Galaxies and Stellar Populations

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Overview of talks

Lecture 1 ("static" view of nearby gals):

- Historical background
- Redshift surveys
  - e.g. 2dFGRS, SDSS
- Galaxy morphologies
  - ellipticals versus spirals; radial profiles
- Galaxy colours
  - evolution of stellar populations
- Galaxy scaling relations
  - e.g. fundamental plane; Tully-Fisher
- Measuring star formation rates
- The role of environment
Overview of talks

Lecture 2 (galaxy formation & evolution)

• Hierarchical galaxy formation
  → Origin of galaxy types

• Galaxy luminosity functions
  → Schechter functions; characteristic luminosities
  → Origin and evolution of the luminosity function

• Evolution of galaxies
  → Cosmic star formation history
  → Early formation of ellipticals
  → Downsizing
Things I won’t talk about
(or only briefly touch upon)

Clustering of galaxies & large-scale structure:
• Galaxies trace dark matter \Rightarrow since dark matter is clustered, so are galaxies. See Carlos Frenk’s talk.

Dark matter:
• The mass of galaxies can be dominated by dark matter, as evidenced by e.g. flat rotation curves.

Detailed structure of our galaxy (& others):
• Thin & fat disks, bulge, halo, bars, star clusters, stellar orbits, streams, etc

Supermassive black holes, and active galaxies
• See talk by Andy Fabian
Discovery of galaxies

Orion

Andromeda
In 1924 Hubble measured the distances to nebulae and showed that (although some were nearby star forming regions), more were distant systems of stars.

1 galaxy = 100 billion stars
Galaxies everywhere

30 arcminutes (= 0.5 deg)

At 20th magnitude (the limit of photography on a 1m telescope) most objects are galaxies.
The Hubble Deep Field

Extremely deep image (to 28th magnitude) of a small area of sky - about 2.7 square arcmins.

Over 100 billion galaxies over the whole sky

All different sizes, shapes, and colours......
Measuring redshifts

Spectroscopy reveals emission and absorption lines of atoms. These signatures allow redshift ($z$) to be measured.

$$z = \left(\frac{\lambda_2}{\lambda_1}\right) - 1$$

From Hubble’s Law, $v = H_0 d$, we then get the distance.
Redshift surveys

Measuring redshifts for galaxies on a strip on the sky, gives a ‘slice of the universe’
The 2dFGRS has measured the redshifts of nearly 250,000 nearby galaxies in two narrow strips of sky.
Sloan Digital Sky Survey (SDSS)

SDSS is an on-going 5-band imaging plus spectroscopic survey, aiming to take spectra of $10^6$ galaxies ($z_{med} \sim 0.1$)
Classifying Galaxies

Hubble decided to classify galaxies on the basis of their morphology (his “Tuning Fork” diagram):

- Ellipticals
  - E0
  - E5
  - S0

- Spirals
  - Sa
  - Sb
  - Sc
  - larger bulge, less dusty gas, tighter spiral arms

- Barred spirals
  - SBa
  - SBB
  - SBC

- Irregulars

+ Irregulars
de Vaucouleurs profiles

The radial surface brightness profiles of many elliptical galaxies can well-approximated by an “r^{1/4}” law, first proposed by de Vaucouleurs in 1948:

\[ I(r) = I_e \exp(-7.67[(r/r_e)^{0.25} - 1]) \]

where \( I_e \) is the surf. bright. at the half-light radius \( r_e \)
Deviations from the $r^{1/4}$ law

The de Vaucouleur law is only an empirical model, not an exact formula. Galaxies deviate from it, e.g.

- Some ellipticals have flat cores, others are cuspy
- cD galaxies (at cluster centres) have extended haloes

“Sersic” profiles ($\exp(-r^{1/\eta})$) law, with variable $\eta$) allow more general fits. Massive gals tend to have higher $\eta$. 

Inner radial profiles of two ellipticals: one cuspy and the other with a flat core.
Spiral disks: exponential profiles

The surf. brightness profiles of spirals are best fitted as the sum of two components (whose relative weights vary):

- **Bulge**: fitted with a de Vaucouleurs law
- **Disk**: fitted as an exponential disk, \( \exp(-r) \), Sersic index \( n=1 \)

Examples of radial fits to spiral galaxies
Galaxy colours

As well as different morphologies, galaxies exhibit a wide range of colours.

To understand the origin of galaxy colours it is necessary to first look in some detail at the spectra and lifecycles of the stars which make up the galaxies.
The luminosity - temperature diagram of stars was produced by Ejnar Hertzsprung in 1911 and independently by Henry Russell in 1913.

High mass stars 'live fast, die young'. They are much brighter, bluer, and shorter lived than lower mass stars. ($L \propto M^{3.5}$ to first order, so lifetime $t \propto M/L \propto M^{-2.5}$)
The more massive, hotter stars (esp. O and B classes) are especially brighter and bluer, at wavelengths shorter than 4000 Ang.
Galaxy spectral energy distributions

With our knowledge of stellar spectra and lifetimes, we can model the colour of a galaxy at any age, for any given star forming history. (e.g. Bruzual & Charlot, PEGASE...)

Young star forming galaxies are blue; old galaxies are red.

Figure: Spectral energy distribution evolution following an instantaneous burst of star formation.
Morphology vs colour classification

Note that ellipticals are much redder than spirals: classification by colour instead of morphology would have lead to similar broad classes.
Local galaxy redshift surveys demonstrate that galaxies separate well into two distinct classes:

1) High mass, passive, high surface brightness, galaxies.
   [largely bulge-dominated]

2) Lower mass, star forming, low surface brightness galaxies
   [largely disk-dominated]
Scaling relations of galaxies

The properties of galaxies (sizes, masses, surface brightnesses, velocity dispersions, etc) are not random, but follow very tight scaling relations.

- The fundamental plane
- The mass-metallicity relation
- The colour-magnitude relation
- The Tully-Fisher relation
- The black-hole mass vs bulge mass relation
The fundamental plane

For ellipticals (and spiral bulges), the radius, surface brightness, and velocity dispersion are tightly correlated:

\[ r_e \propto \sigma^{1.2} I_e^{-0.8} \]

Note that since

\[ M \propto r_e \sigma^2 \]
\[ L \propto I_e r_e^2 \]

then the FP basically says that:

\[ M/L \propto M^{0.25} \]

The fundamental plane for ellipticals in the Coma cluster (Jörgensen et al 1996).
Mass-metallicity relation

High mass galaxies have higher metallicities than lower mass galaxies.

This is believed to be because low mass galaxies lose their metals in supernova winds.
Colour-magnitude relation

Ellipticals (& spiral bulges) also follow a colour-magnitude relation, with very little scatter.

The slope is mostly due to the mass-metallicity relation (although there may also be age effects).

Figure: U-V vs V colour-magnitude relation for the Coma cluster (Terlevich et al 2001).
Early formation of ellipticals

The small scatter in the colour-magnitude is remarkable.

If only 1% of the mass of a galaxy is recently formed stars, these will dominate the blue light of the galaxy and introduce much scatter into the C-M relation.

The lack of scatter implies near-simultaneous formation of ellipticals, at high-z.
Tully-Fisher relation for disks

Spiral disks show a tight relation between their luminosity and their circular velocity. Empirically we find: \( L \propto v^4 \)

The correlation is not surprising since both \( L \) and \( v \) are functions of galaxy mass - but the exact power law does not drop easily out of theory.
It has recently been discovered that essentially all nearby galaxies have a supermassive black hole at their centres, with $M_{\text{black-hole}} \propto M_{\text{bulge}}$. 

![Graph showing the relationship between black-hole mass and bulge mass.](image)
Black-hole mass vs bulge mass

It has recently been discovered that essentially all nearby galaxies have a supermassive black hole at their centres, with $M_{\text{black-hole}} \propto M_{\text{bulge}}$

This implies that the build-up of galaxies and their central black holes are tightly coupled.

A popular current hypothesis for is that feedback effects from AGN activity associated with growing black holes can control the growth of their surrounding galaxies [see Andy Fabian's talk]
Star-formation indicators

The colour of a galaxy gives a guide as to whether it is forming stars or not, but we are often also interested in the rate at which a galaxy forms stars.

We have a number of ways to measure this:

1. Emission line luminosity (usually Hα or [OII]).
   - Emission lines are produced when atoms/ions are excited by ionising photons. The number of ionising photons is proportional to the number of young massive stars, and hence to the SFR.
2. Radio luminosity

- Star forming galaxies emit at radio wavelengths due to the radio synchrotron emission of their supernovae. The rate of supernovae is proportional to the SFR.

3. Rest-frame UV luminosity

- Because the only stars that emit significantly in the rest-frame UV are the most massive, shortest lived ones, the rest-frame UV luminosity measures the number of these, and hence the current SFR. This indicator is widely used at high redshift.
Beware the role of dust

Dust particles within galaxies, particularly associated with star forming regions, absorb ultraviolet light

⇒ dusty galaxies appear redder and fainter.

This needs to be corrected for.

Further, the absorbed energy is reprocessed and emitted thermally at infrared wavelengths.

Rapidly SF galaxies can therefore emit copious amounts of energy at IR wavelengths. These are known as ULIRGs (ultra-luminous infrared galaxies). They are often merging galaxies. At high redshifts they are sub-millimetre galaxies.
4) The IR (or sub-mm) luminosity of a galaxy is dependent on the SFR (though with a temperature dependence).
The Role of Environment

Galaxy clusters provide evidence that some galaxies properties are shaped by environment

- cluster centers are dominated by luminous ellipticals
- these all have similar red colours, indicating a lack of recent SF
- the central cluster galaxy may have unique properties.
Suppressed star formation

The red ellipticals dominating clusters indicate that star formation is suppressed there. What causes this is one of the key questions in astronomy today.

Nature?
• galaxies that form in clusters form earlier, and stop forming stars at an early epoch

Nurture?
• galaxy mergers (gas used in star-forming burst)
• gas lost through repeated tidal interactions with other galaxies (“galaxy harassment”)
• gas lost through ram-pressure stripping
• gas lost through evaporative stripping
Suppressed star formation

Interestingly, studies with 2dFGRS show that SF already begins to be suppressed when the galaxy surface density exceeds $\sim 1$ gal/Mpc$^2$.

This density is lower than that of cluster outskirts, so whatever the suppression mechanism is, it must occur even in groups.

Tidal interactions?

Figure: star formation is suppressed in all dense environments, above 1 galaxy per Mpc. (from 2dFGRS; Lewis et al 2002)
cD galaxies

The central galaxies of rich clusters often have a special nature: multiple nuclei, and extended haloes reaching out to hundreds or thousands of kpc.

This is due to cannibalism of other gals & stripped gas
Ultra-compact dwarfs

In the last few years, a new class of galaxy has been found in the Fornax cluster: “Ultra-compact dwarfs”

These are barely resolved galaxies, which appear to be galaxy bulges for which the entire disk component has been stripped off by the cluster environment.
Galaxies and Stellar Populations

Evolution of the galaxy population
Formation of Galaxies

Monolithic Collapse versus Hierarchical Clustering
Hierarchical build-up of structure

Simulation of structure formation (Hoekstra)
Numerical galaxy formation

Need to decide where and when stars form - not easy

$\Lambda$CDM at $z = 0.0$

8$h^{-1}$ Mpc thick slice

Benson, Cole, Frenk, Baugh & Lacey (1999)
Predictions of theory

Bright galaxies today were assembled from smaller bluer galaxies at high redshift.

This is confirmed by observations.

\( \Lambda \text{CDM} \ CR: z=2.4 \ SFR > 5 \ M_\odot/h/\text{year} \)

Credits: Mathis, Lemson, Springel, Kauffmann, White and Dekel.
Formation of a spiral

Movie Credit: Matthias Steinmetz
Formation of an elliptical

Movie Credit: Matthias Steinmetz

View from above            View from side
Formation of an elliptical

Movie Credit: Josh Barnes, John Hibbert
Galaxy luminosity function

If we look at galaxies at different redshifts, we will often look at galaxies whose other properties (e.g. luminosity) are not directly matched. It is therefore important to carry out comparisons very carefully.

The luminosity function measures the co-moving number density of objects, \( \phi(L) \), in some range (usually logarithmic) of luminosity.

\[
dN = \phi(L) \, d(\log L) \, dV
\]

\( \phi(L) \) lets us assess what galaxies are present in the nearby Universe. It provides a robust handle to look at difference between different set of galaxies. (Not only with z, but also galaxy type, environment...)
Measuring the space density

For a single galaxy, the space density is simply given by the inverse of the volume in which it could be detected.

\[ \varphi(\text{gal}) = \frac{1}{V_{\text{gal}}} = \frac{1}{(V_{\text{max}} - V_{\text{min}})} \]

For a sample of galaxies, the space density of objects of a given luminosity can be estimated (a maximum likelihood estimator) as:

\[ \varphi(L) = \sum \frac{1}{V_{\text{gal}}(i)} \]
The galaxy luminosity function is well approximated by a *Schechter function* (Schechter 1976)

\[ d\phi(L) = \Phi_* \left( \frac{L}{L_*} \right)^\alpha \exp\left( - \frac{L}{L_*} \right) \frac{dL}{L_*} \]
\*L\* is roughly the luminosity at which most of the light of galaxies is emitted. The Milky Way is roughly of \*L\* luminosity.
What causes the shape of the LF?

The shape of the luminosity function is very different from the mass distribution of dark matter haloes.

Too few bright and too few faint galaxies
What causes the shape of the LF?

Low masses:
Heating by ionising photons & gas loss in supernovae make SF inefficient in small haloes.

High masses:
Origin of feedback is less certain, but recent indications are that it is AGN.
There are two simple ways in which a LF can evolve: changing the space density of galaxies, or changing the luminosity of each galaxy.

**Pure density evolution:**
\[
\phi(L, z) = f(z)\phi(L, z = 0)
\]

**Pure Luminosity evolution:**
\[
\phi(L, z) = \phi\left(\frac{L}{g(z)}, z = 0\right)
\]
The reality is that evolution is a mixture of density and luminosity evolution - and different galaxy types evolve differently.

Out to z~1 it is a reasonable approximation to assume pure luminosity evolution going as:

$$L_\star \propto (1+z)^3$$
Aside: photometric redshifts

Galaxy redshifts can be measured from spectra (from emis. or absorp. lines, or features like 4000Å break). However, getting spectra is very time-consuming. An alternative approach is photometric redshifts.

- Measure galaxy colours at different wavelengths
- Make a set of “model galaxy spectra” of different ages and star formation histories.
- Compare data with model spectra at different redshifts, & minimise $\chi^2$
Photo-z’s: choice of filters

For specific problems, a small number of filters may be sufficient, if they are well chosen. cf. the “ugr” filter combination (left) with “gri” (right) at z<0.6.
Photo-z’s: COMBO-17 survey

The more filters you have, the better the accuracy of the photometric redshifts.

The COMBO-17 survey has deeply imaged a square degree of sky in 17 broad and medium band filters.
These plots compare the photo-z's that COMBO-17 determines with measured spectroscopic redshifts.

With this many filters, photometric redshifts are accurate to ~0.01 in redshift for the bright and moderate objects.

NB: there are some outliers!
Lyman drop-out technique

Pioneered by Chuck Steidel et al in the 1990’s, the Lyman break technique selects galaxies at a given redshift by looking for a break in colour between 2 bands.

Originally designed to find $z \sim 3$ gals (and finding thousands) it has been used to find gals out to $z \sim 6$. 
Cosmic Star Formation history

The global star formation rate in the Universe has declined dramatically since $z \sim 1$. Without dust extinction corrections it appeared to peaking in the past at $z \sim 2$, but it now appears roughly level over the range $2 < z < 4$. 
Heavens et al used spectra from the SDSS survey to derive statistically the past SF history of each galaxy. This lets us study the SFH of low mass gals which we don’t have the sensitivity to see at high-z. Result: high mass galaxies formed their stars at higher-z than low mass gals.
Evidence for early formation of ellipticals: evolution of the F.P.

- Mass to light ratio evolves very slowly: \( \Delta \log(M/L) \propto 0.40z \)
- Scatter around scaling relations shows no significant increase with redshift.

Implies that (at least the most massive) cluster ellipticals were in place at early cosmic epochs, with fairly passive evolution thereafter.
Further evidence for early formation of ellipticals

"Extremely red objects": old red elliptical galaxies of age $\sim 3-4$ Gyr at $z \sim 1.5$
Reconciling hierarchical clustering with downsizing

Hierarchical clustering: small things form first, and build up into larger things

Galaxy “Downsizing”: more massive galaxies form earlier

At first glance, these two results seem to be totally contradictory, so it is necessary to think more carefully about what is going on.
Histories of different galaxies

**Giant ellipticals:**
- These are massive galaxies
- Built up from small clumps
- Were at high peak in primordial density fluctuations
- Therefore, “small clumps” formed their stars early.
- The “clumps” come together later (but a while ago).
- Major merger destroyed disk, and made elliptical
- AGN activity stopped further star formation?

**Low mass galaxy:**
- Found at lower peak in primordial fluctuations
- Therefore its small clumps formed later
- The galaxy is still being assembled now
- No major merger, so still disk dominated
Summary

Galaxies in the nearby Universe fall into two broad categories, roughly passive, bulge dominated and star-forming disk dominated.

The properties of these galaxies follow well-defined scaling relations.

Galaxies are build up through hierarchical clustering, from smaller building blocks.

More massive galaxies formed their stars and began their assembly earlier: downsizing.
Outstanding questions
(a biased subset: there are many more!)

• How exactly does “feedback” work to control the growth of galaxies?

• When did the first galaxies form, and what was their early evolution?

• What is the role of environment in galaxy formation and evolution?

• How do we explain the details of the structures of different galaxies?