The Evolution of the Visible and Hidden Star Formation in the Universe: Implication from the Luminosity Functions at FUV and FIR

T. T. Takeuchi\textsuperscript{1}, V. Buat\textsuperscript{2}, and D. Burgarella\textsuperscript{2}

Abstract. Based on GALEX and IRAS/Spitzer datasets, we have found that both FUV and FIR luminosity functions (LFs) show a strong evolution from $z = 0$ to $z = 1$, but the FIR LF evolves much stronger than the FUV one. Consequently, the FIR/FUV luminosity density ratio increases from 4 ($z = 0$) to 15 ($z = 1$). It means that more than 80% of the star-forming activity in the Universe is hidden by dust at $z = 1$. To explore this issue further, we have performed a combined analysis of the galaxy sample in FUV and FIR. For the Local Universe we used GALEX-IRAS sample, whereas at $z = 1$ we used the Lyman-break galaxy sample selected by GALEX bands constructed by Burgarella et al. (2005), which is known to be representative of visible (i.e., non-obscured) star-forming galaxies at $z = 1$. From these datasets, we constructed the LFs of the FUV-selected galaxies by the survival analysis to, take into account the upper-limit data properly. We discovered that the FIR LF of the Lyman-break galaxies show a significant evolution comparing with the local FIR LF, but it is a factor of 2–3 lower than the global FIR LF (Le Floc'h et al. 2005). This indicates that the evolution of visible galaxies is not strong enough to explain the drastic evolution of the FIR LF. Namely, a FIR-luminous, rapidly diminishing population of galaxies is required.

1. Introduction

Newly formed massive stars emit strong far-ultraviolet (FUV) radiation. However, the attenuation of the FUV light by the interstellar dust is a major issue to derive quantitative SFR from the FUV, even at low-$z$ (e.g., Buat et al. 2005). On a global point of view, the recent observations conducted by Spitzer and GALEX have allowed to build the total-IR (TIR) and FUV luminosity functions and densities from $z = 0$ to $z = 1$ (Arnouts et al. 2005; Schiminovich et al. 2005; Le Floc'h et al. 2005; Pérez-González et al. 2005). Connecting what is seen in FIR and FUV (rest frame) from low- to high-$z$ is crucial to understand above issues, but a new challenge at the same time. In this work, we try to examine which population is responsible for the different evolutions of FUV and FIR galaxies through univariate and bivariate luminosity functions (LFs). At FUV, we made use of GALEX datasets, and at FIR, we used IRAS data for the local sample and Spitzer data for higher-$z$ ones. We use the cosmological parameters $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

\textsuperscript{1}Astronomical Institute, Tohoku University, Sendai, Japan

\textsuperscript{2}Laboratoire d’Astrophysique de Marseille, Marseille, France
2. Univariate Analysis

The evolution of the FUV and dust LFs are shown in Fig. 1. Local LFs at FUV and FIR are taken from Wyder et al. (2005) and Takeuchi et al. (2003), respectively. 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. In the FUV, the main contributor is \( L_* \) galaxies, with fainter galaxies emitting a non-negligible fraction of energy at \( z > 0 \).

By integrating the LFs over luminosities, we obtain luminosity densities at FUV and FIR. Both luminosity densities show a significant evolutionary trend, but the dust luminosity density evolves much faster than that of the FUV. Consequently, the ratio \( \rho_{\text{dust}}/\rho_{\text{FUV}} \) increases toward higher \( z \), from \( \sim 4 \) (local) to \( \sim 15 \) (\( z \approx 1 \)), i.e., the dust luminosity dominates the universe at \( z \approx 1 \) (Takeuchi et al. 2005a).

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),

\[
\log L(\text{FUV}) = 9.51 + \log \text{SFR} . \tag{1}
\]

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

\[
\log L(\text{dust}) = 9.75 + \log \text{SFR} . \tag{2}
\]
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 30% 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. 1. We clearly see that the fraction of hidden SFR increases with redshifts, and at $z \sim 1$ more than 80% of the cosmic SFR is hidden by dust.

3. Bivariate Analysis: Star-formation LF in the Local Universe

We could see that most of the star-forming activity in the Universe is hidden by dust at $z \sim 1$. Then, a natural question arises: which population of galaxies is due to this evolution? To explore this issue further, we made bivariate LF analysis at FUV and FIR. First we have carefully constructed FUV and FIR-selected samples based on GALEX and IRAS data. Using these datasets, we estimated the distribution of the total luminosity from young stars (star-formation luminosity). Again following Hirashita et al. (2003), we account for the dust heating by stars older than 100 Myr. Then the star-formation luminosity is expressed as $L_{\text{SF}} = L_{\text{FUV}} + (1 - \eta)L_{\text{TIR}}$ where $\eta$ is the fraction of the TIR emission by old stars. We adopt $\eta = 0.3$ (Hirashita et al. 2003; Iglesias-Páramo et al. 2006). Therefore $L_{\text{SF}}$ can be written as $L_{\text{SF}} = L_{\text{FUV}} + 0.7L_{\text{TIR}}$. The star formation luminosity function from young stars is calculated for each sample using the $1/V_{\text{max}}$ weighting method. For details of the upper limit treatment, see Buat et al. (2006). We found that the 60 $\mu$m luminosity is a robust tracer of the luminosity of young stars, while the FUV flux alone (without any correction) misses a large part of the total emission of the FUV selected galaxies. This trend is related to the relation found between the luminosity (or star formation rate) of the galaxies and their dust attenuation (e.g., Buat & Burgarella 1998). Both luminosity functions are consistent for intermediate luminosities: in the nearby universe these galaxies are detected equally well in FIR and in FUV. For $L_{\text{SF}} \geq 5 \times 10^{10} L_\odot$, the star-formation LF issued from the FIR selection is higher than that from the FUV one and the discrepancy increases with the luminosity: we miss intrinsically bright galaxies which appear much fainter in FUV. Deeper wide-area surveys like those of AKARI are waited for further analysis. Details of the sample construction and analysis are thoroughly explained by Buat et al. (2006). Then, how is the situation at higher redshifts? We tried to explore it by using a Lyman-break galaxy sample at $z \sim 1$ in the next section.

4. Bivariate Analysis: Lyman-break galaxies at $z = 1$

Lyman-break galaxies (LBGs) at $z \sim 1$ are selected by making use of GALEX FUV and NUV bands (Burgarella et al. 2006). It is a suitable method to pick up actively star-forming galaxies at these redshifts. To see this, we first estimated the LF of LBGs and compared it with the total LF of FUV-selected galaxies at $z \sim 1$. We have used the LBG sample in the Chandra Deep Field South prepared by Burgarella et al. (2006). For the LF estimation, we applied $1/V_{\text{max}}$ and $C$-methods according to the recipes of Takeuchi, Yoshikawa, & Ishii (2000) and
Takeuchi et al. (2000). The LFs are shown in Fig. 2. We see that both agree very well at the brighter regime, though LBGs are much fewer than purely FUV-selected ones at the faint end.

Then, how much is the contribution of the LBGs to the total dust emission? We can address this issue by estimating the dust LF of LBGs. For this, we used Spitzer MIPS 24 µm flux to estimate the total dust luminosity. Since at $z \sim 1$ it corresponds to 12 µm, we made use of the conversion formula provided by Takeuchi et al. (2005b). The validity of this formula is guaranteed by a comparison with longer wavelength observation at FIR (Takeuchi et al. 2006). In this analysis, we applied the Kaplan–Meier estimator to obtain the dust LF, to utilize the information of upper limit data properly. The obtained LF is shown in the right panel of Fig. 2. We found that the dust LF of LBGs is a factor of 2–3 lower than that of the total dust LF of IR-selected galaxies at the same redshifts (Le Floc’h et al. 2005). This suggests that the evolution of visible galaxies is not strong enough to explain the drastic evolution of the FIR LF, and a FIR-luminous, rapidly diminishing population of galaxies is required.

Acknowledgments. We thank the GALEX team.

References

Arnouts, S., et al. 2005, ApJ, 619, L43
Buat, V., & Xu, C. 1996, A&A, 306, 61
Buat, V., & Burgarella, D. 1998, A&A, 334, 772
Buat, V., et al. 2005, ApJ, 619, L51
Buat, V., et al. 2006, ApJS, in press (astro-ph/0609738)
Burgarella, D., et al. 2006, A&A, 450, 69
Hirashita, H., Buat, V., & Inoue, A. K. 2003, A&A, 410, 83
Iglesias-Páramo, J., et al. 2006, ApJS, 164, 38
Le Floc’h, E., et al. 2005, ApJ, 632, 169
Leitherer, C., et al. 1999, ApJS, 123, 3
Schiminovich, D., et al. 2005, ApJ, 619, L47
Pérez-González, P. G., et al. 2005, ApJ, 630, 82
Salpeter, E. E. 1955, ApJ, 121, 161
Takeuchi, T. T. 2000, Ap&SS, 271, 213
Takeuchi, T. T., Yoshikawa, K., & Ishii, T. T. 2000, ApJS, 129, 1
Takeuchi, T. T., Yoshikawa, K., & Ishii, T. T. 2003, ApJ, 587, L89
Takeuchi, T. T., Buat, V., & Burgarella, D. 2005a, A&A, 440, L17
Takeuchi, T. T., et al. 2005b, A&A, 423, 432
Takeuchi, T. T., et al. 2006, A&A, 448, 525
Wyder, T., et al. 2005, ApJS, 619, L15