THE ASTROPHYSICAL JOURNAL, 427:140–154, 1994 May 20

LUMINOSITY EVOLUTION AND DUST EFFECTS IN DISTANT GALAXIES: IMPLICATIONS FOR THE OBSERVABILITY OF THE EARLY EVOLUTIONARY PHASES

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Received 1993 June 23; accepted 1993 November 18

ABSTRACT

We explore effects of luminosity evolution in normal galaxies by means of a spectrophotometric model treating in a self-consistent way the energy emitted by various stellar generations at different metallicities, the opacity of the enriched interstellar gas, and the flux reradiated by dust in the far-infrared. The very wide spectral coverage of the model, ranging from UV to far-IR and radio wavelengths, allows us for the first time to relate so diverse observational facts as the counts of galaxies in optical and K bands, the absence of high-redshift ($z > 1$) galaxies in faint optical samples, and the galaxy counts at far-IR and radio wavelengths.

A consistent picture obtains assuming that during the main phases of energy production by stellar nucleosynthesis most of the optical radiation might have been obscured by an enriched ISM and reradiated at longer wavelengths. We suggest that signs of this can already be read in deep *IRAS* and possibly also sub-millijansky radio counts: observational techniques—including optical identifications and spectroscopy of samples selected at longer wavelengths and measurements of the background radiation in the IR and sub-millimeter domains—are proposed to check this possibility. If this view is correct, the search for primeval objects and distant evolving galaxies (of which the recently discovered IRAS F10214+4724 may be a prototype) would have better chances if performed in the IR through radio spectral domain rather than in the optical: it should concentrate, in particular, on faint IR and radio-selected sources with very faint or undetected optical counterparts.

Subject headings: galaxies: evolution — galaxies: ISM — galaxies: luminosity function, mass function — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

The information on processes that led to the formation and evolution with cosmic time of galaxy populations has dramatically grown in the last 10 years, thanks to several dedicated observational campaigns. Improved techniques of imaging and photometry have allowed us to reach in the optical-UV source fluxes corresponding to areal densities of more than 300,000 galaxies per degree^2, and in the radio centimetric to almost ten thousands per degree^2. Current spectroscopy techniques allow redshift determination for entire samples of galaxies as faint as $B \sim 25$. At the same time, the use of cooled space-borne telescopes in the mid- and far-IR have provided access to wavelength bands where dust reradiation shows up.

Excess numbers of galaxies are detected at faint flux levels in all the explored wavebands, which cannot be explained by simple extrapolations to the past of the locally observed numbers of galaxies, under the assumption that the average luminosities and space densities kept constant with time (see, among others, Tyson 1988; Broadhurst, Ellis, & Shanks 1992; Lilly, Cowie, & Gardner 1991; Metcalfe et al. 1991).

Sometimes a natural explanation of this excess (e.g., Koo 1989; Guiderdoni & Rocca-Volmerange 1990; Yoshii & Takahara 1988; Charlot & Bruzual 1991) was in terms of a mild luminosity evolution of the galaxy populations, which increases the luminosity distance and the volume available to the sampling. An increase with redshift of the star formation rate (SFR), hence of the luminosity, is naturally expected in this framework, due to the larger fraction of the gaseous component in galaxies at earlier times.

Such a situation was complicated, however, by the evidence, based on spectroscopic follow-up of galaxies detected at various faint limiting magnitudes, that the sources responsible for the excess in optical counts are located at moderately low redshifts ($z \sim 0.3$–0.5; see Broadhurst, Ellis, & Shanks 1988; Colless et al. 1990, 1993; Cowie, Songaila, & Hu 1991). As for today, just one galaxy down to $B = 25$ has been found beyond $z = 0.8$ in the complete B-band–selected samples reported by Colless et al. (1993). Given the fairly large number (some hundreds) of galaxies for which redshifts have been measured, and thanks to the detailed evaluation of various instrumental effects (e.g., those related to the limited sensitivity of the surveys to extended low-surface brightness objects), this already appears as a very robust conclusion. Such evidence contrasts with plausible effects of luminosity evolution, that would make higher redshift galaxies to appear well above the survey limits.

The currently available constraints on the evolution of optically selected galaxies may then be briefly summarized as follows: (1) Galaxies with typical luminosities of the order of the Schechter's L_* (i.e., roughly $M_B < -20$) have essentially not evolved with time; (2) low-luminosity, sub-L_* galaxies, on the contrary, should have strongly evolved in number and/or luminosity to explain the faint optical counts and be, at the

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same time, consistent with the locally observed numbers of dwarf galaxies. Our main concern in this paper is with the first point.

A currently debated picture (e.g., Rocca-Volmerange & Guiderdoni 1990; Broadhurst et al. 1992; Carlberg 1992; Carlberg & Charlot 1992), in which the luminous galaxies that we see today are the products of the merging of smaller units in the past, has the attractive feature of relating the two points above: the increase in the number of low-luminosity galaxies with look-back time is simply the effect of counting the subunits that have subsequently merged into the larger aggregates. This *merging* hypothesis, however, is not free of some serious problems. The well-defined morphological properties of the nearby bright galaxies are not easily reconciled with the idea that they are the result of a relatively recent coalescence. A quantitative assessment by Ostriker (1990) and Toth & Ostriker (1992) of the effect of merging and accretion on the thickness of the galactic disk shows that only a few percent of the galaxy baryonic content could have been accreted in the last several Gyr, and this constraint directly applies whenever a sizeable disk component is present, that is, to spirals and lenticular galaxies. As for the early-type galaxies, colors and the tightness of the distribution about the so-called "fundamental plane" provide strong indications that they are old ($z_F > 2$) and essentially coeval, later additions probably corresponding to no more than 10% of the present luminosity (Renzini 1993). Also, faint galaxies in the relevant magnitude range $22 < B < 26$ appear to be even less spatially clustered than local galaxies, contrary to the expectation if they are in the process of merging (Efstathiou et al. 1991; Pritchet & Infante 1992). Finally, the merging timescale implied by the analysis of Carlberg (1992) and needed to explain the faint galaxy counts is uncomfortably higher than current estimates based on local galaxy samples.

In view of these difficulties of the *merging* paradigm, we thought it worthwhile to investigate the alternative approach based on the assumption that the galaxy mass function did not change significantly during the cosmic time accessible to the observations (of course, this does not mean that major mergers, followed by strong dissipation, could not have taken place during the early formation phases of ellipticals; see, e.g., Kormendy & Sanders 1992). This approach essentially separates the fate of the bright end from that of the faint end of the galaxy luminosity function and implies that a new population of faint blue galaxies, unrelated to the normal galaxy populations, turns on at redshifts around $z = 0.5$ and then quickly disappears (Cowie 1991).

This paper is devoted to an exploration of the effects of luminosity evolution in *normal* galaxies, under the assumption of a mass function roughly constant with time. General, virtually model-independent arguments show that appreciable luminosity evolution should have characterized the stellar populations of at least some classes of galaxies. The radiation outputs of early-type galaxies and of the spheroidal components of later (Sa–Sb) types, in particular, are expected to evolve significantly with time due to the fast decrease of the star formation rate with galactic age. The main point we want to address here is where is the corresponding excess electromagnetic emission hidden, since optical observations reveal that probably only a fraction of it came out at optical wavelengths?

We seek solutions of this problem by exploiting a number of data available in the optical, infrared, submillimetric, and radio domains. Such constraints are confronted with predictions of physical, although somewhat simplified, models of galaxy evolutionary synthesis (Mazzei, Xu, & de Zotti 1992; Mazzei, de Zotti, & Xu 1994), which take into account in a self-consistent way the evolution of the various stellar generations, the fractional mass in gas and its metallicity, the corresponding internal extinction, and far-IR reradiation of the interstellar dust. The different evolution patterns pertaining to early- and late-type galaxies and needed to reproduce their present colors, morphologies, and different histories of metal enrichment are applied to local luminosity functions differentiated among the various morphological types, to build up a fully self-consistent picture. To anticipate the main results, we not only substantiate and quantify the point raised earlier by van den Berg (1990, 1992), Wang (1991a, b, c), and Kormendy & Sanders (1992)—among others—that dust absorption may have a major effect in preventing detection of high-z star-forming early-type galaxies in the optical, but we also argue that signatures of their emissions can already be seen in faint source surveys performed in far-IR and radio bands. The latter are then suggested to be ideal to look for the expected effects of luminosity evolution in distant early-type galaxies (De Zotti, Mazzei, & Franceschini 1994).

In this context, the recently discovered infrared galaxy IRAS F10214+4724 at $z = 2.286$ (Rowan-Robinson et al. 1991) may well represent a first example of the potential efficiency of mid-/far-IR surveys in detecting high-redshift galaxies.

The present analysis is essentially confined to the past evolutionary history of the local normal galaxy population. Questions concerning the appearence of a new population of sub-L_* blue objects at faint flux limits in the optical, X-ray, and radio bands will be addressed in a subsequent paper.

In § 2 and the Appendix we summarize the main features of the galaxy models adopted for our analysis. In § 3 we discuss how the extinction by interstellar dust may affect optical surveys. The energy absorbed at optical-UV wavelengths is reemitted in the far-infrared, and the effects of this on source counts and redshift distributions are described in § 4. We also show that the sensitivity currently reached by FIRAS on *COBE* is close to constraining such emissions. In § 5 we address the point that radio observations, weakly affected by the ISM in these dusty galaxies, may add further relevant information. We discuss finally in § 6 a number of already feasible tests—from spectroscopic follow-up of IR and radio-selected samples, to *HST* and *COBE* observations—to check the model.

We adopt throughout for the Hubble parameter the value $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. THE GALAXY MODEL

The basic assumptions of the adopted galaxy models, which allow us to derive the broad-band spectra of galaxies and their evolution with cosmic time over the whole frequency range from UV ($\lambda = 0.06$ μm) to millimeter ($\lambda = 1000$ μm) wavelengths, are discussed in the Appendix. We only mention here that they provide full description of the chemical evolution of the interstellar medium, adopting a Schmidt law for the evolution of the star formation rate

$$\psi(t) = \psi_0 f_g^n \, M_\odot \text{ yr}^{-1} , \quad (1)$$

where f_g is the fractional mass of gas and ψ_0 the star formation rate at the galaxy's birth epoch. We then compute the synthetic spectra of stellar populations at any galaxtic time, estimate the average correction due to internal extinction by the enriched ISM, and predict the diffuse dust reradiation at infrared wavelengths. Mid-IR emission from hot dust in circumstellar envelopes is also computed.

The galaxy models have been specifically applied to pure disk galaxies (with an obvious emphasis on the Milky Way) by Mazzei et al. (1992, hereafter MXD92) and to pure spheroids by Mazzei et al. (1994, hereafter MDX94). In all cases, the predicted reddened spectra at the present time (which approximately corresponds to galactic ages of $t = 15$ Gyr and $t = 12$ Gyr for $q_0 = 0.05$ and $q_0 = 0.5$, respectively) have been successfully compared to the observed broad-band spectra of various galaxy types. Additional constraints are offered by metallicity determinations in present-day galaxies and, for pure disks, by the evolution of metal content inferred from observations of the Milky Way.

The most critical parameter, whose variation is able to account roughly for the whole Hubble sequence, is the initial star formation rate ψ_0. Low values of ψ_0 correspond to slow initial star formation activity and a slowly declining SFR with time, the standard scenario for late-type systems. Values in the range $1 < \psi_0 < 30\ M_\odot\ \mathrm{yr}^{-1}$ (for a galactic mass of $10^{11}\ M_\odot$) describe morphological types ranging from Sa through irregular galaxies. Here $\psi_0 = 10$ is assumed for pure disks. The corresponding bolometric evolution of such galaxies and changes in the shape of the broad-band spectrum turn out to be very slow, as shown in detail by Figure 4 in MXD92: at any wavelengths in the range 3–1000 μm such variations are less than a factor 2 for galactic ages passing from 2 to 15 Gyr.

Higher values of ψ_0 produce a drastically different evolutionary behavior, due to the rapid decline of the gas fraction, hence of the SFR: this corresponds to early-type systems. The initial SFR adopted for such systems was $\psi_0 = 100\ M_\odot\ \mathrm{yr}^{-1}$. In this case not only the bolometric output changes by factors ~ 10 from $t \sim 1$ Gyr to the present time, but also the spectral shape has a drastic evolution. Under the assumption of a dust-to-gas ratio proportional to the metallicity, in the presence of a quickly metal-enriched ISM, a significant fraction of the huge output during the early epochs of the evolution is absorbed by dust and re-emitted in the far-infrared, where the luminosity may be three orders of magnitude larger in the past than for local E/S0 galaxies. All this is somewhat dependent on the detailed scaling of the SFR in equation (1) with the residual gas fraction: a fast gas consumption and metal production is obtained with the exponent n set to 0.5, while for a more canonical $n = 1$ the evolution is less extreme. The latter case implies a residual fraction of gas $f_g(2\ \mathrm{Gyr}) \simeq 10\%$ at $t = 2$ Gyr and a gas metallicity of $\sim Z_\odot$, while the corresponding figure in the former case is $f_g(2\ \mathrm{Gyr}) \sim 1\%$, but with a 3–4 times solar metallicity. This and equations (A5) and (A6) entail that for $n = 0.5$ an important fraction of galactic time is spent by spheroids in a condition of heavy optical-UV extinction, hence of strong IR emission. At the moment, both evolution models are viable, bringing to properties of early-type galaxies at the present time consistent with the data. Faint galaxy surveys in the optical and IR are then required to discriminate among these two possibilities.

We will call in the following the $n = 1$ and 0.5 models for spheroids the *moderately extinguished* and the *opaque* cases.

We assume that the time-dependent broad-band spectra of all galaxy types may be described as a linear combination of the spheroidal and disk components described above. We make a distinction of the galactic zoo into the following three classes:

1. *Early-type galaxies*, including ellipticals and S0's: these are assumed to follow the evolutionary pattern of spheroids;
2. *Disk-Dominated galaxies*, essentially spirals of all morphological subtypes, in which a nonnegligible spheroidal component is present;
3. *Starbursting galaxies*, that is, objects whose current bolometric luminosity is produced by a violent starburst.

For the second class we follow Franceschini et al. (1991a) in representing the typical spiral as a linear combination of a pure disk and a pure spheroid, such that the spheroidal component contributes 15% on average of the B-band flux in present-day spirals.

The third class corresponds to classical optical starbursts and ultra-luminous *IRAS* galaxies, and includes morphologically peculiar, interacting, non-Seyfert Markarian galaxies. Although their space density is low, they are among the most luminous galaxies today, probably triggered by galaxy collisions. They have been kept separate from the spiral class, their photometric evolution being highly uncertain. We have conservatively assumed their luminosity evolution is very low and adopt for them a pure disk model. Any positive effects of evolution for this class, too, which may be expected on consideration of the larger collision probability in the past, reinforce the conclusions of this paper.

For early-type galaxies (class 1) the same stellar population model has been adopted for both E's and S0's (namely, that corresponding to $\psi_0 = 100\ M_\odot\ \mathrm{yr}^{-1}$ and either $n = 0.5$ or 1), but the fraction of UV-optical light absorbed and reradiated in the IR turns out to be slightly larger (by a factor of ~ 3; see Mazzei & de Zotti 1994a) for S0 than for E galaxies at the present time. This entails that the evolution of the far-IR emission is somewhat slower for S0's. For this reason we have produced two different models of far-IR photometric evolution for the two classes (see Figs. 5 to 10).

3. GALAXY EVOLUTION IN THE OPTICAL

3.1. *Basic Assumptions and Model Parameters*

Once the evolutionary histories of the spectral energy distributions are defined, the knowledge of the local space density for the various morphological and luminosity classes of galaxies allows us to elaborate detailed predictions about the statistical properties of their distant counterparts, under the assumption that only the galaxy luminosities, and not their number, change with cosmic time.

The problem of a careful estimate of the galaxy local luminosity function (LLF) is in our case alleviated by the fact that we are mainly interested here in normal-to-high luminosity galaxies. For absolute magnitudes brighter than, say, $M_B \sim -19$, the galaxy LF is much better defined than for fainter objects, because the correspondingly larger sample volumes reduce the effects of inhomogeneities in the galaxy distribution and the uncertainties in the estimate of galaxy distances due to deviations from the Hubble flow.

Of the many papers reporting determinations of LLFs, very few differentiate among the various morphological classes. The deeepest surveys, providing better estimates of the LLF thanks to the larger sample volumes, are also those for which the morphological classification of galaxies is more difficult. A good balance between depth of the galaxy samples used and morphological information available has been obtained by Francechini et al. (1988) with a sample of 1671 galaxies brighter than $m_{Zw} = 14.5$. A comparison of the corresponding global LLF with those derived by Efstathiou, Ellis, & Peterson (1988), Loveday et al. (1992), and De Lapparent, Geller, & Huchra (1989) shows a good agreement for the luminosity bins $M_{Zw} < -18$, in which we are now mostly interested. For $M_{Zw} > -18$ our old LLF shows a significant excess, probably due to the effect of the local clustering affecting more our estimate than those based on deeper samples. We report in Figure 1 the currently adopted LLFs for various galaxy classes, transformed to the B band using the relation $B - m_{Zw} = 0.25$. The LLFs in our original paper have been scaled here so as to make the corresponding global function to fit into the Efstathiou et al. and de Lapparent et al. best estimates. As anticipated, the scaling factor turned out to be appreciable only for the faintest magnitude bin.

A test of consistency for the adopted global LLF is provided by a comparison with the observed counts of galaxies. We report in Figure 2 the B-band differential counts $N(B)$ versus predictions for various galaxy populations. Panels *a*, *b*, and *c* refer to various assumptions about the role of internal extinction in galaxies, as will be discussed in detail later on. The counts are normalized to $10^{0.45(B-16)}$ deg^{-2} mag^{-1}, to expand the scale. Details on the computation of counts, luminosity, and redshift distributions, etc., can be found in Franceschini et al. (1991a).

We see in Figure 2 that the global predictions, sum of the contributions of the early-type, spiral, and starburst classes, fit the observed counts for $B < 18$. Because at such bright magnitudes the counts are essentially contributed by local unevolved objects, this agreement confirms that the adopted is a fair representation of the galaxian LF in the local universe. This conclusion does not depend on any assumptions about the role of dust extinction in galaxies.

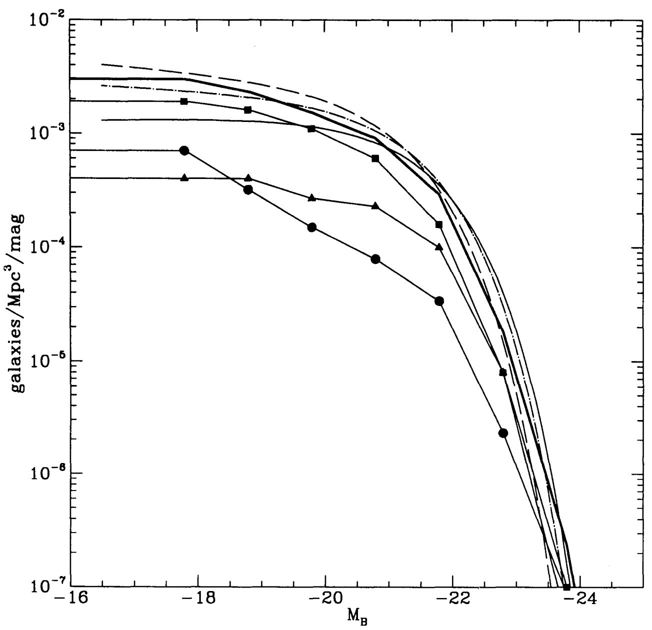

FIG. 1.—Adopted B-band local luminosity functions for spiral/irregular (*solid squares*), E/S0 (*solid triangles*), and starburst (*solid circles*) galaxies. The corresponding total LLF (*heavy solid line*) is compared with published estimates by Efstathiou et al. (1988) (*dot-dashed line*), de Lapparent et al. (1989) (*long-dashed line*) and Loveday et al. (1992) (*thin solid line*). Note that our LLFs have been derived from those by Franceschini et al. (1988), down-scaled by factors of 2.5 and 1.2 in the magnitude bins at $M_B = -17.8$ and $M_B = -18.8$ (see § 3.1).

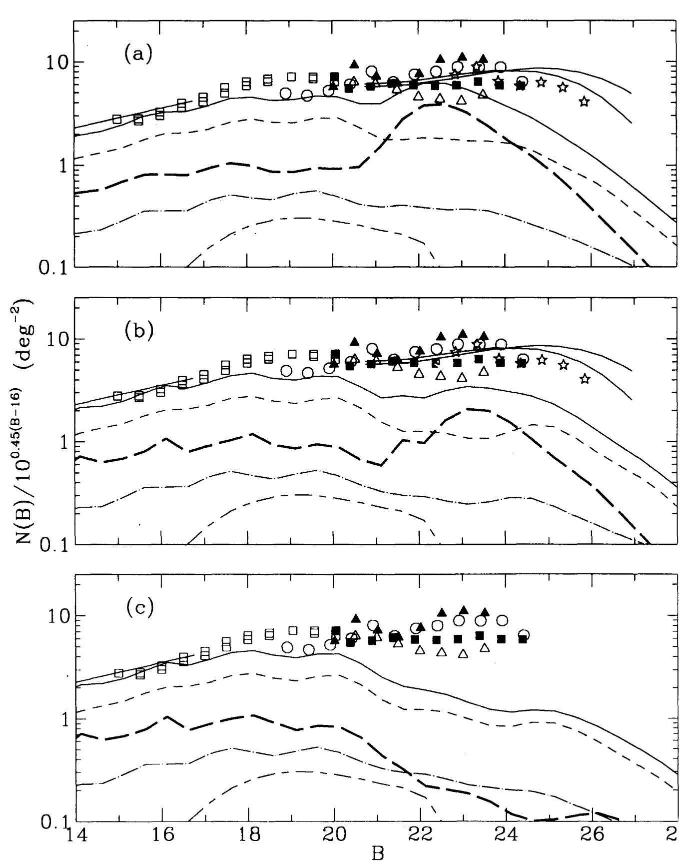

FIG. 2.—Differential counts of galaxies in the B-band, normalized to $10^{0.45(B-16)}$ deg^{-2}, adapted from Maddox et al. (1990). *Short-dashed line*: predicted counts of spirals/irregulars; *heavy long-dashed line*: E/S0 galaxies; *dot-long dashed line*: starbursts; *long-short-dashed line*: AGNs and QSOs; *solid line*: total counts. (*a*) Model with no dust extinction. (*b*) Moderate dust extinction (case with $n = 1$ in the dependence of SFR on fractional mass of gas). (*c*) Heavy dust extinction (case with $n = 0.5$).

At fainter magnitudes various effects make any predictions quite more uncertain. Distant regions in the spacetime start to be sampled, whose younger galaxy populations may differ significantly in luminosity from those observed locally. In addition, low-luminosity objects at moderate redshifts, whose space densities are poorly known, contribute to the counts. Finally, uncertainties in the cosmological model (parameterized by the constant q_0) and about the galaxy birth epoch (t_F) also affect the counts.

The predicted contributions of normal galaxies to the counts in Figure 2 are based on the choice of an Einstein–de Sitter ($q_0 = 0.5$) world model and of $t_F = 1$ Gyr, corresponding to a redshift $z_F = 4.5$. With these assumptions, normal galaxies tend to underpredict the observed counts already for B fainter than 18, the deviation becoming more and more significant at increasing amount of absorbing dust.

Slightly improved number counts at faint magnitudes may be obtained for lower values of q_0, because of the increased volume sampled to a given limiting magnitude (Koo 1986;

Guiderdoni & Rocca-Volmerange 1987). This effect, in any case, is not enough to reconcile the observed numbers of faint galaxies in the B band with the observed low average volume density of galaxies in the local universe. We also note, in passing, that, although small values of q_0 provide good fits to the K-band counts down to the faintest magnitudes, the corresponding average $B-K$ colors of galaxies fainter than $K = 18$ turn out to be much redder than observed by Gardner, Cowie, & Wainscoat (1993). For a closure world model the constraints set by K-band observations are less a problem: in this case the expected number of very red galaxies at faint magnitudes is smaller (Fig. 3), and there is room for a population of faint blue objects to contribute at $K > 17$, similarly to what they do in the B band. We will adopt in the following $q_0 = 0.5$, a value favored by current theories of the early universe.

A further important parameter is the galaxy formation time t_F. The available data on disk galaxies indicate relatively recent formation times, or an earlier formation of the spheroid, followed by later accretion of a disk. Note that the moderate luminosity evolution of disks makes the corresponding choice of t_F irrelevant (our adopted value of $t_F = 1$ Gyr is dictated by the need of accounting for the spheroidal component). The definition of t_F is much more critical for the faster evolving early-type systems. Adoption of $t_F = 1$ Gyr in this case too appears as a good compromise: a much shorter time would run into problems with the collapse time of the protogalactic cloud, while a larger t_F would imply formation at too small redshifts ($z < 3$–4), corresponding to ages for current early-type galaxies much younger than allowed by evolutionary synthesis models (e.g., Renzini 1993).

It is interesting to note that the age of the infrared galaxy IRAS F10214+4724, as inferred by Rowan-Robinson et al.

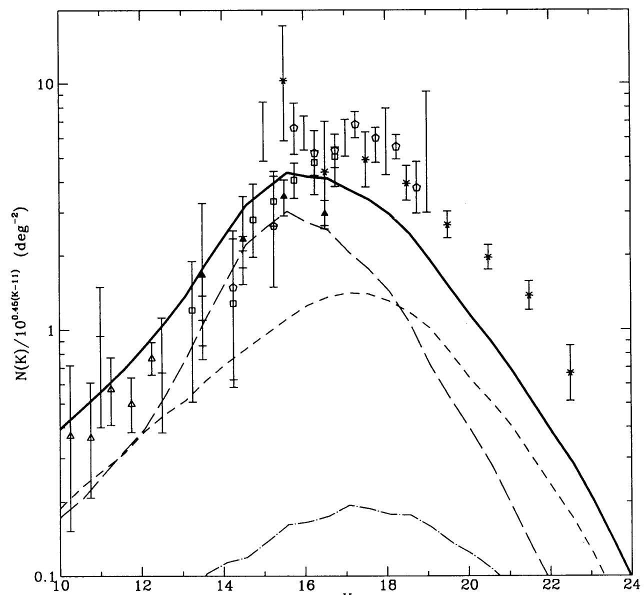

FIG. 3.—Comparison of observed differential counts in the K band (2.2 μm) as reported by Gardner et al. (1993), normalized to $10^{0.45(K-11)}$ deg^{-2}, with predictions of galaxy evolution models. The heavy solid line corresponds to the global contribution of galaxies for a model with $q_0 = 0.5$ and strong dust extinction (other lines representing the partial contributions of various galaxy classes—line types as in Fig. 2). A population of blue objects contributing at $K > 17$ is required to explain the faint counts and the blue observed $B-K$ colors, similarly to what is required in the B band at $B > 20$.

(1993) using photometric evolution models fit to optical broadband colors, and by Mazzei & de Zotti (1994b) fitting the whole UV-millimeter spectral energy distribution, turns out to be ~ 1 Gyr: at $z = 2.286$ this just corresponds to a formation epoch $t_F = 1$ Gyr ($z_F \sim 5$ in a closure world model), quite in agreement with our adopted value.

The assumption that a unique law rules the evolution of all early-type galaxies, irrespective of their present luminosity, might be disputed. It is not clear, in particular, how many objects in the highest luminosity bins of our best-guess LLF in Figure 1 might be the result of substantial merging events. This may happen if, for example, the original sample on which the LLF is based would include a significant number of galaxy groups (whose most luminous galaxies have probably formed by accretion). For extreme objects of this kind the past photometric evolution should have been quite peculiar. To account for this, we have also considered in our subsequent analysis, together with the LLF in Figure 1, the case of a LLF of early-type galaxies cutoff above $M_B = -21.5$: for lower luminosities we will assume that merging, if any, has contributed only a negligible fraction of the present galactic mass. We will see that, although the detailed predictions about the number of high-z galaxies may somewhat change, our basic conclusions are not affected.

3.2. *Effects of Dust Extinction*

Figure 2 shows the effect on counts of dust absorption during early evolutionary phases: the prominent peak in Figure 2a at $B \simeq 22$–24 contributed by strongly evolving, unobscured early-type galaxies (and due to the UV emission of massive stars redshifted into the B passband) tends to disappear in the more extinguished cases of Figures 2*b* and 2*c*. This effect has an even more relevant impact on the redshift distributions for magnitude-limited samples, the peak in the counts being mostly contributed by high-redshift objects.

Spectroscopic surveys down to $B \sim 25$ have been published by various groups (Broadhurst et al. 1988; Colless et al 1990, 1993; Lilly et al. 1991; Cowie et al. 1991). In the most recent report, Colless et al. (1993) have been able to reduce to 4% the incompleteness for $B < 22.5$: they show that none of the 100 observed galaxies (out of a sample of 104) has $z > 0.7$. Similarly impressive is the result by Cowie et al. (1991) on a complete sample of 22 galaxies to $B < 24$, for which the highest redshift is 0.73. The latter result was also confirmed by further observations of 10 extremely faint galaxies to $B < 25$ by Colless et al. The authors conclude that, to a very significant confidence level (99%), these data allow no more than 1 mag of luminosity evolution of L_* galaxies by $z = 1$.

All this severely challenges any evolutionary synthesis models. We report in Figure 4*a* the predicted redshift distributions $D(z)$ with limiting magnitudes $B = 22.5$ and 24, for a model based on best-fit parameters as discussed in § 3.1 and *no dust extinction.* The corresponding differential counts appear in Figure 2*a*. This model predicts that 40% of all detected objects with $21 < B < 22.5$ and some 50% of those with $B < 24$ should have $z > 0.7$ and up to $z = 3$. These numbers, which take into account the missing fraction of faint blue objects needed to bring the predicted counts into agreement with the observations, are quite significantly inconsistent with the observed lack of high-z galaxies. What remains to be explained is why the expected strong UV emission of massive stars, during the first few Gyr of enhanced star formation in

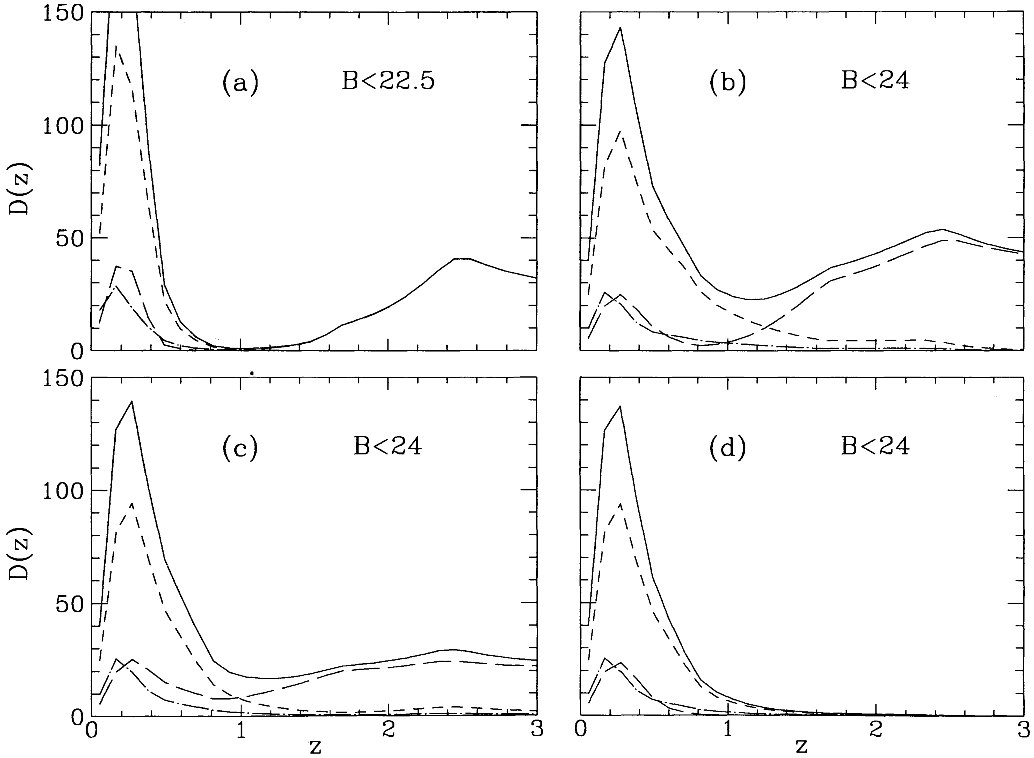

FIG. 4.—Predicted redshift distributions of evolution models in the B band. (a, b) Transparent case (for two relevant limiting magnitudes). The overall median redshift in (a) is 0.48, in (b) it rises to 1.65 because of the contribution of many early-type galaxies at $z > 1$. (c) Moderate extinction case (median redshift 0.7). (d) Strong extinction case (median redshift 0.26). Note that these contributions to $D(z)$ are to be added to those of the faint blue galaxy population at $B > 20$. Lines as in Fig. 2.

early-type galaxies in particular, is not observed, assuming they were present at $z = 1$ and beyond.

Our proposed answer to this question is that obscuration by a dust-enriched ISM prevents the detection of high-z galaxies. Our physical evolution model allows us to test this idea in detail. As a first step, we have tried a model of the spheroidal component in galaxies characterized by a slow metal enrichment of the ISM, hence by a moderate extinction during the early evolutionary phases. This corresponds to the case with $n = 1$ in the relationship between SFR and the fractional mass of gas. It implies roughly 30% of the bolometric emission of a spheroid at $t_G = 2$ Gyr being dust-obscured. As indicated by Figure 4b, however, such moderate extinction is not enough to reconcile the predicted fractions of high-z galaxies with the observations: 15% of all objects in the magnitude range $21 < B < 22.5$ would be expected in this case at $z > 0.7$, and a correspondingly higher fraction for $B < 24$.

Decreasing the birth epoch (increasing z_F) of early-type galaxies could alleviate to some extent the problem. For $t_F = 5 \times 10^8$ yr, the fraction of $23 < B < 24$ high-z objects would now amount to 40%. Still a fraction of 25% of faint ($B < 24$) objects would fall at unacceptably high z even adopting a t_F value for E/S0 galaxies as small as 10^8 yr (or $z_F = 20$).

A heavier extinction of the optical-UV flux is therefore called for to get better consistency with the available redshift information. A model for the spheroidal component characterized by a faster metal production, such as the one with $n = 0.5$ in equation (1), does the job entirely. From Figure 4c, less than 1% of $21 < B < 22.5$ objects and less than 10% of those with $B < 24$ are expected beyond $z = 0.7$, such small fractions being now essentially the high-z tail of the weakly evolving disk galaxy population.

As anticipated, these effects of dust extinction are reflected in the differential counts. The bump predicted for early-type galaxies at $B \simeq 22$–24 in Figure 2 vanishes in passing from the unabsorbed to the heavily absorbed case. In the latter, the high optical depth to UV photons for a large fraction of the active star-forming phase makes ellipticals virtually disappear from surveys at $B > 22$. This effect could be tested by morphological studies with the *HST* of faint field-galaxy samples. In the case of a constant galactic mass function, a new population of medium-to-low luminosity blue objects, not represented in local galaxy samples, is then required to explain the counts at $B \gtrsim 20$–23 and possibly also those at $K > 18$.

4. DUST RERADIATION AT FAR-INFRARED WAVELENGTHS

If during some evolutionary phases the absorbed UV-optical light has been an important fraction of the total emission, as suggested above, the corresponding dust reradiation might be detectable in the far-IR. General arguments help in elucidating the point.

Far-IR data on the Milky Way indicate that dust reradiates an important fraction ($\simeq \frac{1}{3}$) of the total starlight (Wright et al. 1991; Sodrowski et al. 1987), and similar values for the average ratio $L_{\rm FIR}/L_{\rm bol}$ are also found for nearby disk galaxies (Xu & de Zotti 1989). Thus the ratio $L_{\rm FIR}/L_{\rm bol}$ of far-IR to bolometric radiation cannot have increased with look-back time by more than a factor of a few. In addition, more or less direct evidence on the galactic disk shows that its metallicity and SFR have not varied significantly after formation. In conclusion, apart

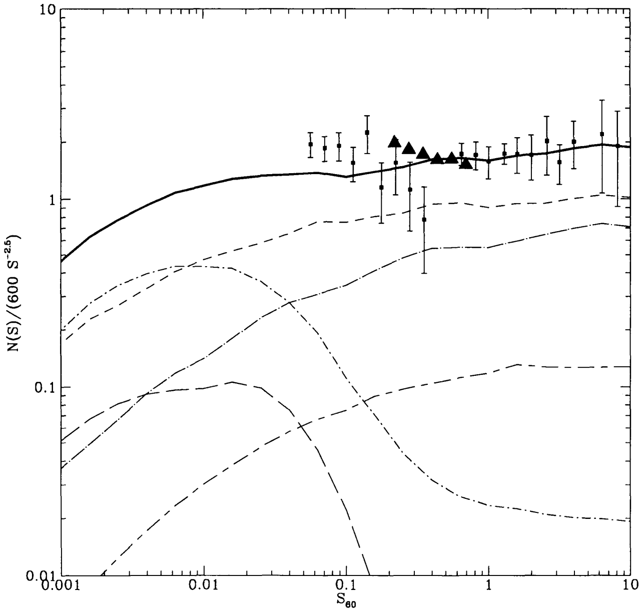

FIG. 5*a*

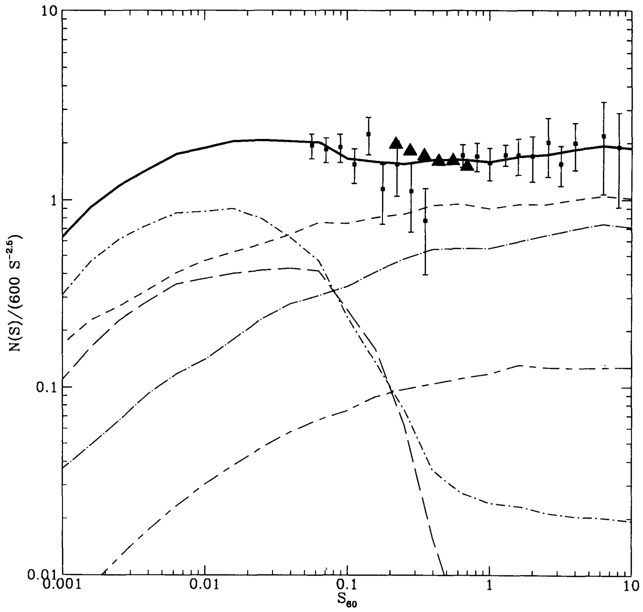

FIG. 5*b*

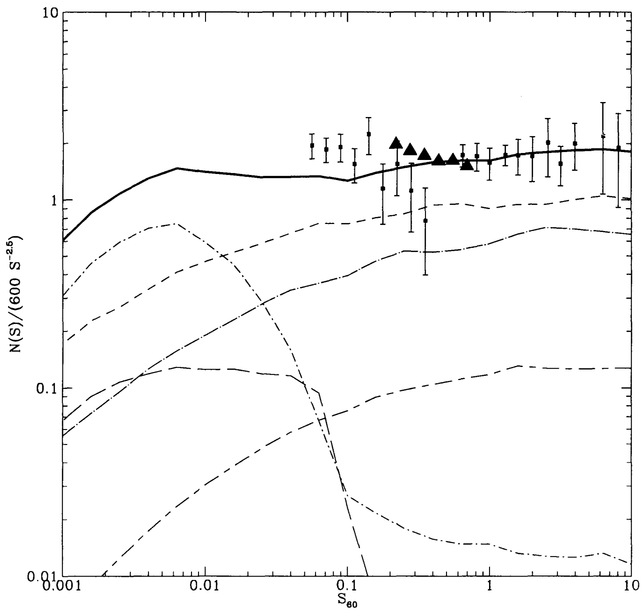

FIG. 5*c*

FIG. 5.—Normalized differential counts of galaxies at 60 μm, observations vs. prediction of two optically extinguished cases: (*a*) moderate extinction, (*b*) strong extinction, (*c*) strong extinction model applied to a LLF cutoff at the bright end as discussed in § 3.1. *Short-dashed line*: Sp/Ir; *dot-long-dashed line*: starbursts; *dot-short dashed line*: S0 galaxies: *long-dashed line*: ellipticals; *long-short dashed line*: Seyfert galaxies; *heavy solid line*: total prediction.

from the small contribution of the spheroidal component, both $L_{\rm bol}$ and $L_{\rm FIR}$ in disk galaxies could not have varied but slowly during galactic evolution.

The reverse might have been the case for early-type systems, in particular if the active-star-forming luminous phase just after formation occurred in dust-enshrouded OB complexes as we often see in the Milky Way today. In such an event, the far-IR/optical ratio could have increased from the local value of less than 1% to roughly unity or more. Together with the evolution implied by the fast increase of the SFR with decreasing galactic age, this could result in $L_{\rm FIR}$ being several hundred times higher during early evolutionary phases. We have previously seen (§ 2) that such a possibility is determined by the rate of metal enrichment of the ISM in the early evolutionary phases. Even a small fraction of metals, condensing into dust grains, may produce appreciable extinction and dust reradiation in a phase during which an important fraction of the baryonic content was still in a gaseous form, such a phase also coinciding with that of major energy production by stellar nucleosynthesis.

All this is expected to produce very different behaviors in the far-IR counts of late- and early-type galaxies. Due to the still sizeable fraction of mass in the gaseous component, the former dominate galaxy samples and counts at bright far-IR fluxes, as apparent in the *IRAS* survey, where the latter, almost deprived of an ISM, contribute only a negligible fraction. On the other hand, later-type galaxies evolve weakly at most at far-IR wavelengths and thus have quickly converging counts, while the dramatic evolution of $L_{\rm FIR}$ for early-type systems would make them important, or dominant, contributors to the faint source counts.

Detailed, although simplified, modeling allows us to quantify these statements. Figure 5 reports comparisons of 60 μm differential counts, as derived from the *IRAS* survey (Hacking & Houck 1987; Hacking, Condon, & Houck 1987; Lonsdale & Hacking 1989), with predictions based on the moderately extinguished and opaque cases for the spheroidal components in galaxies, as discussed in §§ 2 and 3. We see that the spiral and starburst normalized counts dominate at the Jy level, but quickly converge thereoff, in spite of the contribution of an evolving spheroidal component that we have allowed in such galaxies (see § 2). This is due to the *K*-correction implied by the steeply decreasing spectra shortward of $\lambda = 60$ μm. Disk galaxies by themselves can hardly account for the flat observed normalized counts down to $S_{60} = 50$ mJy.

Even a moderate dust extinction during the early evolutionary phases of E and S0 galaxies (case $n = 1$) produces ultra-

Euclidean evolutionary slopes in the flux range from 1 Jy to 10 mJy in Figure 5*a*. Early-type galaxies, in such case, would start to contribute to the observed counts at the faintest flux limits reached by *IRAS*, $S_{60} \sim$ 50–100 mJy. A close agreement with the observed faint 60 μm counts is found by adopting the opaque evolution model (Fig. 5*b*).

Note that the same opaque model consistent with optical data on high-z galaxies is also the one best fitting the available 60 μm counts. Unfortunately, *IRAS* was not so sensitive, nor was it dedicated to deep integrations, to provide good samples at faint enough flux limits to allow for a strong point to be made here. Although free from cirrus contamination (Hacking et al. 1989), the only complete sample of a few tens of galaxies fainter than 0.1 Jy (Hacking & Houck 1987; Hacking et al. 1987) is not totally reliable because of the uncertain effect of galaxy clustering, that could in principle be responsible for at least part of the observed enhancement with respect to the no-evolution prediction. We must wait for new and deeper sky surveys by future missions (ISO, FIRST, SIRTF); here again identifications of the optical counterparts of faint far-IR sources could be very informative. Predicted redshift and magnitude distributions for galaxies selected at 60 μm are in Figures 6 and 7.

These results are based on local luminosity functions at 60 μm derived using the available local bright galaxy samples. The LLFs for spiral and starburst galaxies are now well defined for a wide range of luminosities (Saunders et al. 1990; Franceschini et al. 1988). For E and S0 galaxies, instead, its determination is still subject to significant uncertainties, because of their elusiveness at far-IR wavelengths. The present determination is based on the optically selected sample discussed by Franceschini et al. (1988), implemented with pointed *IRAS* observations by Knapp et al. (1989). The optical LLFs have been transformed from the B band to 60 μm adopting an average flux ratio of $(\nu L_\nu)_{60}/(\nu L_\nu)_B = 7 \times 10^{-3}$ for E's and of $(\nu L_\nu)_{60}/(\nu L_\nu)_B = 2 \times 10^{-2}$ for S0's, as derived from our statistical analysis. We note that our basic conclusions are not affected by uncertainties in the determination of the optical and far-IR LLFs or of the far-IR to optical flux ratio of early-type galaxies: changing them would alter the predicted counts at flux levels ($S_{60} \gtrsim$ 0.01–0.1 Jy) where they are in any case a marginal component of the extragalactic sky. More conservatively, we reported in Figures 5*c*, 6, 7, and 9 predicted far-IR counts, z, and B distributions derived adopting a 60 μm LLF for early-type galaxies based on a B-band LLF cutoff at $M_B > -21.5$ (see § 3.1), hence neglecting the contribution of very massive E/S0's whose luminosity evolution is particularly uncertain.

The two predicted counts of early-type galaxies at 60 μm in Figures 5*b* and 5*c* imply that from roughly 30 to a few sources like IRAS F10214+4724 could be found in the sample of 1440 galaxies over 700 deg^2 brighter than 0.2 Jy discussed by Rowan-Robinson et al. (1991), to be compared with the roughly 70 far-IR sources still missing a redshift determination.

We have shown, on quite general grounds, that if we assume that E/S0 galaxies (which are roughly 30% of all normal galaxies; e.g., Bingelli 1987) during early evolutionary phases were optically thick, then the corresponding energy production is expected to show up in the far-IR at flux levels of $S_{60} \sim$ 10 mJy, independently of the adopted world model.

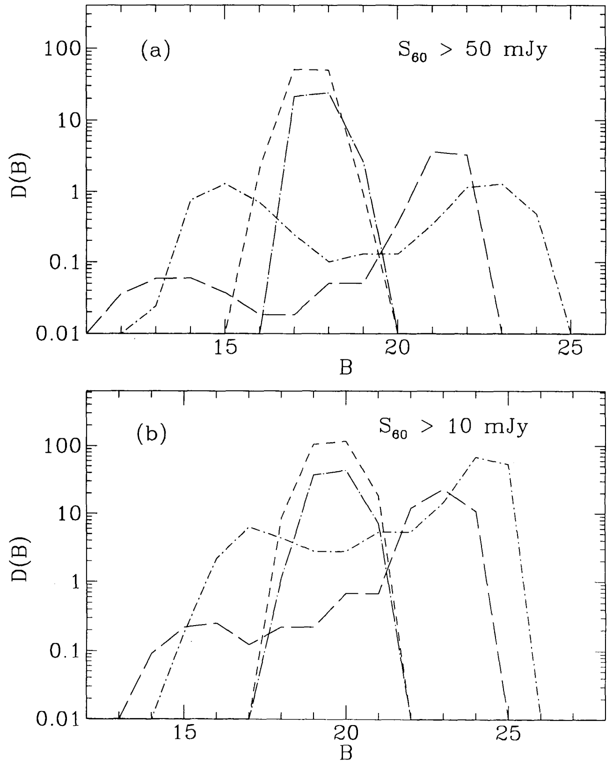

FIG. 7.—Predicted B-magnitude distributions corresponding to the evolution models in Fig. 6. Meaning of lines as in Fig. 5.

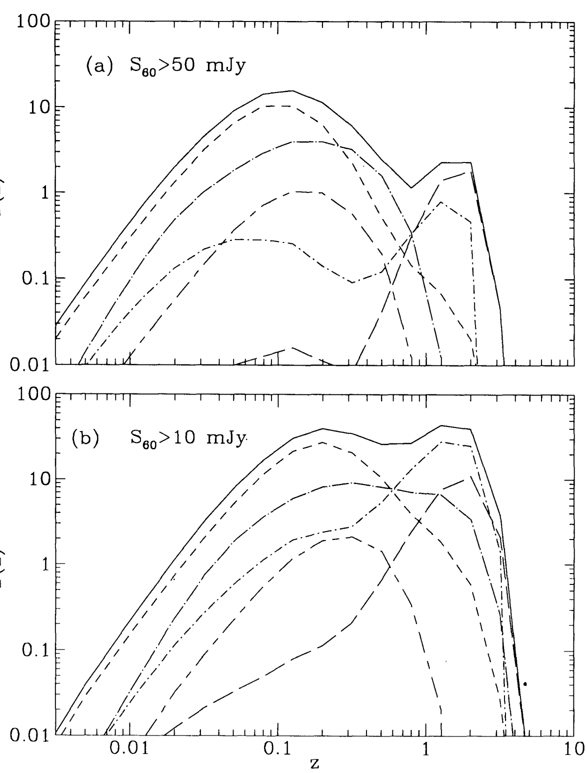

FIG. 6.—Predicted redshift distributions for deep 60 μm flux-limited samples based on the heavily absorbed model and a LLF cutoff at the bright end as discussed in § 3.1. Meaning of lines as in Fig. 5. (*a*) Flux limit of the deepest *IRAS* survey by Hacking & Houck (1987); (*b*) planned deep surveys with ISO (Cesarsky et al. 1993 and references therein).

5. CONTRIBUTION OF DISTANT EVOLVING GALAXIES TO SUBMILLIJANSKY RADIO SAMPLES

Although radio emission is only a tiny fraction of the bolometric output from normal galaxies, it is however an important tracer of their star formation activity.

While the blue luminosity provides a poor measure of the recent star formation, because of dust extinction in star-forming molecular clouds and confusion by old stellar populations, the radio luminosity is essentially determined by the star formation rate of short-lived stars more massive than 5–8 $M_\odot$, producing supernova remnants, relativistic electrons and H II regions. The radio, likewise the far-IR, emission is optically thin at all wavelengths, even for the most intense starbursting regions (see Condon 1992). In addition, mapping with radio interferometers to arcsecond resolution provides a dramatic advantage with respect to far-IR detectors (e.g., *IRAS*) in terms of the limiting fluxes and cosmic distances reachable.

The energy output from early active star-forming phases in galaxies is then expected to have an already observable counterpart in the radio. We briefly discuss here rough predictions of the radio centimetric outcome of our galaxy models. We adopt a simplified approach exploiting the well-known relationship between radio and far-IR luminosities in galaxies, rather than by a detailed modeling of the supernova production, which would need introducing further free parameters.

The existence of a tight, roughly linear, relationship between radio and far-IR luminosities has been established for almost all classes of normal and starburst galaxies (from disk to early-type systems with residual star formation), for optical, radio, and infrared-selected samples (Helou, Soifer, & Rowan-Robinson 1985; Wunderlich, Klein, & Wielebinski 1987; Dressel 1988; Wrobel & Heeshen 1988). It has been also confirmed for faint sources in the deep 60 μm *IRAS* survey (Hacking et al. 1989). The linearity of the relation is proven in particular for moderate-to-high luminosity galaxies. Deviations from it have been found only for low-luminosity objects, where the radio flux falls short of the far-IR flux (possibly due to diffusion of the relativistic electrons), and perhaps for the prototype primeval galaxy IRAS F10214+4724, whose radio emission falls short of the estimated far-IR flux (somewhat dependent on the dust model) by factors of 3–10 (Rowan-Robinson et al. 1993).

The *K*-correction to the radio fluxes has been estimated using a power-law index $\alpha_R = 0.7$. For all galaxy classes we have adopted an average flux ratio

$$\log L_{5\,\mathrm{GHz}} = \log L_{60} - 2.1$$

with no dispersion.

We compare in Figure 8 predictions of the two already discussed models (the moderately extinguished and the opaque) with observed normalized differential counts at 5 GHz (Fomalont et al. 1991). The thick dashed line corresponds to the contribution of bright nuclear nonthermal sources, that is, powerful radio sources and radio-loud quasars, as derived from evolution models by Franceschini et al. (1989). We see in Figure 8*a* that in the moderately opaque case distant galaxies would contribute only a fraction (20%–30%) of the observed count level, while the heavily absorbed model could potentially explain most of the submillijansky flattening of the radio counts over a couple of decades in flux (Fig. 8*b*). Here again, a model characterized by fast evolution of the SFR at least for a population of spheroid-dominated galaxies, by heavy dust extinction of the optical-UV light, and by strong far-IR reradiation would also have the additional merit of substantially contributing to (and possibly explaining) the observed submillijansky radio counts over an appreciable flux range.

Predicted contribution of distant evolving galaxies to the

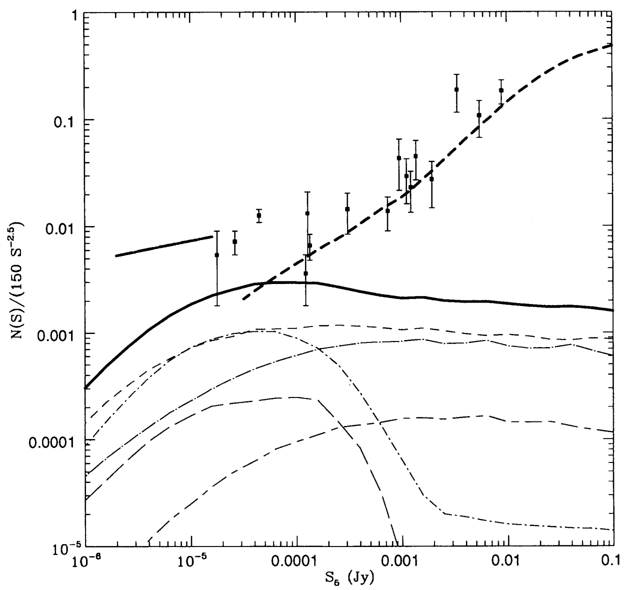

FIG. 8*a*

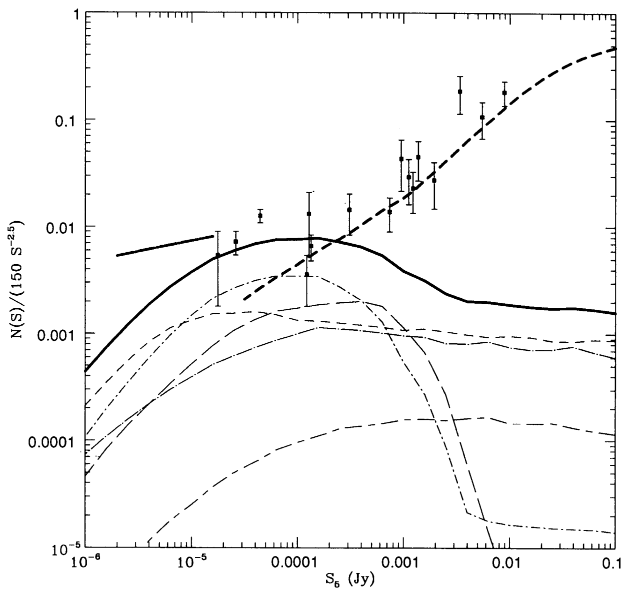

FIG. 8*b*

FIG. 8.—Predicted normalized differential counts of galaxies vs. observations at 5 GHz. The faintest ($S_5 \geq 16$ μJy) complete sample of radio sources has been obtained with more than 100 hr integration with VLA (Fomalont et al. 1991). An extrapolation of the counts to $S_5 \sim 1$ μJy (*thick dot-dashed line*) has been obtained from a *P*(*D*) analysis. Meaning of the lines as in Fig. 5. The heavy dashed line is the predicted contribution of powerful radio sources and radio-loud quasars, estimated from models by Danese et al. (1987) and Franceschini et al. (1989). (*a*) Moderate absorption model. (*b*) Strong absorption model.

redshift distributions at two relevant 5 GHz flux limits are reported in Figure 9 for our more interesting case of strong galactic evolution.

A note about the faintest 5 GHz counts inferred from $P(D)$ analyses. Even for the most evolving model of Figure 8*b*, the predicted counts of galaxies are not able to explain the observed excess below 10 μJy, an indication that the faint blue objects appearing in optical counts are emerging at those faint radio fluxes.

6. DISCUSSION

Dynamical interpretations of the observed morphology of various classes of galaxies, studies of metallicity for stellar generations of various ages in the Galaxy, and analyses of spectrophotometry and of color and metallicity gradients in extragalactic systems suggest the following evolutionary picture for the stellar and gaseous components in galaxies.

Systems dominated by a disk and gas-rich irregulars should have formed relatively recently, their averaged star formation rate evolving quite moderately, from values of few tens to the present values of few $M_\odot$/yr per 10^{11} $M_\odot$ of baryonic mass. For a typical Salpeter's IMF, the metallicity of gas has reached roughly solar values within 1 Gyr of the formation. Since diffuse dust absorbs and reradiates at far-IR wavelengths already one-third on average of the bolometric stellar radiation in nearby disk galaxies, then optical, radio, and far-IR emissions from such systems should not have evolved by more than a factor of a few during most of their lifetime. Merging should have proceeded in these systems so slowly not to perturb appreciably the ordered motions observed in thin disks (Tremaine 1980; Toth & Ostriker 1992).

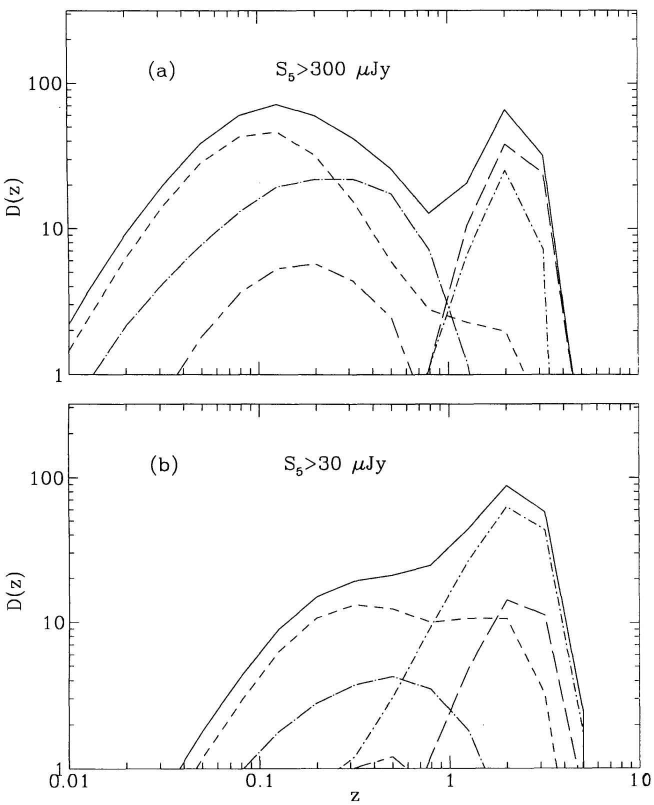

FIG. 9.—Predicted redshift distributions for 5 GHz flux-limited samples and two relevant flux limits (the brighter corresponding to submillijansky samples—see Windhorst et al. 1985 and Condon & Mitchell 1984; the fainter to the deeper microjansky sample by Fomalont et al. 1991). Case of strong absorption and LLF conservatively cutoff at radio luminosities corresponding to the $M_B = -21.5$ limit as discussed in § 3.1. Meaning of lines as in Fig. 5.

Systems dominated by a more or less flattened spheroidal component, such as early-type (E and S0) galaxies and spiral bulges, should have followed a rather different evolution pattern. Two alternative scenarios may be envisaged. The classical one is to assume that the major events of star formation in their history should have occurred within the first (few) Gyr of their birth, on a timescale short enough to avoid collapsing of an exceedingly large fraction of mass into a flattened rotation-supported disk and to explain the observed colors and metallicity gradients. The alternative picture is that such systems may be the result of the merging of already formed smaller subunits, in which a significant fraction of the primeval gas has already turned into stars.

From the arguments mentioned in § 1 and others (e.g., those based on the inferred properties of absorption-line–selected galaxies in the line of sight of distant quasars; see Steidel 1993), it is quite plausible that the mass function of normal medium-size field galaxies has not changed significantly during a substantial fraction of the Hubble time.

Decades of observational and interpretational efforts (Kennicutt 1983; Sandage 1986; Gallagher, Hunter, & Tutukov 1984; Arimoto & Yoshii 1987; van den Berg 1992) concur to indicate that the SFR in the spheroidal components of galaxies was high somewhere in the past. The lack of any evidence in the optical band of the correspondingly larger bolometric outputs at $z > 1$, coupled with indications from far-IR and radio observations of excess counts at faint fluxes with respect to no-evolution predictions, may indicate that significant dust extinction is intervening, making the optical band not suited for investigations of such early phases of galaxy evolution, while selections at longer wavelengths could provide better tools to this purpose. We have shown, through detailed modeling, that the right amount of dust needed to reconcile model predictions with the observed z-distributions of faint galaxies would also explain the excess 60 μm counts by *IRAS* and significantly contribute to the submillijansky counts of radio sources.

We note, in passing, that the effect of dust extinction has been advocated by various authors to explain the failure to find any Lyα emissions from primeval galaxies in current searches based on spectroscopic surveys and narrow-band imaging (De Propris et al. 1993; Djorgowski & Thompson 1992). Dust extinction and resonant scattering have also been advocated to explain the observed lack of Lyα emission from damped Lyα absorbers in the direction of high-z quasars, interpreted as galaxy-sized, gas-rich, star-forming objects, possibly protodisks (Charlot & Fall 1991; Pei, Fall, & Bechtold 1991; Elston et al. 1991). It would be natural, in our scheme, to associate these objects with early disks: the inferred moderate extinction may be understood if we consider that the relatively low star formation activity characterizing their early evolution (§ 2) could not generate large amounts of metals and too much dust in the ISM. A rather different behavior is expected for spheroid-dominated primeval galaxies, whose abundant metal-enriched ISM would provide strong extinction in the optical. One such object at $z = 2$ with a SFR of over 100 $M_\odot$/yr could have already been detected through IR spectroscopy by Elston et al. (1991). The probability of observing objects of this kind as damped Lyα absorbers, however, might be reduced by two effects: (1) their active star formation phase begins at $z \gtrsim 4$–5 and by $z = 2$–3 much of the ISM has already turned into stars, so that very high-z target quasars would be needed; (2) the occurrence of a dusty star-forming spheroid in the line of sight to a high-z quasar may cause an extinction so strong as to prevent detection of the quasar. Optical and near-IR studies of bright empty-field radio selected sources, possibly related to high-z radio-loud quasars and luminous radiogalaxies, might prove to be interesting in this context. Note, in any case, that the fractional sky coverage of such dust forming spheroids should not be much larger than 10%, unless their sizes were implausibly larger than those of the present-day galaxies.

A further consequence of our proposed scheme is that early active star formation in protogalaxies would not likely originate the ionizing flux for the IGM, as suggested by Cowie (1988) and Songaila, Cowie, & Lilly (1990). Other energy sources are then required: quasars, both the optically selected and the X-ray selected populations, are not far from producing the required flux.

A final note about the detailed evolutionary behavior of star formation in distant galaxies; It is debated how long the main phase of star formation in early-type galaxies lasted. Someone, often in the framework of hierarchical galaxy formation scenarios, has suggested that the observability of such a phase could be strongly reduced by a delayed formation, in which case the peak luminosity would be reduced with respect to classical predictions (Baron & White 1987). Others emphasize that various arguments, based on the observed homogeneity of spectral, dynamical, and photometric properties of ellipticals, indeed suggest that they formed during a rather short time interval at fairly high redshifts (Renzini 1993). Our basic argument is not sensibly affected by such details: in particular, a delayed star formation activity would decrease the intrinsic brightness, but also shift it to epochs so late as to fall into the observability domain of faint spectroscopic surveys.

In some sense, one of the merits of our proposed interpretation is to bring into observability—through long-wavelength observations—the major phase of star, metal, and energy production in the history of galaxies. Any alternatives to this scheme, among those we are able to envisage (e.g., widespread *merging*, or a very high redshift of formation—$z_F > 10$—in an open universe), would imply that such a phase might be hard to observe at all in the future. We list in the following some straightforward tests of our hypothesis.

1. *Deep imaging of faint optical sources with the HST*. The capability of *HST* to perform imaging and morphological analyses at very faint magnitudes has been demonstrated by Dressler (1992) and Griffiths (1992). Analyses of this sort on complete galaxy samples might provide a direct test that, due to strong extinction during the active phase, early-type galaxies start to disappear from optical samples already at $B \sim 22$–23. Following Figure 2, the fraction of E's and S0's in complete samples at $B = 24$ is strongly dependent on the opacity of the bright star-forming phase: a lack of sources with $r^{-1/4}$-law profiles in these samples would be taken as an indication in favor of our model. (Note that the reverse may not be true: if dust is concentrated in the star-forming regions rather than perfectly mixed with stars, as assumed in our extinction model, it could not affect the observability of the older steller population.)

2. *Near- and mid-infrared faint source surveys*. Because of the reduced effect of dust extinction, source selection at wavelengths longwards of the B band would be expected to provide galaxies at increasingly larger redshifts. An effect of this kind might be seen in the I-band selected sample of Lilly (1993), where six out of 25 confirmed galaxies are found at $z > 0.8$. The effect, however, is confused in the optical by the large fraction of faint blue objects observed at moderate z. The latter are probably avoided by K-band surveys down to $K \sim 18$ (Gardner et al. 1993). We would predict that some 5%–10% of galaxies detected to this limit would lie at $z > 1$. Of course, the most distant of them would also be the most heavily extinguished, hence the most difficult to observe spectroscopically.

Passing to even longer wavelengths, three effects concur in making high-z galaxies more easily accessible: the decreasing effect of dust extinction, the K-correction becoming positive for spectra peaking at $\lambda \simeq 1$ μm, and the still positive luminosity evolution. The first chance to access this still unexplored wavelength domain will be provided by the ISO mission in the coming years. Important shares of observation time with the most sensitive filter ($5 < \lambda < 8.5$ μm) of the ISO imager will be dedicated to deep surveys (Cesarsky et al. 1993).

3. *Optical identifications and spectroscopy of far-IR and radio-selected samples at faint fluxes*. This is the basic strategy we suggest to detect actively star-forming galaxies at high redshifts, and, at the same time, the sharpest test we propose to check our suggestion of heavy dust effects in such objects. Our modeling implies that star-forming early-type galaxies could start to appear in 6 μm selected samples at fluxes of $S_{60} \sim 100$ mJy (Fig. 5). The recently discovered high-redshift infrared galaxy IRAS F10214+4724 (Rowan-Robinson et al. 1993) fits perfectly into the proposed scheme of opaque forming spheroids. It is interesting to note that its 60 μm flux coincides with the survey limit (0.2 Jy), in keeping with the predicted steep rise of the counts (see Fig. 5). The exact fraction of $z > 1$ galaxies expected in current deep far-IR and radio surveys depends on details of the evolution scheme and of the galaxy's LLF: these translate into an uncertainty in the predicted counts, as shown by various panels in Figure 5. For the heavily absorbed model, as much as 20 of the 98 sources in the faintest complete sample by Hacking et al. (1987) down to $S_{60} = 50$ mJy might be evolving early-type galaxies at $z > 0.6$, but the number reduces to a few adopting a LLF devoid of very luminous objects (Fig. 6*a*). Eighty percent of the far-IR sources in the Hacking's et al. (1987) sample to 50 mJy have been identified as galaxies in POSS plates, but no z-information is available. We would expect high-z galaxies to fall in the magnitude range $20 \lesssim B \lesssim 25$ (Fig. 7). Of course, given the large error box of *IRAS* ($\sim 1' \times 1'$), the identification is difficult, unless the size of the far-IR box is reduced. Observations with 10 μm array cameras or with the VLA could be very helpful in this respect.

Better chances to discover high-redshift galaxies through observations at far-IR wavelengths will be provided in the near future by the ISO mission. Current sensitivity estimates (ESA 1991) show that a few square degrees could be covered to $S_{60} \simeq 10$ mJy in a reasonable amount of time. At this limit various tens of dusty galaxies like IRAS F10214+4724 may be detected: most of them might be high-redshift objects, if our approach is correct (Fig. 6*b*). This and previous considerations make ISO a very promising tool to detect and study galaxies in early dust-enshrouded phases of evolution.

As shown by Figure 8, a disadvantage of radio observations, even at the faintest limits currently reachable with the VLA, is the contamination of samples by radio-loud quasars and powerful radiogalaxies. In addition, our model predictions are rather uncertain here (§ 5). We certainly would expect that some of the faintest radio detected sources (e.g., Fomalont et al. 1991) might belong to the high-redshift population (see Fig. 9 for the strongly evolving case); the exact amount, however, is hard to say. Identification of the faintest radio sources could require imaging to 28th magnitude, a prediction consistent with preliminary information reported by Fomalont et al. Programs of radio source identification and spectroscopy are proceeding very fast and are expected to provide important information in a short time.

4. *Measurements of the extragalactic background in the IR and submillimeter.* The *COBE* satellite has been collecting information on the extragalactic background emission from 1 μm to several millimeters: data analysis is underway, and some preliminary results have already been published. We show in Figure 10 limits on the sky background at $\lambda > 400$ μm from FIRAS, recently reported by Wright et al. (1993) and Mather et al. (1993). The figure emphasizes the basic problem of such observations: the subtraction of the foreground emissions, in this case that of cold dust in the Galaxy. Data with error bars are estimates of the residual background after subtraction of the best-fit CMB spectrum and of the Galaxy emission obtained attributing the whole DIRBE map signal at 240 μm to the latter: this procedure assumes that any isotropic signal with a spectrum similar to that of the Galaxy is negligible. A more conservative upper limit (shaded region) was obtained using a plane parallel model for the galactic emission ($\sim$ csc $|b|$). We see that even the heavily absorbed model is not yet strongly constrained by *COBE* data, but further improvements in the analysis might start to be informative.

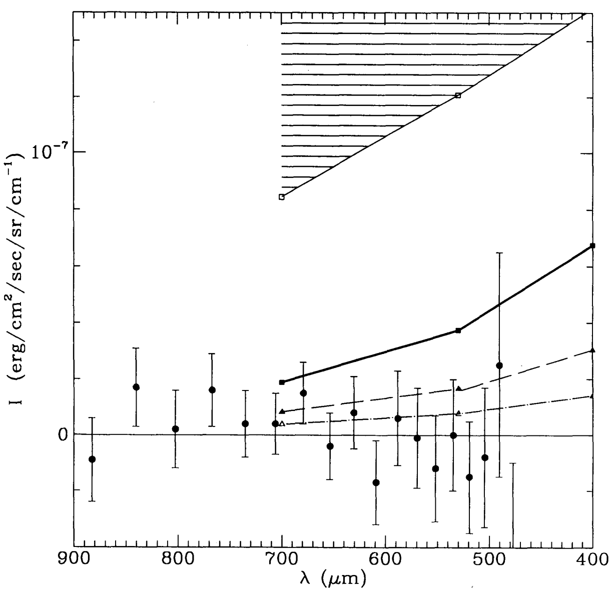

FIG. 10.—Limits on the sky background from *COBE* FIRAS data reported by Wright et al. (1993), compared with predictions of the opaque model. The shaded region marks the 2 σ upper limit on any residual isotropic component, after subtraction of the CBR and of the contribution from the Galaxy. *Data with error bars*: residual background from Mather et al. (1993) obtained attributing the whole DIRBE map signal at 240 μm to the Galaxy (such assumption is of course inconsistent with the diffuse extragalactic flux predicted by our models, which is a nonnegligible fraction of the 240 μm DIRBE signal). *Dot-dashed line*: contribution from ellipticals; *long dashed line*: from S0's; *thick solid line*: total predicted contribution.

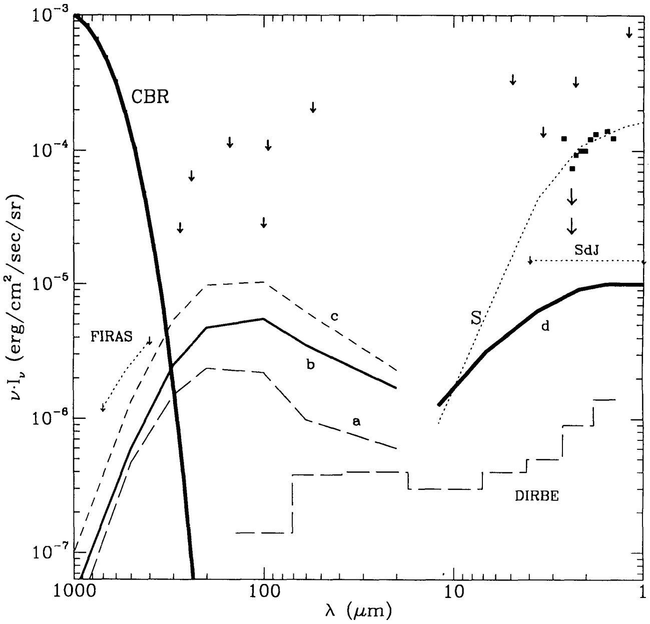

FIG. 11.—Extragalactic background light at infrared through submillimeter wavelengths. Data and upper limits on the background are from Hauser et al. (1991), Noda et al. (1992), Oliver, Rowan-Robinson, & Saunders (1992), and Franceschini et al. (1991b). (*a*) No evolution (already inconsistent with 60 μm counts); (*b*) moderately opaque case; (*c*) opaque case; (*d*) galaxy contribution in the near-IR, rather unsensitive to effects of dust extinction in the sources. Current 2 σ limits from FIRAS on *COBE* in the submillimeter and Stecker & de Jager (1993) in the near-IR are reported as dotted lines. Line marked S corresponds to the contribution of stars fainter than $K = 3$ (see Franceschini et al. 1991a). The expected DIRBE sensitivities are also shown.

The DIRBE experiment on *COBE* has the final target of detecting the extragalactic background light over a very wide frequency range. We provide in Figure 11 estimates of the contributions of bright distant galaxies to such a background.

7. CONCLUSIONS

We have exploited detailed models of photometric evolution for various classes of galaxies over a very wide spectral domain—from UV-optical to far-infrared and radio wavebands—to analyze observational constraints on galaxy luminosity evolution. The models provide a description of the spectrophotometric properties of the various stellar generations, taking into account the effects of the gas metallicity both on stellar atmospheres and on the opacity of the residual interstellar gas. The energy reradiation in the far-IR from the absorbing dust is also estimated in a consistent way.

The wide spectral coverage allows us for the first time to relate so diverse observational facts as the optical and K-band counts, the lack of high-redshift galaxies in optical samples to $B \sim 25$, and the excess counts in far-IR and radio-selected samples of galaxies with respect to no-evolution predictions.

Among the various alternatives for galaxy formation and evolution, we find concurrent indications in favor of a model in which a large fraction of the energy produced by stars of the early generations is absorbed by dust and reradiated at IR wavelengths (to avoid conflicting with optical redshift surveys) and partly comes out directly in the radio. The latter two spectral domains are suggested to contain crucial information about processes of formation and evolution of bright galaxies. Counts at 60 μm by *IRAS* and at radio centimetric wavelengths to very faint flux limits may already reflect such evolution effects.

We then suggest that some of the future observational efforts dedicated to searches of high-redshift and primeval galaxies should concentrate on faint IR and radio-selected sources with very faint or not yet detected optical counterparts.

The particular case of galaxy formation and early evolution we have illustrated has the merit of bringing into the observability domain the early phases of galaxy evolution. Viable alternatives are either *merging* of small protogalactic systems (but this has to face a number of counterarguments; see § 1) or a very high redshift of galaxy formation in an open universe (but this has to be reconciled with observations of faint galaxies in the K band). Both of them push the bright evolution phase of galaxies to limits not currently reachable by the observations.

We acknowledge fruitful discussions with M. Rowan-Robinson, G. Fasano, and G. Lake, and comments by L. Cowie, G. Djorgowski, and R. Ellis. We are indebted to the referee, S. J. Lilly, for a careful reading of the manuscript and helpful comments. Work was supported in part by ASI and by the EEC Program "Human Capital and Mobility."

APPENDIX A

THE GALAXY MODEL

We describe the basic assumptions of our adopted galaxy models. For more detailed descriptions we defer to the original papers by MXD92 and MDX93.

A1. THE CHEMICAL EVOLUTION MODEL

For the star formation rate $\psi(t)$ the Schmidt (1959) parameterization has been adopted:

$$\psi(t) = \psi_0 f_g^n \, M_\odot \ \mathrm{yr}^{-1} , \tag{A1}$$

where f_g is the fractional mass of gas in the galaxy and $f_g = m_{\mathrm{gas}}/m_{\mathrm{gal}}$, assumed to be initially unity ($m_{\mathrm{gal}} = 10^{11} \, M_\odot$). The cases with $n = 0.5$, 1, and 2 have been explored.

The initial mass function (IMF), $\phi(m)$, has a Salpeter (1955) form:

$$\phi(m)dm = A\left(\frac{m}{M_\odot}\right)^{-2.35} d\left(\frac{m}{M_\odot}\right) \quad m_l \le m \le m_u , \tag{A2}$$

with $m_u = 100 \, M_\odot$ and $m_l = 0.01 \, M_\odot$.

The influence of a different choice of the power-law index, n, for the dependence of the SFR on the gas density has been discussed by Mazzei (1988). The effects of different choices for the IMF and its lower mass limit, m_l, are analyzed in MXD92 for late-type systems and in MDX93 for early-type galaxies. The general conclusion is that the overall evolution of late-type systems is weakly depending on n, whereas stronger differences could arise for early-type systems.

The galaxy is assumed to be a close system, that is, both outflow and inflow of intergalactic gas has been neglected. Supernova-driven galactic winds may well be important during the early evolutionary stages of ellipticals, particularly for lower mass objects (Brocato et al. 1990). On the other hand, the extended hot coronae around these galaxies, indicated by X-ray observations (e.g., Trinchieri & Fabbiano 1985), may imply the existence of massive halos, capable of hampering or even of preventing steady galactic winds, or of accretion flows. In any case, a reliable modeling of these effects is very difficult.

The gas is assumed to be well mixed and uniformly distributed. However, recycling is not instantaneous, that is, stellar lifetimes are properly taken into account.

The variations with galactic age of the fractional gas mass $f_g(t)$ (and, through eq. [1], of the SFR $\psi[t]$), and of the gas metallicity $Z_g(t)$ are obtained by numerically solving the standard equations for the chemical evolution of the Galaxy (Tinsley 1980).

A2. THE PHOTOMETRIC EVOLUTION MODEL

A2.1. *The Synthetic Starlight Spectrum*

The synthetic spectrum of stellar populations as a function of the galactic age was derived from UV to N band (10.2 μm). The contribution of a stellar generation of age τ to the integrated luminosity in the passband $\Delta\lambda$ is given by

$$l_{\Delta\lambda}(\tau) = \int_{m_{\mathrm{min}}}^{m_{\mathrm{max}}(\tau)} \phi(m) 10^{-0.4[M_{\Delta\lambda}(m,\tau) - M_{\mathrm{Sun}}]} dm \, L_\odot \, M_\odot^{-1} , \tag{A3}$$

where m is the initial stellar mass, m_{min} is the minimum mass represented in the isochrone, $m_{\mathrm{max}}(\tau)$ is the maximum mass of stars still visible at the age τ, that is, the largest mass which has not yet reached the stage of either the final explosion or of the formation of a collapsed remnant, $M_{\Delta\lambda}(m, \tau)$ is the absolute magnitude of a star of initial mass m and age τ, and $M_{\mathrm{Sun}} = 4.72$ is the bolometric luminosity of the Sun.

The global luminosity at the galactic age t is then obtained as the sum of the contributions of all earlier generations, weighted by the appropriate SFR:

$$L_{\Delta\lambda}(t) = \int_0^t \psi(t - \tau) l_{\Delta\lambda}(\tau) d\tau \, L_\odot . \tag{A4}$$

The number of stars born at each galactic age t and their metallicity are obtained by solving the equations governing the chemical evolution, with the SFR and IMF specified above. Their distribution in the H-R diagram has been described using the theoretical isochrones derived by Bertelli et al. (1990) for metallicities $Z = 0.001$ and 0.02, extended by Mazzei (1988) up to 100 $M_\odot$ and to an age of 10^6 yr. Isochrones include all evolutionary phases from the main sequence to the stage of planetary ejection or of carbon ignition, as appropriate given the initial mass.

Following Sandage (1986) the value of ψ_0 (eq. [A1]) is left to span from 100 to 3 $M_\odot$ yr^{-1} to describe the chemical and photometric properties of the galaxies of different morphological types.

A2.2. *Correction for Internal Extinction*

The internal extinction has been taken into account assuming that stars and dust are well mixed. A plane-parallel geometry has been adopted for disk galaxies, while a spherical symmetry, with the stellar distribution conveniently described by King's (1962) law, was used to represent spheroidal galaxies (E, S0, and spiral bulges). The dust-to-gas ratio was assumed to be proportional to a power of the metallicity, as in Guiderdoni & Rocca-Volmerange (1987), so that

$$\tau_\lambda(t) = \tau_{0_\lambda}\left[\frac{Z_g(t)}{Z_g(15)}\right]^s\left[\frac{f_g(t)}{f_g(15)}\right], \tag{A5}$$

with $s = 1.6$ for $\lambda > 2000$ Å and $s = 1.35$ for $\lambda < 2000$ Å. We have adopted the interstellar extinction curve given by Seaton (1979) for $\lambda \leq 0.37$ μm and by Rieke & Lebofsky (1985) at longer wavelengths. The index 15 refers to a galactic age, t, of 15 Gyr.

A2.3. *Emission from Circumstellar Dust*

The mid-IR emission from circumstellar dust shells was assumed to be dominated by OH/IR stars. The spectrum of OH 27.2 + 0.2 (Baud et al. 1985) was assumed to be representative for stars of this class (see also Cox, Krügel, & Mezger 1986). Then the total luminosity of OH/IR stars in the passband $\Delta\lambda$ is given by

$$L_{\mathrm{OH},\Delta\lambda}(t) = F\int_{t_{\mathrm{AGB}}(m_{\mathrm{up}})}^{t} d\tau\,\psi(t-\tau)\int_{m_{l,\mathrm{OH}}(\tau)}^{m_{u,\mathrm{OH}}(\tau)} \phi(m)10^{-0.4[M_{\Delta\lambda}(m,\tau)-M_{\mathrm{Sun}}]}dm\,L_\odot\,, \tag{A6}$$

where $t_{\mathrm{AGB}}(m_{\mathrm{up}})$ is the time when the first OH/IR stars appear, $m_{l,\mathrm{OH}}(\tau)$ ($\geq m_{\mathrm{HeF}}$) and $m_{u,\mathrm{OH}}(\tau)$ ($\leq m_{\mathrm{up}}$) are the minimum and the maximum mass of OH/IR stars of age τ. The coefficient F is determined from the condition that OH/IR stars account for 10% of the observed 12 μm luminosity of our galaxy (Ghosh, Drapatz, & Peppel 1986; Boulanger & Pérault 1988), taken to be $L_{12\,\mu\mathrm{m}} \simeq 1.3 \times 10^8$ $L_\odot$ μm^{-1} after Pérault et al. (1990), that is, $L_{\mathrm{OH},12\,\mu\mathrm{m}}(t = 15\ \mathrm{Gyr}) \simeq 1.3 \times 10^7$ $L_\odot$ μm^{-1}. $F = 0.05$ is found, in good agreement with Herman & Habing's (1985) estimate.

A2.4. *Diffuse Dust Emission*

The diffuse dust emission spectrum takes into account the contributions of two components: warm dust, located in regions of high radiation field intensity (e.g., in the neighborhood of OB clusters), and cold dust, heated by the general interstellar radiation field.

The model allows for a realistic grain-size distribution and includes PAH molecules (see Xu & de Zotti 1989 and MXD92 for more details). The amount of starlight absorbed and reemitted by dust is determined at each time using the model for internal extinction mentioned above.

The relative contributions of the warm and cold dust components are allowed to evolve with galactic age: the warm/cold dust ratio is assumed to be proportional to the star formation rate.

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