What are the Galaxies Contributing to the Cosmic Infrared Background?

B. Guiderdoni

Institut d’Astrophysique de Paris, 98bis Boulevard Arago, F–75014 Paris, France

Abstract. Recent optical 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 of luminosity absorbed by dust and released in the IR/submm wavelength range. A new constraint is set by the possible detection of the Cosmic Infrared Background. We briefly review the observations and use a semi–analytic model of galaxy formation and evolution to predict number counts consistent with the level of the background. It turns out that the predictions fairly accomodate preliminary data at 175 and 850 µm. This suggests that a significant fraction of star/galaxy formation at high z is hidden by dust.

1. Introduction

The picture of galaxy formation and evolution which is progressively emerging from deep optical surveys is fascinating. The measurement of the cosmic star formation rate (hereafter SFR) density of the universe up to z ~ 4 from rest–frame UV fluxes seems to show a strong peak at z ~ 1.5 and suggests that we could have seen the bulk of star formation in the universe (Lilly et al. 1996; Madau et al. 1996). This high SFR seems to be correlated with the decrease of the cold–gas comoving density in damped Lyman–α systems between z = 2 and z = 0 (Storrie–Lombardi et al. 1996). 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.

However, we have only a partial view on galaxy evolution since most of the observational data come from optical surveys which probe the rest–frame UV and visible emission of high–z galaxies. A still unknown fraction of star/galaxy formation is hidden by dust which absorbs UV/visible starlight and re–radiates at larger wavelengths. At low z, the IRAS satellite has discovered a sequence of IR properties, from “normal spirals” to the “luminous IR galaxies” (hereafter LIRGs), mostly 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.
Figure 1. FIRAS residuals in the cleanest regions of the sky (solid line), and the CIRB (dotted line).

Figure 2. Diffuse backgrounds in the FIR/submm and in the optical. Solid triangles: COBE/DIRBE upper limits (Hauser 1995). Thick solid line: CIRB (Puget et al. 1996; Guiderdoni et al. 1997a). Solid hexagons: Cosmic Optical Background from faint galaxy counts (Williams et al. 1996). Long–dashes–and–short–dashes: predictions without evolution. Dots–and–short–dashes: quiescent star formation history. Solid line : scenario A without ULIRGs. Dots–and–long–dashes: scenario E with ULIRGs, fitting the CIRB. See Guiderdoni et al. (1997b) for details.
In contrast, we know very little about galaxy evolution at high $z$ in this wavelength range. Faint galaxy counts with IRAS seem to show a strong luminosity and/or density evolution at $z \lesssim 0.2$, but it is difficult to extrapolate this trend to higher redshifts on a firm ground. The Cosmic Infrared Background (hereafter CIRB) detected by Puget et al. (1996) in FIRAS residuals sets strong constraints on the presence of a population of IR/submm sources. We hereafter briefly review the observational case (in Sec. 2) and use a semi-analytic modelling of galaxy formation and evolution to predict number counts (in Sec. 3).

2. 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 (Williams et al. 1996).

![Figure 3](image-url)

Figure 3. 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–$\alpha$ absorbers. Lower panel: rest–frame luminosity densities.
The re–analysis of COBE/FIRAS residuals between 200 µm and 2 mm has led Puget et al. (1996) to discover the presence of an isotropic component which is likely to be the long-sought CIRB. Several steps are necessary in order to remove the foreground Galactic components and extract the isotropic residual identified as the CIRB. Whereas, at the wavelengths probed by FIRAS, the interplanetary emission is small and easily removed, the emission from interstellar dust mixed with the different gas phases of the interstellar medium is the dominant component. In order to address this problem, the original method of Puget et al. was applied again by Guiderdoni et al. (1997a), but only in the cleanest regions with very low HI column densities ($N_{HI} \leq 1 \times 10^{20}$ atoms cm$^{-2}$ instead of $N_{HI} \leq 4.5 \times 10^{20}$ atoms cm$^{-2}$). In that case, the residual component totally dominates the emission, as shown in Fig. 1. Fig. 2 shows that the CIRB intensity per frequency decade $\nu I_\nu \simeq (7 \pm 0.3) \times 10^{-9}$ W m$^{-2}$ sr$^{-1}$ near 300 µm is a factor of 5 higher than the no-evolution prediction obtained by a simple extrapolation of the IR luminosities of local galaxies.

Such a detection yields 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 optical background estimated by summing up faint galaxy counts down to the deepest limit so far available which is given by the Hubble Deep Field (Williams et al. 1996), and suggests that a significant fraction of the energy of young stars is absorbed by dust and released in the IR/submm.

The DIRBE instrument on COBE has given so far upper limits on the IR background at wavelengths between 2 and 300 µm (Hauser 1995). However Schlegel et al. (1997) extract a uniform background radiation from DIRBE observations at the levels $\nu I_\nu \simeq (17 \pm 4) \times 10^{-9}$ W m$^{-2}$ sr$^{-1}$ at 240 µm and $\nu I_\nu \simeq (32 \pm 13) \times 10^{-9}$ W m$^{-2}$ sr$^{-1}$ at 140 µm. At least the value at 240 µm, where the foregrounds are less important, seems to be consistent with the estimate from FIRAS. A more thorough analysis of the DIRBE data is currently undertaken by the DIRBE team.

3. Semi–analytic modelling

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 Dark Matter cosmological scenario ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 1$, $\Lambda = 0$, $\Omega_b = 0.05$, $\sigma_8 = 0.67$), 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. 3 shows the predicted comoving SFR, gas, and luminosity densities in the universe, for these scenarios. The strong episode of star formation at $z \sim 1$ 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. The predicted backgrounds generated with our scenarios are displayed in Fig. 2. Scenario E nicely fits the level and shape of the CIRB.

Figure 4. Predictions for faint galaxy counts at 15 \( \mu \text{m} \), 60 \( \mu \text{m} \), 175 \( \mu \text{m} \), and 850 \( \mu \text{m} \) for scenario E fitting the CIRB. See text for the keys of the symbols.

The corresponding predictions for faint galaxy counts are given in Fig. 4, with data from IRAS counts at 60 \( \mu \text{m} \) (Lonsdale et al. 1990; open stars), the ISO–HDF follow–up with ISOCAM at 15 \( \mu \text{m} \) (Oliver et al. 1997; solid squares) to be compared with data from the IRAS survey (Rush et al. 1993; solid dot), preliminary data for the Lockman Hole (Kawara et al. 1998, in preparation; open dot) and the Marano field (Puget et al. 1998, in preparation; solid triangles) with ISOPHOT at 175 \( \mu \text{m} \), and the first deep field observed with the JCMT/SCUBA at 850 \( \mu \text{m} \) (Smail et al. 1997; open squares). The agreement of the predictions with the data seems good enough to suggest that these counts do probe the evolving population contributing to the CIRB. The model shows that 15 % and 60 % of the CIRB respectively at 175 \( \mu \text{m} \) and 850 \( \mu \text{m} \) are built up by objects brighter than the current limits of ISOPHOT and SCUBA deep fields. It is also possible to get predicted redshift distributions for these counts. The predicted median redshift of the ISO–HDF is \( z \sim 0.8 \). It increases to \( z \sim 1.5 \) for the deep ISOPHOT surveys, and to \( z \gtrsim 2 \) for SCUBA, even if the latter value seems to be very sensitive to the details of evolution.
4. Conclusions

With ISO and SCUBA, 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 residuals which is probably the CIRB. The data seem to be consistent with a strong evolution. Significant progress in resolution and/or sensitivity expected from forthcoming satellites such as WIRE, SIRTF, and FIRST will show the high-redshift counterparts of local ULIRGs. The “discovery potential” of the forthcoming IR/submm observations is very exciting.

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