leq 20.15$, taken from Franceschini et al. (1998), is compared to the model predictions. Note that only 15 out of 35 redshifts in Franceschini et al. (1998) are spectroscopically measured; the rest are photometric redshifts. Among the three models, model E2 fits the data best. It should be noted that, as discussed in Benitez et al. (1999) and Rodighiero, Franceschini, & Fasano (2001), some high-$z$ E/S0 galaxies may have been missed in the Franceschini et al. (1998) investigation.

4. COUNTS IN UV, OPTICAL, NIR, AND MIR BANDS

Both the E/S0 galaxies and the dusty galaxies contribute significantly in these bands. Since the three E/S0 models predict almost identical counts (difference $\lesssim 0.1$ dex), in the rest of the paper we shall present only the results from model E2 ($z_{peak} = 2, \omega = 2$ Gyr).

In Figures 13, 14, and 15 the contributions of E/S0 galaxies to the counts in these bands (as predicted by model E2) are added to the contributions of dusty galaxies as predicted by models S1, S2, and S3, respectively. These model predictions are compared to observations in the vacuum UV (2000 Å), the $B$ and $R$, the NIR $K$, and the MIR 6.7 (ISOCAM) and 12 μm ($IRAS$ and ISOCAM) bands. Between the three figures, the differences in the total counts in the bands plotted are generally within the uncertainties of data. The model predictions can account for all counts in the $R$, $K$, and MIR bands. On the other hand, the model predictions are significantly lower than the counts observed in the 2000 Å band (Milliard et al. 1992). For the $B$ band, the model predictions are slightly lower ($\sim 0.3$ dex) than the

Fig. 11.—Color vs. redshift diagrams of E/S0 galaxies. Model predictions are compared with observations (open diamonds; Franceschini et al. 1998).
observed counts for $B > 20$ mag. These results strongly hint at a population of star-forming galaxies that are IR-quiet (very low dust attenuation/emission) and therefore are seen only in the UV and the blue bands (see § 7.3 for more discussion).

In the bright end of the $K$-band counts, the prediction by S1+E2 (Fig. 13) is in good agreement with the morphologically segregated counts reported by Huang, Cowie, & Luppino (1998), namely, at $K \lesssim 17$ the E/S0 galaxies contribute about 50% of the counts, and at fainter magnitudes the contribution from lute-type galaxies becomes more and more dominant. The predictions by S2+E2 and S3+E2 on the E/S0 contribution to $K$-band counts at $K = 16$ are $\sim 30\%$ and $\sim 40\%$, respectively, slightly less than the observational result of Huang et al. (1998).

The three models fit the faint, submillijansky ISOCAM 6.7 $\mu$m counts very well. However, predictions of S1+E2 are about a factor of 3 lower than the ELAIS counts (Serjeant et al. 2000) at a few millijansky level. For these counts, predictions by S3+E3 have the best agreement with, although being still about 50% less than, the data. It should be noted that, as indicated by the large discrepancy between the ELAIS 15 $\mu$m counts of Serjeant et al. (2000) and Gruppioni et al. (2002), the uncertainties of the ELAIS 6.7 $\mu$m counts of Serjeant et al. (2000) may be significantly larger than reported.

The scatters of the ISOCAM 12 $\mu$m data (Clements et al. 1999) are large, indicating significantly larger uncertainties than the Poisson noise (error bars in the plot). The three brightest ISO points may suffer serious biases caused by errors in galaxy/star separation (Clements et al. 1999) and so are likely to be less reliable than other data points. If this is indeed the case, then, among the three models, the predictions of S1+E2 have the best agreement with the data. The effect of the Local Supercluster (Lonsdale et al. 1990) can be seen in the bright IRAS 12 $\mu$m counts.

5. COUNTS AND CONFUSION LIMITS IN SIRTF BANDS

The E/S0 galaxies contribute significantly only to the four IRAC bands (3.6, 4.5, 5.8, and 8 $\mu$m), while the three MIPS bands (24, 70, and 160 $\mu$m) will see only dusty galaxies.

Model predictions of contributions by E/S0 galaxies and by different populations of dusty galaxies to the counts in three SIRTF bands (3.6, 24, and 70 $\mu$m bands) are plotted in Figure 16. The total counts by the three different models are very close to each other, although the relative contributions from normal galaxies and from starbursts are very different. This can be understood by the fact that, tuned to fit the same counts in the ISO bands that cover a wide wavelength range from 6.7 to 170 $\mu$m, these models are forced to produce similar counts in the MIR and FIR bands.

The $3\sigma$ confusion limits are given in Table 3 for all seven SIRTF bands. These are calculated by the method described in Xu et al. (2001) and assuming that SIRTF (85 cm dish) is diffraction limited in all bands (so the beams can be approximated by the Airy function). Since this idealized assumption may not be true, particularly for the short-wavelength IRAC bands (e.g., the 3.6 and 4.5 $\mu$m bands), the results for those bands should be treated as lower limits. The confusion limits predicted by the three different models differ by up to 80%. The largest difference occurs for the 70 $\mu$m band. These differences reflect the real uncertainties, mostly due to the uncertainties in the ISO data, which are the major constraints to the models.

6. COLORS AS MODEL DISCRIMINATORS FOR DUSTY GALAXIES

In empirical evolution models, different populations of dusty galaxies are distinguished by different SEDs. Therefore, the most direct method to distinguish models predicting different dominant populations for IR sources is
to compare the predicted color distributions with the observations.

In Figure 17 we compare predictions of the three models for evolution of dusty galaxies (Table 1) for colors of ISO galaxies. The detection limits are set to be $f_{6.7\mu m} \geq 30$ µJy, $f_{15\mu m} \geq 100$ µJy, $f_{90\mu m} \geq 100$ mJy, $f_{170\mu m} \geq 180$ mJy, $R \leq 24$ mag, and $K \leq 20$ mag. The predictions for $f_{15\mu m}/f_R$ and $f_{15\mu m}/f_K$ are compared to the data of ISOCA 15 µm
sources in HDF-N (Aussel et al. 1999; Cohen et al. 2000; Hogg et al. 2000). It appears that, for ISO galaxies, only the $f_{15}/f_K$ color is a good model discriminator in the sense that the peaks of the color distributions predicted by the three models are separated from each other. The data seem to favor model S1, which predicts a peak in the $f_{15}/f_K$ color distribution right at the place where the data peak.

However, this data set is again too small (30 galaxies) and error bars too large to distinguish the three models.

SWIRE, a SIRTF Legacy Science program, will survey 65 deg$^2$ of sky in all seven SIRTF bands (3.6, 4.5, 5.8, 8, 24,

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**Fig. 14.—Counts in the UV (2000 Å), $B$, $R$, and $K$ bands. Predictions of model S2 (for dusty galaxies) plus predictions of model E2 (for E/S0 galaxies) are compared to data. Data points are the same as in Fig. 13.**

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[3] See http://www.ipac.caltech.edu/SWIRE.
70, and 160 \( \mu m \) bands. Extensive ground-based follow-up observations in the optical, NIR, and radio bands will be carried out. These survey areas will also be observed in the far-UV (1500 and 2300 \( \AA \)) by the Galaxy Evolution Explorer\(^4\) (GALEX) in the deep survey mode. In Figure 18, compared to predicted confusion limits in Table 3, it appears that SWIRE surveys will be confusion limited in the 70 and 160 \( \mu m \) bands. Extensive ground-based follow-up observations in the optical, NIR, and radio bands will be carried out. These survey areas will also be observed in the far-UV (1500 and 2300 \( \AA \)) by the Galaxy Evolution Explorer\(^4\) (GALEX) in the deep survey mode. In Figure 18, 

\(^4\) See http://www.srl.caltech.edu/galex.
model predictions for the distributions of six colors of SWIRE galaxies are plotted. These colors are selected among many possible combinations to illustrate how the colors of SWIRE galaxies can discriminate the models. Model simulations of sky coverage of 5 deg$^2$ are carried out. For each plot, the samples of simulated sources are selected according to SWIRE's sensitivity limits or, for the 70 and 160 $\mu$m bands, the confusion limits. It is also required that $R/C24 < 20$ mag and $K/C20 < 20$ mag when the $R$- and $K$-band data are involved. In four ($f_{70\mu m}/f_{8\mu m}$, $f_{24\mu m}/f_{3.6\mu m}$, $f_{24\mu m}/f_{8\mu m}$, and $f_{24\mu m}/f_K$) of the six colors plotted, the peaks of models S1 (starbursts dominant) and S2 (normals dominant) are clearly separate. Among these, the peak of the distribution predicted by model S3 (intermediate model) is close to that of S1 in the $f_{70\mu m}/f_{8\mu m}$ color plot, close to that of S2 in the $f_{24\mu m}/f_{3.6\mu m}$ color plot, and more ambiguous in the other two plots. Given the large sky coverage of SWIRE, which is 13 times larger than what is simulated here, it is very hopeful that these color distributions will indeed provide clues to the question of which population is dominant among IR sources.

7. DISCUSSION

7.1. Evolution of SEDs of Starburst Galaxies

As pointed out in Xu et al. (2001), the most important assumption in our models for the evolution of dusty galaxies is that high-redshift (i.e., $z \geq 1$) star-forming galaxies have the same SEDs as their local counterparts when the luminosity is the same. Since our SEDs cover from the UV all the way through to the radio wave band, the validity of this assumption demands similarity between high-redshift and local galaxies in many physical conditions, a requirement that seems too strong to be fulfilled in the strict sense. Particularly, the long-term SFH plays an important role in the optical and NIR emission of galaxies, and it is obvious that high-redshift galaxies have a very different long-term SFH (i.e., much younger) than local galaxies. Does this mean that
our predictions for the optical/NIR flux densities of high-redshift dusty galaxies are flawed and therefore unreliable? Our argument to dispute this suspicion is based on the fact that high-redshift galaxies (particularly IR-selected galaxies), already detected or to be detected in future surveys, are almost exclusively high-luminosity galaxies (less luminous galaxies with high redshift are too faint to be detected). As their local counterparts, these high-redshift figures...
ULIRGs must host very powerful starbursts or AGNs as energy sources that contribute much of the emission even in the NIR bands (~40% for the local ULIRGs; Surace, Sanders, & Evans 2000; Scoville et al. 2000). Therefore, as far as the detectable IR sources are concerned, the difference in the underlying old population between the high-redshift dusty star-forming galaxies and their local counterparts does not affect very seriously our model predictions.
Recent multi-wave band observations of SCUBA galaxies (Smail et al. 2002), LBGs (Adelberger & Steidel 2000), and ISO-CAM galaxies (Flores et al. 1999a; Aussel et al. 1999; Cohen et al. 2000; Elbaz et al. 2002) are consistent with our assumption that high-redshift star-forming galaxies have similar SEDs as their local counterparts, particularly when binned according to the luminosity (as stressed by Adelberger & Steidel 2000). On the other hand, some new observations hint at possible systematic differences between high-redshift and local ULIRGs. The Hubble Space Telescope (HST) image of SCUBA galaxy SMM J14011+0252 (Ivison et al. 2001) shows that the star formation activity in that source is widely spread (up to a few kiloparsecs), a situation remarkably different from typical ULIRGs found in the local universe (Sanders & Mirabel 1996). Compared to centrally concentrated starbursts found in most of the local ULIRGs, galaxies with such widely distributed starbursts are expected to have less steep MIR slopes (i.e., smaller $f_{25\mu m}/f_{12\mu m}$ ratios) and cooler FIR color (i.e., larger $f_{100\mu m}/f_{60\mu m}$ ratios). This is due to the less intense radiation field (less warm dust emission in the 25 and 60 $\mu$m bands) and less dust opacity (less extinction for FIR fluxes).

Indeed, Chapman et al. (2002) found that two sources detected by both the FIRBACK $170\mu m$ band survey (Puget et al. 1999; Dole et al. 2001) and SCUBA (Scott et al. 2000), one at $z = 0.91$ and the other at $z = 0.46$, have significantly cooler dust temperatures ($T_{\text{dust}} \sim 30$ K) compared to $T_{\text{dust}} \sim 50$ K found for typical ULIRGs such as Arp 220. They argue that this may indicate that the starbursts in these systems are also extended. Given the small amount of information and the possible bias for cooler galaxies due to the submillimeter selection (Chapman et al. 2002), it is still too early to tell whether high-redshift ULIRGs are systematically more extended and therefore have SEDs closer to less luminous local interacting galaxies (such as the Antennae galaxies) that are in earlier stages along the merger sequence. Future surveys like SWIRE will address these questions.

7.2. E/S0 Evolution and Starburst Evolution

Comparisons between predictions of E/S0 evolution models and observational data (Figs. 11 and 12) indicate that the intermediate model (model E2), which assumes a peak formation redshift of $z_{\text{peak}} = 2$, is the favorite among the three models. This is in agreement with some previous works (Franceschini et al. 1998; Rodighiero et al. 2001; Im et al. 2002). This model can reproduce well the trend in the color-z plots and also fit the redshift distribution very well. However, particularly in the $B-K$ versus $z$ plot, the data show significantly larger dispersion than the model predictions. There are two possible causes for this:

1. In our simple models, we have assumed that all of the E/S0 galaxies are formed through the same starburst procedure, which means that their stellar populations have the same metallicity for a given age. It is known (e.g., Worthy 1994) that local E/S0 galaxies of similar ages have different metallicity, which is a major cause of the different $L/M$ ratios and colors among these galaxies. Therefore, by neglecting these effects, our models leave some of the scatter in the color distributions unaccounted for.

2. Some of the blue E/S0 galaxies in the data (Franceschini et al. 1998) may not be true E/S0 galaxies. According to Im et al. (2002), many of these “blue interlopers” have strong, narrow emission lines, suggesting that they are low-mass starbursts rather than massive E/S0 galaxies.

In fact, there is still a lack of consensus in the definition of E/S0 galaxies in deep surveys. Using a strict algorithm selecting the most symmetric and smooth galaxies, Im et al. (2002) found far less blue sources among their E/S0 sample than, e.g., Schade et al. (1999) and Menanteau et al. (1999), whose samples were selected with less strict algorithms. A related uncertainty in our models is the choice of the exclusion of galaxies younger than 1 Gyr ($z < 3.2$). This choice is not entirely arbitrary: pushing the cutoff toward younger ages means more galaxies with high $L/M$ ratios, which in turn results in too high model predictions for optical and NIR counts. This shows that the question of where to put the boundary between E/S0 galaxies and poststarbursts deserves more investigation.

If E/S0 galaxies are formed through mergers (Toomre 1978; Kormendy & Sanders 1992), then their evolution is linked to the evolution of starburst galaxies, which are closely related to mergers (Sanders & Mirabel 1996). Our results indeed indicate some synchronization between the two populations, in the sense that the peak of the formation function of E/S0 galaxies in the best-fit model ($z_{\text{peak}} = 2$) is close to the peak of the evolution functions of starburst galaxies ($z_{\text{peak}} = 1.4$). Future works exploring this possible link will provide important constraints to the evolution of both populations.

7.3. IR-quiet Star-forming Galaxies

Our results (Figs. 13–15) show that only a small fraction (10%–20%) of UV-selected galaxies (as in the sample of the FOCA survey; Milliard et al. 1992) are IR-bright, as indicated by the small contribution of simulated dusty galaxies to the UV counts (the E/S0 galaxies contribute even less). This suggests a separate population of IR-quiet, UV-bright galaxies that dominate the UV-selected samples. Such a population is also needed for the $B$-band counts because our simulations underpredict 30%–50% of observed counts in that band, while fully accounting for the $R$- and $K$-band counts (Figs. 13–15). The best candidates for such galaxies are the low-metallicity (therefore low dust content) blue dwarf galaxies such as I Zw 18 (Searle & Sargent 1972). There is an apparent link between this IR-quiet star-forming galaxy population and the “faint blue galaxies” found in deep optical surveys (for reviews see Koo & Kron 1992; Ellis 1997). What is the relation between this population and the dusty (IR-bright) star-forming galaxies? How does this population evolve (backwardly) with the redshift, and how does this evolution correlate with the evolution of IR-bright galaxies? Are LBGs, being selected by the UV flux in the rest frame, more closely related to the IR-quiet star-forming galaxies or to the dusty star-forming galaxies (as argued by Adelberger & Steidel 2000)? Answers to these questions will help to unify the pictures of galaxy formation/evolution seen in different wave bands. We plan to address these questions in our future work, particularly in connection with the forthcoming GALEX and SWIRE missions.
8. SUMMARY

New models for the evolution of extragalactic IR sources are presented in this paper. The models for dusty and E/S0 galaxies, the latter contributing significantly to counts at wavelengths $\lambda < 10 \mu m$, have been developed separately.

Compared to previously published models in Xu et al. (2001), the new models for evolution of dusty galaxies in this work have the following improvements:

1. The evolution functions have the form of the smoothly joined three-piece power law (Fig. 1), instead of the sharply joined two-piece power law.

2. New LLFs at 25 $\mu m$, which take into account the evolution effects, are used for the three dust galaxy populations (i.e., normal late-type galaxies, starburst galaxies, and galaxies with AGNs).

3. The UV portion ($\lambda < 3000 \AA$) of the SEDs in the SED library is constrained by an empirical correlation between $f_{UV}$ and $B-K$, instead of merely an extrapolation of the optical SED ($\lambda > 4000 \AA$).

In order to address the question of whether normal late-type galaxies or starburst galaxies dominate among IR sources of $z > 0.5$, three new models are developed: (1) model S1—starburst galaxies dominant; (2) model S2—normal galaxies dominant; and (3) model S3—intermediate between S1 and S2. Predictions of these three models for counts in various bands are fairly close to each other; therefore, they can hardly be distinguished using the counts. They can also fit very well the LFs of ISO 15 $\mu m$ sources in three redshift intervals ($0.4 < z \leq 0.7, 0.7 < z \leq 1, 1 < z \leq 1.3$). In principle, they can be distinguished by redshift distributions of FIR sources, but the large beams of FIR detectors (such as the ISOPHOT cameras) make it rather difficult to pin down the optical counterparts (usually very faint) of faint FIR sources. At the same time, the peaks in the distributions of several IR and optical colors predicted by these models have separate locations. We argue that these color distributions are the best tools to distinguish these models. There is only a very limited amount of multi-wave band data available for high-redshift dusty galaxies in the literature (mostly for ISO/CAM 15 $\mu m$ sources), a situation that will be drastically improved when SIRTF is launched and SWIRE surveys are available.

The models for E/S0 galaxies follow a simple, passive evolution approach. The basic assumption is that there has been no star formation in an E/S0 galaxy since its initial formation. Instead of assuming that all E/S0 galaxies formed at once together (as in the classical monolithic galaxy formation scenario), the E/S0 galaxies are assumed to form in a broad redshift range (Franceschini et al. 1998), specified by a truncated Gaussian function. The SEDs of different ages are calculated using the GRASIL code of Silva et al. (1998). No dust emission is considered in these models. Three such models with different E/S0 formation histories are calculated: model E1 ($z_{peak} = 5, \omega = 0.5$ Gyr) is close to the classical monolithic scenario; model E2 assumes a later and broader E/S0 formation epoch ($z_{peak} = 2, \omega = 2$ Gyr); model E3 ($z_{peak} = 1, \omega = 3$ Gyr) assumes that most of the E/S0 galaxies are formed at $z > 1$, as the hierarchical galaxy formation works have advocated (Kauffmann et al. 1993; Kauffmann & Charlot 1998). Comparisons with limited data (e.g., colors and redshift distribution) available for morphologically identified E/S0 galaxies at $z \sim 1$ indicate that model E2 can fit the data best among the three models. This suggests a synchronization between the evolution of E/S0 galaxies and that of starburst galaxies, in the sense that the peak of the formation function of E/S0 galaxies ($z_{peak} = 2$) is close to the peak of the evolution functions of starburst galaxies ($z_{peak} = 1.4$). Combining model predictions by E2 with those by S1, S2, and S3 (dusty galaxy evolution models), comparisons with number counts in different wave bands (Figs. 13–15) indicate that E/S0 galaxies contribute up to 30%–50% of the optical/NIR counts in the bright end and about 20%–30% of the ISO/CAM 6.7 $\mu m$ band counts. Their contributions to counts in the UV (2000 A) and in the longer wavelength IR (≥12 $\mu m$) bands are negligible.

Using these new models for extragalactic IR sources, particularly including E/S0 galaxies, we made new predictions for the counts and confusion limits in the SIRTF bands. The results indicate that SWIRE surveys will be confusion limited in the 70 and 160 $\mu m$ bands. The confusion limits predicted by different models differ by up to 80%. These differences reflect the uncertainties of these predictions.

This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work has made use of data products from the Two Micron All Sky Survey (2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. C. K. Xu, C. J. Lonsdale, and D. L. Shupe were supported by the SIRTF Legacy Science Program provided by NASA through a contract with the Jet Propulsion Laboratory, California Institute of Technology.

APPENDIX A

NEW 25 $\mu m$ LOCAL LUMINOSITY FUNCTIONS FOR THREE POPULATIONS

In Xu et al. (2001), LLFs were presented for three population subsamples: AGNs, normal late-type galaxies, and starbursts. The subsamples were determined by IRAS colors. We have extended this work to take into account the effects of luminosity evolution on the LLF estimates and to include a more comprehensive uncertainty analysis.

We recomputed the population LLFs including a luminosity evolution term of the form $(1 + z)^q$, for values of $q = 0, 3.0,$ and 4.5. This factor is applied to both the source luminosity and the minimum luminosity detectable at the source’s redshift. The shape parameters are tabulated in Table A1.
The resulting LLFs (with same normalization constant applied) are plotted as visibilities in Figure 19a (solid line is no evolution; dashed line is $q = 3.0$; dot-dashed line is $q = 4.5$). There is a small difference between the LLFs at large luminosities. The model calculations in this paper use the LLFs with $q = 3.0$.

We performed an analysis of the covariance of the fitted parameters, using the information matrix (Efstathiou, Ellis, & Peterson 1988). In Figures 19b, 19c, and 19d we have plotted the 68% confidence intervals in pairs of the parameters as ellipses under the assumption of normally distributed uncertainties (Avni 1976; Press et al. 1992, pp. 689–699). In general, the parameters are not strongly correlated, except for $\alpha$ and $\beta$ for AGNs. This correlation is explained by the distribution of this population at higher relative redshifts; the high-luminosity slope of the LF depends on the sum of $\alpha$ and $\beta$, so the parameters are degenerate when $\alpha$ is not well determined at low luminosities. For the same reason, the confidence intervals for AGNs for

| Population     | $q$ | $\alpha$ | $\beta$ | $L_\star^*$ | $\alpha + \beta$ |
|----------------|-----|----------|---------|-------------|------------------|
| AGNs           | 0.0 | 0.336    | 1.691   | $6.9 \times 10^9$ | 2.027         |
|                | 3.0 | 0.329    | 1.713   | $6.6 \times 10^9$ | 2.042         |
|                | 4.5 | 0.326    | 1.724   | $6.5 \times 10^9$ | 2.040         |
| Starbursts     | 0.0 | 0.265    | 2.283   | $7.9 \times 10^9$ | 2.548         |
|                | 3.0 | 0.265    | 2.275   | $7.7 \times 10^9$ | 2.540         |
|                | 4.5 | 0.264    | 2.300   | $7.9 \times 10^9$ | 2.564         |
| Normals        | 0.0 | 0.482    | 3.875   | $5.7 \times 10^9$ | 4.357         |
|                | 3.0 | 0.480    | 3.992   | $5.8 \times 10^9$ | 4.472         |
|                | 4.5 | 0.479    | 4.055   | $5.8 \times 10^9$ | 4.534         |

* In units of $L_\odot$.  

Fig. 19.—(a) 25 $\mu$m LLFs of three populations of dusty galaxies. Different lines denote different assumptions on the evolution of the sources: solid line is for no evolution; dashed line is for $q = 3.0$; dot-dashed line is for $q = 4.5$. (b), (c), and (d) Plots of pairwise covariance of the LLF parameters. The ellipses show the 68% confidence intervals. The lines are the same as in (a).
\( \alpha \) and \( L_* \) are larger for the other populations. The variations in the parameters with evolution exponent are for the most part small compared to the uncertainties in the parameters.

APPENDIX B

EXTRAPOLATION OF SEDs TO THE UV BANDS

In Xu et al. (2001), the UV (1000–4000 Å) SEDs are extrapolations from data points in the \( B, J, H, \) and \( K \) bands and therefore are not well constrained. In this work, this is improved by introducing the following constraints:

1. The UV–\( B \) versus \( B–K \) correlation. The correlation is established using a sample of galaxies detected in both the vacuum UV bands (1500–2500 Å) and the FIR bands (IRAS). The sample is taken from Xu & Buat (1995). The \( K \)-band magnitudes are found in the 2MASS database. In Figure 20, the UV–\( B \) versus \( B–K \) color-color plot for this sample is presented. The sample is divided into galaxies with AGNs (\( f_{60\mu m}/f_{25\mu m} < 0.4 \)), galaxies with IR excess (\( f_{60\mu m}/f_{25\mu m} \geq 0.4 \) and \( L_{\text{FIR}}/L_B > 0.5 \)), and normal late-type galaxies (\( f_{60\mu m}/f_{25\mu m} \geq 0.4 \) and \( L_{\text{FIR}}/L_B \leq 0.5 \)). Data of the three ULIRGs observed by Trentham, Kormendy, & Sanders (1999) in UV using HST are also plotted. They follow the same trend of IR excess galaxies, although with larger scatters. We found that the trend for normal late-type galaxies can be well fitted by the function

\[
\log \left( \frac{\nu f_\nu(2000 \text{ Å})}{\nu f_\nu(4400 \text{ Å})} \right) = \begin{cases} 
-0.2 - 0.3[(B - K) - 2]^2, & (B - K) > 2, \\
-0.2 - 0.1[(B - K) - 2], & (B - K) \leq 2,
\end{cases}
\]

and for galaxies with AGNs and galaxies with IR excess, it can be well fitted by a two-step linear function,

\[
\log \left( \frac{\nu f_\nu(2000 \text{ Å})}{\nu f_\nu(4400 \text{ Å})} \right) = \begin{cases} 
-0.4[(B - K) - 2], & (B - K) > 2, \\
0, & (B - K) \leq 2.
\end{cases}
\]

2. The UV slope. We use the following relation between the UV slope \( \beta (F_\lambda \propto \lambda^\beta, 1200 \text{ Å} < \lambda < 2600 \text{ Å}) \) and the \( L_{\text{FIR}}/L_B \) ratio, found by Calzetti et al. (1995), to constrain the slope of the UV SEDs between 1200 and 2600 Å:

\[
\beta = 1.12 \log \left( \frac{L_{\text{FIR}}}{L_B} \right) - 0.94.
\]
3. Lyman break. A sharp drop-off is imposed to the SEDs shortward of 912 Å: the flux density decreases by a factor of 30 from 912 to 700 Å. There is a less steep drop-off, about a factor of 5, from 1200 to 912 Å, which is to mimic the effect of the Lyα absorption.

As an example, the model SED of M82 is compared to data in Figure 21.

REFERENCES

Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Altieri, B., et al. 1999, A&A, 343, L65
Aussel, H., Cesarsky, C. J., Elbaz, D., & Starck, J. L. 1999, A&A, 342, 313
Avni, Y. 1976, ApJ, 210, 642
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999, ApJ, 518, L5
Barger, A. J., & Cowie, L. L. 2000, ApJ, 544, 81
Benitez, N., Broadhurst, T., Bouwens, R., Silk, J., & Rosati, P. 1999, ApJ, 515, L65
Bershady, M. A., Lowenthal, J. D., & Koo, D. C. 1998, ApJ, 505, 50
Bertin, E., Dennefeld, M., & Moshir, M. 1997, A&A, 323, 685
Blain, A. W. 1999, MNRAS, 309, 955
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632
Boyle, B. J., Shanks, T., Croom, S. M., Smith, R. J., Miller, L., Loaring, M., & Heymans, C. 2000, MNRAS, 317, 1014
Calzetti, D., Bohlin, R. C., Kinney, A. L., Stochi-Bergmann, T., & Heckman, T. M. 1994, ApJ, 445, 136
Chapman, S. C., et al. 2002, ApJ, 573, 66
Chary, R. R., & Elbaz, D. 2001, ApJ, 556, 562
Clements, D. L., Desert, F.-X., & Franceschini, A. 2001, MNRAS, 325, 665
Clements, D. L., Desert, F.-X., Franceschini, A., Reach, W. T., Baker, A. C., Davies, J. K., & Cesarsky, C. 1999, A&A, 346, 383
Cohen, J. G. 2002, ApJ, 567, 672
Cohen, J. G., Hogg, D. W., Blandford, R., Cowie, L. L., Hu, E., Songaila, A., Shopbell, P., & Richberg, K. 2000, ApJ, 538, 29
Dole, H., et al. 2001, A&A, 372, 364
Dwek, E., & Arendt, R. G. 1998, ApJ, 508, L9
Dwek, E., & Slavin, J. 1994, ApJ, 436, 696
Eales, S. A., Lilly, S. J., Webb, T., Dunne, L., Gear, W., Clements, D., & Yun, M. 2000, AJ, 120, 2244
Efstathiou, A., et al. 2000, MNRAS, 319, 1169
Efstathiou, G., Ellis, R. S., & Peterson, B. A. 1988, MNRAS, 232, 431
Engen, J. O., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Elbaz, D., Cesarsky, C. J., Chamiel, P., Franceschini, A., Fadda, D., & Chary, R. R. 2002, A&A, 384, 848
Elbaz, D., et al. 1999, A&A, 351, L37
Ellis, R. S. 1997, ARA&A, 35, 389
Fang, F., Shupe, D., Xu, C., & Hacking, P. 1998, ApJ, 500, 693
Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 2000, ApJ, 544, 81
Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Flores, H., et al. 1999a, A&A, 343, 389
———. 1999b, ApJ, 517, 148
Fox, M. J., et al. 2002, MNRAS, 331, 839
Franceschini, A., Aussel, H., Cesarsky, C. J., Elbaz, D., & Fadda, D. 2001, A&A, 378, 1
———. 1999a, A&A, 351, L37
Ellis, R. S. 1997, ARA&A, 35, 389
Fang, F., Shupe, D., Xu, C., & Hacking, P. 1998, ApJ, 500, 693
Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 2000, ApJ, 544, 81
Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Flores, H., et al. 1999a, A&A, 343, 389
———. 1999b, ApJ, 517, 148
Fox, M. J., et al. 2002, MNRAS, 331, 839
Franceschini, A., Aussel, H., Cesarsky, C. J., Elbaz, D., & Fadda, D. 2001, A&A, 378, 1
Franceschini, A., Danese, L., De Zotti, G., & Xu, C. 1998, MNRAS, 233, 175
Franceschini, A., Silva, L., Fasano, G., Granato, G. L., Bressan, A., Arnouts, S., & Danese, L. 1998, ApJ, 506, 600
Franceschini, A., et al. 1997, in The Far Infrared and Submillimetre Universe, ed. A. Wilson (Noordwijk: ESA), 159
Gallego, J., Zamorano, J., Aragon-Salamanca, A., & Rego, M. 1995, ApJ, 455, L1
Gardiner, J. P., Sharples, R. M., Carrasco, B. E., & Frenk, C. S. 1996, MNRAS, 282, L1
Gispert, R., Lagache, G., & Puget, J. L. 2000, A&A, 360, 1
Glazebrook, K., Blake, C., Economou, F., Lilly, S., & Colless, M. 1999, MNRAS, 306, 843
Gorjian, V., Wright, E. L., & Chary, R. R. 2000, ApJ, 536, 550
Granato, G., Lacey, C. G., Silva, L., Bressan, A., Baugh, C. M., Cole, S., & Frenk, C. S. 2000, ApJ, 542, 710
Gregorich, D. T., Neugebauer, G., Soifer, B. T., Gunn, J. E., & Herter, T. L. 1995, AJ, 110, 259
Gruppioni, C., Lari, C., Pozzi, C. F., Zamorani, G., Franceschini, A., Oliver, S., Rowan-Robinson, M., & Serjeant, S. 2002, MNRAS, 335, 831
Hacking, P. B., Condon, J. J., & Houck, J. R. 1987, ApJ, 316, L15
Hogg, D. W., et al. 2000, ApJS, 127, 1
Huang, J.-S., Cowie, L. L., & Luppino, G. 1998, ApJ, 496, 31
Hedges, D. H., et al. 1998, Nature, 394, 241
Im, M., et al. 2002, ApJ, 571, 136
Ivison, R., Small, I., Frayer, D. T., Kneib, J.-P., & Blain, A. W. 2001, ApJ, 561, L45
Ivison, R., et al. 2002, MNRAS, 337, 1
Juvela, M., Mattila, K., & Lemke, D. 2000, A&A, 360, 813
