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GALAXY EVOLUTION

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1. Introduction

Galaxy evolution is one of the most active research areas in astrophysics. In the preface of his famous book *The Realm of the Nebulae* (1936), Edwin Hubble wrote: 'the book is believed to furnish an authentic picture of a typical case of scientific research in the process of development'. This statement is still true today for galaxy evolution.

It is widely accepted that galaxy evolution occurs within the framework of a Λ Cold Dark Matter cosmology; that is to say that clustering and merging is how galaxies gain in mass, and can also determine the shape and structure of galaxies.

Galaxy formation and evolution is a complex combination of hierarchical clustering, gas dissipation, merging and secular evolution. While gravity drives the bottom-up assembly of cosmic structures, gas cools at the centers of dark matter halos forming a disk that acquires angular momentum through tidal torques from nearby structures. Gas eventually fragments and forms stars. The mass and the angular momentum that settle into the disk are assumed to be fixed fractions of the mass and the angular momentum of the halo respectively. Since the mass and the size of the halos are tightly linked to the density of the Universe at the time the halos were formed, disk galaxies are expected to grow with cosmic time.

For reviews and books on this subject, see Avila-Rees 2006; Kormendy & Kennicutt 2004; Spinrad 2005; Keel 2002.

In this paper I would like to address the following question: What observational evidences do we have for galaxy evolution? Before doing so I will introduce some important concepts regarding galaxy structure and properties.

I will only focus on galaxies in the local universe. We can ask ourselves what is the importance of their study. As it was pointed out by Sandy Faber in the Conference Summary of the first Vatican meeting on formation and evolution of galaxy disks held in 2001, galaxies are the crossroads of astronomy because they look up to cosmology and they look down to the interstellar medium and star formation. They are the true link between the present universe we observe and the properties of the early universe. Galaxies evolve according to the initial and boundary conditions given by cosmology. As Vera Rubin has pointed out nearby galaxies are the best laboratories to test a 'nearby cosmology'. The study of galaxies is crucial when trying to connect our knowledge of the universe as a whole with the formation of stars and planets.

2. Galaxy components and properties

A galaxy is a system of stars, gas, dust and dark matter gravitationally bound together with a mass ranging from 10 million to 1000 billion times that of the sun. The stellar component is distributed in a spheroidal component (the bulge and the halo) and in a flat component (the disk). Some spiral galaxies show a bar and ring structures in the disk component. Gas and dust are the material between stars and it is called interstellar medium. This is the material from which new stars form. We don't know yet the nature of dark matter. We have detected and weighted the dark matter and we also know that it does not emit light. We do know that dark matter is located in the galaxy halos.

These galaxy components (stars, interstellar medium, and dark matter) vary from galaxy to galaxy and define the morphology of a galaxy. Galaxies have a disk component and a spheroidal component. Stars in the disk are bluer and younger than stars of in the spheroidal components.

Edwin Hubble classified galaxies in spirals and ellipticals. He also noticed that there is small fraction of galaxies that can be grouped in a third major type called irregular galaxies.

With the advent of a wealth of data coming from surveys like Sloan Digital Sky Survey, COMBO-17, etc., it has become clear that there is a bimodal distribution of galaxy colors at all redshifts[1] $z < 1$ (see Bell *et al.*

[1] The redshift is usually characterized by a dimensionless quantity called z. The largest observed redshift, corresponding to the greatest distance and furthest back in time, is that of the cosmic microwave background radiation; the numerical value of its redshift is about z=1089 and z=0 corresponds to present time. The correspondence between redshift and time depends on the cosmological model adopted.

2007 and references within). It is possible to identify a red sequence of non-star forming galaxies and blue cloud of star-forming galaxies. According to this scheme ellipticals and early type spirals (spirals with a prominent bulge) would be part of the red sequence while late-type spirals (spirals with a small bulge and rich in gas and dust) and irregulars would form the blue cloud.

3. Galactic time scale

Galaxies are tracers of cosmic evolution over the last 13 billion years. Galactic time scale is the combination of two clocks. One time scale is the cosmological one (the Hubble time, i.e. basically the age of the universe) and the other scale is related to stellar evolution. The combination of both gives rise to galaxy evolution.

I would like to recall an observational obvious fact in the study of galaxy evolution. We never see an object to evolve from or to and we only have a 'snapshot' in time.

4. Which properties of galaxies can evolve and be measured?

Is there any way of measuring or detecting galaxy evolution? To answer this question we need to find galaxy properties that can evolve and be measured.

Due to the nuclear stellar evolution we expect to observe evolution in the stellar content which is shown in the change of color and luminosity measurable in galaxies at different redshifts. Intimately connected with the evolution of the stellar content is the evolution of the gas mass fraction. We expect a 'noisy' decline of the gas mass fraction with time, given the evidence for clustering mergers of gas rich systems and ejection to the interstellar medium of material released by supernovae. Since generations of stars continually recycle the same galactic matter through their cores, chemical evolution is an inevitable by-product of continual star formation.

Galaxies also evolve or transform due to the interaction with other galaxies. Galaxies are not exactly 'island universes'; they don't evolve in isolation. Spiral galaxies tend to collect in groups of galaxies, which contain up to several dozen galaxies. Elliptical galaxies are more common in clusters of galaxies. Mergers are an important factor that drives galaxy evolution. Merger rates increase with cosmic lookback time when the universe was smaller and galaxies were closer.

5. Evolution of the stellar content

One way to quantify galaxy evolution is through the calculation of the growth of stellar mass in galaxies.

As Bell *et al.* (2007) have pointed out, recent observations have demonstrated a significant growth in the integrated stellar mass of the red sequence. In their paper, they use the COMBO-17 photometric redshift survey in conjunction with deep Spitzer 24 mm data to explore the relationship between star formation and the growth of stellar mass. They calculate star formation rate (stars formed per unit of time in M_{sun} yr^{-1}) functions in four different redshift slices between z=0 and z=1, also splitting them into contributions from the red sequence and blue cloud for the first time. They find that the growth of stellar mass since z=1 is consistent with the integrated star formation rate.

6. The cosmic star formation history: galaxy evolution in the act

The cosmic star formation history is one of the primary goals of galaxy formation and evolution studies. The modeling of galaxy evolution requires a better understanding of the relationships between large-scale star formation rate and the physical properties of the parent galaxies.

Star forming galaxies in the local universe provide vital clues to the evolutionary properties of galaxies and the physical processes that derive that evolution. In the last 15 years hundreds of nights on the largest telescopes in the world are being used to measure the star formation properties of distant galaxies and the star formation history of the universe. Ironically, until few years ago, we had a more complete inventory of star formation rates for galaxies with redshifts ($z>3$) than for galaxies in the local universe ($z<0.03$).

Luckily, ideal samples, which meet these requirements, now exist. The Local Volume Legacy survey (Lee *et al.* 2008) is a project that looks through data already collected by the Spitzer Space Telescope for a sample of 258 galaxies located within 11 megaparsecs (about 36 million light years; on the scale of a visible universe that extends nearly 14 billion light years across, this counts as the 'local' volume of space). This included all known galaxies within the closest 3.5 megaparsecs, and a sampling of spiral and irregular galaxies from the larger and more representative region.

The goal is to produce a census of the local galactic neighborhood, with data in many different colors, including even the faintest galaxies, taking advantage of Spitzer's high resolution and ability to measure wavelengths of light that cannot be seen from the surface of the Earth. These data will then be compared with data on the same objects from a number of other surveys, using both large Earth-based telescopes.

This Local Volume Legacy project will fill in critical gaps in the current Spitzer coverage of the galaxies in the Local Volume, providing spectral energy distribution coverage from the ultraviolet to the far-infrared, and thus supplying the astronomical community with a core archival data set on the galactic neighborhood.

7. Chemical evolution

Another property that we can measure to monitor in galaxies is the abundant of heavy elements (metallicity) in the stellar population and in interstellar medium. Although our understanding of the actual physical process of star formation and its interaction with interstellar medium is acutely limited, models and observations have shown the evolution of metallicity in the galactic structural components (disk, bulge, and halo). For instance the enriched gas from the halo can pollute the bulge stars and the later forming disk during the process of galaxy formation.

As Tremonti *et al.* (2004) have pointed out stellar mass and metallicity are two of the most fundamental physical properties of galaxies. Both are metrics of the galaxy evolution process, the former reflecting the amount of gas locked up into stars, and the latter reflecting the gas reprocessed by stars and any exchange of gas between the galaxy and its environment. Understanding how these quantities evolve with time and in relation to one another is central to understanding the physical processes that govern the efficiency and timing of star formation in galaxies. They have presented the mass-metallicity relation for 53,000 star-forming galaxies in the Sloan Digital Sky Survey at z~0.1. Their results imply that metallicity is not a straightforward metric of galaxy evolution because metals can escape galactic potential wells.

8. Dynamical evolution. Galaxy transformation. Secular Evolution

Changes in the galactic structure are the result of the exchange energy and angular momentum between the different components: disk, bars, and rings and with environment through interactions and mergers.

Transformations in morphology, and not just in stellar content, can be observed and interpreted through computer simulations. Two processes rule galaxy evolution, the hierarchical clustering process and the secular evolution. Hierarchical clustering is a violent and rapid mechanism that dominated the growth of galaxies at early times of the universe. On the other hand, secular evolution is slow but will be dominant in the future universe.

Which signs can we find in galaxies that can lead us to think that there is or there was a merger in act? These are some:

– Images of pairs of galaxies may reveal tails and bridges of stars and gas that are signs of interactions.
– Counter-rotation. In some galaxies that otherwise look pretty 'normal', there is evidence that one of the components is counter-rotating or rotating orthogonally to the other component. For example, in a stellar disk, the inner disk is rotating in the opposite direction of the outer disk, or the spheroidal component regarding the disk component.
– Structural details in elliptical galaxies. For instance, elliptical galaxies with dust lanes have undergone a major event at some point in their evolution. The younger population of stars in these galaxies could have formed at a later stage of the evolution of the galaxy through either a merger event or a secondary in situ star-formation burst by the acquisition of gas from the environment.
– Observations show that collisions trigger bursts of star formation.
– N-body simulations of such collisions confirm that the merger of two spiral galaxies can form an elliptical galaxy.

Series of simulations by Debattista *et al*. (2006) to study the secular evolution of disk galaxies in a ΛCDM universe have shown that during disk assembly, secular evolution must have played a role in shaping the structure of disk galaxies as we see them at z=0. Bars can drive a substantial redistribution of mass and angular momentum in the disk. A possible product of bar-driven evolution is the formation of a bulgelike component.

Which structural properties of present-day disk galaxies are primordial and which are the result of internal evolution? Observations by Lilly *et al*. (1998) suggest that the structural properties of disk galaxies have not changed substantially since then. If the quiescent phase of disk assembly starts early, as current cosmological simulations suggest, secular evolution might have already been operating by z~1.

There is also recent evidence for a rapid secular galaxy evolution. Genzel *et al*. (2008) have provided observational evidence that massive bulges may have formed on a timescale of 1–3 10^9 years through secular evolution from gas-rich, turbulent disks.

They speculate that the thick, old stellar disks seen in the Milky Way and nearby galaxies are the remnants of this phase.

9. Final thoughts

These are not conclusions; it would be conceited on my side to do so with the abundant literature in this field that I have not covered. I have only tried to show in this paper that we have a coherent picture for the evolving process in galaxies with robust observational evidence well integrated and understood in the framework of the ΛCDM scenario.

There are still some unsolved problems for the ΛCDM scenario such as the nature of dark matter, halo density profiles of dark matter, the excess of substructure (satellite galaxies), the early formation of massive red elliptical galaxies, size of and angular momentum of the disks, etc. These important issues are not discussed in this paper.

There is also a need of a better understanding of the star formation physics that can explain the relationship between the star formation properties that we observe at the galactic scale and the properties and physical processes that we observe at a smaller scale.

Our knowledge of galaxy evolution showcases our understanding of cosmology, stellar evolution, and galaxy dynamics. It is an excellent example of how scientific knowledge achieved independently can be put together to shed light on a complex process that involves other physical processes at different scales. Our scientific understanding of galaxy evolution is still evolving…

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