Lecture 14 : Evolution of galaxies

1 Evolution of galaxies : Observational constraints

1.1 Number counts

A classic way of studying the distribution and evolution of objects is with the help of number counts. It is difficult however to have number counts of galaxies in optical, especially because of the K-correction. One needs a good idea of the typical ultraviolet spectrum of normal galaxies in order to estimate the number counts of galaxies at high redshift. Unfortunately, there are hardly any systematic study of ultraviolet spectra of galaxies. This problem is minimum at the infrared wavebands, say, at K band (2.2 μ). This is because (1) it is much less affected by dust extinction and (2) even at $z \sim 4$ the observed light was emitted at 400 nm in the galaxies' rest frame and therefore the K-correction is better known.

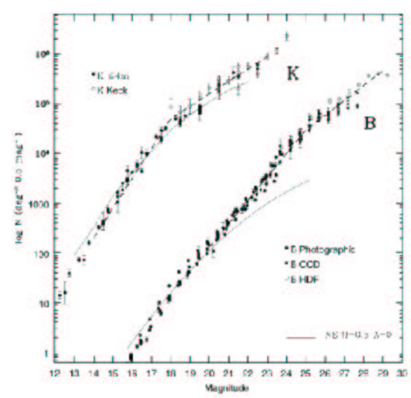

Figure 1: Number counts of galaxies (N($< M$))in B and K band (Metcalfe et al 1996). the K magnitudes are offset by 1 dex for clarity.

The number counts (in B(440 nm), and K(2.2 μ)) as shown here have been compiled from both ground based and HDF data. The data in the K-band is fairly consistent with the expectations of no-evolution models with $\Omega \sim 0.5, \Lambda = 0$ We should recall that most of the light in this band comes from old stellar population, and passive evolution of galaxies is therefore not unexpected. The counts in B band show some excess of faint galaxies, below about $B \sim 23$. This is known as the '**faint blue galaxy problem'**.

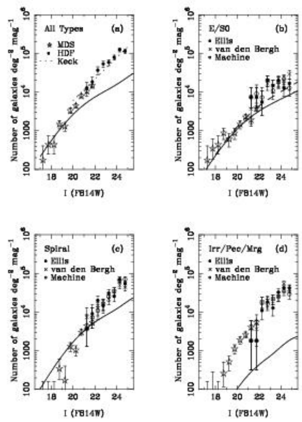

Figure 2: Number-magnitude relations for morphologically segregated sample from HDF and MDS (medium deep survey) (Abraham et al 1996). The no-evolution $\Omega = 1$ curve is from Glazebrook et al (1995). The dashed line in E-SO diagram is that for $\Omega = 0.1$.

morphology types of galaxies, it appears that the spheroidal and spiral populations more or less follow the expectations of a no-evolution model, while irregular-peculiar-merger galaxies show a clear excess relation to their populations in the bright galaxy samples (which amount to only 1-2% of the galaxy population). Visual impression of the HDF also suggests that there is a large fraction of merger/irregular galaxies at faint magnitudes.

1.2 Evolution of luminosity function

The results of a spectroscopic study from Canada-France Redshift Survey (CFRS) and Autofib-LDSS survey with Anglo-Australian telescope are shown here. The CFRS study shows that the luminosity function shifts towards larger luminosities at high redshift, whereas the Autofib-LDSS survey shows that the change is primarily with sub-L_* galaxies.

Homework on calculation of infrared luminosity evolution in time for a passively evolving galaxy (Gunn 1978) : show that $L \propto (1+z)$

It is interesting to note here that for passively evolving galaxies, one only expects a modest change in magnitude (around unity) at $z \sim 1$, which is consistent with the above mentioned evolution of luminosity function for massive galaxies.

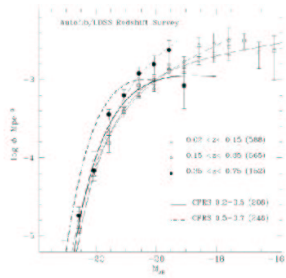

Figure 3: The rest-frame B (AB) luminosity function at various redshift range from the Autofib/LDSS data (Ellis et al 1996). They are compared with the CFRS data from Lily et al 1995. A $\Omega = 1$ universe with $hH = 50$ km/s/Mpc is assumed. (From Ellis 1997, ARAA, 35, 389)

1.3 Evolution of massive galaxies

There are some observational clues to the evolution of massive galaxies at moderate redshifts.

- The evolution in red and infrared luminosity function is not significant in the redshift range $1 < z < 2$ and is consistent with passive evolution.

- Observations of massive ellipticals at high z associated with strong radio sources show that the stellar content has not changed much in this redhshift range. Best et al (1998) showed from their study of 3CR radio galaxies that the stellar content is remarkably constatn around 5×10^{11} $M_\odot$. Also, Dunlop etal (1996) showed that the stellar population of radio galaxy LBDS 53W091 ($z = 1.55$) is old, similar to the conclusion of Lily (1988) for the radio galaxy 0902+34 at $z = 3.4$ (similarly for LBDS 53W069 at $z = 1.43$ (Dey 1997).

- Studies of Lyman-break galaxies show that these galaxies at $z \sim 3$ are very similar to L_* galaxies today, with similar number densities.

It is then reasonable to assume that most massive galaxies formed their stellar populations at $z \geq 3$ and have been passively evolving since then.

1.4 Faint blue galaxies

The nature of the faint blue galaxies is still not clear. The main problem is that it is difficult to do spectroscopy at this faint level even with large 8-m class telescopes. It is possible that dwarf galaxies, giant galaxies or even interacting/merger galaxies are seen as the faint blue galaxies, perhaps all of them contributing to the phenomenon.

The CFRS survey showed that massive galaxies had larger star formation rates at $z \sim 1$, and so some of the blue galaxies could be $L \geq L_{|}ast$ galaxies undergoing bursts of star formation. It is also possible that many of them are interacting galaxies. Le Fèvre et al (1997) showed that the number density of merger galaxies (defined as galaxies with companions withina projected radial distance of $10h^{-1}$ kpc, with with a magnitude difference of 1.5 of the brighter galaxy) increases sharply with redshift. Im et al (1995) showed that many faint blue galaxies in the HDF sample had half-light radius of $\theta = 0.2$ arc sec, much less than the expected angular size of non-evolging $L_{|}ast$ galaxies. Many faint blue galaxies are therefore compact star-forming dwarf galaxies.

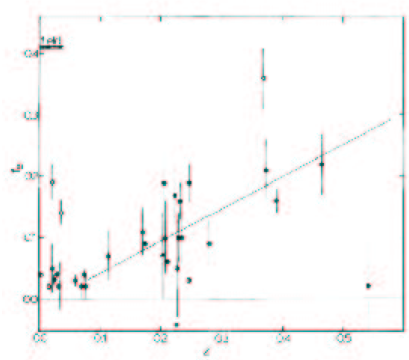

Figure 4: Butcher-Oemler effect (Butcher & Oemler, 1984, ApJ, 285, 426)

Ferguson (1997) argued that it is difficult to distinguish, with present data, different models, say: (1) the faint blue galaxies are star-bursting dwarf galaxies which began to form stars at $z \sim 1$ as they were inhibited from doing so at higher z because of UV backtround radiation (Babul and Rees 1992, MN, 255, 346); (2) faint blue galaxies arise from luminosity evolution of galaxies with redshift. Of course the redshift distribution of faint blue galaxies in these two models are very different : (1) predicts a peak around $z \sim 1$ and (2) predicts a uniform redshift distribution. blue galaxies, but this difference can be distinguishable only at faint magnitudes around $I = 28$. This therefore remains an open problem.

1.5 Evolution in clusters : Butcher-Oemler effect

It has been found that the fraction of blue galaxies in clusters increases with z, which implies that cluster galaxies had a higher star formation rate at higher z. This **Butcher-Oemler effect** is difficult to measure, as it is difficult to remove the foreground spiral galaxies in the field sometimes, and therefore its strength is uncertain. It has been estimated that the fraction increases from less than 5% for nearby populations to as large as 50% for $z \sim 0.4$.

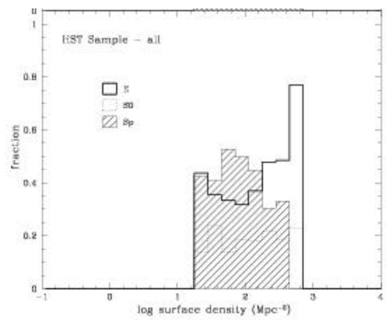

Figure 5: The morphology-density relation for 10 clusters at $z \sim 0.5$ in the same format as Dressler's original morphology-density relation for local clusters.

It is also interesting to compare the morphology-density relation for present-day clusters with that of high-z clusters as found from HST studies (Dressler et al 1997 ApJ 490, 577). It is found that (1) the local surface density of galaxies is higher, perhaps because of the fact that these selected clusters are very rich, (2) the fraction of spiral galaxies at high z is larger than in local clusters, (3) the overall fraction of SO galaxies is very much less than in the local sample, and (4) the fraction of spheroidal galaxies is as large as the local sample.

This again means that elliptical galaxies, even in clustes, were already well formed at high z, which means that it is unlikely that most ellipticals in clusters formed out of mergers of spirals in clusters. It also means that the population of SO galaxies have grown in this redshift range. It is then likely that a number of spiral galaxies have transformed into SO galaxies, perhaps due to galaxy harassment or mergers.

1.6 Lyman break galaxies

With the recent advent of 8-m and 10-m telescopes one has been able to study very high redshift galaxies, which were too faint for spectroscopic studies earlier. A

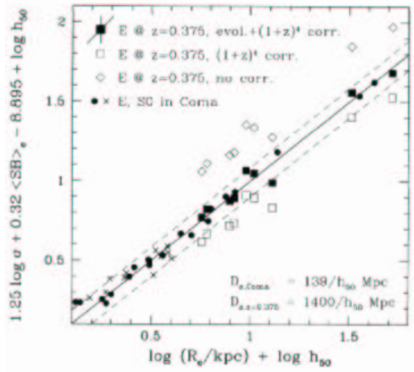

Figure 6: This comparison of the effective physical radius of ellipticals in Coma and in Abell 370 ($z = 0.375$) shows that ellipticals have not evolved much in this redshift range (Bender et al 1998, ApJ, 493, 529).

significant discovery has been made with the use of Lyman-break filters. Spectra of normal galaxies show a break at $912\AA$ as practically no stars are hot enough emit significant radiation in this range. Also these photons can be absorbed in the ISM of host galaxies, and in the intervening IGM. Therefore using appropriate filters, one can look for galaxies which show up in some bands and do not show up in others.

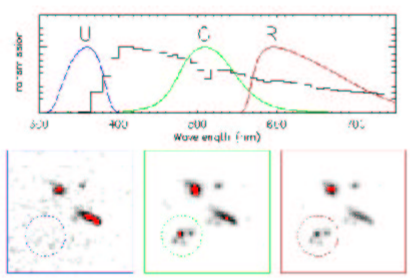

Figure 7: A Lyman-break galaxy is shown in the dashed circle (based on HST images); it is detected in G and R filters and not in the U filter. This filter is sensitive to flux from the blue side of Lyman edge for $z \geq 2.5$.

Spectroscopic studies of these **Lyman-break galaxies (LBG)** have confirmed their photometric redshift estimate. From the rest-frame UV luminosity, one can easily estimate the current star-formation rate a 50–$70h_{50}^{-2}$ $M_\odot$ per yr. This estimate could be a lower limit due to dust extinction, and can be larger than this in reality by factors of 3-7. The estimated comoving density (from ground based study) is $\sim 8.5 \times 10^{-4} h_{50}^{3}$ Mpc^{-3} (for $q_o = 0.5$) at $z \sim 3$, or about the same density of present day L_* galaxies. LBGs from HDF are more numerous (7 x larger) but it could be due foreground galaxies at lower redshift. Since the age of the universe at $z \sim 3$ is about 15% of its present value, then the above star formation rate maintained in the redshift range $4-2$ can make a stellar content of $\sim 10^{11}$ M$_\odot$.

One interesting aspect of LBGs is their clustering in space. Steidel et al (1998, ApJ, 492, 428) discuss sudden 'peaks' in the redshift distribution of LBGs and estimate the associated structures are as massive as local rich clusters, with $M \sim 10^{15}$ M$_\odot$. In the cold dark matter cosmology, if LBGs are identified as high-σ peaks in the density field, then they are expected to be clustered, since rare peaks are usually clustered. Mo & Fukugita 1997 (ApJ, 467, L9) argued that the clustering is consistent with observations, in the context of a ΛCDM universe if LBGs have masses comparable to local $L_| ast$ galaxies.

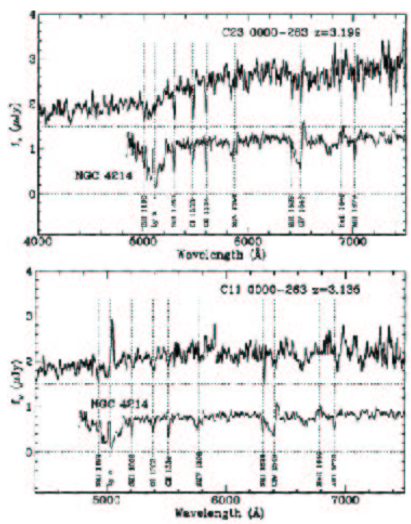

Figure 8: Spectra of two LBG are compared with that of a star-forming knot in the Wolfe-Rayet galaxy NGC 4214 placed at the same redshift (Giavalisco 1998). Notice the P-Cygni profile of CIV line.