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Deep galaxy surveys: The IR/submm window

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Abstract. Recent optical/NIR observations have led to a significant progress in our understanding of galaxy formation and evolution. However, our view on the deep universe is currently limited to the starlight which directly escapes from high-redshift galaxies, since we so far ignore the fraction absorbed by dust and released in the IR/submm wavelength range. Here we review the current accessibility of this new window for the investigation of high-redshift galaxy evolution. While the on-going deep surveys with ISO are probing the universe at $z{\sim}1$, a new generation of instruments and satellites in the next eight years will complete, and perhaps strongly modify, our understanding of galaxy evolution at $z{\geq}1$.

Keywords: cosmology - galaxies: formation - galaxies: evolution - infrared - submm

1. Introduction

This paper presents a review of the current stage of our knowledge on galaxy formation and evolution from deep optical and IR surveys. Spectacular breakthroughs have been made recently by the Hubble Space Telescope and the large, ground-based telescopes, as well as by the advent of new detectors in the NIR. The picture of galaxy formation and evolution which is progressively emerging is fascinating, and seems to naturally fit in the paradigm of hierachical structure formation which has been developed by converging theoretical efforts during the last fifteen years. Nevertheless, we shall argue that we have only a partial view on galaxy evolution since most of the observational data come from optical and NIR surveys which probe the rest-frame UV and visible emission of galaxies. A still unknown fraction of star/galaxy formation is hidden by dust which absorbs UV/visible starlight and re-radiates at longer wavelengths. The current and the next generation instruments working in the IR/submm range are soon to provide us precious information on the optically - dark side of galaxy formation and evolution.

2. Deep galaxy surveys in the optical

The modelling of galaxy evolution is now constrained by the abundant observational data obtained by optical/NIR surveys of high-redshift objects. The picture of galaxy evolution which is progressively emerging can be quickly summarized as follows:

1. After pioneering works from ground-based telescopes, the Hubble Deep Field has revealed a new lore of faint objects (Williams et al. 1996). Faint counts show the presence of a large number of blue galaxies, well in excess of no-evolution predictions.
2. The deep redshift surveys reveal that these blue objects as "sub-L^*" galaxies undergoing strong bursts of star formation (Lilly et al. 1995; Ellis et al. 1996; Cowie et al. 1996).
3. The fraction of blue objects with unclassified/peculiar morphologies showing signs of tidal interaction and merging (Abraham et al. 1996) increases from local samples to the HST high-resolution observations of the Medium Deep Survey (Griffiths et al. 1994) and HDF (Williams et al. 1996).
4. The global star formation rate (hereafter SFR) density of the universe declined by a factor of about ten since redshift $z \sim 1$ (Lilly et al. 1996; Madau et al. 1996; Sawicki et al. 1997; Connolly et al. 1997). At $z \sim 4$, it was only twice the current rate. As a consequence, we could have seen the bulk of star formation in the universe.
5. This high SFR seems to be correlated with the decrease of the cold-gas comoving density in damped Lyman-α systems (DLA) between $z=2$ and $z=0$ (Storrie-Lombardi et al. 1996).
6. The metallicity of DLAs scatters around $Z \sim 0.1 Z_\odot$ at $z=2$ (Pettini et al. 1997). The high SFR observed at $z \sim 1$ would be responsible for the strong enrichment of local galaxies.

These results nicely fit in a view where star formation in bursts triggered by interaction/merging consumes and enriches the gas content of galaxies as time goes on. Indeed, such a scenario is qualitatively predicted within the paradigm of hierarchical growth of structures in which galaxy formation is a continuous process.

3. The optically–dark side of galaxies

Nevertheless, it should be emphasized that this seemingly consistent view is entirely based on UV/visible observations. A significant amount of star formation might be completely hidden in heavily-extinguished galaxies which are missed by the above-mentioned surveys. This hidden fraction might induce a strong revision of the picture summarized in Sec. 2. For instance, the comoving SFR densities based on rest-frame UV observations (at 2800 Å or 1600 Å) might be underestimated if extinction is strong. Moreover, dusty DLAs might hide the background quasars and make them disappear from magnitude-limited samples which are used for absorber statistics. As a consequence, only DLAs with the smallest gas contents and metallicities would appear in current surveys. Pei and Fall (1995) have attempted to model such an effect under simplifying assumptions.

We still know very little about the "optically-dark" side of galaxy evolution. The IRAS satellite has discovered a sequence of IR properties, from "normal spirals" to "mild starbursts", and finally to the "luminous IR galaxies" (hereafter LIRGs), most interacting systems, and the spectacular "ultraluminous IR galaxies" (hereafter ULIRGs), which are mergers (Sanders and Mirabel 1996) and emit more than 95% of their energy in the IR. While about one third of the

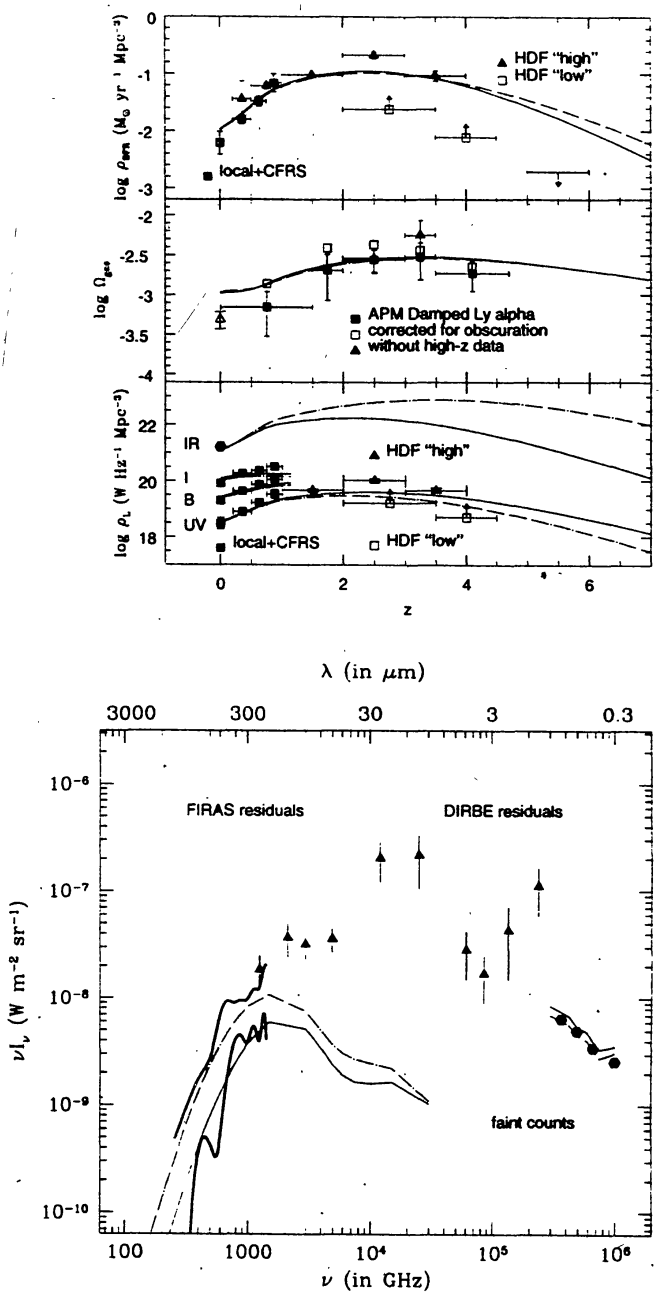

Figure 1. Panel a (top): Evolution of the "cosmic constraints" for scenario A (solid line) without ULIRGs and scenario E (dots and long dashes) with a fraction of ULIRGs increasing with z. Upper panel: comoving star formation rate density as computed from rest-frame UV luminosity densities, by using Salpeter IMF with slope 1.35 without extinction. Middle panel: cold gas density parameter in damped Lyman-α absorbers. Lower panel: rest-frame luminosity densities. Panel b (bottom): Diffuse backgrounds in the FIR/submm and in the optical. The solid triangles show the level of COBE/DIRBE upper limits from Hauser (1996). The thick solid lines give the CIRB detection at ± 1σ per point from the re-analysis of the COBE/FIRAS residuals initiated in Puget et al. (1996), and revisited in Guiderdoni et al. (1997). The solid hexagons show the Cosmic Optical Background obtained by summing up faint galaxy counts down to the Hubble Deep Field limit.

bolometric luminosity of the local universe is released in the IR/submm (Soifer and Neugebauer 1991), we know very little about galaxy evolution at high z in this wavelength range. Faint galaxy counts with IRAS do not probe deeper than $z \sim 0.2$ (Ashby et al. 1996). These surveys seem to show a strong luminosity and/or density evolution, but it is difficult to extrapolate this trend to higher redshifts on a firm ground. As we shall see in Sec. 5, the ISO satellite is currently completing this picture, in a broader wavelength range from a few μm to 200 μm.

In order to analyse the current data and make predictions for forthcoming observations, we have chosen to model galaxy evolution by using the so-called "semi-analytic" approach which has been rather successful in reproducing the overall properties of galaxies in the optical range. We have elaborated an extension of this type of method to the IR/submm range. Details of the modelling, and extensive predictions are given elsewhere (Guiderdoni et al. 1997a, b). In the Standard Cold Dard Matter cosmological scenario (H_0=50 kms^{-1} Mpc^{-1}, Ω_0=1, Λ=0, Ω_b=0.05, σ_8=0.67), we have designed a family of plausible evolutionary scenarios with different fractions of ULIRGs. In the following, scenario A has no ULIRGs and scenario E has a fraction of ULIRGs increasing with z.

Fig. 1a shows the predicted comoving SFR, gas, and lumniosity densities in the universe, for these scenarios. The strong episode of star formation at z~1 corresponds to the decrease of the gas density in the universe. The local luminosity densities in the UV, visible and IR are accommodated by all our evolutionary scenarios, though they predict high-z IR luminosity densities which are strongly different.

4. The diffuse background due to galaxies

The epoch of galaxy formation can be observed in the background radiation which is produced by the accumulation of the light of extragalactic sources along the line of sight. The search for the "Cosmic Optical Background" currently gives only upper limits. The shallowing of the HDF faint counts suggests that we are now close to convergence and that an estimate of the COB can be obtained by summing up the contributions of faint galaxies.

The DIRBE instrument on COBE has given upper limits on the IR background at wavelengths between 2 and 300 μm (Hauser 1996). The re-analysis of COBE/FIRAS residuals between 200μm and 2mm, has led Puget et al. (1996) to discover the presence of an isotropic component which is likely to be the long-sought "Cosmic Infrared Background" (hereafter CIRB). If it is confirmed, such a detection would yield the first "post-IRAS" constraint on the high-z evolution of galaxies in the IR/submm range, before the era of ISO results. Its level is comparable to the estimate of the optical background and suggests that a significant fraction of the energy of young stars is absorbed by dust and released in the IR/submm.

Fig. 1b displays the predicted backgrounds generated with our scenarios, which nicely reproduce the optical background, and predict a CIRB which fall within the $\pm 1\sigma$ range of the observed isotropic component.

5. The present: deep surveys with ISO

Several deep surveys being analysed are scheduled as below:

1. With the ISOCAM camera (Cesarsky et al. 1996):
    - ELAIS covers 15 deg^2 at a sensitivity level of about 1mJy at 15μm (Rowan-Robinson et al., 1997, in preparation).
    - The DEEP surveys cover a field of about 400 arcmin^2, at a sensitivity level of several hundreds μJy at 15 μm (Cesarsky et al. 1997, in preparation). Deeper exposures are obtained for sub-areas.
    - The ISO-HDF survey is a follow-up of the HDF plus neighbouring fields, at a 10σ sensitivity of 54 μJy at 15 μm in the central region (Serjeant et al. 1997, and related papers; Aussel et al. 1997).
    - An Ultra-deep survey covers a small area at a typical sensitivity of a few tens μJy at 6.7 μm, and is likely to reach the confusion limit (Taniguchi et al. 1997, in preparation).
2. With ISOPHOT far-infrared cameras PHT-C100 and C200 (Lemke et al. 1996):
    - The SLEW serendipity survey already acquired 1700 deg^2 in the A&A November 1996 issue. It will cover 15% of the sky at the end of the mission and will detect point sources at a typical sensitivity of 1 Jy (Bogun et al. 1996).
    - The Lockman hole survey includes four 22×22 arcmin^2 fields which are observed with 128 sec/px at 90 and 175 μm to a 1σ sensitivity of 30 mJy (Kawara et al. 1997, in preparation).
    - The Marano field survey covers a 30×30 arcmin^2 field which are observed with 512 sec/px at 90 and 175 μm to a 1σ sensitivity of 18 mJy (Puget et al. 1997, in preparation).

Fig. 2a shows the predictions of the faint counts at 15 μm and 175 μm, with the results of the ISO-HDF deep survey (Oliver et al. 1997) and the very preliminary results of the Lockman hole survey (Kawara et al. 1997, in preparation). The objects detected by this latter survey are very faint or invisible on the POSS prints. The evolutionary scenarios used to disentangle the CIRB into discrete sources predict that these objects are probably located at redshifts z £ 1. The 15 μm surveys are favoured by the good sensitivity of ISOCAM, but they mostly probe the PAH features and the redshifted starlight of old stellar populations, which are not very sensitive to evolution. In contrast, ISOPHOT surveys with the 175 μm filter are not as detective, but they probe the strong sensitivity of the submm range to evolution, also at $z \sim 1$.

6. Future instruments

The results of ISO will give the first view on the IR evolution of galaxies at z ~1. Two instruments will probe a similar wavelength range in the next future:

1. The Wide-Field Infrared Explorer (WIRE), with a 0.3 m aperture, will be launched by NASA in 1998 (for an updated review, see Hacking et al. 1997). It will survey hundreds of deg^2 at 12 and 25 μm. Its spatial resolution (20 arcsec at 12 μm and 24 arcsec at 25 μm) limits its detectivity to the confusion limit at the 0.1 - 1.0 mJy sensitivity level, depending upon wavelength and evolution.

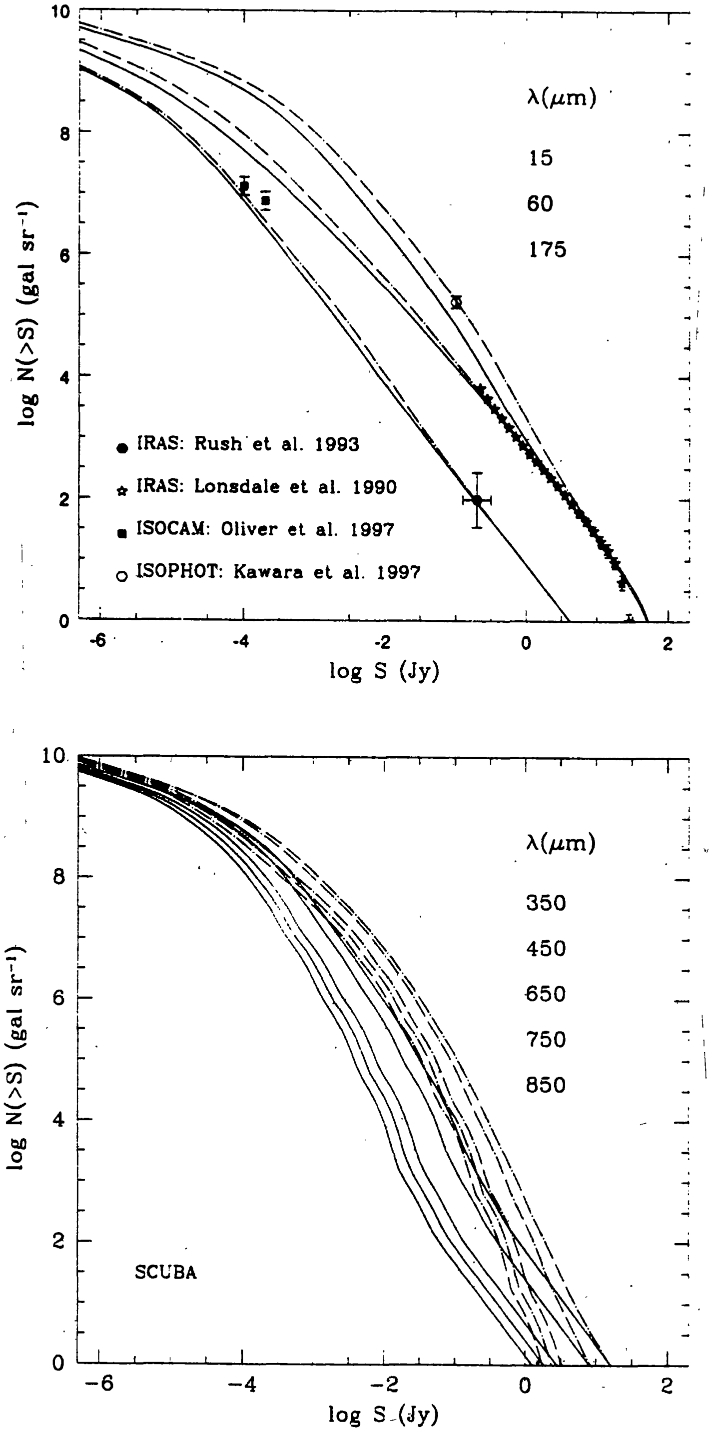

Figure 2. Panel a (top) : Predictions for faint counts at 15 μm, 60 μm and 175 μm (from bottom to top) for scenarios A and E. Note that the 15 μm fluxes only include dust emission, and are lower limits for $z \geq 1$. Panel b (bottom): Predictions at SCUBA wavelengths for scenarios A and E. In contrast with counts at wavelengths smaller than 100 μm, the submm counts are very sensitive to the details of the high-z evolution.

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2. The Space Infrared Telescope Facility (SIRTF), with a 0.8 m aperture, will be launched by NASA in 2001 (for an updated review, see e.g. Werner 1997). It covers a wavelength range 3.5 - 160 μm with a 1.5 arcsec pixel size. The mapping and imaging instrument has 1σ sensitivities (for 500 sec of integration) amounting to 48 μJy (24 μm), 0.2 mJy (70 μm) and 1.5 mJy (160 μm).

As shown by Fig. 2b, the submm range is spectacularly sensitive to high-redshift galaxy evolution, because of the shift of the 100 μm spectral bump into the observing bands. Several instruments are to work in this wavelength range which is so far almost unexplored for galaxy evolution:

1. The Submillimetre Common User Bolometer Array (SCUBA) which is implemented at the 15m James Clerk Maxwell Telescope (Cunningham et al. 1994), and observes in the narrow atmospheric windows.

2. The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a joint US and German project of an aircraft-borne 2.5m telescope designed to work between 0.3 μm and 1.6mm (for an updated review, see e.g. Graham 1997). Its first scientific flight is scheduled in 2001.

3. The Far Infra-Red and Submillimetre Telescope (FIRST) is an ESA cornerstone mission designed to observe in the 85 to 600 μm range, with a 3m aperture (for an updated account of the mission, see e.g. Pilbratt 1997). It could be launched in 2004-2005.

4. The PLANCK surveyor is a CMB mission which will map the submm/mm anisotropies at a scale of a few arcmin, with a 1.5 m aperture, in several channels between 350 μm and 9.5 mm (for an updated account of the mission, see e.g. Tauber 1997). It could be launched in 2004-2005.

At the 1 to 10 mJy sensitivity level which is foreseen for a deep survey with SCUBA, it is expected that faint counts will strongly discriminate between evolutionary scenarios and begin to "break" the CIRB into discrete units.

The relative performances of these instruments for detecting a $10^{12} L_{bol\odot}$ galaxy (similar to Arp 220) are compared in Fig. 3a and 3b. Fig. 3a summarizes the typical 10σ instrumental sensitivities. PLANCK (as well as IRAS) will be able to achieve an all-sky survey of objects at a typical depth of $z \sim 0.1$. ISO, WIRE and SOFIA are probing or will probe the universe at $z \sim 1$. Finally, SIRTF, and especially SCUBA and FIRST will be able to probe the deep universe beyond $z \sim 1$. Fig. 3b gives $10 S_{conf}$, where the confusion limit is defined from the differential counts dN/dS by $S_{conf} = (\int_0^{3S_{conf}} S^2 (dN/dS) \Omega dS)^{1/2}$ and Ω is the diffraction beam. As it appears from the direct comparison of confusion limits (for our scenarios of evolution) with instrumental noises in Fig. 3a and 3b, deep surveys with SIRTF (with an aperture D=0.8 m), SOFIA (D = 2.5 m), FIRST (D = 3m), and even SCUBA (D = 15m) are likely to be confusion limited at the largest wavelengths, especially if evolution is strong. The fluctuation analysis will yield information on the evolution below the confusion limit.

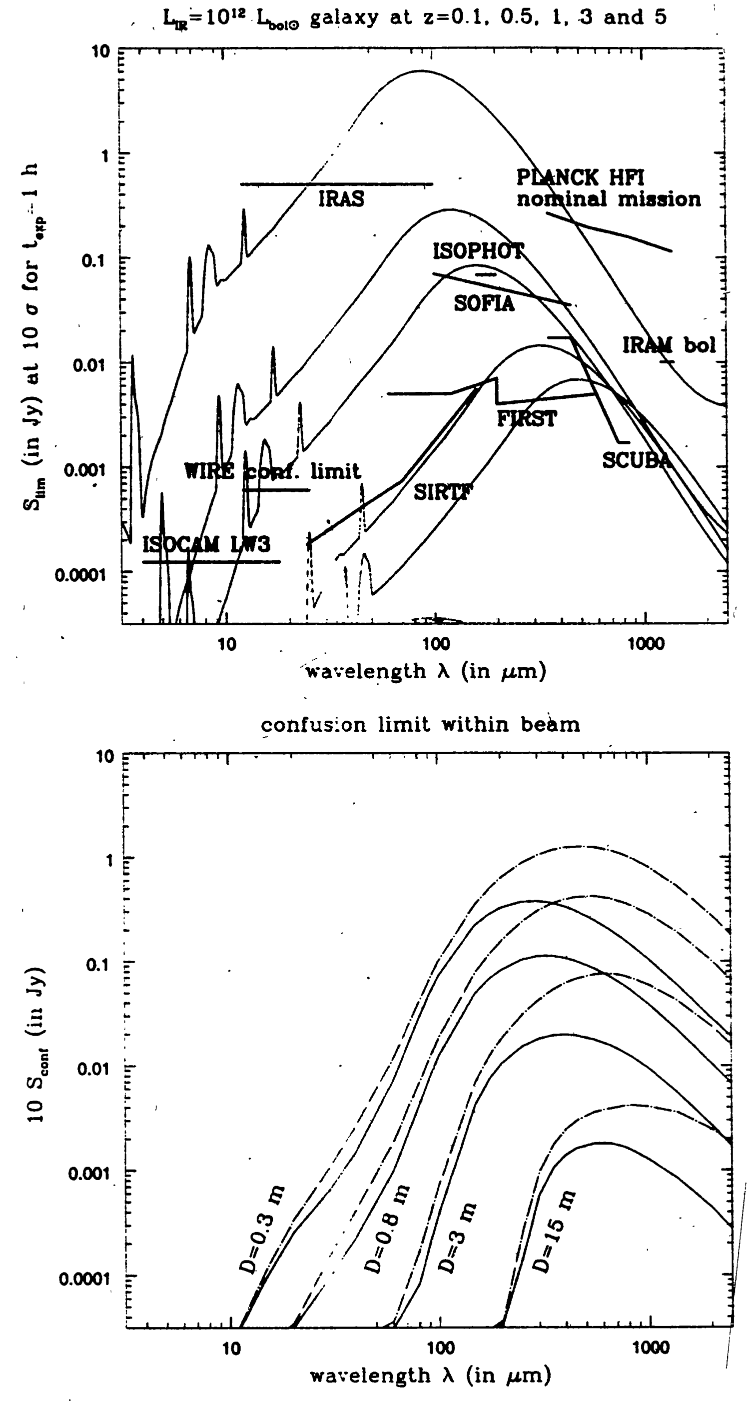

Figure 3. Panel a (top) : Observer-frame model spectra of a $L_{IR} = 10^{12}L_\odot$ galaxy at increasing redshifts (from top to bottom). The reader is invited to note that the apparent flux in the submm range is almost insensitive to redshift, because the shift of the 100 μm bump counterbalances distance dimming. Typical instrumental sensitities (at 10σ) are schematically drawn for current and forthcoming instruments. Panel b (bottom): Confusion limits (at 10σ) in the diffraction beam for scenarios A and E.

7. Conclusions

A new window is now open to deep extragalactic surveys. A large number of objects are expected from current models of galaxy evolution in the IR/submm. These models accommodate local IR data and follow the high-redshift evolution of the "cosmic constraints" (that is, the comoving SFR, gas and UV/optical/NIR luminosity densities), as well as the high level of the isotropic component in COBE/FIRAS residuals which is likely the CIRB. While the twenty high redshift objects which have been so far detected by their submm radiation are mostly submm counterparts of radiogalaxies and quasars, some of them being lensed (see e.g. the review by Huges et al. 1997), significant progress in resolution and sensitivity will show the high-redshift counterparts of ULIRGs, and maybe a large population of forming galaxies similar to IRAS 10214+4724 (Rowan-Robinson et al. 1991). Since new phenomena are usually discovered as soon as a new wavelength range is open for systematic exploration, the "discovery potential" of the next submm observations is very exciting.

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