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Infrared Excess–Ultraviolet Spectral Slope (IRX–β) Relation from MUSYC–GOODS-*Herschel* Data

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The galaxy spectra we observe are attenuated by dust, produced in galaxies themselves. However, in studies of galaxy evolution, a genuine galaxy spectrum without attenuation is often needed, and the evolution of the attenuation curve is also fundamental for the investigation for the evolution of dust in galaxies. We show one of the important aspects of dust attenuation, the infrared excess-ultraviolet spectral slope (IRX–β) relation by using the data from MUSYC and GOODS-*Herschel* projects. We found that the IRX–β relation does not show significant evolution from $z = 0$ to $z \simeq 3$, with a very large scatter.

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1. Introduction

The formation and evolution of galaxies in the Universe is one of the central topics in extragalactic astrophysics for some decades. Since we measure the star formation rate in galaxies basically by the ultraviolet (UV) photons from OB stars, the biggest obstacle is the dust attenuation. Indeed, [1] discovered that the local fraction of the hidden star formation is 50–60 %, while the fraction at $z = 1$ reaches around 90 %. Later work confirmed this "dusty era of the Universe", and revealed that the dominance of the hidden SF continues even toward higher redshifts ($z \sim 3$) (e.g., [2, 3]).

The most straightforward way to estimate the dust attenuation may be to measure the ratio between UV and IR luminosities since the energy of the absorbed UV photons by dust is re-emitted at IR. However, in spite of the recent advent of large infrared (IR) space facilities like *Spitzer*, *AKARI*, and *Herschel*, it is still not an easy task to measure the IR emission of high-z galaxies mainly because of the limited angular resolution and sensitivity of instruments. Then, if there is any method to measure the dust attenuation without IR measurements, it would make the estimation of the SF rate much easier.

Meurer et al. [4] proposed a relation between the UV spectral slope β and the ratio between IR and UV luminosities, $L_{\rm TIR}/L_{\rm FUV}$, traditionally referred to as the IR excess (IRX). Since we can estimate the IRX only from β, i.e., it does not require an IR observation, this method has become very popular in high-z galaxy research. The original relation of [4] was obtained for a sample of UV-luminous nuclear starbursts. They found that the relation is tight, but subsequent studies revealed that this does not hold for dusty starburst or quiescently star-forming galaxies. Takeuchi et al. [5] reexamined the original sample of [4] and found that the UV flux densities were underestimated because of the small photometric aperture of *IUE*, and proposed a corrected formula by using *GALEX* and *AKARI* imaging data. Since the new relation is below the curve of [4], now quiescent star-forming galaxies follow their revised relation, but the discrepancy of IR luminous galaxies is larger ([6]). Thus, further investigation is needed to understand the physics behind the IRX-β relation.

Throughout this paper, we adopt a cosmological model $(h, \Omega_{\rm M0}, \Omega_{\Lambda 0}) = (0.7, 0.3, 0.7)$ ($h \equiv H_0/100[{\rm km\,s^{-1}}]$) unless otherwise stated.

2. Data

We constructed a sample of ~ 2000 galaxies whose redshifts are from $z = 0$ to $z \sim 6$, by making use of multiwavelength data in the Chandra Deep Field South (CDFS) obtained by the MUSYC (Multiwavelength Survey with Yale-Chile[1]: [7]) and GOODS-*Herschel* ([8]). The data are prepared in the same way as those used by [9]. The resulting sample of objects which are securely detected both in MUSYC and GOODS-*Herschel* datasets consists of 2,028 galaxies. Basically these galaxies have photometric measurements at 35 bands. The MUSYC project also provide photometric redshifts (photo-z) ranging $0 < z < 6$.

[1]URL: http://www.astro.yale.edu/MUSYC/.

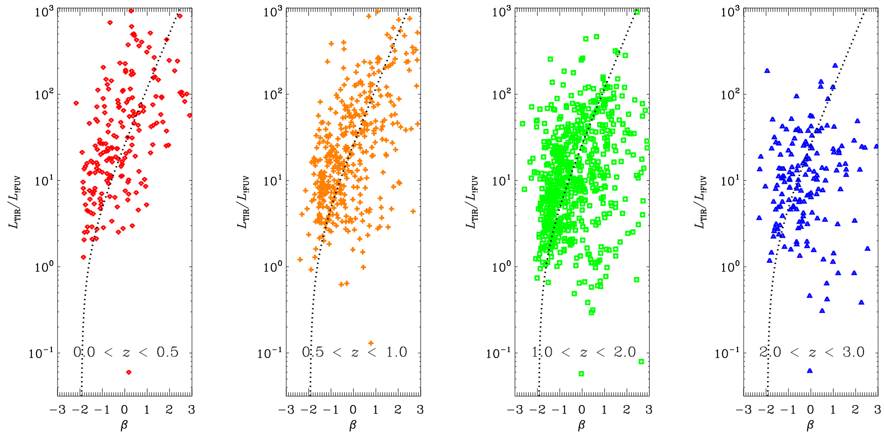

Figure 1: The IRX-β relation obtained from the sample. The redshift bins are [0, 0.5], [0.5, 1.0], [1.0, 2.0], and [2.0, 3.0].

3. Result and Discussion

3.1 IRX-β from MUSYC-GOODS-*Herschel*

In Fig. 1 shows the evolution of the IRX-β relation of our sample as a function of redshift. From the top-left to the bottom-right, the redshift bins are $z = [0.0, 0.5]$, [0.5, 1.0], [1.0, 2.0] and [2.0, 3.0]. We clearly see the redshift (in)dependence on of the IRX-β relation for our galaxies. The sample galaxies follow the Meurer relation (dotted curves: [5]) *on average* with a very large dispersion around it, and no significant evolution is found with redshift.

However, if we look carefully, a population of low IRX galaxies (with red color) seems to appear at higher redshifts (bottom-right corner in the panels). They make the dispersion of the relation larger at higher redshifts. In order to examine what these objects are, we investigate the dependence of these galaxies on some physical parameters in the next subsection.

3.2 Dependence on some physical quantities

We explored the dependence of the position of sample galaxies on the IRX-β plane on some physical quantities: UV luminosity, IR luminosity, and star formation rate (SFR). The luminosities are measured with $L_\odot$.

We find a tendency of increasing UV-luminous galaxies delineating the lower envelope of the distribution of galaxies on the IRX-β plane. In particular, we see some extreme objects which are very luminous in UV but very red in terms of β. These two features look rather enigmatic since usually UV-luminous objects have steeply rising UV SED toward shorter wavelengths.

Next we consider the IR luminosity dependence. Many previous authors pointed out that IR-luminous galaxies are located in the upper-left region of the IRX-β diagram. However, we also see an increase of IR-luminous galaxies at lower-right region, i.e., the same region as where the above-mentioned peculiar UV-luminous galaxies are located. This implies that these objects has very red UV color, UV luminous, and IR-luminous at the same time.

As for the SFR-dependence of the location of the galaxies, we find galaxies with high SFR in the upper-left region. These are typical luminous or ultraluminous IR galaxies (LIRGs or ULIRGs). However, we also see, as a direct consequence of the above discussion, high-SFR galaxies in the lower-right region.

One possible explanation would be that these are very clumpy starburst galaxies with very patchy dust distribution having distinct UV bright regions and IR bright regions at once. Of course another, uninteresting possibility is that we have some poor photometric measurements or incorrect photo-zs for these objects.

To summarize, we found the following facts.

1. The *average* IRX–β relation does not show significant evolution from $z = 0$ to $z \simeq 3$.
2. The data show, however, a very large scatter around the average IRX–β relation found by [4] and modified by [5].
3. We find a population of galaxies which emerges at high redshifts ($z > 1.0$), located in the lower-right region of the IRX–β diagram.
4. This peculiar population of galaxies are very red in terms of β, but UV-luminous and IR-luminous at the same time.

Much more analysis is needed to clarify what this emerging population of galaxies is.

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