THE FIR/SUBMM WINDOW ON GALAXY FORMATION

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Abstract

Our view on the deep universe has been so far biased towards optically bright galaxies. Now, the measurement of the Cosmic Infrared Background in FIRAS and DIRBE residuals, and the observations of FIR/submm sources by the ISOPHOT and SCUBA instruments begin unveiling the “optically dark side” of galaxy formation. Though the origin of dust heating is still unsolved, it appears very likely that a large fraction of the FIR/submm emission is due to heavily—extinguished star formation. Consequently, the level of the CIRB implies that about 2/3 of galaxy/star formation in the universe is hidden by dust shrouds. In this review, we introduce a new modeling of galaxy formation and evolution that provides us with specific predictions in FIR/submm wavebands. These predictions are compared with the current status of the observations. Finally, the capabilities of current and forthcoming instruments for all–sky and deep surveys of FIR/submm sources are briefly described.

1 Introduction

Recent observational breakthroughs have made possible the measurement of the Star Formation Rate (SFR) history of the universe from rest–frame UV fluxes of moderate– and high–redshift galaxies (Lilly et al. 1996, Madau et al. 1996, 1998). The strong peak observed at \(z \sim 1.5\) seems to be correlated with the decrease of the cold–gas comoving density in damped Lyman–\(\alpha\) systems between \(z = 2\) and \(z = 0\) (Lanzetta et al. 1995, 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. Such a view is qualitatively predicted within the paradigm of hierarchical growth of structures in which galaxy formation is a continuous process (see e.g. Baugh et al. 1998).

However, these observational data come from optical surveys that probe the rest–frame UV and visible emission of high–\(z\) galaxies. In the early universe, what fraction of star/galaxy formation was hidden by dust that absorbs UV/visible starlight and thermally re–radiates at larger wavelengths? In the local universe (and thanks to IRAS and ISO observations), we know that about 30 % of the bolometric luminosity of galaxies is radiated in the IR (Soifer & Neugebauer 1991), and that a large fraction of dust heating is due to young stellar populations.
Genzel et al. (1998). Now, IR/submm observations are beginning to unveil what actually happened at higher redshift.

We might have kept so far the prejudice that high–redshift galaxies have little extinction, simply because their heavy–element abundances are low (typically 1/100 to 1/10 of solar at z > 2). However, low abundances do not necessarily mean low extinction. For instance, if we assume that dust grains have a size distribution similar to the one of our Galaxy \( n(a)da \propto a^{-3.5} \) with \( a_{\text{min}} \leq a \leq a_{\text{max}} \), and are homogeneously distributed in a region with radius \( R \), the optical depth varies as \( \tau \propto a_{\text{min}}^{-0.5} R \) while the total dust mass varies as \( M_{\text{dust}} \propto a_{\text{max}}^{0.5} R^3 \). For given dust mass and size distribution, there is more extinction where grains are small, and close to the heating sources. This is probably the reason why Thuan et al. (1998) observed a significant dust emission in the extremely metal–poor galaxy SBS0335-052.

In this context, we hereafter briefly review the attempts to correct the UV fluxes emitted by high–redshift galaxies for the effect of extinction, as well as recent measurements of the “Cosmic Infrared Background” (hereafter CIRB), and deep surveys at FIR/submm wavelengths. These observations strongly suggest that a significant fraction of the young stellar populations is hidden by dust. Finally, we propose a semi-analytic modeling of galaxy formation and evolution in which the computation of dust extinction and emission is explicitly implemented. This model is helpful to prepare forthcoming observations in the FIR/submm range.

2 The issue of extinction in high–redshift galaxies

Deep spectroscopic surveys and the development of the powerful UV drop–out technique have led to the reconstruction of the cosmic SFR comoving density (Lilly et al. 1996, Steidel & Hamilton 1993, Steidel et al. 1996, 1999, Madau et al. 1996, 1998). However, a complete assessment of the effect of extinction on UV fluxes emitted by young stellar populations, and of the luminosity budget of star–forming galaxies is still to come.

The cosmic SFR density determined only from UV observations of the Canada–France Redshift Survey has been recently revisited with a multi–wavelength approach including IR, submm, and radio observations. The result is an upward correction of the previous values by an average factor 2.9 (Flores et al. 1999). At higher redshift, various authors have attempted to estimate the extinction correction and to recover the fraction of UV starlight absorbed by dust (e.g. Meurer et al. 1997, Pettini et al. 1998). It turns out that the observed slope \( \alpha \) of the UV spectral energy distribution \( F_{\lambda}(\lambda) \propto \lambda^{-\alpha} \) (say, around 2200 Å) is flatter than the standard value \( \alpha_0 \simeq -2.5 \) computed from models of spectrophotometric evolution. The derived extinction corrections are large and differ according to the method. For instance, Pettini et al. (1998) and coworkers fit a typical extinction curve (the Small Magellanic Cloud one) to the observed colors, whereas Meurer et al. (1997) and coworkers use an empirical relation between \( \alpha \) and the FIR to 2200 Å luminosity ratio in local starbursts. The former authors derive \( \langle E(B-V) \rangle \simeq 0.09 \) resulting in a factor 2.7 absorption at 1600 Å, whereas the latter derive \( \langle E(B-V) \rangle \simeq 0.30 \) resulting in a factor 10 absorption. This discrepancy suggests sort of a bimodal distribution of the young stellar populations: the first method would take into account the stars detected in the UV with relatively moderate reddening/extinction, while the second one would phenomenologically add the contributions of these “apparent” stars and of heavily–extinguished stars.

Fig. 1 shows the cosmic SFR comoving density in the early version (no extinction), and after the work by Flores et al. (1999) at z < 1 and extinction corrections.
Figure 1: The evolution of the cosmic Star Formation Rate comoving density $\rho_{\text{SFR}}$ with redshift $z$. For the Canada–France Redshift Survey ($z < 1$), the solid dots and error bars drawn with dotted lines and solid lines respectively give values uncorrected for extinction (Lilly et al. 1996), and values estimated from a multi–wavelength analysis including IR, submm, and radio data (Flores et al. 1999). For the Hubble Deep Field, the open squares and error bars drawn with dotted lines and solid lines respectively give values uncorrected for extinction (Madau et al. 1996, 1998), and values corrected for an average $< E(B−V) >= 0.09$ and the SMC extinction curve (Pettini et al. 1998). The corrections derived by Meurer et al. (1997) would shift the corrected points upwards by $\sim 0.5$ dex. Finally, the open triangles show values determined from the HDF by a method with photometric redshifts involving visible and near–IR photometry (Connolly et al. 1997). The rest–frame UV fluxes are converted into SFRs with the spectrophotometric model described in Guiderdoni et al. (1998), and a Salpeter IMF. The solid line shows the best model in the latter paper (the so–called “model E”).

3 The diffuse IR/submm background and submm counts

A lower limit of the “Cosmic Optical Background” (hereafter COB) is currently estimated by summing up the faint counts obtained in the Hubble Deep Field (HDF), and from ground–based observations. The shallowing of the slope suggests that the counts are close to convergence.

In the submm range, Puget et al. (1996) discovered an isotropic component in the FIRAS residuals between 200 $\mu$m and 2 mm. This measure was confirmed by subsequent work in the cleanest regions of the sky (Guiderdoni et al. 1997), and by an independent determination (Fixsen et al. 1998). The analysis of the DIRBE dark sky has also led to the detection of the isotropic background at 240 and 140 $\mu$m, and to upper limits at shorter wavelengths down to 2 $\mu$m (Schlegel et al. 1998, Hauser et al. 1998). Recently, a measure at 3.5 $\mu$m was proposed by Dwek & Arendt 1998. The results of these analyses seem in good agreement, though the exact level of the background around 200 $\mu$m is still a matter of debate. The controversy concerns the correction for the amount of Galactic dust in the ionized gas uncorrelated with the HI gas.

It appears very likely that this isotropic background is the long–sought CIRB. As shown in
Figure 2: The cosmic optical and infrared backgrounds (respectively COB and CIRB). The COB (solid square, solid dots, and open square) is obtained from the faint counts and compiled by Pozzetti et al. (1998). The solid triangle gives an upper limit by Vogel et al. (1995). The thick solid lines show the CIRB extracted from FIRAS residuals in the cleanest regions of the sky (Puget et al. 1996; Guiderdoni et al. 1997). The thin lines bracket the range that is consistent with the error bars. The solid squares give the upper limits and detections (at 140 and 240 µm) from DIRBE (Hauser et al. 1998). The no–evolution curve (dotted line) is computed from the local IRAS luminosity function extrapolated to $z = 8$, for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$. The solid line shows the best model (the so–called “model E”) in Guiderdoni et al. (1998).

If the dust that emits at IR/submm wavelengths is mainly heated by young stellar populations, the sum of the fluxes of the CIRB and COB gives the level of the Cosmic Background associated to stellar nucleosynthesis (Partridge and Peebles 1967). The bolometric intensity (in W m$^{-2}$ sr$^{-1}$) is:

$$I_{bol} = \int \frac{\epsilon_{bol} \, dl}{4\pi \, (1 + z)^4} = \frac{c \eta \rho_Z(z = 0)}{4\pi \, (1 + z_{eff})}$$

(1)

where the physical emissivity due to young stars at cosmic time $t$ is $\epsilon(t) = \eta(1 + z)^3 d\rho_Z(t)/dt$ and $z_{eff}$ is the effective redshift for stellar He and metal nucleosynthesis. The census of the local density of heavy elements $\rho_Z(z = 0) \sim 1 \times 10^7$ $M_\odot$ Mpc$^{-3}$ gives an expected bolometric intensity of the background $I_{bol} \simeq 50(1 + z_{eff})^{-1}$ nW m$^{-2}$ sr$^{-1}$. This value is roughly consistent with the observations for $z_{eff} \sim 1 - 2$.

Of course, it is not clear yet whether star formation is responsible for the bulk of dust heating, or there is a significant contribution of AGNs. In order to address this issue, one has first to identify the sources that are responsible for the CIRB. At low $z$, it is well known that the IRAS satellite has discovered “luminous IR galaxies” (hereafter LIRGs), mostly interacting systems, and the spectacular “ultraluminous IR galaxies” (hereafter ULIRGs), which are
mergers and emit more than 95% of their energy in the IR (see e.g. the review by Sanders and Mirabel 1996). The question of the origin of dust heating in these heavily-extinguished objects is a difficult one, because both starburst and AGN rejuvenation can be fueled by gas inflows triggered by interaction. However, according to Genzel et al. (1998), the starburst generally contributes to 50–90% of the heating in local ULIRGs. Now, it is very likely that the high-redshift counterparts of the local LIRGs and ULIRGs are largely responsible for the CIRB, but the redshift evolution of the fraction and power of AGNs that are harbored in these distant objects is still unknown.

Various submm surveys have been achieved or are in progress. The FIRBACK program is a deep survey of 4 deg$^2$ at 175 µm with the ISOPHOT instrument aboard ISO. The analysis of about 1/4 of the Southern fields (that is, of 0.25 deg$^2$) unveils 24 sources (with $S_\nu > 100$ mJy), corresponding to a surface density five times larger than the no-evolution predictions based on the local IR luminosity function (Puget et al. 1998). The total catalogue of the 4 deg$^2$ will include about 275 sources (Dole et al. 1999). The radio and optical follow-up for identification is still in progress. This strong evolution is confirmed by the other 175 µm deep survey by Kawara et al. (1998). Various deep surveys at 850 µm have been achieved with the SCUBA instrument at the JCMT (Smail et al. 1997, Hughes et al. 1998, Barger et al. 1998, Eales et al. 1998). They also unveil a surface density of sources (with $S_\nu > 2$ mJy) much larger than the no-evolution predictions (by two or three orders of magnitude!). The total number of sources so far discovered in SCUBA deep surveys now reaches about 40 (see e.g. Blain et al. 1998). The tentative optical identifications seem to show that some of these objects look like distant ULIRGs (Smail et al. 1998, Lilly et al. 1999). In the HDF, 4 of the brightest 5 sources seem to lie between redshifts 2 and 4 (Hughes et al. 1998), but the optical identifications are still a matter of debate (Richards, 1998). The source SMM 02399-0136 at $z = 2.803$, which is gravitationally amplified by the foreground cluster A370, is clearly an AGN/starburst galaxy (Ivison et al. 1998, Frayer et al. 1998). Fig. 3 gives an account of the faint counts in the submm range.

4 Modeling dust spectra in a semi-analytic framework

Various models have been proposed to account for the FIR/submm emission of galaxies and to predict forthcoming observations. The level of sophistication (and complexity) increases from pure luminosity and/or density evolution extrapolated from the IRAS local luminosity function with $(1+z)^n$ laws, and modified black-body spectra, to physically-motivated spectral evolution.

Guiderdoni et al. (1998) proposed a consistent modeling of IR/submm galaxy counts in the paradigm of hierarchical clustering. Only stellar heating is taken into account. The IR/submm spectra of galaxies are computed in the following way: (i) follow chemical evolution of the gas; (ii) implement extinction curves which depend on metallicity as in the Milky Way, the LMC and SMC; (iii) compute $\tau_\lambda$; (iv) assume the so-called “slab” geometry where the star and dust components are homogeneously mixed with equal height scales. (v) compute a spectral energy distribution by assuming a mix of various dust components. The contributions are fixed in order to reproduce the observational correlation of IRAS colours with total IR luminosity (Soifer & Neugebauer 1991).

These FIR/submm spectra are implemented in a semi-analytic model of galaxy formation and evolution. This type of model has been very effective in computing the optical properties of galaxies in the paradigm of hierarchical clustering. We only extend this approach to the IR/submm range, and take the standard CDM case with $H_0=50$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 1$, $\Lambda = 0$, $\Omega_\Lambda = 0$. 
Figure 3: Predictions for faint counts at 15 $\mu$m, 60 $\mu$m, 175 $\mu$m, and 850 $\mu$m. These predictions correspond to model E and have been obtained before the data, on the basis of the CIRB and IRAS counts. Open stars: Faint Source Survey (Lonsdale et al. 1990). Solid hexagon: Rush et al. (1993). Solid squares: ISO–HDF with ISOCAM at 15 $\mu$m (Oliver et al. 1997). Open hexagon: ISOPHOT at 175 $\mu$m (Kawara et al. 1998). Solid triangles: one of the Southern fields of the ISOPHOT FIRBACK survey (Puget et al. 1998). Open squares: deep SCUBA survey (Smail et al. 1997).

and $\sigma_s = 0.67$. We assume a Star Formation Rate $SFR(t) = M_{\text{gas}}/t_*$, with $t_* \equiv \beta t_{\text{dyn}}$ and a Salpeter IMF ($x = 1.35$). The efficiency parameter $1/\beta = 0.01$ gives a nice fit of local spirals. The robust result of this type of modeling is a cosmic star formation rate history that is too flat with respect to the data.

As a phenomenological way of reproducing the steep rise of the cosmic SFR history from $z = 0$ to $z = 1$, we introduce a “burst” mode of star formation involving a mass fraction that increases with $z$ as $(1 + z)^4$, with ten times higher efficiencies $1/\beta = 0.1$. In order to reproduce the level of the CIRB, we have to assume that a small fraction of the gas mass (typically less than 10 %) is involved in star formation with a top–heavy IMF in heavily–extinguished objects (ULIRG–type galaxies). The so–called “model E” with these assumptions fairly reproduces the cosmic SFR and luminosity densities, as well as the CIRB (see fig. 1 and 2).

Fig. 3 gives the predictions of number counts at 15, 60, 175, and 850 $\mu$m for this model. 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 $\mu$m and 850 $\mu$m are built up by objects brighter than the current limits of ISOPHOT and SCUBA deep fields. The predicted median redshift of the ISO–HDF is $z \sim 0.8$. It increases to $z \sim 1.2$ for the deep ISOPHOT surveys, and to $z \geq 2$ for SCUBA, though the latter value is very sensitive to the details of the evolution.

An extension of the spectra and counts to the near–IR, optical and ultraviolet ranges is in progress (Devriendt et al. 1999, Devriendt & Guiderdoni 1999). A fit of a typical ULIRG is proposed in fig. 4 as an example of what can be obtained with these extended spectra.
5 Future instruments

Fig. 5 gives the far–UV to submm spectral energy distribution that is typical of a \( L_{\text{IR}} = 10^{12} L_{\odot} \) ULIRG at various redshifts. This model spectrum is taken from the computation of Devriendt et al. (1999). The reader should note the specific behavior of the observed flux at submm wavelengths, where the shift of the 60 – 100 \( \mu m \) rest–frame emission bump counterbalances distance dimming. The instrumental sensitivities of various past and on–going satellite and ground–based instruments are plotted on this diagram : the IRAS Very Faint Source Survey at 60 \( \mu m \), ISOCAM at 15 \( \mu m \), ISOPHOT at 175 \( \mu m \), the IRAM interferometer at 1.3 mm, SCUBA at 450 and 850 \( \mu m \), and various surveys with the VLA. Forthcoming missions and facilities include WIRE, SIRTF, SOFIA, the PLANCK High Frequency Instrument, the FIRST Spectral and Photometric Imaging REceiver, and the imaging modes of the SUBARU IRCS and VLT VIRMOS instruments. Finally, the capabilities of the NGST, MMA/LSA and Infrared Space Interferometer (DARWIN) are also plotted.

The final sensitivity of the next–generation instruments observing at FIR and submm wavelengths (WIRE, SIRTF, SOFIA, PLANCK, FIRST) is going to be confusion limited. However, the observation of a large sample of ULIRG–like objects in the redshift range 1–5 should be possible. More specifically, the all–sky shallow survey of PLANCK HFI, and the medium–deep survey of FIRST SPIRE (to be launched by ESA in 2007), will respectively produce bright \( (S_\nu > \text{a few} \ 100 \ \text{mJy}) \) and faint \( (S_\nu > \text{a few} \ 10 \ \text{mJy}) \) counts that will be complementary. A 10 deg\(^2\) survey with SPIRE will result in \( \sim 10^4 \) sources. The study of the 250/350 and 350/500 colors are suited to point out sources which are likely to be at high redshifts. These sources can be eventually followed at 100 and 170 \( \mu m \) by the FIRST Photoconductor Array Camera & Spectrometer and by the FTS mode of SPIRE, to get the spectral energy distribution at \( 200 \leq \lambda \leq 600 \ \mu m \) with a typical resolution \( R \equiv \lambda/\Delta \lambda = 20 \). After a photometric
Figure 5: Observer–frame model spectra of a $L_{\text{IR}} = 10^{12}L_\odot$ ULIRG 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 $\mu$m bump counterbalances the distance dimming. The instrumental sensitivities of various past, current, and forthcoming instruments (ground–based and satellite–borne telescopes) are plotted. This figure is available upon request to guider@iap.fr.

and spectroscopic followup, the submm observations should readily probe the bulk of (rest–frame IR) luminosity associated with star formation. The reconstruction of the cosmic SFR comoving density will thus take into account the correct luminosity budget of high–redshift galaxies. However, the spatial resolution of the submm instruments will be limited, and only the MMA/LSA should be able to resolve the FIR/submm sources and study the details of their structure.

6 Conclusions

1. There is now strong evidence that high–redshift galaxies emit much more IR luminosity than predictions based on the local IR luminosity function, without evolution. The submm counts seem to unveil the bright end of the population that is responsible for the CIRB.

2. The issue of the relative contributions of the starbursts and AGNs to dust heating is still unsolved. Local ULIRGs seem to be dominated by starburst heating, but the behavior
at higher redshift is unknown.

3. It is difficult to correct for the influence of dust on the basis of the optical spectra alone. Multi–wavelength studies are clearly necessary to address the history of the cosmic SFR density, through a correct assessment of the luminosity budget.

4. Under the assumption that starburst heating is dominant, simple models in the paradigm of hierarchical clustering do reproduce the current IR/submm data.

5. The current studies on faint counts at submm wavelengths will guide models for the preparation of the observing strategies with forthcoming instruments: e.g., SIRTF, SOFIA, the PLANCK High Frequency Instrument, the FIRST Spectral and Photometric Imaging Receiver, and the MMA/LSA. A large number of high–redshift sources should be observable with these IR/submm instruments.

References

[1] Barger, A.J., Cowie, L.L., Sanders, D.B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., Okuda, H., 1998, Nature, 394, 248
[2] Baugh, C.M., Cole, S., Frenk, C.S., Lacey, C.G., 1998, Astrophys. J., 498, 504
[3] Blain, A.W., Kneib, J.P., Ivison, R.J., Smail, I., 1998, Astrophys. J., in press
[4] Connolly, A.J., Szalay, A.S., Dickinson, M., SubbaRao, M.U., Brunner, R.J., 1997, Astrophys. J., 486, L11
[5] Devriendt, J.E.G., Guiderdoni, B., Sadat, R., 1999, Astron. Astrophys., submitted
[6] Devriendt, J.E.G., Guiderdoni, B., 1999, in preparation
[7] H. Dole, G. Lagache, J.L. Puget, H. Aussel, F.R. Bouchet, D.L. Clements, C. Cesarsky, F.X. Désert, D. Elbaz, A. Franceschini, R. Gispert, B. Guiderdoni, M. Harwit, R. Laureijs, D. Lemke, A.F.M. Moorwood, S. Oliver, W.T. Reach, M. Rowan–Robinson & M. Stickel, 1999, in Proceedings of the ISO conference: The Universe as seen by ISO, P. Cox et al. (eds)
[8] Dwek, E., Arendt, R.G., 1998, Astrophys. J., 508, L9
[9] Eales, S., Lilly, S., Gear, W., Dunne, L., Bond, J.R., Hammer, F., Le Fèvre, O., Crampton, D., 1998, Astrophys. J., in press
[10] Fixsen, D.J., Dwek, E., Mather, J.C., Bennett, C.L., Shafer, R.A., 1998, Astrophys. J., 508, 123
[11] Flores, H., Hammer, F., Thuan, T.X., Cesarsky, C., Désert, F.X., Omont, A., Lilly, S.J., Eales, S., Crampton, D., Le Fèvre., O., 1999, Astrophys. J., in press
[12] Frayer, D.T., Ivison, R.J., Scoville, N.Z., Yun, M., Evans, A.S., Smail, I., Blain, A., Kneib, J.P., 1998, Astrophys. J., in press
[13] Genzel, R., Lutz, D., Sturm, E., Egami, E., Kunze, D., Moorwood, A.F.M., Rigopoulou, D., Spoon, H.W.W., Sternberg, A., Tacconi–Garman, L.E., Tacconi, L., Thatte, N., 1998, Astrophys. J., 498, 579
[14] Guiderdoni, B., Bouchet, F.R., Puget, J.L., Lagache, G., Hivon, E., 1997, Nature, 390, 257
[15] Guiderdoni, B., Hivon, E., Bouchet, P.R., Maffei, B., 1998, Mon. Not. Roy. Astron. Soc., 295, 877
[16] Hauser, M.G., Arendt, R., Kelsall, T., Dwek, E., Odegard, N., Welland, J., Freundenberg, H., Reach, W., Silverberg, R., Modeley, S., Pei, Y., Lubin, P., Mather, J., Shafer, R., Smoot, G., Weiss, R., Wilkinson, D., Wright, E., et al., 1998, Astrophys. J., 508, 25
[17] Hughes, D., Serjeant, S., Dunlop, J., Rowan–Robinson, M., Blain, A., Mann, R.G., Ivison, R., Peacock, J., Efstathiou, A., Gear, W., Oliver, S., Lawrence, A., Longair, M., Goldschnidt, P., Jenness, T., 1998, Nature, 394, 241
Ivison, R.J., Smail, I., Le Borgne, J.F., Blain, A.W., Kneib, J.P., Bézecourt, J., Kerr, T.H., Davies, J.K., 1998, Mon. Not. Roy. Astron. Soc., 298, 583
Kawara, K., Sato, Y., Matsuhara, H., et al., 1998, Astron. Astrophys., 336, L9
Lanzetta, K.M., Wolfe, A.M., Turnshek, D.A., 1995, Astrophys. J., 440, 435
Lilly, S.J., Le Fèvre, O., Hammer, F., Crampton, D., 1996, ApJ, 460, L1
Lilly, S.J., Eales, S.A., Gear, W.K.P., Hammer, F., Le Fèvre, O., Crampton, D., Bond, J.R., Dunne, L., 1999, Astrophys. J., in press
Lonsdale, C.J., Hacking, P.B., Conrow, T.P., Rowan–Robinson, M., 1990, Astrophys. J., 358, 60
Madau, P., Ferguson, H.C., Dickinson, M.E., Giavalisco, M., Steidel, C.C., Fruchter, A., 1996, Mon. Not. Roy. Astron. Soc., 283, 1388
Madau, P., Pozzetti, L., Dickinson, M.E., 1998, Astrophys. J., 498, 106
Meurer, G.R., Heckman, T.M., Lehnert, M.D., Leitherer, C., Lowenthal, J., 1997, Astron. J., 114, 54
Oliver, S.J., Goldschmidt, P., Franceschini, A., Serjeant, S.B.G., Efstathiou, A.N., et al., 1997, Mon. Not. Roy. Astron. Soc., 289, 471
Partridge, B., Peebles, P.J.E., 1967, Astrophys. J., 148, 377
Pozzetti, L., Madau, P., Zamorani, G., Ferguson, H.C., Bruzual, G.A., 1998, Mon. Not. Roy. Astron. Soc., 298, 1133
Pettini, M., Steidel, C.C., Adelberger, K., Kellogg, M., Dickinson, M., Giavalisco, M., 1998, in ‘ORIGINS’, ed. J.M. Shull, C.E. Woodward, and H. Thronson, ASP Conference Series, astro-ph/9707200
Puget, J.L., Abergel, A., Bernard, J.P., Boulanger, F., Burton, W.B., Désert, F.X., Hartmann, D., 1996, Astron. Astrophys., 308, L5
Puget, J.L., Lagache, G., Clements, D.L., Reach, W.T., Aussel, H., Bouchet, F.R., Cesarsky, C., Désert, F.X., Dole, H., Elbaz, D., Franceschini, A., Guiderdoni, B., Moorwood, A.F.M., 1998, Astron. Astrophys., in press
Richards, E.A., 1998, submitted, astro-ph/9811098
Rigopoulou, D., Lawrence, A., Rowan–Robinson, M., 1996, Mon. Not. Roy. Astron. Soc., 278, 1049
Rush, B., Malkan, M.A., Spinoglio, L., 1993, Astrophys. J. Suppl. Ser., 89, 1
Sanders, D.B., Mirabel, I.F., 1996, Ann. Rev. Astron. Astrophys., 34, 749
Schlegel, D.J., Finkbeiner, D.P., Davis, M., 1998, Astrophys. J., 500, 525
Smail, I., Ivison, R.J., Blain, A.W., 1997, Astrophys. J., 490, L5
Smail, I., Ivison, R.J., Blain, A.W., Kneib, J.P., 1998, Astrophys. J., 507, L21
Soifer, B.T., Sanders, D.B., Madore, B.F., Neugebauer, G., Danielson, G.E., et al., 1987, Astrophys. J., 320, 238
Steidel, C.C., Hamilton, D., 1993, Astron. J., 105, 2017
Steidel, C.C., Giavalisco, M., Pettini, M., Dickinson, M., Adelberger, K.L., 1996, Astrophys. J., 462, L17
Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., Pettini, M., 1999, Astrophys. J., in press
Storrie–Lombardi, L.J., McMahon, R.G., Irwin, M.J., 1996, Mon. Not. Roy. Astron. Soc., 283, L79
Thuan, T.X., Sauvage, M., Madden, S., 1999, Astrophys. J, in press, astro-ph/9811126
Vogel, S., Weymann, R., Rauch, M., Hamilton, T., 1995, Astrophys. J., 441, 162.