

The evolution of the ultraviolet and infrared luminosity densities in the universe at $0 < z < 1$

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Abstract. The ratio between far-ultraviolet (FUV) and infrared (IR) luminosity densities from $z = 0$ to $z = 1$ is discussed by using the luminosity functions (LFs) of both wavelengths. The FUV LF ($z = 0-1$) based on *GALEX* has been reported by Arnouts et al. (2005, ApJ, 619, L43), whilst for the IR LF, we used the *IRAS PSCz* 60- μm LF for the local universe and the *Spitzer* 15- μm LF at higher- z as used by Le Floch et al. (2005, ApJ, in press). Both luminosity densities show a significant evolutionary trend, but the IR evolves much faster than the FUV. Consequently, the ratio $\rho_{\text{dust}}/\rho_{\text{FUV}}$ increases toward higher- z , from ~ 4 (local) to ~ 15 ($z \approx 1$). It is also shown that more than 70% of the star formation activity in the universe is obscured by dust at $0.5 \lesssim z \lesssim 1.2$.

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

1. Introduction

Dust attenuation is one of the most fundamental obstacles when we study the star formation activity of galaxies. Since ultraviolet (UV) radiation is emitted by young stars, it is in principle directly related to the recent star formation rate (SFR). However, the use of UV light to trace the SFR is strongly hampered by the presence of dust, which absorbs and scatters the UV photons and finally re-emits the energy in the IR (mainly far-IR: FIR). Therefore, the UV and IR emissions play complementary roles in estimating the recent SFR of galaxies.

In particular, the effect of dust has given rise to a long lasting debate on the cosmic star formation history (e.g., Hopkins 2004). The most direct way to address this issue is to compare the observed cosmic luminosity densities in UV and IR. In such studies, the luminosity function (LF) of galaxies is the starting point (e.g., Takeuchi et al. 2000). In this work, we investigate the evolution of FUV and IR LFs.

A highly reliable LF in the FUV has recently been published based on new UV data obtained by *GALEX*¹ (e.g., Arnouts et al. 2005). In the IR, Takeuchi et al. (2003b) constructed a 60 μm LF from *IRAS PSCz* (Saunders et al. 2000). Hereafter, we indicate IR emission integrated over 8–1000 μm by a subscript “dust”. For higher- z , first results from *Spitzer*² have been recently reported (Le Floch et al. 2005; Pérez-González et al. 2005). Making use of these LFs, we calculate

the luminosity density at both wavelengths to examine the SFR history in the universe at $0 < z < 1$.

Throughout this manuscript, we adopt a flat lambda-dominated cosmology with $(h, \Omega_0, \lambda_0) = (0.7, 0.3, 0.7)$, where $h \equiv H_0/100$ [$\text{km s}^{-1} \text{Mpc}^{-1}$], Ω_0 is the density parameter, and λ_0 is the normalized cosmological constant.

2. Luminosity functions

We define the luminosity function as a number density of galaxies whose luminosity lies between a logarithmic interval $[\log L, \log L + d \log L]$:³ $\phi(L) \equiv dn/d \log L$. Here we define the luminosity at a certain wavelength band by $L \equiv \nu L_\nu$.

2.1. The FUV luminosity function

Wyder et al. (2005) estimated the local LF of galaxies at FUV (1530 Å) from *GALEX* data in overlapped regions with 2dFGRS (Colless et al. 2001). The local FUV LF is well described by a Schechter function (Schechter 1976)

$$\phi(L) = (\ln 10) \phi_* \left(\frac{L}{L_*} \right)^{1-\alpha} \exp \left[- \left(\frac{L}{L_*} \right) \right]. \quad (1)$$

At $z = 0$, $(\alpha, L_*, \phi_*) = (1.21, 1.81 \times 10^9 h^{-2} L_\odot, 1.35 \times 10^{-2} h^3 \text{Mpc}^{-3})$.

Arnouts et al. (2005) presented the evolution of the *GALEX* FUV LF using the VIRMOS VLT Deep Survey (VVDS: see, Le Fèvre et al. 2003). They found that the FUV LFs at higher z are also well fitted by the Schechter function. Arnouts et al. (2005) directly measured the parameters

³ We denote $\log x \equiv \log_{10} x$ and $\ln x \equiv \log_e x$.

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¹ URL: <http://www.galex.caltech.edu/>.

² URL: <http://www.spitzer.caltech.edu/>.

Table 1. Schechter parameters for FUV luminosity function (converted from Arnouts et al. 2005).

| Redshift | α | $L_*(\text{FUV})$ $h^{-2} [L_\odot]$ | ϕ_* $h^3 [\text{Mpc}^{-3}]$ |
|----------|----------|---|-------------------------------------|
| 0 | 1.21 | 1.81×10^9 | 1.35×10^{-2} |
| 0.2–0.4 | 1.19 | 2.43×10^9 | 1.95×10^{-2} |
| 0.4–0.6 | 1.55 | 6.75×10^9 | 5.38×10^{-3} |
| 0.6–0.8 | 1.60 | 9.32×10^9 | 5.25×10^{-3} |
| 0.8–1.2 | 1.63 | 1.19×10^{10} | 3.63×10^{-3} |

(α , L_* , ϕ_*) at each redshift bin. They reported that the α and L_* monotonically increase with z , while the ϕ_* decreases with z . We adopt the converted values of the parameters in Eq. (1) (Table 1).

2.2. The IR luminosity function

Contrary to the FUV LF, the local IR LF is not well-fitted by a Schechter function, although it can be expressed as a function given by Saunders et al. (1990) which is defined as

$$\phi(L) = \phi_* \left(\frac{L}{L_*} \right)^{1-\alpha} \exp \left\{ -\frac{1}{2\sigma^2} \left[\log \left(1 + \frac{L}{L_*} \right) \right]^2 \right\}. \quad (2)$$

We use the parameters for the local 60 μm LF, given by Takeuchi et al. (2003b). We converted the 60 μm luminosity to that of the total dust emission by adopting the average 60 μm -to-dust flux ratio of 2.5 estimated from the PSCz sample of Takeuchi et al. (2005a). This luminosity-independent conversion can be justified because of the tight linear correlation of the two quantities (correlation coefficient $r = 0.991$).

Since most of the galaxies in IRAS PSCz are local ($z < 0.1$), we need a deep survey result to evaluate the evolution of the IR LF. Recently, very important results from *Spitzer* MIPS 24- μm observations have been reported on the mid-IR (MIR: 12 or 15 μm) LF (Le Floch et al. 2005; Pérez-González et al. 2005). These authors reported a very strong evolution trend for the MIR LF. Hereafter we adopt Le Floch et al. (2005) because their LFs are given in a form identical to the one adopted by us. However, we remark that Pérez-González et al. (2005), although adopting a different form to our study and that of Le Floch et al. (2005), nonetheless also reached consistent conclusions on the amount of the evolution.

Le Floch et al. (2005) first estimated nonparametric 15- μm LFs for each redshift bin at $0 < z < 1$ from MIPS 24- μm data by the $1/V_{\text{max}}$ method. Then, using some spectral energy distribution (SED) templates, they converted their 15- μm luminosity to the total dust luminosity. Based on these nonparametric LFs at $0 < z < 1$, they estimated the evolution rate of the IR LF, by adopting the form

$$\phi(L, z) = g(z)\phi_0 \left[\frac{L}{f(z)} \right], \quad (3)$$

where $\phi_0(L)$ is the local functional form of the LF. They assumed a power-law form for the evolution functions $f(z)$ and $g(z)$ as

$$f(z) = (1+z)^Q, \quad g(z) = (1+z)^P. \quad (4)$$

Through a χ^2 minimization between the nonparametric LFs and Equation (3), they obtained the parameter values as $Q = 3.2^{+0.7}_{-0.2}$ and $P = 0.7^{+0.2}_{-0.6}$. This means that $L_* \propto (1+z)^{3.2}$ and $\phi_* \propto (1+z)^{0.7}$ in Eq. (2), whilst α remains constant.

Here we mention the uncertainty in the conversion of luminosities. Le Floch et al. (2005) converted the local 60- μm LF of Takeuchi et al. (2003b) to the dust LF by using their model SED templates. Since their conversion procedure is different from ours, we examined their consistency. The difference between their conversion and ours does not exceed 5-%, thus we judge the difference to be negligible for the subsequent analysis at 60 μm for $z = 0$.

At higher- z , they convert L_{15} to L_{dust} by SED templates. We also consider the potential systematic uncertainty introduced by this procedure. In particular, the evolution of the population causes an increase of the fraction of IR luminous galaxies (LIRGs, ULIRGs), which may have different SEDs to less active galaxies. This can lead a systematic change of the corresponding template SED with z . To evaluate this uncertainty, Le Floch et al. (2005) made a comparison between several IR SED templates (Dale et al. 2001; Chary & Elbaz 2001; Dale & Helou 2002; Chial 2003; Lagache et al. 2003, 2004). From their Fig. 8, they estimated the typical uncertainty to be ~ 0.2 dex. We further extended their test using some other SED libraries (Efstathiou et al. 2000; Efstathiou & Rowan-Robinson 2003; Takeuchi et al. 2001a,b), and confirm their claim. The good linearity between MIR (IRAS 12 and 25 μm) and dust luminosities at a very wide range of luminosity ($10^6 L_\odot$ – $10^{13} L_\odot$) (Takeuchi et al. 2005a), even for galaxies with extreme SEDs (see, e.g., Takeuchi et al. 2003a, 2005b), also ensures the robustness of the estimation. In summary, the uncertainty of the dust luminosity estimation is a factor of three. We should keep this uncertainty in mind for the following.

3. Result and discussion

3.1. Evolution of the luminosity contribution in the FUV and IR

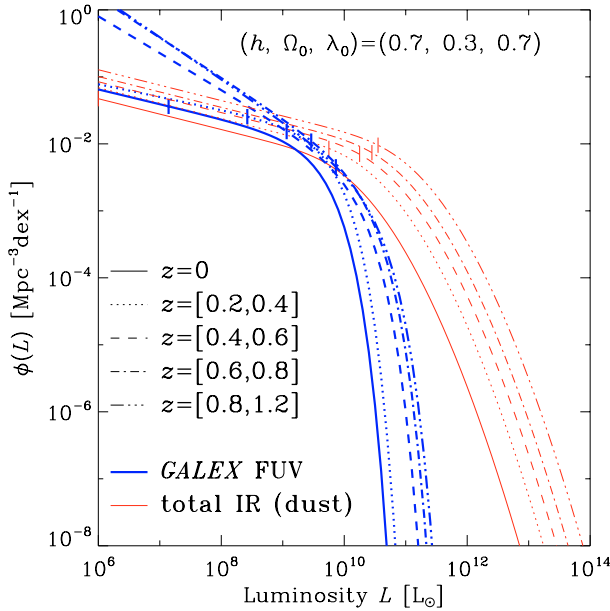
The evolution of the FUV and dust LFs are shown in Fig. 1. First, it is worth mentioning the (well-known) difference of the local LF shape of FUV and dust: for the dust LF, bright galaxies ($L \gtrsim 10^{10} L_\odot$) are much more numerous than those in the FUV. This leads to the difference in the main population contributing to the total emitted energy. The product $L\phi(L)$ represents the energy contribution of galaxies with luminosity L (see Fig. 2). In the FUV, the main contributor is L_* galaxies, with fainter galaxies emitting a non-negligible fraction of energy at $z > 0.5$. In contrast, the effect of the evolution appears in the bright end for the dust LF. The contribution from the most luminous galaxies increases with redshift.

3.2. Evolution of the FUV and dust luminosity densities and the mean dust attenuation

For FUV, we integrate $L\phi(L)$ over $L_{\text{FUV}} = 10^6 L_\odot$ – $10^{15} L_\odot$ at each z to obtain the evolution of the FUV luminosity density ρ_{FUV} , while for the dust, we first construct a LF at a

Table 2. Evolution of the FUV and dust luminosity densities, the mean dust attenuation, and the converted cosmic SFR densities.

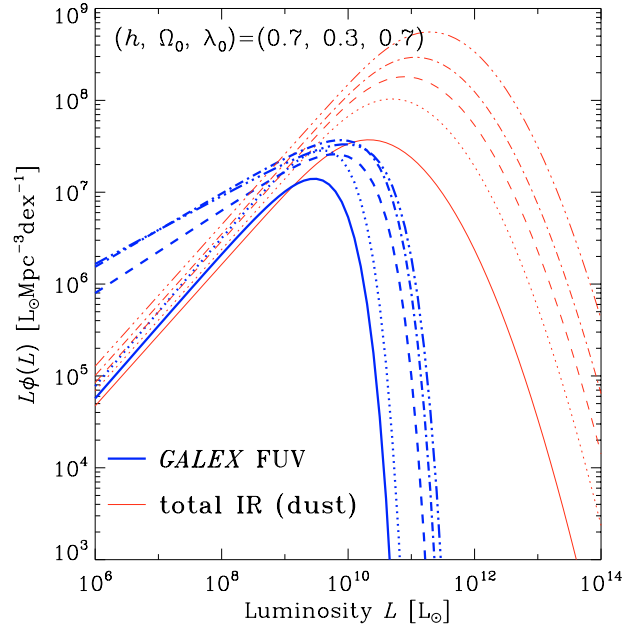
| Redshift | ρ_{FUV} $h [L_{\odot} \text{Mpc}^{-3}]$ | ρ_{dust} $h [L_{\odot} \text{Mpc}^{-3}]$ | $\rho_{\text{dust}}/\rho_{\text{FUV}}$ | $A(\text{FUV})$ [mag] | $\rho_{\text{SFR}}(\text{FUV})$ $h [M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}]$ | $\rho_{\text{SFR}}(\text{dust})$ $h [M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}]$ | Hidden SFR fraction |
|----------|--|---|--|--------------------------|---|--|------------------------|
| 0 | 2.71×10^7 | $1.02^{+0.59}_{-0.37} \times 10^8$ | $3.75^{+2.19}_{-1.38}$ | $1.29^{+0.32}_{-0.30}$ | 8.37×10^{-3} | $1.08^{+0.63}_{-0.40} \times 10^{-2}$ | $0.56^{+0.11}_{-0.11}$ |
| 0.2–0.4 | 5.44×10^7 | $2.83^{+1.65}_{-1.82} \times 10^8$ | $5.19^{+3.04}_{-1.92}$ | $1.52^{+0.34}_{-0.32}$ | 1.68×10^{-2} | $3.02^{+1.76}_{-1.11} \times 10^{-2}$ | $0.64^{+0.10}_{-0.11}$ |
| 0.4–0.6 | 6.96×10^7 | $4.94^{+2.89}_{-1.82} \times 10^8$ | $7.09^{+4.14}_{-2.62}$ | $1.75^{+0.35}_{-0.33}$ | 2.15×10^{-2} | $5.27^{+3.08}_{-1.94} \times 10^{-2}$ | $0.71^{+0.09}_{-0.10}$ |
| 0.6–0.8 | 1.06×10^8 | $8.05^{+4.71}_{-2.97} \times 10^8$ | $7.58^{+4.43}_{-2.80}$ | $1.80^{+0.36}_{-0.34}$ | 3.28×10^{-2} | $8.59^{+5.02}_{-3.17} \times 10^{-1}$ | $0.72^{+0.08}_{-0.10}$ |
| 0.8–1.2 | 1.00×10^8 | $1.52^{+0.89}_{-0.56} \times 10^9$ | $15.1^{+8.86}_{-5.59}$ | $2.34^{+0.39}_{-0.37}$ | 3.10×10^{-2} | $1.62^{+0.95}_{-0.60} \times 10^{-1}$ | $0.84^{+0.05}_{-0.07}$ |

**Fig. 1.** The evolution of the luminosity function (LF) of galaxies in the far-ultraviolet (FUV: 1530 Å) obtained by *GALEX* and infrared (dust: 8–1000 μm) obtained from *IRAS PSCz* ($z = 0$) and *Spitzer* at higher- z . Thick lines show the LFs in the FUV, and thin lines depict those of dust. Vertical tick marks on the LF indicate the lowest luminosity limits above which the observed data exist.

given z according to Eqs. (3), and (4) with the estimated value of Le Flocc’h et al. (2005), and integrate $L\phi(L)$ over the same range as that of FUV galaxies. The densities depend very little on the integration luminosity range: even if we change the lower bound to 1 L_{\odot} , the integrated value only increases by 0.4% for the dust luminosity and by 3% in the FUV luminosity.

The luminosity densities are summarized in Table 2. Both luminosity densities show a significant evolutionary trend, but the dust luminosity density evolves much faster than that of the FUV. In Table 2, we only list the systematic uncertainty potentially introduced by the choice of SED templates. For statistical errors, see Schiminovich et al. (2005) for the FUV and Le Flocc’h et al. (2005) for 15 μm. Consequently, the ratio $\rho_{\text{dust}}/\rho_{\text{FUV}}$ increases toward higher- z , from ~ 4 (local) to ~ 15 ($z \approx 1$), i.e., the dust luminosity dominates the universe at $z \sim 1$.

The FUV-to-dust luminosity density ratio can be interpreted as the global mean dust attenuation in the universe.

**Fig. 2.** The evolution of the contribution of galaxies to the luminosity density in the FUV and IR. The meaning of the different lines are the same as that of Fig. 1.

Buat et al. (2005) provided a formula which relates the dust to FUV flux ratio to the dust attenuation in the FUV, $A(\text{FUV})$ [mag], as

$$A(\text{FUV}) = -0.0333y^3 + 0.3522y^2 + 1.1960y + 0.4967, \quad (5)$$

where $y \equiv \log(F_{\text{dust}}/F_{\text{FUV}})$ and $F = \nu S_{\nu}$ (S_{ν} : flux density). The mean attenuation obtained by Eq. (5) is also tabulated in Table 2.

3.3. Fraction of obscured star formation

We interpret the data in terms of SFR. Assuming a constant SFR over 10^8 yr, and Salpeter initial mass function (IMF) (Salpeter 1955, mass range: 0.1–100 M_{\odot}), Starburst99 (Leitherer et al. 1999) gives the relation between the SFR and $L(\text{FUV}) \equiv \nu L_{\nu}$ at FUV (1530 Å),

$$\log L(\text{FUV}) = 9.51 + \log \text{SFR}. \quad (6)$$

For the IR, to transform the dust emission to the SFR, we assume that all the stellar light is absorbed by dust. Then, we obtain the following formula under the same assumption for

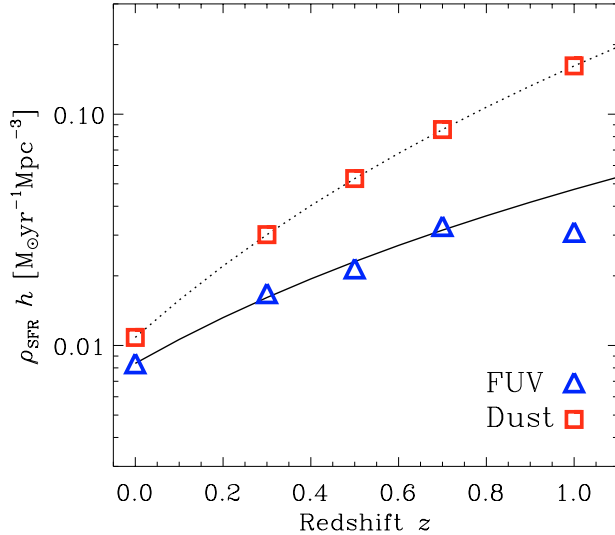


Fig. 3. The evolution of the star formation densities derived from FUV and dust. Typical statistical error is about a factor of two, and systematic uncertainty related to IR SED template is about ~ 0.2 dex.

both the SFR history and the IMF as those of the FUV,

$$\log L(\text{dust}) = 9.75 + \log \text{SFR}. \quad (7)$$

However, a significant fraction of the dust emission is due to the heating of grains by old stars which is not directly related to the recent SFR. Hirashita et al. (2003) found that about 40% of the dust heating in the nearby galaxies comes from stars older than 10^8 yr. Adopting this correction, we obtained the evolution of the star formation rate densities from FUV and dust ($\rho_{\text{SFR}}(\text{FUV})$ and $\rho_{\text{SFR}}(\text{dust})$) which are presented in Fig. 3 and Table 2.

The evolution of ρ_{dust} and ρ_{FUV} (therefore $\rho_{\text{SFR}}(\text{dust})$ and $\rho_{\text{SFR}}(\text{FUV})$) is described by the form of $(1+z)^R$. The power-law index R of ρ_{dust} is estimated to be 3.9 ± 0.4 by Le Floch et al. (2005), and for ρ_{FUV} , Schiminovich et al. (2005) give an index of 2.5 ± 0.7 (dotted and solid curves in Fig. 3). The evolution of ρ_{dust} is slightly stronger than suggested by Lagache et al. (2003), but consistent with those given by Chary & Elbaz (2001) and Takeuchi et al. (2001a). Pérez-González et al. (2005) adopted a linear relation between the SFR and the dust luminosity given by Kennicutt (1998) and obtained the evolution of the SFR density as $\rho_{\text{SFR}}(\text{dust}) \propto (1+z)^{4.0 \pm 0.2}$, which is in perfect agreement with the above result for the dust luminosity. Therefore, this is a robust conclusion which does not depend on the adopted LF functional shape for the fitting or the details of the conversion from dust emission to the SFR.

The fraction of obscured SFR density is also presented in Table 2. About half of the star formation activity is obscured in the local universe, while at $0.5 \lesssim z \lesssim 1.2$, about 70% of the total SFR is hidden by dust. In particular, the obscured SFR fraction reaches more than 80% at $z \approx 1$. The result is consistent

with a previous suggestion from the optical-to-FIR luminosity density ratio (e.g., Takeuchi et al. 2001c). This result should substantially change the way we see the SFR history at high- z .

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