The Universe at Redshifts from One to Two for Early-Type Galaxies: Unveiling the Formation Epoch with FMOS

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Abstract

In this article, luminosity function of passively evolving galaxy and its evolution at $1 < z < 2$ is discussed. It is expected to provide clues to formation epochs of early-type galaxies and their histories of mass assembly. The high multiplicity and wide field of view of FMOS will enable us to collect a large number of galaxy spectra from a wide survey area, which are important to investigate cosmic variance with good statistics. Also, they will allow us to perform deep exposures, which are essential to study quiescent galaxies without emission lines.

1. Formation epoch of early-type galaxy

Generally speaking, no vigorous star formation is ongoing in early-type (elliptical and S0) galaxy, and the bulk of stars are considered to be old. Indeed, the colour-magnitude relation and the fundamental plane seem to evolve passively up to $z \sim 1$, suggesting that their star formation activities stopped at some early epochs (e.g., $z > 2$) and most of the stars formed in a short duration (e.g., < 1 Gyr) in their histories (Treu 2003 and references therein). On the other hand, there are increasing pieces of evidence from spectroscopy that elliptical galaxies in the local universe are not homogeneously old: Less massive ellipticals and/or ellipticals in lower density regions may tend to be younger (Caldwell, Rose & Concannon 2003; Trager et al. 2000). Their smaller ages may imply that some of the elliptical galaxies formed in the recent past.

However, we need to carefully interpret these implications from their stellar populations, because it is not necessarily evident that the stellar ages tell us when the elliptical galaxies formed. They are in fact luminosity weighted ages of the stellar contents and thus likely to reflect the most recent epochs of non-negligible amount of star formation in the galaxies. If most of the stars formed when an elliptical galaxy formed, the situation may be simple. Nevertheless, some secondary star formation may refresh the stellar content and make it harder to connect the luminosity weighted age to the galaxy formation epoch. And in particular, if elliptical galaxies form in a more hierarchical manner, their stellar ages may be much less directly connected with the galaxy formation epochs. Therefore, we need to investigate evolution of luminosity function of elliptical galaxy and its evolution to know when they appeared, as well as to investigate their stellar populations.

2. Luminosity function at $z < 1$

Recently, some results from the big imaging survey COMBO-17 have been published (e.g., Wolf et al. 2003). The results are based on the data which are moderately deep ($R \sim 26$ mag (5σ)) over a wide field ($\sim$ 2800 square arcmin) thus having good statistics ($\sim$ 25000 galaxies). The multi-band photometry covering from 3640 Åto 9140 Åwith 17 broad- and medium-band filters also allows well-defined photometric redshifts.

Using the data from COMBO-17, evolutions of luminosity function and rest frame B-band luminosity density of early-type galaxies were recently investigated (Bell et al. 2003). They sampled galaxies on the red sequence as early-type. Although generally speaking it is not very evident whether red galaxies are really early-type galaxies especially at high redshifts (e.g., van Dokkum et al. 2001), the imaging data from the follow-up program with HST/ACS (GEMS; Rix et al. 2004) suggest that most of them ($\sim$ 85 %) are indeed morphologically early-type (Bell et al. 2004). The evolutions were investigated up to $z \sim 1.2$ and claim a significant decrease in number density of early-type galaxies compared with passive evolution. However they are still consistent with the scenario that about half of the early-type galaxies in the local universe were already in place at $z \sim 1$.

In fact, there are several ways of constructing a sample of early-type galaxies and one sample may lead to a different result from those based on the other sample selections. However, with regard to evolution of luminosity function, all the results from morphological selection (Im et al. 2002), selections based on multi-band photometry (Chen et al. 2003) and spectroscopy (Pozzetti et al. 2003) are consistent with that from COMBO-17 and they basically suggest a mild evolution up to $z = 1$ and that about half or more of the local early-type galaxy population are already in place at $z \sim 1$.

3. Any "bona-fide" elliptical galaxy at $z > 2$?

Before looking at the situation at $1 < z < 2$, it is worth mentioning whether there are promising candidates for early-type galaxies at redshifts beyond 2. One candidate galaxy population may be radio galaxies. Their $K - z$ diagram indicates that radio galaxies occupy the massive end of galaxies at all redshifts up to ~ 3 and the boundary is actually consistent with the evolutionary track of a massive and old galaxy expected for passive evolution (e.g., Rocca-Volmerange et al. 2004). Some of the high redshift radio galaxies at $z > 2$ indeed have de Vaucouleurs law-like surface brightness profiles (e.g., Pentericci et al. 2001)[1]. However, the bulk of galaxies are likely to be quite different from those in the local universe. Although there are a few galaxy populations which are considered to be candidates for progenitors of early-type galaxies: Lyman Break Galaxies, SCUBA galaxies, and red galaxies from FIRES, most of them seem to be star forming galaxies and no clear Hubble sequence does not seem to appear. In other words, current data sets do not seem to have revealed yet a population of passively evolving early-type galaxies at $z > 2$, although our current understanding of the galaxy populations in this epoch may be still incomplete.

4. What are expected at $1 < z < 2$?

Then, how can those two epochs, $z < 1$ and $z > 2$, be linked consistently with each other on the time sequence ? One simple possibility is that a population of galaxies cease their star forming activities, get into a passive evolution phase, and a significant number of early-type galaxies (about half or even more of the local population is possible) reveal in this redshift range (cf. Glazebrook et al. 2004). If this is the case, how could we see this evolution observationally ?

4.1 Luminosity function of passively evolving galaxies and its evolution

Conducting deep redshift survey over a wide area on the sky, luminosity function of passively evolving galaxy and its evolution would be investigated in this redshift range. This is a straightforward extension of the studies at $z < 1$ and could allow one to find out formation epochs of the early-type galaxies which are already in place at $z = 1$. Extremely Red Objects (EROs) are considered to be promising candidates for passively evolving galaxies at $z > 1$ and their properties have been extensively studied (e.g., Cimatti et al. 2002). However, almost all the studies rely on photometric data and this largely limits our understandings of EROs, even of what EROs are. Although a colour-colour diagram in the optical and near-infrared bands may provide some clues to classifying EROs (e.g., Mannucci et al. 2002), the age-dust-metallicity degeneracy and its interplay with lack of information on their redshifts can prevent us from fully understanding the galaxy population (Mobasher et al. 2004; Pierini et al 2004). Spectroscopic study of EROs, which is still in an early stage (Yan & Thompson 2003; Cimatti et al. 2003), should be performed more extensively.

One interesting aspect is evolution of luminosity function at $1 < z < 2$. Although the universe ages only by ~ 2.5 Gyr from $z = 2$ to 1, the evolution could be significant if about half of the local early-type galaxy population appeared in this epoch. Although galaxies in this redshift range tend to be treated as one population in most of the studies, Miyazaki et al. (2003) studied evolution of the rest frame B-band luminosity function of passive EROs. Their data suggest that while the luminosity function at $1 < z < 1.5$ is consistent with the prediction for passive evolution, that at $1.5 < z < 2.5$ is largely discrepant from the passive evolution case, which may imply that we are witnessing the epoch of mass assembly of early-type galaxy (cf. Caputi et al. 2004). One shortcoming is, however, that the current accuracy of photometric redshift ($\Delta z \sim 0.2 - 0.3$) can be too coarse for studying luminosity function and its evolution in this rather narrow redshift range. More accurate redshifts and better classification of EROs should be secured with spectroscopy.

4.2 Search for galaxies at post star formation phases: self-regulation of star formation or environmental effect ?

After the progenitors of early-type galaxies ceased their star forming activities, they could experience post-starburst phase characterised by strong Balmer absorption lines. Therefore, formation of early-type galaxy may also be revealed by searching for a population of such post-starburst galaxies. Also, an interesting question would be how the star formation stopped. The galaxies may have finished the star formation by, e.g., simply expending gas or expelling it as a galactic wind. Otherwise, some environmental effects might have worked. Accordingly, mapping out three dimensional large scale structures through redshift survey may well give us some hints for what kind of processes work to stop the star formation.

[1] In fact, the properties of the radio galaxies such as morphology and star forming activities seem to be rather diverse especially at higher redshifts (e.g., van Breugel et al. 1998; Simpson 2004, private communication).

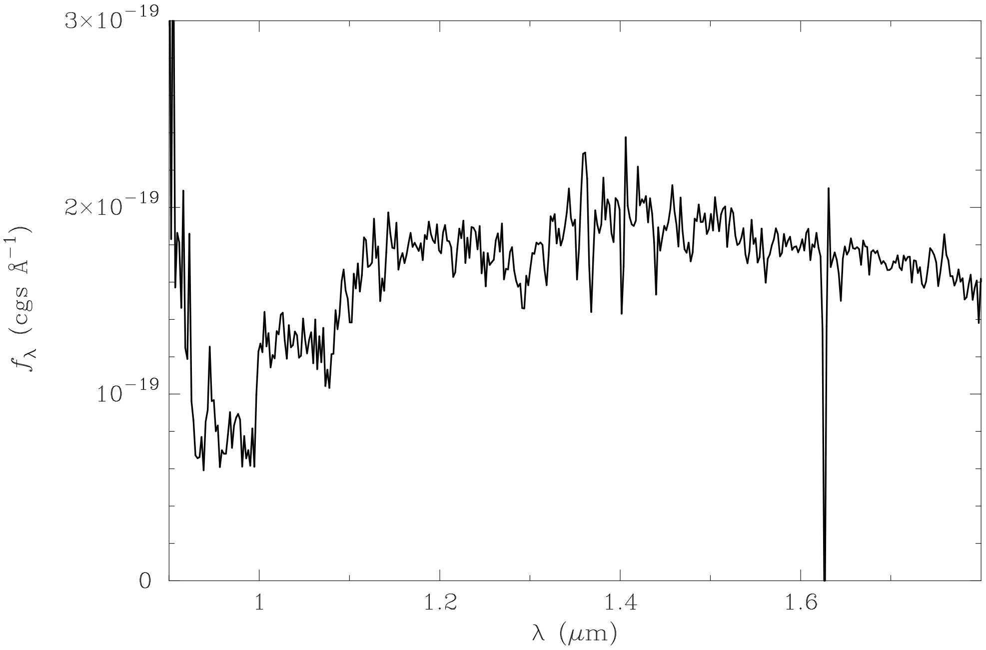

Figure 1: A simulated spectrum with the image simulator of a galaxy dominated by old stellar population at $z = 1.5$ with $H = 20.5$ ($L \sim L^*$ at the redshift). 8 hours on-source integration, $0\overset{\prime\prime}{.}5$ seeing, and an elevation of 50° ($\sec z = 1.5$) are assumed.

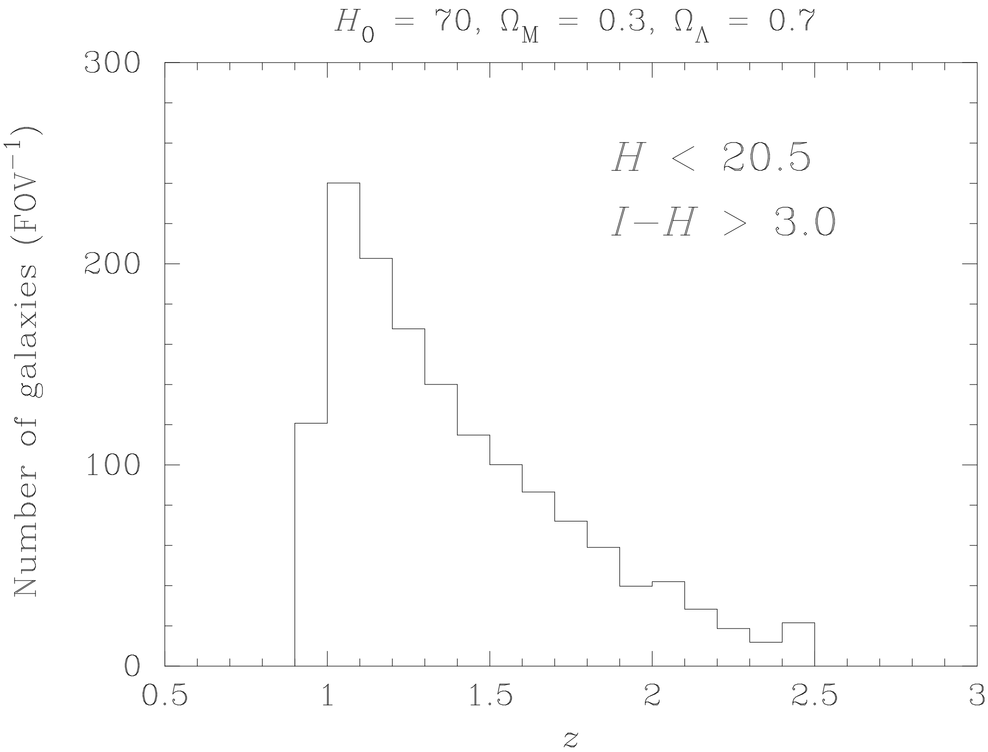

Figure 2: Estimated number of elliptical galaxies with $H \leq 20.5$ mag and $I - H \geq 3$ (nearly equivalent to $R-K \geq 5$ or $I-K \geq 4$ for ERO; Chen et al. 2002). The local luminosity function by Gardner et al. (1997) and a passive evolution model for $z_f = 10$ are assumed. PEGASE Ver 2.0 (Fioc & Rocca-Volmerange 1997) was used to construct the model spectra.

5. Prospects for FMOS survey

Firstly, since not starburst galaxies but rather quiescent galaxies at $z > 1$ are targeted, deep observations are desired for extracting information on redshift and galaxy type using absorption lines. We also need to collect a large sample from a large area not only for good statistics but also for estimating cosmic variance. Although all of these issues are practically challenging, FMOS will be a powerful tool enough to meet these requirements. The first reason for this is its wide spectral coverage in the near-infrared. This will allow us to access well known spectral features in the rest frame optical bands for galaxies at $z > 1$ and also provide a lot of chance to catch spectral features to determine redshifts. Secondly, the high multiplicity and wide field of view will make observations highly efficient. It is stressed here that there are two directions to exploit these strengths: not only for collecting a larger number of spectra but also for carrying out a longer integration. As shown by a simulated spectrum with the image simulator in Figure 1, 8 hours integration can provide a quality spectrum of a galaxy at $z = 1.5$ with $H = 20.5$ mag dominated by old stellar population. Although redshifts may be able to be determined with less deep data, they will be necessary to extract more detailed information such as Balmer absorption line strength. The number of the field of view to be observed is an issue. Even though ERO-like red galaxies are observed with FMOS down to $H = 20.5$ mag, collecting galaxies at $z \sim 2$ is unlikely to be very easy (see Figure 2 as a reference). At least a few shots would be required to derive luminosity function with good statistics, although more detailed estimations are necessary for defining strategies. Finally, it should be mentioned that the UKIDSS (Almaini, Edge, in this proceeding) and its optical counterpart with Subaru/Suprime-Cam (Yamada, this proceeding) will be able to provide imaging data sets compatible with such a spectroscopic survey with FMOS. These data will be indispensable mainly in selecting targets for follow-up spectroscopy with FMOS.

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