Deep Near-Infrared Universe Seen in the Subaru Deep Field

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Abstract. The Subaru Deep Field provides the currently deepest K-selected sample of high-z galaxies ($K' \sim 23.5$ at $5\sigma$). The SDF counts, colors, and size distributions in the near-infrared bands are carefully compared with pure-luminosity-evolution (PLE) as well as CDM-based hierarchical merging (HM) models. The very flat faint-end slope of the SDF $K'$ count indicates that the bulk (more than 90%) of cosmic background radiation (CBR) in this band is resolved, even if we take into account every known source of incompleteness. The integrated flux from the counts is only about a third of reported flux of the diffuse CBR in the same band, suggesting that a new distinct source of this missing light may be required. We discovered unusually red objects with colors of $(J-K) > 3–4$, which are even redder than the known population of EROs, and difficult to explain by passively evolving elliptical galaxies. A plausible interpretation, which is the only viable one among those we examined, is that these are dusty starbursts at high-z ($z \sim 3$), whose number density is comparable with that of present-day ellipticals or spheroidal galaxies, as well as with that of faint submillimeter sources. The photometric redshift distribution obtained by $BVRIz'JK'$ photometries is also compared with the data, and the HM model is found to predict too few high-z objects at $K' \lesssim 22$ and $z \lesssim 2$; the PLE model with reasonable amount of absorption by dust looks more consistent with the data. This result is apparently in contradiction with some previous ones for shallower observations, and we discuss the origin of this. These results raise a question for the HM models: how to form massive objects with starbursts at such high redshifts, which presumably evolve into present-day elliptical galaxies or bulges?

1. Introduction

The Subaru Deep Survey is a systematic project of the 8.2m Subaru telescope to study the deep extragalactic universe. The Subaru Deep Field was selected near the north Galactic pole, avoiding large Galactic extinction and nearby galaxy clusters, and the airmass of this field is smaller than the Hubble Deep Field at Mauna Kea (Maihara et al. 2000). The wide field near-infrared (NIR) camera CISCO took a very deep NIR $2' \times 2'$ image in $J$ and $K'$ bands, with $5\sigma$ magnitude limits of 25.1 and 23.5. This is the deepest image in the $K$ band taken so far, providing a unique $K$-selected sample of galaxies which should be useful for
study of faint, high-\(z\) galaxies. The field was also deeply followed-up by optical instruments of FOCAS and Suprime-Cam. Here we review some interesting implications obtained by these data set, focusing on NIR galaxy counts, colors, and photometric-redshift distribution, compared with some theoretical models of galaxy formation and evolution. Although omitted here, some interesting results for the clustering of Lyman break galaxies and Lyman alpha emitters at \(z \sim 4\) have been obtained in the SDF and another project of the Subaru/XMM-Newton deep survey, thanks to the very wide field of the Suprime-Cam. See Ouchi et al. (2001, 2002) for these.

2. NIR Galaxy Counts and Contribution to CBR

Figure 1 shows \(K\) band SDF galaxy counts, compared with those estimated by other observations (Totani et al. 2001a). Here, we plot counts multiplied by flux, rather than count itself, to show the contribution to the cosmic background radiation (CBR) per magnitude. Both the raw and corrected counts assuming point sources are showing very flat faint-end slope, with rapidly decreasing contribution to CBR beyond \(K \gtrsim 18\). Therefore the extrapolation of the galaxy counts into fainter magnitudes does not significantly increase EBL but converges to a finite EBL flux, and this means that the bulk of EBL from galactic light has already been resolved into discrete galaxies. These results require that the diffuse EBL in NIR bands should not be different from the count integrations, provided that the ordinary galactic light is the dominant source of the EBL in these bands, as generally believed. However, a few recently reported detections of diffuse EBL in these bands suggest that the diffuse CBR flux in \(K\) bands is consistently higher than the count integrations by a factor of \(~3\): \(\nu I_\nu = 27.8 \pm 6.7 \text{ nW m}^{-2}\text{sr}^{-1}\) (Cambrésy et al. 2001), 29.3 \(\pm\) 5.4 (Matsumoto 2000), and 20.2 \(\pm\) 6.3 (Wright 2001), which should be compared with the integration of \(K\) counts (\(~8 \text{ nW m}^{-2}\text{sr}^{-1}\)).

If the discrepancy between the diffuse EBL and count integration is real, it might suggest the existence of very diffuse component which is different from normal galaxies. Before deriving this extraordinary conclusion, however, all possible systematic uncertainties in the above estimates must extensively be checked. One of such systematics is the contribution to EBL by the galaxies missed in deep galaxy surveys. Since galaxies are extended sources, the detectability near the detection limit is not as simple as point sources. Furthermore, the well-known effect of the cosmological dimming of surface brightness \([S \propto (1 + z)^{-4}]\) should make high-\(z\) galaxies very difficult to detect, while such objects may have a significant contribution to EBL. The photometry scheme could also be a problem, because there is considerable uncertainty in the estimate of the magnitude of faint galaxies because of ‘growing’ the photometry beyond the outer detection isophotes of galaxies.

Therefore we estimated the contribution to CBR by galaxies missed in SDF, based on a realistic theoretical model of galaxy counts which includes all known physical or observational selection effects and incompleteness, based on the method presented in Yoshii (1993) and Totani & Yoshii (2000). First, we construct a model of galaxy counts which best fits to the observed raw (i.e., uncorrected) counts, taking into account all the above selection effects. Then we
Figure 1. The contribution to EBL by galaxies in the K band. The filled circles are the raw SDF counts in isophotal magnitude, while the symbols $\odot$ are the counts in total magnitude which are corrected for incompleteness assuming point sources (Maihara et al. 2000). The dashed line is the prediction by a PLE model for which the selection effects under the observational conditions of SDF are taken into account, fitting to the raw counts. The solid line is the same prediction, but the selection effects are not included. For detail, see Totani et al. (2001a). The two dotted lines are model predictions with and without selection effects, using the same PLE model but including a simple number evolution of $\eta = 1$.

can calculate the true galaxy counts and EBL flux using the same model without selection effects, and comparison between the true counts and observed counts gives an estimate of contribution by missing galaxies. The results are shown in Fig. 1, where the dashed line is the best-fit model to raw SDF counts taking into account the selection effects in theoretical calculation, while the solid line is the same model but without the selection effects. By this procedure, we found that the correction by the incompleteness would increase the CBR from galaxies by at most 10%, which is too small to reconcile the count integrations and diffuse CBR measurements (Totani et al. 2001a). Therefore we conclude that there must be a new source of CBR in the NIR band, which must be very different and distinct populations from known galaxies, unless some unknown systematics have affected the diffuse CBR measurements significantly.

The model shown in the dashed and solid lines is a so-called pure-luminosity-evolution (PLE) model without number evolution, including five types of galax-
ies (E/S0, Sab, Sbc, Scd, and Sdm), whose detail is given in Totani & Yoshii (2000). In fact, all the SDF NIR data of counts, \((J-K)\) colors, and size distributions are well described by this rather simple model in the popular \(\Lambda\)-dominated flat universe, without any indication of number evolution. This is somewhat in contrast to the result of the same model against HDF galaxies, where a modest number evolution of \(\eta \sim 1\) is required to fit the data \([\phi \propto (1+z)^{-\eta}, L^* \propto (1+z)^{-\eta}]\) (Totani & Yoshii 2000). This is the most naturally explained by different merging histories for different galaxy types; longer wavelengths are dominated by earlier types. Therefore, these results indicate that elliptical galaxies which are dominant in the \(K\) band are evolving without significant change of number density from \(z \sim 2\) to the present (Totani et al. 2001c). A number evolution of \(\eta \sim 1\) for elliptical galaxies is already inconsistent with the data, as shown by dotted lines in Fig. 1.

On the other hand, a study of SDF K counts by a hierarchical merging (HM) model based on CDM-based structure formation is presented in Nagashima et al. (2002), where the selection effects are carefully taken into account in a similar way. The HM also fits to the SDF counts in low density cosmological models, but the PLE and HM models are giving different predictions in the redshift distribution, which will be discussed later.

2.1. Unusually Red Objects

An interesting discovery by SDF is the existence of unusually red objects in NIR colors, with \(J-K \gtrsim 3-4\). The brightest four objects of them are presented in Maihara et al. (2000), and a more careful analysis has been performed to estimate the number fraction of such objects as a function of \(K\) magnitude (Totani et al. 2001b). They found that the number fraction of such objects sharply rises with increasing magnitude from \(K \sim 20\), reaching a few percent at the faintest magnitudes (see Fig. 2). It should be noted that such NIR color is even redder than the known population of the extremely red objects (EROs), which are defined by red optical-NIR colors such as \(R-K > 5\); typical EROs have \(J-K\) of at most 2. Furthermore, such red NIR color cannot be explained by passively evolving elliptical galaxies at any reasonable redshift without extinction by dust (Totani et al. 2001b), while recent studies of EROs indicate that the majority of them are passively evolving ellipticals (e.g., Daddi et al. 2000).

Then two interpretations remain for these hyper extremely red objects (HEROs). One is ultra-high \(z\) objects at \(z \sim 10\), the red color being due to the Lyman-break between \(J\) and \(K\) bands. Since HEROs are too faint to measure redshifts, it is difficult to verify observationally. However, theoretically it is very unlikely; the rest-frame UV luminosity indicates star formation rate of more than \(100M_\odot/\text{yr}\), but there should be very few objects which are massive enough to allow such high SFR at \(z \sim 10\), according to the widely believed CDM-based structure formation theory. The other interpretation is that they are dusty starbursts, which often show very red colors. In fact, Totani et al. (2001b) has shown that the colors and counts of HEROs are well reproduced by a simple model if present-day elliptical galaxies have formed by starbursts with a reasonable amount of dust (i.e., inferred from model metallicity) at \(z \sim 3\).

This redshift is similar to those estimated for the faintest submillimeter sources in recent years. Interestingly, the counts of HEROs are roughly the
Figure 2. Number fraction of galaxies redder than several threshold $J - K$ colors (indicated in each panel), as a function of $K$ magnitude. Filled circles are the data of the SDF. The error bars are 1σ, while the upper limits shown by arrows are at the 95% confidence level. The upper limit at $K = 20$ is from Scodellio & Silva (2000, filled square). The solid line is the model prediction with the formation redshift $z_F = 3$ and our standard dust-extinction normalization. See Totani et al. (2001b) for the detail for other curves.

same with the faintest SCUBA sources, and submm flux expected by the dusty-starburst model of HEROs is in fact close to the SCUBA sensitivity limit. A detailed modeling of FIR-submm counts by Totani & Takeuchi (2002) has indeed shown that SCUBA counts are nicely explained by the dusty starbursts of forming elliptical galaxies which are also responsible for HEROs. These results suggest an interesting possibility that HEROs and SCUBA sources are the same population, which will evolve into present-day elliptical galaxies or bulges. It is very important to examine the correlation between these two. Ultimate confirmation of this hypothesis would be brought in the NGST and ALMA era.

2.2. Photometric Redshift Distributions: PLE vs. HM

Both the PLE and HM models fit to the SDF $K$ galaxy counts. It may be because the galaxy counts do not have enough power to discriminate these two, or may be because galaxies dominant in the $K$ band in the HM model have only small or negligible number evolution. This degeneracy can be broken by redshift distribution; especially a $K$-selected sample has a strong power for the discrimination, since $K$-band light traces the stellar mass which has formed so
Figure 3. The normalized cumulative redshift distribution of SDF sample separated by $K'$ magnitude. The thick solid histograms show the result of the SDF photometric redshifts. The shaded regions show ±3σ deviated counts estimated by Monte Carlo realizations when photometric redshift errors are taken into account. (Poisson fluctuation of number of galaxies is not included.) The thick dashed lines denote the prediction of the PLE model in Totani et al. (2001), while the thick dotted lines for the HM model in Nagashima et al. (2002). The predictions of dust-free PLE and HM in Kauffmann & Charlot (1998) are also shown in the top panel by thin dotted and dashed lines, respectively.

far, rather than star formation rate at that time. Though spectroscopic redshifts are unavailable for the faintest SDF galaxies, a reasonably reliable test is possible by the photometric redshift technique, as is done by Kashikawa et al. (2002). The result is shown in Fig. 3, in a form of cumulative $z$-distribution separated by $K'$ magnitude intervals.

In bright magnitude ranges of $K' < 22$, the observed distribution is somewhat between the two models of PLE and HM. Although in the range of $21 \leq K' \leq 22$ the HM model looks better than the PLE, statistical fluctuation is large because of the small number of galaxies. The Kolmogorov-Smirnov (KS) test gives a chance probability of 2 and 1% of getting the observed distribution from the PLE model. Considering model uncertainties which is not taken into account in the KS test, it is impossible to reject this model. On the other hand, the deficit of high-$z$ galaxies in the HM model at $K' > 22$ is statistically much more significant (chance probabilities of $6 \times 10^{-6}$ and $5 \times 10^{-15}$ at $22 \leq K' \leq 23$ and $23 \leq K' \leq 24$, respectively). It should also be noted that the HM model used
here gives $z$-distribution more weighted to high redshifts compared with another HM model of Kauffman & Charlot (1998) (see the top panel). We emphasize that this is a “blind” test, i.e., the models shown here are those fitting best only to the SDF counts as described in Totani et al. (2001c) and Nagashima et al. (2002) without further tuning of parameters to the new photo-$z$ data of Kashikawa et al. (2002).

These results seem to be controversial when compared with several previous papers doing a similar test (but in shallower magnitudes). Fontana et al. (1999) and Rudnick et al. (2001) claimed that the photometric redshift distribution at $K < 21$ is consistent with HM models, but not with PLE models. Firth et al. (2002) reached a similar conclusion using a sample of $H < 20$. It should be noted that PLE models used by these groups are either dust-free or assuming only constant extinction at the level of Galactic extinction. Such PLE models are inconsistent with the observed $z$-distribution since they predict too many high-$z$ galaxies which are visible because of strong starbursts assumed in the formation of elliptical galaxies (see top panel of Fig. 3 for the dust-free PLE prediction by Kauffmann & Charlot 1998). However, dust-free model is obviously unrealistic, especially for initial starbursts expected for elliptical galaxies. We know that starbursting populations of galaxies quite often show strong extinction and reddening. A chemical evolution model of elliptical galaxies also suggests that the amount of metal produced in the initial starburst phase is huge, and hence strong extinction seems quite plausible (Totani & Yoshii 2000). The PLE model used here (dashed line in Fig. 3) is taking into account the extinction by a reasonable amount of dust inferred from chemical evolution. In addition, observational selection effects discussed in §2 may also have affected previous results. (The theoretical predictions by our PLE and HM models appropriately included all known selection effects under the SDF condition).

Cimatti et al. (2002) compared a spectroscopic redshift distribution at $K < 20$ obtained by the K20 survey with the latest PLE and HM models. In fact, they found that, if dust extinction is taken into account (another option is using the Scalo IMF rather than the Salpeter), the difference between PLE and HM models becomes much smaller than previously claimed. They found that such PLE models are in reasonable agreement with the data, but on the other hand, HM models predict too many low redshift galaxies.

3. Concluding Remarks

From these results, we conclude that the deepest $K$-selected sample of the SDF is in overall agreement with the simple picture of PLE for early type or elliptical galaxies, but the present version of HM models has a problem in the redshift distribution of the faintest galaxies. Considering the overall success of the CDM structure formation theory against various tests not based on galaxy luminosity and star formation activities (e.g., clustering properties or abundance of galaxy clusters), it is reasonable to think that the problem identified for HM models is related with the treatment of star formation activity. It must incorporate a population of massive and dusty starbursts at high redshift ($z \gtrsim 3$), which presumably evolved into present-day elliptical galaxies or bulges without significant number evolution.
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