GALAXIES

NOVA Fall School 2004
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Part 1:
Why study galaxies?
Galaxies lie at the crossroads of astronomy

The study of galaxies brings together nearly all astronomical disciplines:

- stellar astronomy --- the formation and evolution of stars in galaxies
- “gastrophysics” --- the behavior of and the interaction between gas in and between galaxies
- high and low energy processes --- from dust to AGN
- cosmology --- the formation and evolution of galaxies
And uses nearly all observational techniques...

- from low-frequency radio observations (LOFAR)
- through the radio, mm, sub-mm, infrared, optical, and UV bands
- to the X-ray and γ-ray bands
Messier 51: UV, optical, and NIR
Messier 51: Radio (HI and CO), NIR, mid-IR, and X-ray
Galaxies are regular

Galaxies follow, by and large, **scaling relations** (or laws)

like stars --- the HR diagram is a kind of scaling law, in log L vs. log $T_{\text{eff}}$

the HR diagram arise from the fact that stars “forget” their initial conditions on short (hydrodynamic) timescales

in stars, evolution is clean; formation is messy

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**Figure 1** The CMD of the cluster M3 (Buonanno et al. 1986a, 1987). In this diagram, 10,637 stars are plotted, 9879 from a sample that is complete down to $V = 21.5$ and totals $\sim 30,000 \, L_\odot$ of cluster light, while the remaining 758 stars are drawn from a sample that is complete down to $V = 18$ and totals $\sim 50,000 \, L_\odot$ of cluster light. The stars brighter than $V = 18$ therefore belong to a sample totaling $\sim 80,000 \, L_\odot$ of cluster light ($\sim 30\%$ of the total luminosity of M3). More information on this diagram can be found in Table 2. The following classification has been adopted for the various evolutionary stages: 1. main sequence (MS)—core hydrogen-burning phase; 2. blue stragglers (BS); 3. subgiant branch (SGB)—shell hydrogen-burning phase, from the MS turnoff (TO) to the Hayashi line; 4. red giant branch (RGB)—shell hydrogen-burning phase along the Hayashi line, until helium ignition in the core; 5. horizontal branch (HB)—core helium-burning phase; 6. asymptotic giant branch (AGB)—shell hydrogen- and helium-burning phase; 7. post-AGB (P-AGB)—final evolution from the AGB to the white dwarf (WD) stage.
Galaxies, however, do not forget their initial conditions.

Scaling relations tell us about the initial conditions of galaxy formation as well as subsequent processes.

For galaxies, neither formation nor evolution are clean!
Structure and morphology of galaxies

Galaxies are composed of two types of matter:

- **Baryonic matter**---the stuff we’re all made of---which composes roughly 15% of the matter (but only 4.4% of the energy density) in the Universe

- **Dark matter**---the vast majority of which is not baryonic---which composes the other 85% of the mass of the Universe (but only 27% of the energy density)
These types of matter have different radial distributions:

- Baryons are concentrated (primarily) to the inner tens of kpc;
- Dark matter can extend to hundreds of kpc

Why?

- Dissipation --- baryons can lose energy through radiation, but DM can't
Visible (baryonic) components of galaxies

two basic structural components:

- spheroids
  - round(ish), stars on eccentric orbits, low net rotation (usually), high entropy: “hot” systems
- disks
  - flattened, rotating structure, circular orbits, low entropy: “cold”

The “Hubble Sequence” is roughly a continuum of the ratio of these two components
The Milky Way, a typical “disk” galaxy, is a superposition of spheroid (bulge & halo) and disk (thin & thick) components can be distinguished by stellar velocities (relative to the Sun):

- stars with low velocities are disk stars
- stars with high velocities are spheroid stars
Morphological classification

- What are the basic aims of any kind of classification scheme?
- Transform qualitative impression into quantitative information
- Complete
- Unambiguous assignment of every object to a class
- Illuminate physical processes
- Avoid irrelevant detail: economical description
The Hubble Sequence

Classes are E(0-7), S0, Sa, Sb, Sc, Sd, Irr

Three criteria:

- **Primary**: small-scale lumpiness due to star formation now (current SFR)

**THE HUBBLE SEQUENCE IS BASICALLY A SEQUENCE IN PRESENT-DAY STAR FORMATION RATE!**
Criteria, cont.:

Secondary: Bulge (spheroid) to disk ratio (B/D)

Tertiary: Pitch-angle (PA), prominence (APr), and number (m) of spiral arms

Criteria sometimes disagree, like Sa’s with small bulges

Of course, the Hubble Sequence doesn’t satisfy all desires of a classification scheme

Note that many galaxies (peculiars) don’t fit!
B/D ratios along the Hubble Sequence

B/T ratio systematically varies along sequence, as desired, but not monotonically (Kent 1985)

Fig. 6.—Distribution of B/T as a function of morphological type
Why do the Hubble criteria correlate?

- Density-wave theory for spiral structure predicts that number of arms increases when disk mass decreases
  
  \[ f = \frac{\mu(\text{disk})}{\mu(\text{spheroid})} \]  
  (where \( \mu \) is surface density), then \( m \sim 1/f \) (Carlberg 1987)

- Bulges are dense and concentrated, so they have rapidly rising rotation curves and significant differential rotation
  
  - So as B/D increases, arms get tightly wound

- So as B/D increases, lots of tightly-wound arms; as B/D decreases, few loosely-wound arms
Physical parameters along the Hubble Sequence

Figure 2 Global galaxy parameters vs morphological type. Circles represent the RC3-UGC sample; squares the RC3-LSc sample. Filled symbols are medians; open ones are mean values. The lower bar is the 25th percentile; the upper the 75th percentile. Their range measures half the sample. The sample size is given in Table 1. (a) log linear radius $R_d$ (kpc) to an isophote of 25 B mag/arcsec$^2$; (b) log blue luminosity $L_B$ in solar units; (c) log total mass $M_T$ in solar units; (d) log total mass-to-luminosity ratio $M_T/L_B$.

Figure 5 (B – V) color vs morphological type. (Same symbols as in Figure 2.)
Note that the fractional mass of HI relative to the total galaxy mass increases as B/D decreases.

Fuel for star formation increases as B/D decreases, so SFR should increase as B/D decreases.

Can be seen (roughly) from colors as function of type:

- Early-types are red (~no SF)
- Late-types are blue (lots of SF)
integrated overview of Hubble sequence:
- mass increases, B/D increases
- most massive galaxies, largest B/D: EARLY TYPES
- bulges
- rising rotation curves \(\rightarrow\) differential rotation
  - tightly-wound arms
- low disk mass
  - large number of arms
- low HI content
  - low SFR today
least massive galaxies (still on Hubble Sequence): LATE TYPES
- disks
- linear rotation curves $\rightarrow$ solid-body motion
  - loosely-wrapped arms
- high disk mass
  - small number of arms
- high HI content
  - high SFR today
Main question about Hubble Sequence:
why does B/D increase with mass?
mergers help explain this:
mergers make bulges by destroying disks, and make galaxies bigger
therefore, mergers tend to have mass increase as B/D increases
but how did big spirals settle down to have big gas disks without forming stars along the way?
Peculiar galaxies: the “trash heap”
“Peculiar” galaxies can have
- distortions of bulges and disks by gravitational processes
- gas and dust in systems where unexpected, often unrelaxed
- starbursts

Nearly all due to mergers or interactions with other galaxies

Toomre & Toomre (1972): first models of tidal encounters (more at the end of the course!)
Galaxies can move between Hubble classes through the “peculiar” stage

**IRONY:**

“peculiar” galaxies are *actively forming*

Hubble Sequence only fits galaxies *passively forming*!
The Distant Universe: Deep Fields
Using images like this (and the HDF-N,S), we should be able to classify galaxies using the Hubble Sequence at much greater distances, however, there are a few issues to confront:

- Distances are required to understand both the sizes and ages of the galaxies
- Distances require redshifts AND cosmological parameters
- Distant galaxies are younger than those used to define the Hubble Sequence: more peculiar galaxies
- Resolution is poor compared to local galaxies and usually limited to a few bandpasses: and not necessarily those observed for nearby galaxies
But it’s more important to understand the fates of these distant galaxies than their specific types:

- which galaxies become elliptical galaxies today? which become spiral galaxies?
- what did the Milky Way look like at $z=1,2,3,4,...$?
The environments of galaxies

Galaxies do not live in isolation (usually!)

They live in different environments:

- Voids: large empty regions
- Groups: small gravitationally-bound associations
- Filaments: “strings” of galaxies between clusters, bounding voids
- Clusters: large bound structures

Note: astronomers often speak of “the field”---this is the average density region, mostly group-like environments
Does environment affect evolution?

- Dressler (1980) quantified the “morphology-density” relation
- Elliptical galaxies are much more likely to be found in rich, dense clusters than are spiral galaxies: 80% of ellipticals are in clusters
- Spiral galaxies live in “field-like” environments
- This is true even at z~0.5, although effect is not so strong (Dressler et al. 1997)
Dense environments also contain significant amounts of hot gas (the "intracluster medium"=ICM) which can interact with the galaxies.
This hot gas can strip (cold and hot) gas from galaxies “falling” into the cluster

- ram-pressure stripping

Galaxies can also interact within clusters and groups

- clusters: passing encounters, tidal stripping, galaxy “harassment”
- groups: all the above + mergers

So environment does affect evolution!

but details are uncertain and quantification still difficult!
Gravitational Instability
Picture: the formation of galaxies
A quick overview

In a cold dark matter-dominated cosmology (with or without a cosmological constant) with inflation, galaxies arise from overdense regions in the mostly-uniform matter distribution

- galaxies act as “closed” universes
- perturbations get amplified by gravity within and between galaxies
- -> hierarchical clustering
Interactions and mergers change galaxies and give or remove angular momentum (and thus “spin”) 
Mergers disrupt disks and transform them into spheroids
Roughly, we can say that
- **disks** are the portions of galaxies that have formed stars since the last major interaction, while
- **spheroids** are the portions that made stars before or during the last major interactions
What we won’t talk about!

- Active galaxies: that’s Heino’s class!
- Determination of spiral galaxy masses (including rotation curves)
- Cosmic distance scale
- ISM, including details of HI distribution in MW
- Star formation in galaxies