Galaxies: Structure, formation and evolution

Lecture 10

Yogesh Wadadekar

Jan-Feb 2024

13 billion years in 2 minutes - Illustris simulation

Simulations closely match observations

HUDF versus Illustris simulation

Simple model of chemical evolution: Assumptions

- at the formation epoch of the stellar population of a galaxy, at time $t = 0$, no metals were present $Z(0) = 0$.
- the galaxy did not contain any stars at the time of its birth, so that all baryonic matter was in the form of gas
- the galaxy is a *closed system* out of which no matter can escape or be added later on by processes of accretion or merger
- the timescales of the stellar evolution processes that lead to the metal enrichment of the galaxy are small compared to the evolutionary time-scale of the galaxy

Chemical evolution

Of the total mass of a newly formed stellar population, part of it is returned to the ISM by 1. supernova explosions and 2. stellar winds. We define this fraction as R, so that the fraction $\alpha = (1 - R)$ of a newly-formed stellar population remains enclosed in stars. Let q be the ratio of the mass in metals which is produced by a stellar population and then returned into the ISM to initial total mass of the stellar population. The yield $y = q/\alpha$ is defined as the ratio of the mass in metals that is produced by a stellar population and returned into the ISM, and the mass that stays enclosed in the stellar population. q and α can be computed from population synthesis models. If $\psi(t)$ is the star-formation rate as a function of time, then the mass of all stars formed in the history of the galaxy is given by:

$$S(t) = \int_0^t \psi'(t) dt'$$

Chemical evolution

The total mass that remains enclosed in stars is $s(t) = \alpha S(t)$. For a closed system, the sum of gas mass $g(t)$ and stellar mass $s(t)$ is a constant

$$g(t) + s(t) = M_b \Rightarrow \frac{dg}{dt} + \frac{ds}{dt} = 0$$

The mass of the metals in the ISM is gZ it changes when stars are formed. Through this formation, the mass of the ISM and thus also that of its metals decreases. Metals are also returned into the ISM by processes of stellar evolution, virtually instantateneously compared to galaxy evolution timescales. Together, the total mass of the metals in the ISM obeys the evolution equation

$$\frac{d(gZ)}{dt} = \psi(RZ + q) - Z\psi$$

Chemical evolution

Since $dS/dt = \psi$, this can also be written as

$$\frac{d(gZ)}{dS} = (R-1)Z + q = q - \alpha Z$$

Dividing this equation by α and using $s = \alpha S$ and the definition of the yield, $y = q/\alpha$, we obtain

$$\frac{d(gZ)}{ds} = \frac{dg}{ds}Z + g\frac{dZ}{ds} = y - Z$$

For a closed box, $dg/ds = -1$ and $dZ/ds = -dZ/dg$, hence

$$g\frac{dZ}{dg} = \frac{dZ}{d\ln g} = -y$$

This implies:

Chemical evolution

$$Z(t) = -y \ln(g(t)/M_b) = -y \ln(\mu_g)$$

where $\mu_g = g(t)/M_b$ is the fraction of baryons in the ISM. We use the initial conditions that at $t = 0, \mu_g = 1$ and $Z = 0$. From this relation, we can now see that with decreasing gas content in a galaxy, the metallicity will increase; in our simple model this increase depends only on the yield y. Since y can be calculated from population synthesis models, $Z(t)$ is well-defined.

How does this compare with observations?

Actually not very well, because galaxies are by no means isolated systems: **their mass continuously changes through accretion and merging processes.** In addition, the kinetic energy transferred to the ISM by supernova explosions causes an outflow of the ISM, in particular in low-mass galaxies where the gas is not strongly gravitationally bound.

Why is this relation still useful?

The G-dwarf problem

Our simple chemical evolution model predicts that about half of the F- and G-main-sequence stars should have a metallicity of less than a quarter of the Solar value, because they formed early and are long lived. This implies that the chemical evolution of our Galaxy must have been substantially more complicated than described by our simple model.

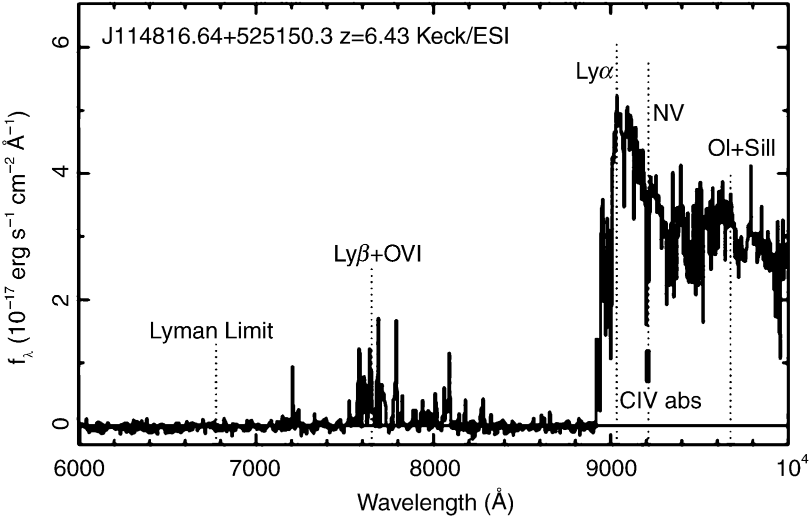
Precision cosmology

For a period of about 5 decades (1950-2000), observational cosmologists were preoccupied with measuring the primary cosmological parameters - H_0, Ω, Ω_m. That era is now over and we have entered the era of precision cosmology. We want to understand how the Universe evolved from a very primitive initial state into what we are observing around us today - galaxies of different morphologies, the large scale structure of their distribution, clusters of galaxies, and active galaxies. We seek to study the formation of stars and of metals, and also the processes that reionised the intergalactic medium.

High redshift galaxies

In 1995, when I was sitting on the other side of the table taking this course, only a few galaxies with $z > 1$ were known; most of them were radio galaxies discovered by optical identification of radio sources. Very distant galaxies are faint, and detecting galaxies at high z is difficult. Blind spectroscopic surveys are not the answer, since galaxies with $R \lesssim 22$ have redshifts $z \lesssim 0.5$, and spectra of galaxies with $R \gtrsim 22$ are only observable with 4-m telescopes and with a very large investment of observing time. Also, the problem of finding a needle in a haystack arises: most galaxies with $R \lesssim 24.5$ have redshifts $z \lesssim 2$, so how can we detect the small fraction of galaxies with larger redshifts?

High redshift QSO

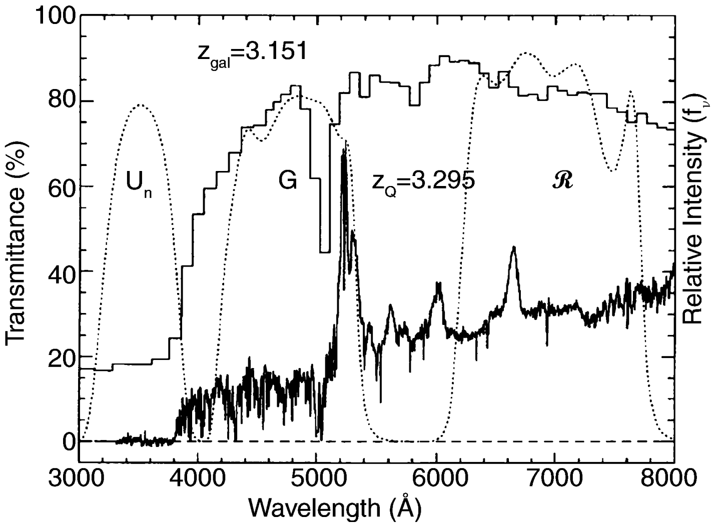


Today hundreds of galaxies and quasars with $z > 6$ have been detected

How to find high redshift galaxies?

- ~~via blind spectroscopy of faint galaxies~~
- via narrow band imaging
- via the **dropout** technique to find LBGs: Since hydrogen is so abundant and its ionization cross-section so large, one can expect that photons with $\lambda < 912$ Å are very heavily absorbed by neutral hydrogen in its ground state. Therefore, photons with $\lambda < 912$ Å have a low probability of escaping from a galaxy without being absorbed. Intergalactic absorption also occurs.

The dropout technique

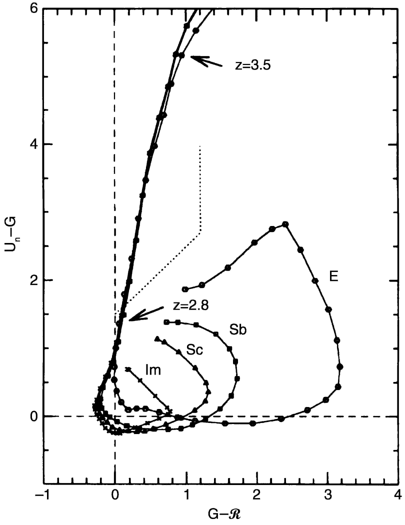


Method first extensively applied in 1996 by Chuck Steidel (Caltech)

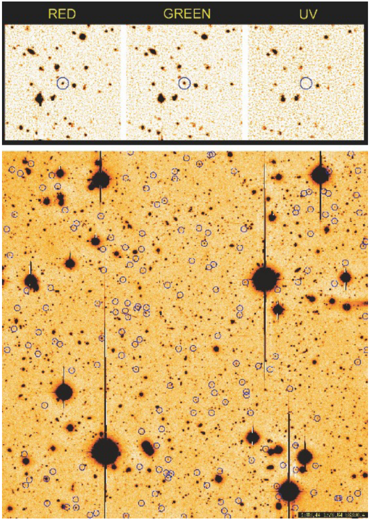
Question

A galaxy has $U - B = -0.2$, another has $U - B = 0.1$. Which galaxy is redder?

Does it work for all Hubble types?

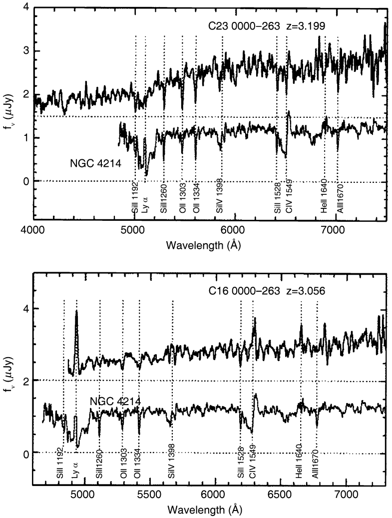


U band dropouts

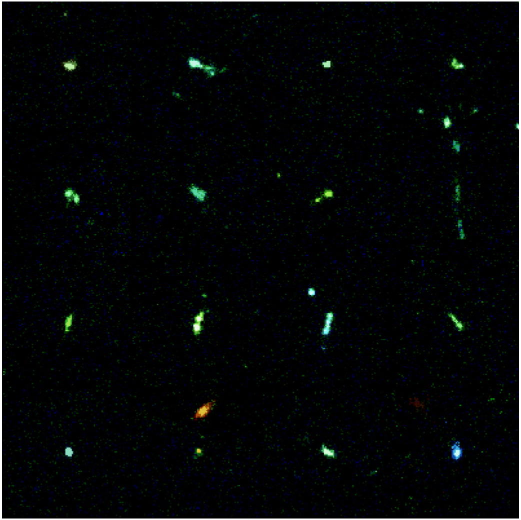


LBG candidate density: 1 arcmin^{-2}

Spectrum of two dropout galaxies



U band dropouts at $z \sim 3$



Wadadekar et al. (2006)

LBG selection bias

LBG color selection is biased towards strongly star-forming galaxies at high redshift. Why?

Question

Do you expect star-forming galaxies to be strongly clustered?

Where do LBGs lie?

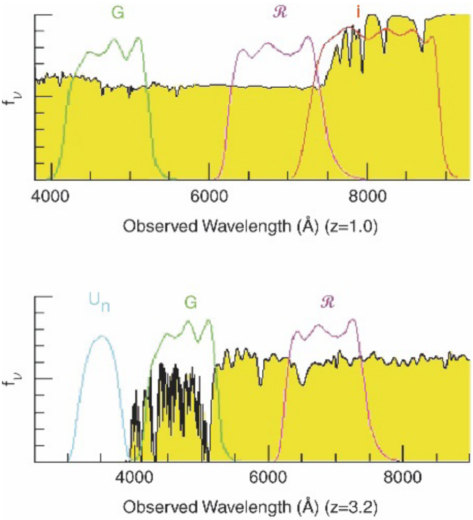
LBGs are rare objects and thus correspond to high-mass dark matter halos. Comparing the observed correlation length r_0 with numerical simulations, the characteristic halo mass of LBGs can be determined, yielding $\sim 3 \times 10^{11} \mathrm{M}_\odot$ at redshifts $z \sim 3$, and $\sim 10^{12} \mathrm{M}_\odot$ at $z \sim 2$. The correlation length is observed to increase with the luminosity of the LBG, indicating that more luminous galaxies are hosted by more massive halos, which are more strongly biased than less massive ones.

What are the local counterparts of LBGs?

If these results are combined with the observed correlation functions of galaxies in the local Universe and at $z \sim 1$, and with the help of numerical simulations, then this indicates that a typical high-redshift LBG will evolve into an **elliptical galaxy** by today. LBGs also lie at the centre of protoclusters.

LBGs drive strong galactic winds

Using the 4000 Å break to find galaxies at $z \sim 1$



What kind of galaxies will this selection technique find?

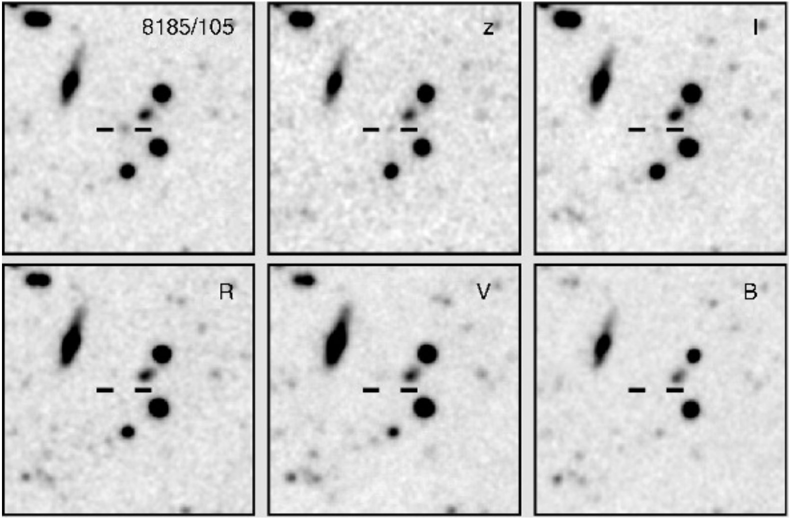
LBGs at low redshift - the redshift desert

We find galaxies at $z \sim 3$ more easily than at $z \sim 1 - 2$. The region between $1 < z < 3$ is called the redshift desert Why?
See article by Renzini and Daddi ESO Messenger 137, 45 for details.

LBGs at low redshift

In recent years GALEX has found 2 populations of low redshift star-forming galaxies. One compact population corresponding to high-z LBGs and a non-compact star-forming population of large disk galaxies.

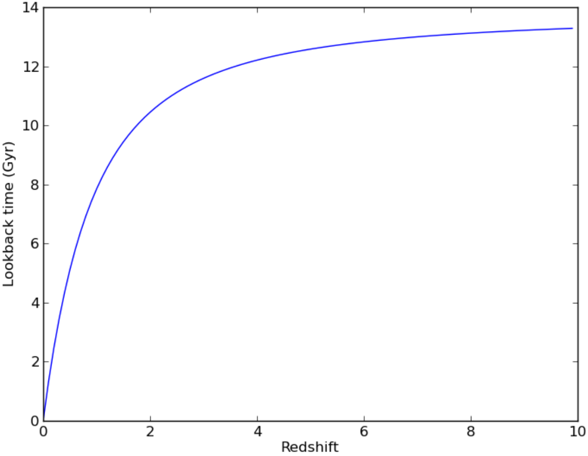
Higher redshift LBGs $z = 5.74$



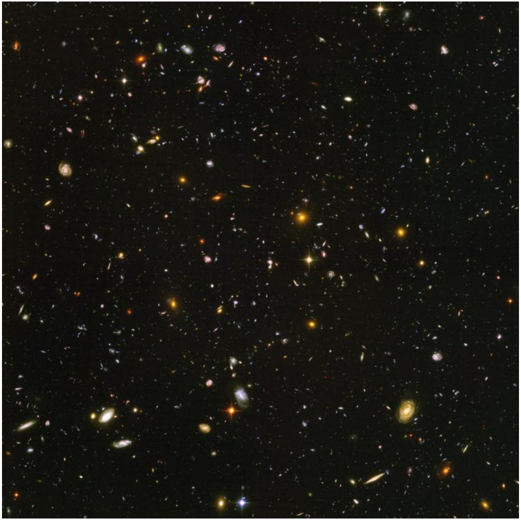
Hubble Deep Field North- Ergodic principle

followed by GOODS, GEMS, COSMOS, CANDELS

Lookback time WMAP9 cosmology



Hubble Ultra Deep Field

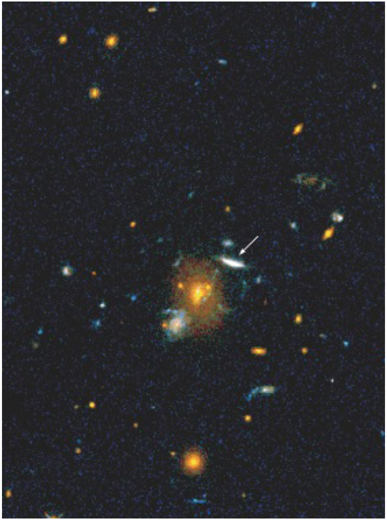


Results from deep fields

Lyman-break galaxies at $z \sim 6$ seem to have stellar populations with masses and lifetimes comparable to those at $z \sim 3$. This implies that at a time when the Universe was 1 Gyr old, a stellar population with mass $\sim 3 \times 10^{10} \mathrm{M}_\odot$ and age of a few hundred million years (as indicated by the observed 4000 Å break) was already in place. This, together with the apparently high metallicity of these sources, is thus another indication of how quickly the early Universe has evolved. The $z \sim 6$ galaxies are very compact, with half-light radii of ~ 1 kpc, and thus differ substantially from the galaxy population known in the lower-redshift Universe.

LBGs are very faint. Is there some geometric configuration that will make their detection easier?

Finding distant normal galaxies magnification ~ 30



Cluster z=0.37, galaxy z=2.72. Most distant normal galaxy known.

To learn more on LBGs

See review by Giavalisco et al. (2002) in ARAA

Starburst galaxies

Milky Way is forming stars with a rate of $\sim 3M_{\odot}$/yr, the star formation rate in starburst galaxies can be larger by a factor of more than a hundred. Dust heated by hot stars radiates in the FIR, rendering starbursts very strong FIR emitters. Many of them were discovered by the IRAS satellite (IRAS galaxies"); they are also called ULIRGs (ultra-luminous infrared galaxies). Negative k-correction

Negative K correction- Arp 220