Galaxies: Structure, formation and evolution

Lecture 16

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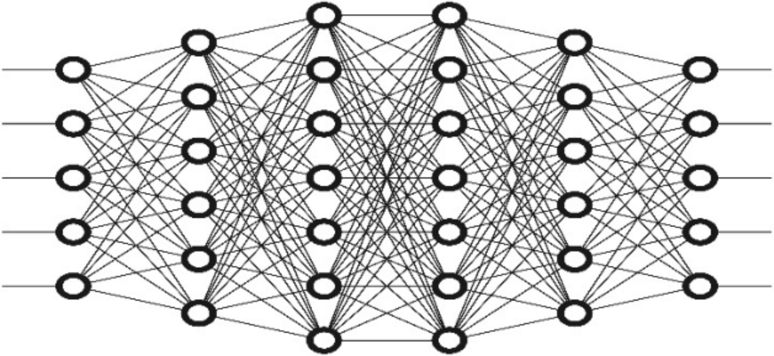
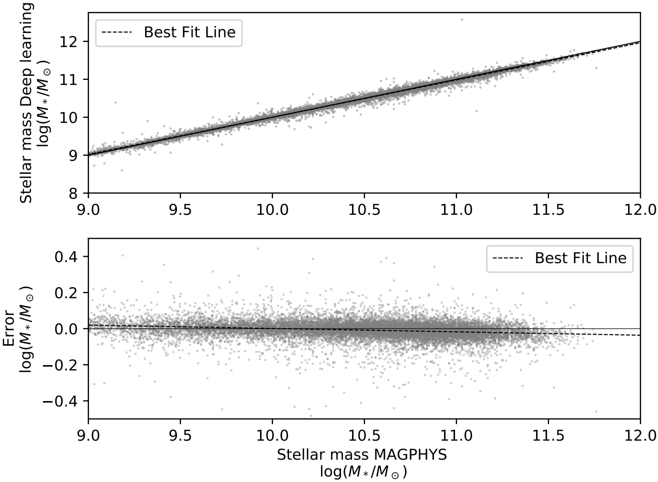
SPS via deep learning



Advantage and disadvantage of the deep learning approach

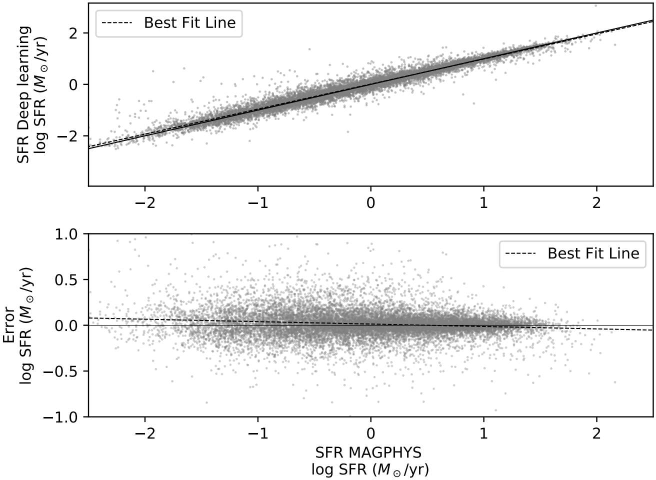
- Once trained, the DL network is very fast. Able to obtain outputs for 20000 galaxies in less than a second.
- Since the deep learning model learns to imitate the SPS model, it can never perform better than the model.
- But the high speed is still useful, given the size of upcoming galaxy surveys - Rubin/LSST will observe $\sim$ 20 billion galaxies.
- A hybrid approach is also possible - use deep learning to narrow down the parameter space and then only fit SPS models only within that restricted space.

Predicting the Stellar Mass



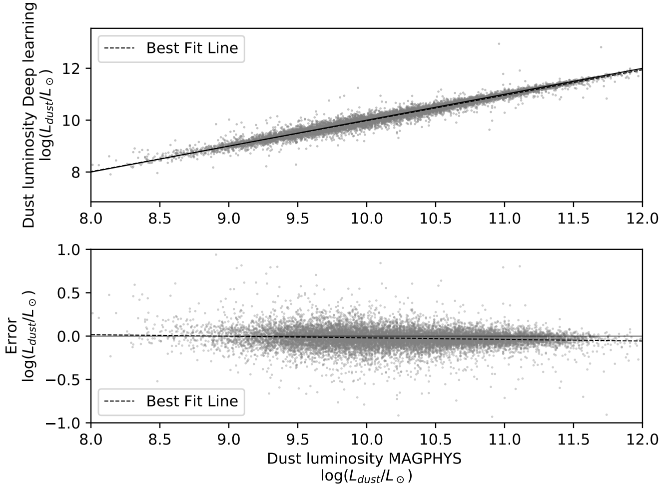
Surana, Wadadekar et al. (2020)

Predicting the SFR



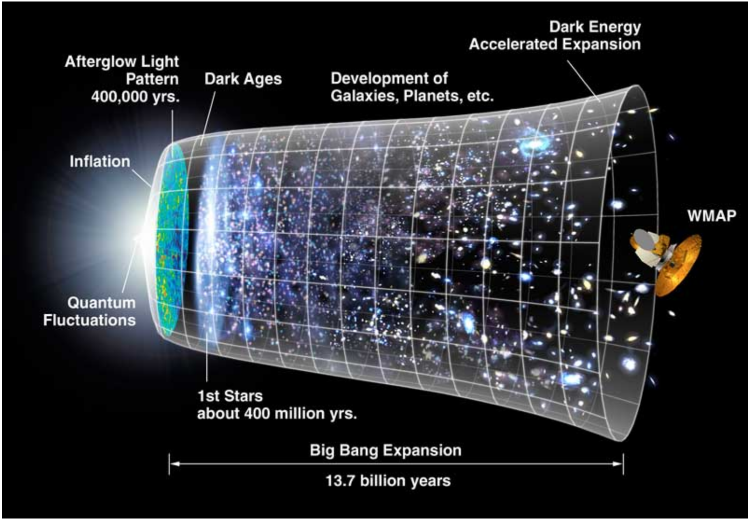
Surana, Wadadekar et al. (2020)

Predicting the dust luminosity



Surana, Wadadekar et al. (2020)

A brief history of the Universe



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.

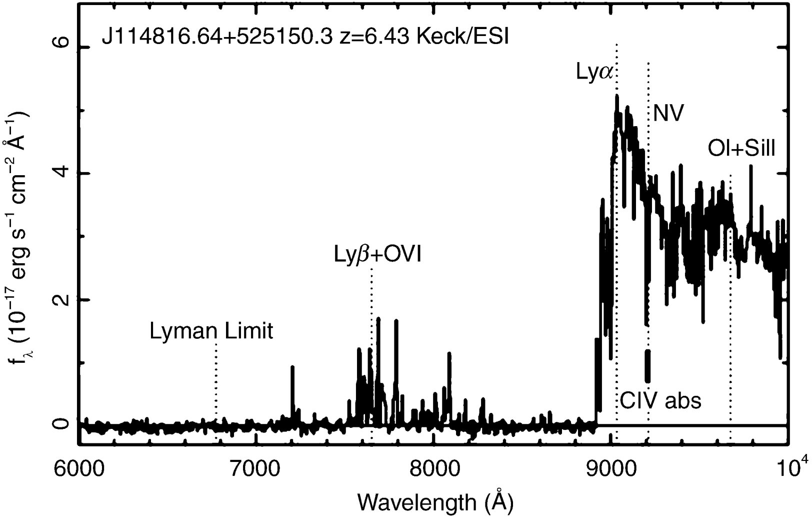
Precision cosmology

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

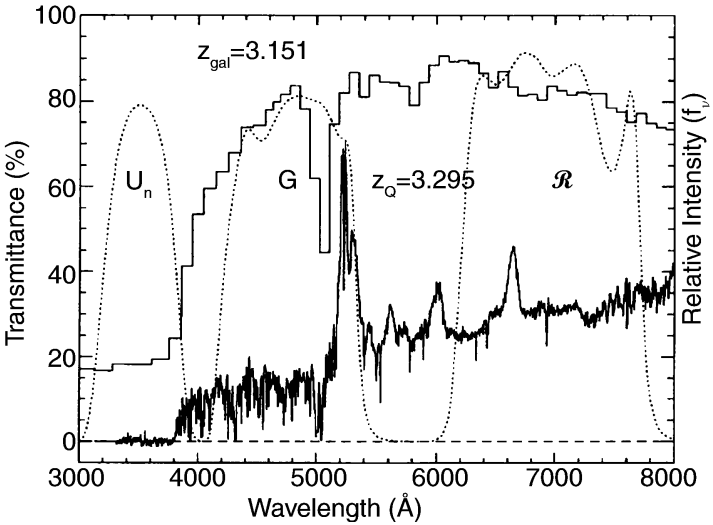


Today hundreds of galaxies and quasars with $z > 6$ have been detected

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