A&A 469, 19–25 (2007)
DOI: 10.1051/0004-6361:20066685
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Astronomy & Astrophysics

The ultraviolet properties of luminous infrared galaxies at $z \sim 0.7$

Is there any evolution in their dust attenuation?

V. Buat[1], D. Marcillac[2], D. Burgarella[1], E. Le Floc'h[2,3], T. T. Takeuchi[4,5], J. Iglesias-Parámo[6], and C. K. Xu[7]

[1] Observatoire Astronomique Marseille Provence, Laboratoire d'Astrophysique de Marseille, BP 8, 133761 Marseille Cedex 12, France
e-mail: veronique.buat@oamp.fr
[2] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
[3] Spitzer fellow, Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
[4] Astronomical Institute, Tohoku University, Aoba, Aramaki, Aoba-ku, Sendai 980–8578, Japan
[5] Institute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464–8601, Japan
[6] Instituto de Astrofísica de Andalucía,CSIC, 18008 Granada, Spain
[7] California Institute of Technology, MC 405-47, 1200 East California Boulevard, Pasadena, CA 91125, USA

Received 3 November 2006 / Accepted 19 February 2007

ABSTRACT

Aims. The total infrared (TIR: 8−1000 μm) and far-ultraviolet (FUV: ~1500 Å) luminosity functions of galaxies and the related luminosity densities $\rho_{\rm TIR}$ and $\rho_{\rm FUV}$ are known to evolve at differemt rates from $z = 0$ to $z \sim 1$: the galaxy populations appear to be brighter in the past at both wavelengths, but the evolution in the TIR is larger than in the FUV. This leads to an increase of the ratio of TIR to FUV luminosity densities $\rho_{\rm TIR}/\rho_{\rm FUV}$ which can be interpreted as a global increase of the dust attenuation from $z = 0$ to $z \sim 1$. Our aim is to understand the origin of this increase: is it entirely due to a variation of the dust attenuation with the luminosity of the galaxies as seen as $z = 0$ or are properties of galaxies evolving with the redshift?
Methods. We focus on infrared galaxies more luminous than $L_{\rm TIR} = 10^{11}\ L_\odot$ at $z \sim 0.7$ observed by SPITZER/MIPS and we measure their ultraviolet emission at 2310 Å from GALEX images. These Luminous InfraRed Galaxies (LIRGs) represent the bulk of the TIR luminosity density at intermediate redshift. The analysis of the ratio of TIR to FUV (rest-frame) luminosity ($L_{\rm TIR}/L_{\rm FUV}$) enables us to discuss and compare their dust attenuation to that of galaxies of similar infrared luminosity selected in the same way in the nearby universe
Results. Some evolution of $L_{\rm TIR}/L_{\rm FUV}$ and therefore of dust attenuation is found: LIRGs at $z = 0.7$ span a larger range of $L_{\rm TIR}/L_{\rm FUV}$ ratios than at $z = 0$ and their mean dust attenuation at FUV wavelengths is found to be ~0.5 mag lower than for their local counterparts. The decrease of dust attenuation is found to be less than that reported in other studies for bright galaxies selected in UV rest-frame at $z = 1$ and 2. A semi-quantitative analysis accounts for the general increase of dust attenuation with the bolometric luminosity of galaxies: it is found that the slight decrease of dust attenuation for LIRGs at $z = 0.7$ remains consistent with the increase of $\rho_{\rm TIR}/\rho_{\rm FUV}$ with redshift.

Key words. galaxies: evolution – dust, extinction – infrared: galaxies – ultraviolet: galaxies

1. Introduction

Rest-frame far-ultraviolet (FUV) and thermal infrared surveys are commonly used to probe star formation in the universe and its evolution as a function of redshift z. The problem of dust attenuation of stellar light in galaxies is central in these analyses not only because it directly affects the FUV emission but also because the infrared output originates from this process. As a consequence the total infrared (TIR) to FUV flux ratio is a robust tracer of dust attenuation in star forming galaxies (e.g. Buat & Xu 1996; Meurer et al. 1999; Gordon et al. 2000).

In a broad sense, both observations (FUV or TIR) have led to similar conclusions: a decrease of the star formation rate (SFR) from $z = 1$ to $z = 0$ (Flores et al. 1999; Le Floc'h et al. 2005; Schiminovich et al. 2005), which is also found from other tracers of star formation (e.g. Hopkins & Beacom 2006, and references therein). Each wavelength range is however sensitive to a specific galaxy population and recovering all the star formation from mono-wavelength observations (ultraviolet or infrared) appears to be difficult, even at low z. For example, Buat et al. (2006) have shown that FUV and TIR surveys of the nearby universe lead to somewhat different sampling of galaxies.

This effect seems to be amplified at higher z. Thanks to recent SPITZER and GALEX surveys the total infrared (TIR) and far-ultraviolet (FUV-1530 Å) luminosity functions were determined from $z = 0$ to $z = 1$ (Arnouts et al. 2005; Le Floc'h et al. 2005): a strong evolution of both luminosity functions is seen but the ratio of luminosity densities $\rho_{\rm TIR}/\rho_{\rm FUV}$ increases from $z = 0$ to $z = 1$ (Takeuchi et al. 2005b). This increase can be explained, at least qualitatively, as follows: dust attenuation is found to increase with the bolometric luminosity or SFR of galaxies in the nearby universe (Wang & Heckman 1996; Buat & Burgarella 1998; Sullivan et al. 2001; Hopkins et al. 2001; Martin et al. 2005; Buat et al. 2005) and at higher z (Reddy et al. 2005; Le Floc'h et al. 2005; Bell et al. 2005). Therefore the general brightening of the galaxies inferred from the evolution of luminosity functions when z increases may also induce an increase in the global dust attenuation.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20066685

Nevertheless, studies of galaxy samples at $z > 0$ have led to rather controversial results about the amount of dust obscuration in bright distant galaxies. Reddy et al. (2005) and Burgarella et al. (2006) used a FUV (rest-frame) like selection at $z = 2$ and $z = 1$ respectively and they found a dust attenuation about ten times lower than in the nearby universe. Conversely, samples selected in the infrared by Choi et al. (2006) or Bell et al. (2005) led to attenuations consistent with the relations found at $z = 0$ between the TIR to FUV flux ratio and the total SFR (or equivalently the luminosity of young stars). From GALEX and SWIRE observations of the ELAIS-N1 field Xu et al. (2006) found no evolution of the TIR to FUV flux ratio of galaxies selected in FUV or at 24 μm between $z = 0$ to $z = 0.6$ except that a slight decrease (by a factor ∼2) of the mean $L_{\rm TIR}/L_{FUV}$ is seen for infrared selected galaxies with $L_{\rm TIR} \sim 10^{11}\ L_{\odot}$. However, the detection rate in the FUV (resp. 24 μm) of galaxies selected at 24 μm (resp. FUV) was only 27% (resp. 20%) and the analysis of Xu et al. (2006) almost entirely relies on stacking.

Here we analyse the ultraviolet properties of Luminous InfraRed Galaxies (LIRGs with $L_{\rm TIR} \geq 10^{11}\ L_{\odot}$) at medium z. Le Floc'h et al. (2005) have shown that LIRGs account for about ∼50% and ∼70% of the total infrared luminosity density at $z \sim 0.7$ and at $z \sim 1$ respectively with only a minor contribution from Ultra Luminous InfraRed Galaxies (ULIRGs with $L_{\rm TIR} \geq 10^{12}\ L_{\odot}$). In comparison, most UV selected galaxies are expected to have a lower TIR luminosity than LIRGs: at $z \sim 1$ Burgarella et al. (2006) found that only 17% of their sample of Lyman Break Galaxies are detected by SPITZER at 24 μm. A preliminary analysis of a FUV selected sample at $z = 0.7$ leads to only 10−15% of the sources having $L_{\rm TIR} \geq 10^{11}\ L_{\odot}$ (Takeuchi et al., in preparation). However, even if they are not numerous, these UV selected galaxies with LIRG luminosities are found to be major contributors to the total star formation density (Burgarella et al. 2007).

We select our sample from the deep SPITZER/MIPS survey of the Chandra Deep Field South (Le Floc'h et al. 2005) focusing on the redshift range 0.6−0.8. GALEX has also surveyed this area and very deep images are available. Therefore, we should have a very high detection rate of LIRGs with GALEX. In Sect. 2, we present the data selection and the measurement of the ultraviolet emission of infrared sources. Then, in Sect. 3, we analyse the ratio of the TIR to FUV luminosity ($L_{\rm TIR}/L_{\rm FUV}$) which is a tracer of dust attenuation in galaxies. A comparison between $z = 0$ and $z = 0.7$ is performed. In Sect. 4 we compare our results to other studies. Section 5 is devoted to conclusions.

Throughout this article, we use the cosmological parameters $H_0 = 70\ {\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\lambda = 0.7$. All magnitudes will be quoted in the AB system. The TIR luminosity $L_{\rm TIR}$ is defined over the wavelength range 8−1000 μm. The FUV luminosity $L_{\rm FUV}$ is defined as νL_ν with L_ν in erg cm^{-2} s^{-1} Hz^{-1}.

2. The data

2.1. Selection of the sample at $z \sim 0.7$

We start with the sample of galaxies in the Chandra Deep Field South (CDFS) used by Le Floc'h et al. (2005) to build TIR luminosity functions from $z = 0$ to $z = 1$. It consists of 2955 sources detected at 24 microns by MIPS with $f_{24} > 83\ \mu$Jy at the 80% completeness limit (Papovich et al. 2004). As explained in Le Floc'h et al. (2005), several spectroscopic surveys (Le Fèvre et al. 2004; Vanzella et al. 2005; Szokoly et al. 2004) are the primary means to assign spectroscopic redshifts to the MIPS sources. Photometric redshifts from COMBO-17 (Wolf et al. 2004) are also used for sources at $z \leq 1.2$ and brighter than $R_{\rm Vega} \sim 24$, when they are accurate enough ($\delta_z/(1+z) \leq 10\%$) for our goals. We refer to Le Floc'h et al. (2005) for more details.

Table 1. Number of sources at $0.6 < z < 0.8$ for the different selections applied to the original sample of galaxies selected at 24 μm. Each row of the table corresponds to an additional selection applied to the original sample of 623 sources (*from top to bottom*). The final sample of LIRGs is described in the last row of the table

	selected at 24 μm	NUV detections
original sample	623	–
one single optical counterpart	558	–
reliable NUV photometry	402	331
LIRGs	190	158

As discussed below, our strategy consists in measuring the near ultraviolet (NUV-2310 Å) emission of these galaxies directly from the GALEX images at the positions of the MIPS sources. We take special care to avoid contamination by sources in the close vicinity of MIPS ones that can also be ultraviolet emitters. Toward this end, we apply strict selection criteria to the initial sample. All the steps followed to build the final sample and described in the Sects. 2 and 3 are summarized in Table 1. First, we work at $z \sim 0.7$, including only sources with a redshift between 0.6 and 0.8; 623 galaxies are thus selected. A single optical counterpart must be found in COMBO-17 within 2 arcsec of the MIPS source position. This tolerance radius was also adopted by Le Floc'h et al. (2005) for their identifications. This choice is motivated by the astrometrical precision of MIPS/24 μm images and the rather large *FWHM* of thet MIPS 24 μm PSF (∼6 arcsec). It also accounts for a potential physical shift between the infrared and optical emission of disturbed objects. Here, we add an additional criterion: we exclude all MIPS sources associated with two or more optical sources within 2 arcsec. 65 sources are dropped and 558 sources are left.

We do not have a complete sample of galaxies selected at 24 μm but we expect to have no strong bias in the selection. Our selection of "isolated" sources (i.e. with only one optical source within 2 arcsec) discriminates against mergers (2 arcsec correspond to 14 kpc at $z = 0.7$). However, this procedure guarantees that the FUV emission is not coming from another source than the MIPS one. Moreover, the reference sample at $z = 0$ used for comparison is built in the same way (cf. Sect. 3.1). To check the effects of the exclusion of confused objects we have also performed all the following analysis including confused sources both at high and low z and the results have been found to be unchanged.

2.2. NUV measurements of the 24 μm sources

GALEX (Morrissey et al. 2005) observed the CDFS for 76 ks in both the FUV (1530 Å) and the NUV (2310 Å) as part of its deep imaging survey. The GALEX field of view (diameter 1.25 deg) is centered at α = 03h32m30.7s, δ = −27 deg 52′16.9″. From the NUV image, we measured the *FWHM* of the PSF to be 4.5 arcsec. Prior to fitting the images for photometry, we applied a median filter of 3 × 3 pixels to enlarge the PSF to ∼6 arcsec and make it similar to that of the MIPS image.

We use DAOPHOT (Stetson 1987) to measure the NUV emission at the location of the 24 μm sources. DAOPHOT was also used by Le Floc'h et al. (2005) to measure 24 μm fluxes. DAOPHOT is well suited for point sources (stellar fields). We must check that we can use it for our GALEX data.

de Mello et al. (2004) have measured the size of UV selected galaxies at intermediate redshifts. In the redshift range 0.6–0.8 ∼ 90% of their observed galaxies have an effective (half light) optical radius R_e lower than 0.8 arcsec (which corresponds to ∼6 kpc at $z = 0.7$). If we assume a Gaussian distribution for the galaxy light, a galaxy with $R_e = 0.8$ arcsec convolved with the GALEX PSF (also assumed to be Gaussian) would appear with a $FWHM \sim 6.7$ arcsec. The photometry is performed on the central 3 arcsec (i.e. 2 pixels for the GALEX images) which encloses 44% of the total energy for a pure PSF (6 arcsec after 3 × 3 median filtering, see above). For the largest objects ($R_e = 0.8$ arcsec) the aperture of 3 arcsec would enclose 40% of the total energy. Therefore we estimate the photometric uncertainty assuming all the sources are point-like to be at most 4%.

The PSF is built using 10 stellar like objects with a FUV magnitude ranging between 17.5 and 19.8 mag. The GALEX field is rather dense with an average of ∼0.06 galaxy per beam. The influence of close neighbours in the measurement of NUV emission is tested by adding artificial sources (ADDSTAR task): since we have excluded all the original MIPS sources with more than one optical source within 2 arcsec we only simulate NUV point sources in the GALEX images located between 2 to 4 arcsec from the objects to be measured. As long as the galaxy has a magnitude lower or equal to NUV = 24 mag the contamination due to neighbours remains low (less than 0.4 mag in the worst cases) but when the source is fainter than NUV = 25 mag the contamination by neighbours can be very high (reaching 1 mag or more), whatever the magnitude and the location of the contaminating source. Therefore we decide to exclude the sources whose measured NUV emission is fainter than NUV = 24.5 mag and which have at least one optical neighbour within 4 arcsec from the MIPS coordinates. At the end we are left with 402 sources for which the measurement of NUV flux is considered reliable. 156 galaxies are excluded because they are fainter than NUV = 24.5 mag and with an optical neighbour within 4 arcsec. As for the confused sources we have checked that including the sources with unreliable NUV photometry (according to our strict criteria) does not modify the results of the subsequent analysis.

331 out of the 402 galaxies are detected in the NUV. When the MIPS source is not detected by GALEX we put an upper limit on the NUV mag: NUV = 26.2 mag. It corresponds to a completeness of 80% and a photometric error of 0.07 ± 0.04 mag. This limit is obtained by simulations of 500 artificial sources added to the original GALEX image (ADDSTAR task). The NUV magnitudes are corrected for foreground Galactic extinction using the dust map of Schlegel et al. (1998) and the Galactic extinction curve from Cardelli et al. (1989).

It might be worth noting that only ∼20% of the NUV sources at $z \sim 0.7$ have a MIPS counterpart brighter than 83 μJy. However, even if these galaxies are far from being a dominant population (in number) for a UV selection, their contribution to the total star formation rate of a UV selected sample is likely to be important because of their very high luminosity: Burgarella et al. (2007) show that they account for ∼2/3 of the total star formation rate of a sample of Lyman Break selected at $z \sim 1$. A full analysis of a FUV (rest-frame) galaxy sample at $z = 0.7$ is underway (Takeuchi et al., in preparation).

3. The $L_{\rm TIR}/L_{\rm FUV}$ ratio of Luminous InfraRed Galaxies

We focus on Luminous InfraRed Galaxies (LIRGs, brighter than 10^{11} $L_\odot$) because the SPITZER/MIPS sample is complete up to $z \sim 1$ for $L_{\rm TIR} > 10^{11}$ $L_\odot$ and these LIRGs are found to be the sources of the bulk of the TIR emission at medium z (Le Floc'h et al. 2005). Our aim is to compare the properties of a sample of LIRGs at $z = 0.7$ to those of a reference sample taken at $z = 0$. The local sample will be defined in Sect. 3.1. Indeed, from $z = 0$ to $z = 0.7$ $\rho_{\rm TIR}$ and $\rho_{\rm FUV}$ are found to increase by factors equal to ∼8 and ∼4 respectively, leading to a net increase of $\rho_{\rm TIR}/\rho_{\rm FUV}$ by a factor ∼2 (Takeuchi et al. 2005b). So, we can expect to find some evolution of the properties of galaxies in this redshift range.

We start by the description of the reference sample in order to define the quantities to be compared with the $z = 0.7$ sample.

3.1. The reference sample at z = 0

Buat et al. (2006) have built a sample of galaxies from the IRAS PSCz cross-correlated with the GALEX All Sky Imaging Survey (AIS) over more than 2000 deg^2. It is a flux limited sample ($f_{60} > 0.6$ Jy) of ∼700 galaxies, most of which have a measured FUV flux at 1530 Å from the GALEX All sky Imaging Survey.

The total infrared (TIR) emission of the galaxies was estimated from their emission at 60 and 100 μm (see Buat et al. 2006, for more details). From this sample we select only LIRGs ($L_{\rm TIR} > 10^{11}$ $L_\odot$). We must restrict the sampled volume to be sure to detect all LIRGs within this volume. The limit $L_{\rm TIR} = 10^{11}$ $L_\odot$ corresponds to $L_{60} = 0.47 \times 10^{11}$ $L_\odot$ for a mean $L_{\rm TIR}/L_{60}$ ratio of 2.13 (the value found for the LIRGs of our reference sample). With $F_{60} > 0.6$ Jy in the PSCz, we must truncate the sample to $v < 16\,000$ km s^{-1}. 98 LIRGs are selected, 91 have a measured FUV flux, and 7 are not detected by GALEX in the FUV. For the latter sources, an upper limit at FUV = 20.5 mag is adopted corresponding to a 3σ detection limit for the GALEX-AIS survey (Morrissey et al. 2005).The criterion applied at $z = 0$ to avoid confused sources was the absence of any neighbour within 1 arcmin from the IRAS source (Buat et al. 2006): it corresponds to a projected distance larger than 14 kpc at the distance of the selected LIRGs. Therefore, a similar criterion has been applied at $z = 0$ and $z = 0.7$ (cf. Sect. 2.1) to select isolated sources.

3.2. The z = 0.7 sample of LIRGS

We choose to work at $z =\sim 0.7$ because there is an over density of galaxies at this redshift in the Chandra Deep Field South (e.g. Wolf et al. 2004). 190 galaxies in our sample of 402 galaxies are selected as Luminous InfraRed Galaxies with $L_{\rm TIR} > 10^{11}$ $L_\odot$, the mean redshift of the LIRGs sample is $\langle z \rangle = 0.70 \pm 0.05$. 158 out of the 190 LIRGs (i.e. 83%) are detected in NUV.

We adopt the total infrared (TIR) emission of these galaxies calculated by Le Floc'h et al. (2005) from their emission at 24 μm. At $z = 0.7$ the GALEX NUV band (2310 Å) corresponds approximately to the rest-frame GALEX FUV one (1530 Å) adopted for the reference sample (1358 Å for the rest-frame UV emission observed in NUV at $z = 0.7$ against 1530 Å for the GALEX FUV band). We explored the size of possible K-corrections. The UV continuum is assumed to be well described by a power-law $f_\lambda \propto \lambda^\beta$ (e.g. Calzetti et al. 2000), where f_λ is expressed in erg cm^{-2} s^{-1} Å^{-1} (or $f_\nu \propto \nu^{-\beta-2}$ where f_ν is expressed in erg cm^{-2} s^{-1} Hz^{-1}). $\beta = -1$ corresponds to a flat distribution in $\nu \times f_\nu$ (no K-correction). Unfortunately β cannot be measured for our sample at $z = 0.7$. At $z = 0$, β can be deduced from the FUV-NUV color measured by GALEX (e.g. Seibert et al. 2005). β is found to vary from −1.5 to 1 which induces $-0.03 \leq \log(\nu f_\nu)_{\rm FUV\ rest-frame} - \log(\nu f_\nu)_{\rm NUV\ observed} \leq 0.10$. Therefore we prefer not to apply any K-correction to the data: we consider the NUV fluxes observed at $z = 0.7$ as rest-frame FUV fluxes directly comparable with the FUV fluxes observed at $z = 0$.

3.3. $L_{\rm TIR}/L_{\rm FUV}$ distributions

$L_{\rm TIR}/L_{\rm FUV}$ is a robust tracer of dust attenuation in star forming galaxies. Quantitative estimates can be made regardless of the details of the geometry and star formation history as long as the galaxies are still forming stars actively (e.g. Buat & Xu 1996; Meurer et al. 1999; Gordon et al. 2000; Calzetti et al. 2000). Buat et al. (2005) have performed calibrations for the GALEX bands. We reproduce their formula for the FUV band:

$$A({\rm FUV})\ [{\rm mag}] = -0.0333\left(\log\frac{L_{\rm TIR}}{L_{\rm FUV}}\right)^3 + 0.3522\left(\log\frac{L_{\rm TIR}}{L_{\rm FUV}}\right)^2 + 1.1960\left(\log\frac{L_{\rm TIR}}{L_{\rm FUV}}\right) + 0.4967 \quad (1)$$

$L_{\rm TIR}/L_{\rm FUV}$ has been found to increase with the bolometric luminosity of young stars in galaxies from $z = 0$ to at least $z = 2$ (e.g. Buat et al. 2006, and references in the introduction). As a consequence, a comparison of $L_{\rm TIR}/L_{\rm FUV}$ distributions can only be valid for galaxies exhibiting the same luminosity distribution. Our selection of LIRGs at $z = 0$ and at $z = 0.7$ compensates for the evolution of the TIR luminosity function reported by Le Floc'h et al. (2005), which leads to brighter galaxies at higher z. Indeed the distributions of $L_{\rm TIR}$ in both samples are found to be very similar with $\langle\log(L_{\rm TIR}/L_\odot)\rangle = 11.22 \pm 0.17$ at $z = 0$ and $\langle\log(L_{\rm TIR}/L_\odot)\rangle = 11.24 \pm 0.20$ at $z = 0.7$. Therefore we can safely compare $L_{\rm TIR}/L_{\rm FUV}$ distributions from both samples.

The histograms of $L_{\rm TIR}/L_{\rm FUV}$ at $z = 0$ and $z = 0.7$ are presented in Fig. 1. We performed statistical tests accounting for non detections to compare the distributions (IRAF/stsdas/analysis/statistics/twosampt task). The two distributions are found to be drawn from different parent populations with a probability larger than 0.99. The Kaplan Meier estimates of their mean are slightly different: $\langle(\log(L_{\rm TIR}/L_{\rm FUV})_{z=0.7}\rangle = 1.673 \pm 0.044$ and $\langle\log(L_{\rm TIR}/L_{\rm FUV})_{z=0}\rangle = 1.897 \pm 0.063$. Note that the uncertainty in the K-corrections (cf. Sect. 3.2) does not affect the robustness of the result, because it implies in most cases an under-estimate of $L_{\rm FUV}$ (at most 0.1 dex) and therefore an over-estimate of $L_{\rm TIR}/L_{\rm FUV}$ at $z = 0.7$.

If we translate these mean values into quantitative measurements of dust attenuation in the FUV using formula (1) we find $\langle A({\rm FUV})\rangle = 3.33 \pm 0.08$ mag at $z = 0.7$ and $\langle A({\rm FUV})\rangle = 3.81 \pm 0.13$ mag at $z = 0$. Thus, a slight difference in the mean dust obscuration can be inferred from these data and the shapes of the distributions are significantly different: the distribution of $L_{\rm TIR}/L_{\rm FUV}$ at $z = 0.7$ appears broader than at $z = 0$ with an extension toward low $L_{\rm TIR}/L_{\rm FUV}$ values.

The difference found between the mean $L_{\rm TIR}/L_{\rm FUV}$ values is small. Therefore one may question whether there are some systematic effects in the derivation of the total infrared luminosity from the observables. Indeed, at $z = 0.7$ $L_{\rm TIR}$ is deduced from the flux observed at 24 μm (14 μm in the rest-frame at $z = 0.7$) by Le Floc'h et al. (2005) using a set of local templates whereas at $z = 0$ $L_{\rm TIR}$ is calculated with a combination of IRAS fluxes at 60 and 100 μm (Buat et al. 2006). Takeuchi et al. (2005a) have proposed a formula to derive $L_{\rm TIR}$ from the luminosity at 15 μm (rest-frame) fully consistent with the IRAS database. To check the robustness of our present results we used the calibration of Takeuchi et al. (2005a) to derive $L_{\rm TIR}$ at $z = 0.7$ from the observed fluxes at 24 μm: we found the results unchanged with $\langle(L_{\rm TIR}/L_{\rm FUV})_{z=0.7}\rangle = 1.660 \pm 0.042$. One must remind, however, that our analysis is based on the hypothesis that local galaxy templates are valid to estimate the total infrared luminosity of high redshift systems (Le Floc'h et al. 2005; Marcillac et al. 2006).

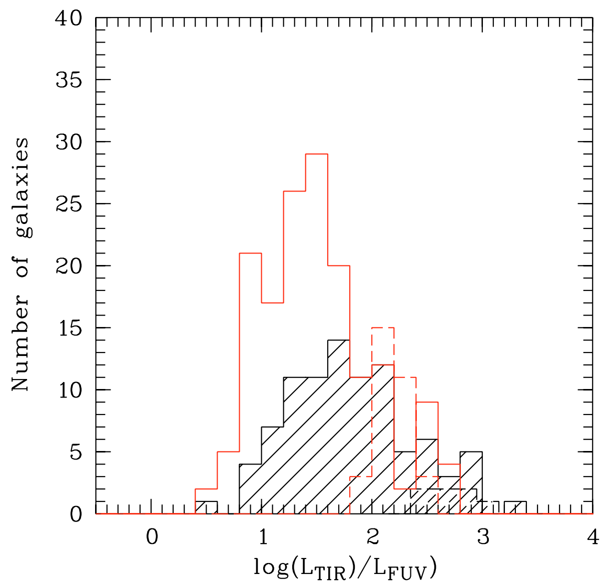

Fig. 1. $L_{\rm TIR}/L_{\rm FUV}$ distribution for LIRGs at $z = 0$ (black, hatched histogram) and $z = 0.7$ (red, empty histogram), for both samples histogram of upper limits are plotted with dashed lines

4. Discussion

4.1. Comparison with previous work

In Fig. 2 is plotted the bolometric luminosity $L_{\rm bol}$, defined as $L_{\rm TIR} + L_{\rm FUV}$, versus $L_{\rm TIR}/L_{\rm FUV}$ for both samples at $z = 0$ and $z = 0.7$. The difference in the distributions is clearly seen with an extension to moderate $L_{\rm TIR}/L_{\rm FUV}$ values at $z = 0.7$ that is not observed at $z = 0$.

For comparison, we have also gathered the results of previous works on the variation of $L_{\rm TIR}/L_{\rm FUV}$ at low and high z. In the nearby universe, we report the mean relations of Buat et al. (2006) which are consistent with other studies of local galaxies (see Buat et al. 2006, for more discussions).

At higher z several recent studies are available. Choi et al. (2006) have selected galaxies at $z \sim 0.8$ at NIR+MIR wavelengths. By comparing the SFR deduced from the TIR emission and the strength of emission lines they measured the extinction in the optical emission lines and found that the corresponding visual extinction varies as $A_{\rm V} = 0.75\log(L_{\rm TIR}/L_\odot) - 6.35$ mag. To compare these results to the present work, we have to translate this visual extinction in the gaseous medium to an attenuation for the ultraviolet stellar continuum. We follow the Calzetti et al. recipe (Calzetti et al. 2000; Calzetti 2001) to be consistent with Choi et al. (2006). For emission lines we adopt a foreground like distribution with a Milky Way extinction curve for a diffuse medium (Cardelli et al. 1989):

$$A_{\rm V} = 3.1\ E(B-V)_{\rm g}$$

where $E(B-V)_{\rm g}$ is the color excess for the gas emission lines.

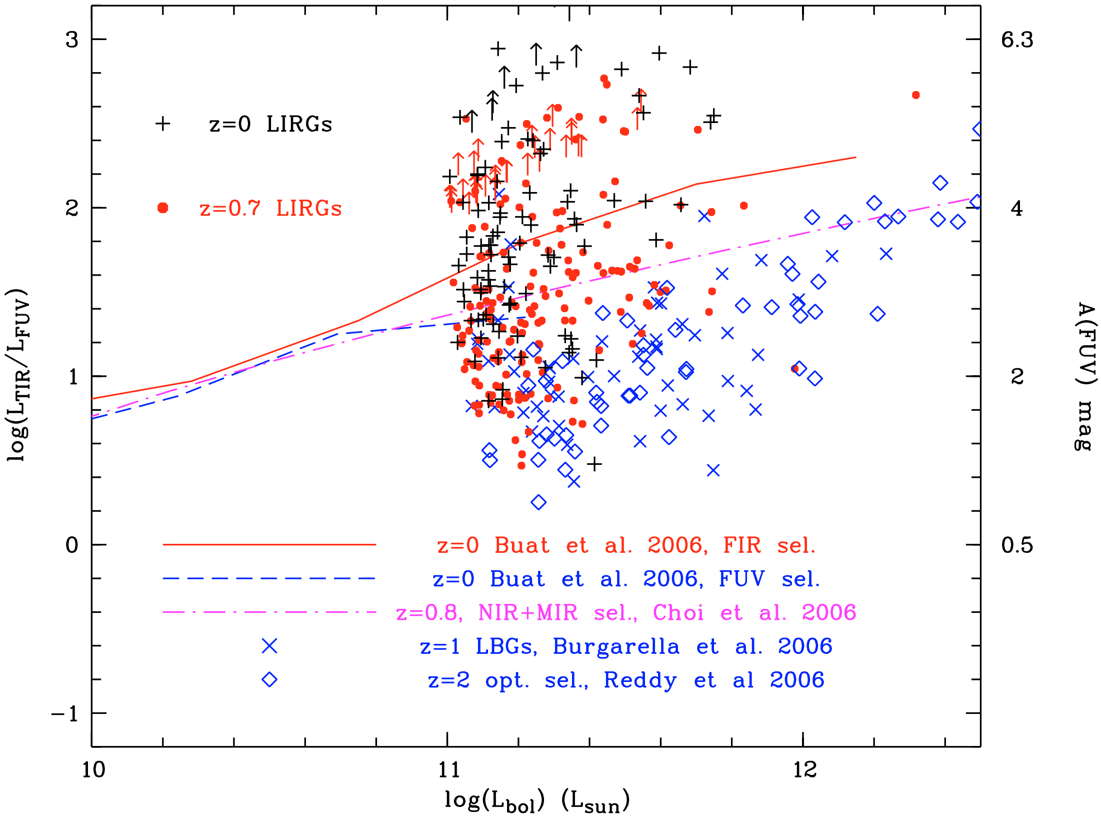

Fig. 2. $L_{\rm TIR}/L_{\rm FUV}$ versus $L_{\rm bol} = L_{\rm TIR} + L_{\rm FUV}$. Vertical right axis: the dust attenuation A(FUV) is calculated with formula (1) in the text. LIRGs are plotted with black "plus" and arrows for our $z = 0$ sample and red dots and arrows for our $z = 0.7$ sample. Blue dashed line: FUV selected sample at $z = 0$ from Buat et al. (2006), red solid line: FIR selected sample at $z = 0$ from Buat et al. (2006). Dot dashed magenta line from Choi et al. (2006). The data from Reddy et al. (2005) are plotted with blue lozanges, and those of Burgarella et al. (2006, 2007) with blue crosses.

The color excess for the stellar continuum $E(B-V)_{\rm s}$ is given by

$$E(B-V)_{\rm s} = 0.44\,E(B-V)_{\rm g}$$

(Calzetti et al. 2000; Calzetti 2001). Then using the reddening curve (Calzetti et al. 2000), we obtain

$$A_{\rm FUV} = k'(1530\text{Å})\,E(B-V)_{\rm s} = 10.33 \times 0.44 \times (A_{\rm V}/3.1)$$

with $k'(1530\text{ Å}) = 10.33$ which gives $A_{\rm FUV} = 1.47\,A_{\rm V}$.

$A_{\rm FUV}$ is linked to $L_{\rm TIR}/L_{\rm FUV}$ via formula (1). The result of these transformations is shown in Fig. 2, note that in the Choi et al. relation the x axis is $L_{\rm TIR}$ and not $L_{\rm TIR} + L_{\rm FUV}$: for the LIRG regime (the topic of the present work) the difference is very small. The relation of Choi et al. (2006) is consistent with the $z = 0$ results at intermediate luminosity. For LIRG luminosities and higher the relation flattens and drops below the relation found for FIR selected galaxies at $z = 0$ (and which is also consistent with the FUV selection at $z = 0$). This trend is fully consistent with the present work and the presence of LIRGs exhibiting a lower $L_{\rm TIR}/L_{\rm FUV}$ ratio.

Therefore, a difference is found between the amount of dust attenuation in LIRGs selected in infrared surveys at $z = 0$ and $z = 0.7$. The mean value of $L_{\rm TIR}/L_{\rm FUV}$ varies by 0.2 dex which translates into a decrease of dust attenuation of ~0.5 mag from $z = 0$ to $z = 0.7$. The distribution of $L_{\rm TIR}/L_{\rm FUV}$ is broader at $z = 0.7$ than at $z = 0$: a population of LIRGs with a moderate $L_{\rm TIR}/L_{\rm FUV}$ ($\log(L_{\rm TIR}/L_{\rm FUV}) \sim 1{-}1.5$ corresponding to an attenuation of ~2−3 mag in FUV) appears at $z = 0.7$. This population is not important at $z = 0$.

A decrease of the dust attenuation can be linked to a lower metallicity in high redshift systems. Indeed, Liang et al. (2004) found a mean metallicity of LIRGs at $z > 0.4$ that is 0.3 dex lower as compared to that of local bright disks. The attenuation of the UV stellar continuum was found to be correlated with metallicity in starburst and normal galaxies at $z = 0$ (Cortese et al. 2006; Heckman et al. 1998). Using the relation given by Cortese et al. (2006): $\log(L_{\rm TIR}/L_{\rm FUV}) = 1.37(12 + \log({\rm O/H}) - 11.36$, we obtain a decrease of $L_{\rm TIR}/L_{\rm FUV}$ of 0.4 dex from $z = 0$ to $z = 0.7$ consistent with what is found in Fig. 2.

The observed decrease of dust attenuation in some LIRGS from $z = 0$ to $z \sim 0.7$ might also be related to the evolution of morphological type for this galaxy population. From $z = 0$ to $z > 0.5$ Melbourne et al. (2005) found a decrease of the number of peculiar/irregular systems exhibiting tidal features, asymmetry or being obvious mergers as compared to spirals, this result is confirmed by Wang et al. (2006) and Bell et al. (2005). If disturbed galaxies are related to merging systems a larger dust attenuation is expected for them (e.g. Sanders & Mirabel 1996) and their lower contribution to LIRGs at high z as compared to low z might imply a decrease of the mean dust attenuation for these galaxies.

At $z = 2$ Reddy et al. (2005) studied star formation and dust obscuration of galaxies predominantly selected in optical (UV rest-frame). We select galaxies with $L_{\rm TIR} > 10^{11}\,L_\odot$ and with $1.9 < z < 2.3$ from their sample (Reddy et al. 2006). In this redshift range, the G-band corresponds to the FUV-band of GALEX in the galaxy rest-frame. We plot these selected data in Fig. 2: they appear to be distributed below our infrared selection. A comparison of the $L_{\rm TIR}/L_{\rm FUV}$ distributions is difficult because of the obvious difference in the luminosity distributions of our samples at $z = 0$ or 0.7 and the Reddy et al. sample at $z = 2$ which contains a relatively large number of ULIRGs ($L_{\rm TIR} > 10^{12}\ L_\odot$). If the comparison is restricted to galaxies with $10^{11} < L_{\rm TIR} < 10^{12}\ L_\odot$, the mean $\log(L_{\rm TIR}/L_{\rm FUV})$ found at $z = 2$ is 0.9 corresponding to 1.85 mag, i.e. ~1.5 mag lower than our mean value at $z = 0.7$ for our selection of LIRGs at 24 μm. The discrepancy seems to be lower for the brightest galaxies (ULIRGs). Given the low number of such bright galaxies in our sample at $z = 0.7$ we cannot make any quantitative comparison; nevertheless in their study of the ELAIS-N1 field Xu et al. (2006) also found that dust obscuration in ULIRGs at $z = 0.6$ is consistent with that obtained at $z = 0$.

At $z = 1$, Burgarella et al. (2006) studied Lyman Break Galaxies (i.e. GALEX FUV dropouts) and also found a low obscuration for the galaxies they detected at 24 μm (only ~15% of their sample is detected at 24 μm). In Fig. 2 we report their data (Burgarella et al. 2007). The obscuration that they obtain is consistent with that found by Reddy et al. (2005) at $z = 2$.

How can the results of Reddy et al. (2005) and Burgarella et al. (2006) at $z \sim 1$ and $z \sim 2$ be reconciled with ours at $z = 0.7$? First we can invoke an evolution with the redshift but $z = 1$ and $z = 0.7$ are separated by only 1.5 Gyr and it is difficult to expect a large evolution during such a short timescale. The most natural explanation is to invoke selection effects since we have a selection at 24 μm (15 μm rest-frame) whereas the selections of Reddy et al. (2005) and Burgarella et al. (2006) are predominantly in the rest-frame ultraviolet. Nevertheless at $z = 0$ Buat et al. (2006) find only a slight difference between a TIR and a FUV selection so we must assume a strong evolution of the properties of intrinsically luminous galaxies with z.

4.2. Do we expect a decrease of dust attenuation for LIRGs at $z \sim 0.7$?

At first glance, we do not expect a decrease of dust attenuation for bright galaxies at $z \sim 0.7$ since (as emphasized in the introduction) the ratio of the luminosity densities $\rho_{\rm TIR}/\rho_{\rm FUV}$ increases with z. Nevertheless, we observe a slight decrease of dust attenuation at a fixed $L_{\rm bol}$. One must also account with the intrinsic brightening of the galaxies when z increases together with the increase of dust attenuation with the bolometric luminosity of galaxies observed at low and high z (cf. Fig. 2). Are all these trends consistent with each other?

We consider these issues according to a rather crude and semi-quantitative analysis (e.g. Xu et al. 2006). On one hand the evolution of luminosity densities in the TIR and FUV from $z = 0$ to $z = 0.7$ has been quantified: Le Floc'h et al. (2005) found that $\rho_{\rm TIR}$ increases as $(1+z)^{3.9\pm0.4}$ and Schiminovich et al. (2005) obtained $(1+z)^{2.5\pm0.7}$ for the evolution of $\rho_{\rm FUV}$. This gives an evolution of $\rho_{\rm TIR}/\rho_{\rm FUV} \propto (1+z)^{1.4\pm0.8}$. Therefore an increase of $\rho_{\rm TIR}/\rho_{\rm FUV}$ by a factor $2.1^{+1.1}_{-0.7}$ is obtained from $z = 0$ to $z = 0.7$.

On the other hand, we can predict very crudely the evolution of dust attenuation of a typical $L^\star_{\rm TIR}$ galaxy from the relation between dust attenuation and the bolometric luminosity of galaxies obtained at $z = 0$. This can be seen as a global trend of the evolution of galaxies selected in infrared, since Le Floc'h et al. (2005) showed that the evolution of TIR luminosity function is approximately described by pure luminosity evolution (PLE) with only a small amount of density evolution. For the purpose of the discussion, let us perform a linear regression between $L_{\rm TIR}/L_{\rm FUV}$ and $L_{\rm bol}$ at $z = 0$: for this purpose, we take the mean values used to plot the solid and dashed lines at $z = 0$ in Fig. 2 (see Buat et al. (2006) for more details) and we find

$$\log\left(\frac{L_{\rm TIR}}{L_{\rm FUV}}\right) = 0.64\ \log(L_{\rm bol}/L_\odot) - 5.5. \quad (2)$$

If we assume that $L_{\rm bol}$ is not very different from $L_{\rm TIR}$ (Buat et al. 2006), Eq. (2) translates into

$$\frac{L_{\rm TIR}}{L_{\rm FUV}} \propto L_{\rm TIR}^{0.6}. \quad (3)$$

As mentioned above, Le Floc'h et al. (2005) found that the typical TIR luminosity $L^\star_{\rm TIR}$ (the knee of the luminosity function) evolves as $(1+z)^{3.2^{+0.7}_{-0.2}}$, according roughly to the PLE. This gives

$$\frac{L_{\rm TIR}}{L_{\rm FUV}} \propto (1+z)^{1.9^{+0.4}_{-0.1}}. \quad (4)$$

Hence, if the $L_{\rm TIR}/L_{\rm FUV}$-$L_{\rm bol}$ relation found at $z = 0$ is still valid at $z = 0.7$, a "typical" TIR selected galaxy brightens with z and would have its $L_{\rm TIR}/L_{\rm FUV}$ increased by a factor of ~3 (2.6–3.4). This factor is, however, slightly higher than that found for the evolution of $\rho_{\rm TIR}/\rho_{\rm FUV}$ (1.4–3.2).

These crude estimates show that a slight decrease of the mean $L_{\rm TIR}/L_{\rm FUV}$ from $z = 0$ to $z = 0.7$ is not inconsistent with the evolution of $\rho_{\rm TIR}/\rho_{\rm FUV}$ in the same redshift range. In comparison Xu et al. (2006) used a steeper regression between $L_{\rm TIR}/L_{\rm FUV}$ and $L_{\rm bol}$ (or similarly SFR) and they found a larger discrepancy, the local relation between $L_{\rm TIR}/L_{\rm FUV}$ and $L_{\rm bol}$ predicting too much evolution of the cosmic dust attenuation.

Thus, there is no need for a global increase of dust attenuation in galaxies with a fixed luminosity and we can explain the bulk of the variation of $\rho_{\rm TIR}/\rho_{\rm FUV}$ with z by *the increase of dust attenuation with the bolometric luminosity of galaxies and the brightening of the galaxies at high z*. Moreover, the evolution of the luminosity functions in the TIR and FUV with redshift does not exclude a slight diminution of $L_{\rm TIR}/L_{\rm FUV}$ and of dust attenuation in individual galaxies ($\Delta(A_{\rm FUV}) \simeq 0.5$ mag from $z = 0$ to $z = 0.7$).

The much lower dust attenuation found in luminous UV selected galaxies at $z = 1$–2 as compared to $z = 0$ risks to be at odd with the evolution of $\rho_{\rm TIR}/\rho_{\rm FUV}$ with z as discussed above since the variation of $\rho_{\rm TIR}/\rho_{\rm FUV}$ does not seem to leave room for a strong decrease of dust attenuation in galaxies forming the bulk of the FUV and TIR luminosity densities. Nevertheless a substantial fraction of the galaxy samples of Reddy et al. (2005) and Burgarella et al. (2006) are not detected in the infrared and these non-detections must be included for a complete statistical analysis. A comparison of well controlled FUV and TIR (rest-frame) selected samples at the same redshift and with a high detection rate at both wavelength (FUV and TIR) will help resolve these issues. Such an analysis is in progress (Takeuchi et al. in preparation).

5. Conclusions

We have measured the FUV (~1500 Å) rest-frame emission of a sample of 190 LIRGs at $z \sim 0.7$; 83% of these galaxies are detected in the FUV. The ratio of the total IR to FUV luminosity, $L_{\rm TIR}/L_{\rm FUV}$, is compared to the one characterizing local galaxies. The two samples at $z = 0$ and $z = 0.7$ are found to be drawn from different parent populations with a broader distribution of $L_{\rm TIR}/L_{\rm FUV}$ at $z = 0.7$ and the presence of distant LIRGs with moderate dust attenuation (A(FUV < 3 mag) as traced by $L_{\rm TIR}/L_{\rm FUV}$. A slight difference of $\langle L_{\rm TIR}/L_{\rm FUV}\rangle$ is found between the two samples (0.2 dex) implying a decrease of the mean dust attenuation of ~0.5 mag from $z = 0$ to $z = 0.7$. A lower dust attenuation in LIRGs at medium z might be related to the decrease of their metallicity. One may also invoke the increased fraction of spiral-like objects in the LIRG population from $z = 0$ to $z > 0.5$ found by several authors. If we assume that disturbed objects are more affected by dust attenuation than undisturbed ones, dust attenuation is expected to decrease when z increases.

Nevertheless, the amplitude of the variation of the dust attenuation obtained for these infrared selected, bright galaxies is much lower than that reported for galaxies of similar luminosities at $z = 1{-}2$, selected in UV-optical and detected in thermal infrared.

The intrinsic brightening of galaxies when the redshift increases together with the well established variation of dust attenuation with the luminosity of galaxies explains the increase of $\rho_{\rm TIR}/\rho_{\rm FUV}$ from $z = 0$ to $z = 0.7$. A slight diminution of dust attenuation in bright galaxies as observed here for the LIRG population remains consistent with the observed evolution of $\rho_{\rm TIR}/\rho_{\rm FUV}$.

Acknowledgements. We thank G. H. Rieke for assistance in polishing the writing. V.B and D.B. gratefully acknowledge "Programme National Galaxie" and "Programme National Cosmologie" support for GALEX/SPITZER-MIPS science analysis. TTT has been supported by The 21st Century Center-of-Excellence Program "Exploring New Science by Bridging Particle-Matter Hierarchy", Tohoku University, and later by Program for Improvement of Research Environment for Young Researchers from Special Coordination Funds for Promoting Science and Technology commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. Support for ELF's work was provided by NASA through the Spitzer Space Telescope Fellowship Program. We finally thank the funding from the MIPS project which is supported by NASA through the Jet Propulsion Laboratory (subcontract #960785).

References

Arnouts, S.,Schiminovich, D., Ilbert, O., et al. 2005, ApJ, 619, L43
Bell, E. F. 2003, ApJ, 586, 794
Bell, E. F., Papovich, C., Wolf, C., et al. 2005, ApJ, 625, 23
Buat, V., & Xu, C. 1996, A&A, 306, 61
Buat, V., & Burgarella, D. 1998, A&A, 334, 772
Buat, V., Iglesias-Páramo, J., Seibert, M., et al. 2005, ApJ, 619, L51
Buat, V., Takeuchi, T. T., Iglesias-Paramo, J., et al. 2006 ApJS, in press [arXiv:astroph/0609738]
Burgarella, D., Péréz-Gonzaléz, P. G., Tyler, K. D., et al. 2006, A&A, 450, 69
Burgarella, D., Le Floc'h, E., Takeuchi, T. T., et al. 2007, MNRAS, submitted
Calzetti D. 2001, PASP, 113, 1449
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Choi, P. I., Yan, L., Im, M., et al. 2006, ApJ, 637, 227
Cortese, L., Boselli, A., Buat, V., et al. 2006, ApJ, 637, 242
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ112, 839
de Mello, D. F., Wadadekar, Y., Dahlen, T., Casertano, S., & Gardner, J. P. 2006, ApJ, 131, 216
Flores, H., Hammer, F., Thuan, T. X., et al. 1999, ApJ, 517, 148
Gordon, K. D., Clayton, G. C., Witt, A. N., & Misselt, K. A. 2000, ApJ, 533, 236
Heckman, T. M., Robert, C., Leitherer, C., Garnett, D. R., & van der Rydt, F. 1998, ApJ, 503, 646
Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142
Hopkins, A. M., Connolly, A. J., Haarsma, D. B., & Cram, L. E. 2001, AJ, 122, 288
Le Fèvre, O., Vettolani, G., Paltani, S., et al. 2004, A&A, 428, 1043
Le Floc'h, E., Papovich, C., Dole, H., et al. 2005, ApJ, 632, 169
Liang, Y. C., Hammer, F., Flores, et al. 2004, A&A423, 867
Marcillac, D., Elbaz, D., Charlot, S., et al. 2006, A&A458, 369
Martin, D. C., Seibert, M., Buat, V., et al. 2005, ApJ, 619, L59
Melbourne, J., Koo, D. C., & Le Floc'h, E. 2005, ApJ, 632, L65
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJ, 521, 64
Morrissey, P., Schiminovich, D., Barlow, T. A., et al. 2005, ApJ, 619, L7
Pérez-González, P. G., Rieke, G. H., Egami, E., et al. 2005, ApJ, 630, 82
Reddy, N. A., Erb, D. K., Steidel, C. C., et al. 2005, ApJ, 633, 748
Reddy, N. A., Steidel, C. C., Erb, et al. 2006, ApJ, 653, 1004
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Saunders, W., Sutherland, W. J., Maddox, S. J., et al. 2000, MNRAS, 317, 55
Schiminovich, D., Ilbert, O., Arnouts, S., et al. 2005, ApJ, 619, L47
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Seibert, M., martin, D. C., Heckman, T. M., et al. 2005, ApJ, 619, L55
Stetson, P. B. 1987, PASP, 99, 191
Sullivan, M., Mobasher, B., Chan, et al. 2001, ApJ, 558, 72
Szokoly, G. P., Bergeron, J., Hasinger, G., et al. 2004, ApJS, 155, 271
Takeuchi, T. T., Buat, V., Iglesias-Pàramo, J., Boselli, A., & Burgarella, D. 2005a, A&A, 440. L17
Takeuchi, T. T., Buat, V., & Burgarella, D. 2005b, A&A, 440. L17
Vanzella, E., Cristiani, S., Dickinson, M., et al. 2005, A&A, 434, 53
Wang, B., & Heckman, T. M. 1996, ApJ, 457, 645
Wang, J. L., Xia, X. Y., Mao, S., et al. 2006, ApJ, 649, 722
Wolf, C., Meisenheimer, K., Kleinheinrich, M., et al. 2004, A&A, 421, 913
Xu, C. K., Shupe, D., Buat, V., et al. 2006, ApJS, in press [arXiv:astro-ph/0701737]