ASTRONOMY 386C: GALAXIES

Note – This is a draft syllabus based my previous Galaxies course. Most (but probably not all) of the material is likely to be covered. I will be bringing the course content more up to date.

1. MORPHOLOGY

1.1 Galaxy Classification Schemes

- The Hubble system
- The de Vaucouleurs system
- The Morgan system: cD galaxies
- Luminosity classification

1.2 Quantitative Morphology

- Correlation of physical parameters with Hubble types

1.3 Physical Morphology

- Galaxy components
- Oval disks
- Flocculent *versus* global spiral structure

2. LUMINOSITY FUNCTIONS

- Definitions
- The Schechter function
- Observations of the field-galaxy luminosity function
- Cluster luminosity functions
- Luminosity functions for different Hubble types
- The mix of different Hubble types: morphology-density relation
- Fraction of all light from bulge + E and disk components

3. ELLIPSOIDS: BULGES, ELLIPTICAL GALAXIES, AND GLOBULAR CLUSTERS

3.1 Surface Photometry

- Review of techniques (photographic, CDD)
- Radial brightness profiles:
  - Systematics
  - Analytic fitting functions
- cD galaxies: properties of cD halos
- Cores: ground-based and *HST* observations

3.2 Families of Ellipsoidal Stellar Systems

- Global and core parameter correlations
- Three kinds of stellar systems: bulges + ellipticals, Sphs, globulars
- Relationship between Sph and S + I galaxies: Introduction

3.3 The Fundamental Plane of Elliptical Galaxies

- Global and core parameter correlations
- Scalar virial theorem; derivation of the fundamental plane equations
- Implications for galaxy formation; $M/L(L)$

3.4 Stellar Dynamics: Observations

- Measurement techniques:
  - cross-correlation, Fourier quotient, Fourier correlation quotient, ...
- Line-of-sight velocity distributions (LOSVDs)
- Observations of rotation and velocity dispersion profiles
- Velocity anisotropy: the $V/\sigma - \epsilon$ diagram
- Observational confirmtaion of triaxiality and anisotropy:
  - Minor-axis rotation
  - Shapes of E galaxies: statistics of apparent shapes
  - Isophote twists
  - Dust rings: implications for E shapes

3.5 Isophote Shapes: Boxy and Disky Es

- Measurements of isophote shapes: $a(4)/a$
- Correlations of $a(4)/a$ with physical properties
- Physical dichotomy of E galaxies into
  - (1) High-L, nonrotating, boxy, anisotropic Es with cuspy cores, and
  - (2) Medium- and low-L, rotating, disky, approximately isotropic and coreless Es
- Proposed revision of the Hubble sequence: boxy E – disky E – S0 – Sa – Sb – Sc – ... – Im
- Exceptions: Boxy bulges and low-L boxy Es: origin

3.6 Collisionless Dynamics: Theory

- Stellar systems are fundamentally more complicated than gases:
  - Long mean free path
- Characteristic times: crossing time; relaxation time
- Distribution function
- Fundamental equations of macroscopic stellar dynamics:
  - Collisionless Boltzmann equation
  - Poisson equation
- First moment equations = basic equations of stellar hydrodynamics:
  - The Jeans equations
- Second moment equations: tensor virial theorem
- Application to $V/\sigma - \epsilon$ diagram $\Rightarrow$ anisotropy

3.7 Galaxy Models. I. $f = f(E, L_z)$

- Jeans Theorem
- Models with $f = f(E)$: polytropes, isothermals, King models
  - Emphasize: similarities between stellar dynamical and gas case (i. e., stars)
  - $\Rightarrow \quad \sigma^2 = kT/m_*$
  - Core mass-to-light ratios
- Models with $f = f(E, L_z)$

3.8 Globular Cluster Observations and Models

- Density distributions
- Velocity dispersion profiles
- Models with a range of stellar masses m_*

3.9 Stellar Orbits in Ellipsoidal Stellar Systems

- Orbits in a spherical potential
- Orbits in axisymmetric potentials: classical integrals
- Orbits in triaxial potentials

3.10 Galaxy Models. II. Galaxy = Σ weight$_i$ orbit$_i$

- Schwarzschild's method; examples
- Spherical maximum entropy models; examples
- Axisymmetric maximum entropy models; examples

3.11 Dynamical Evolution of Ellipticals and Globular Clusters: Theory

- Phase mixing and violent relaxation
    - Origin of the $\rho \propto r^{1/4}$ density distribution
- Two-body encounters and relaxation
    - Heat capacity of a self-gravitating stellar system is negative
    - Core collapse: single-m_* simulations
    - Stopping core collapse via binaries
    - Gravothermal oscillations
    - Complications: range of m_*, primordial binaries, stellar evolution, physical stellar collisions, stellar coalescence, runaway stellar mergers, ...
- External influences:
    - Tidal effects
    - Disruption of globular clusters by galactic disk shocking
    - Relation between present and primordial globular cluster population

3.12 Dynamical Evolution of Ellipticals and Globular Clusters: Observations

- Post-core-collapse density distributions in globulars
- Mass segregation
- Stellar population gradients: blue stragglers
- Stellar population gradients in bulges and Es $\Leftarrow$ effects of high stellar density

3.13 Supermassive Black Holes (BHs) in Galactic Nuclei

- Brief motivation: nucelar activity (see § 9)
- Origin of seed BHs via evolution of dense stellar systems
- Stellar-dynamical search for BHs
- Gas-dynamical search for BHs
- BH demographics
- Flashes when stars are accreted by BHs

4. DISK GALAXIES

4.1 Surface Photometry

- Radial brightness profiles of bulges and disks:
  - Analytic fitting functions
- Disk parameter corrrelations
- Bulge-disk decomposition
- Vertical brightness profiles of disks:
  - Analytic fitting functions
- Thick disks

4.2 Bulge Dynamics

- Evidence that some "bulges" are really disks
- Revised bulge-to-total luminosity ratios as function of Hubble type

4.3 Vertical Structure of Thin Disks: Theory

- The isothermal sheet

4.4 Local Stability of Disks

- Jeans instability: velocity dispersion stabilizes small-scale perturbations
- Rotation stabilizes large-scale perturbations
- Complete stability: Toomre's Q parameter
- Observations: Q in the Galactic solar neighborhood
- Observations: Q in other galaxy disks
- Other disk heating mechanisms:
  - Lumps: the Spitzer-Schwarzschild mechanism
  - Scattering by bars and spiral structure
  - Heating by accreted satellites

4.5 Spiral Structure

- Observations of global spiral structure
- Epicyclic theory
- Kinematic spiral density waves
- Dynamical spiral density waves
- Swing amplification
- Observational consequences and tests
- Alternatives:
  - Self-propagating star formation and flocculent spirals
  - Tidal spirals

4.6 Bars

- Observed properties of SB galaxies: bars, rings, and lenses
- Formation and evolution of bars: n-body simulations
- Importance of bars: secular evolution
  - Orbits in barred potentials
  - Radial transport of gas; star formation
  - Stellar-dynamical secular evolution $\Leftarrow$ density redistribution, angular momentum transport
  - Formation or box-shaped bulges and lenses (?)

4.7 Kinematics of the Galactic Solar Neighborhood

- Standards of rest
- Effects of galactic rotation
  - Intuitive picture
  - Global formulae
  - Local approximations
- Random velocities in the solar neighborhood: velocity ellipsoid
- Asymmetric drift

4.8 Global Structure of the Galaxy

- The Hubble type of the Galaxy
- Galactic parameters
- Thin disk (Population I)
- Stellar halo (Population II)
- Thick disk (Intermediate Population II)
- Evidence that the Galaxy is barred

4.9 Warps in Galaxy Disks

- Observations (mostly H I)
- The problem: formation and maintenance of warps
- The solution: triaxial dark halos?

5. STELLAR POPULATIONS IN GALAXIES

5.1 Stellar Populations at $z \simeq 0$

- History of the discovery of stellar populations in the Galaxy
- Observations of disks
- Star formation history of disks
- Observations of elliptical galaxies
  - Color and line-strength gradients
  - Degeneracy between metallicity and age
  - Current problems: evidence that low-L Es have a variety of ages

5.2 Stellar populations in high-redshift ellipticals

- Line strengths and fundamental plane correlations as function of z:
  - Evidence that giant ellipticals are old
- Star formation history of ellipticals

6. DWARF GALAXIES

6.1 Introduction: Importance of low-L galaxies

- The fundamental observed property of low-L galaxies is low baryon density
- The fundamental theoretical explanation is baryonic blowout by winds
- Implication: dwarf galaxies have an unusually large dark matter fraction

6.2 Observed properties of low-L and low-surface-brightness galaxies

- Fundamental plane parameter correlations
- Selection effects: implications for correlations, L function
- Icebergs and crouching giants: Malin 1 and relatives

6.3 Galaxy Formation. I. Low-Luminosity Galaxies

- Baryonic blowout via galactic winds
    - Recall similarity of dwarf S + I and dSph galaxies
    - Saito-Dekel-Silk mechanism: blowout of baryons by galactic winds
    - Expansion of a stellar system after mass loss
    - Observational evidence for mass loss via galactic winds
    - Stochastic starbursts in dwarf galaxies
- Ram-pressure stripping
    - Evidence for and against
- Other processes: revival of dI galaxies by gas accretion
- Bombproof evidence that dI galaxies evolve into dSphs:
    - The age distribution of stars in dSph galaxies

7. DARK MATTER

7.1 Historical Introduction

- Dark matter in the Galactic disk (Oort)
- Dark matter in the Coma cluster (Zwicky)
- Stability of cold disks *versus* bars (Ostriker & Peebles)

7.2 Observational Evidence for Dark Matter

- H I rotation curves
- Velocity dispersions in dSph galaxies
- Satellites of our Galaxy
- X-ray gas in galaxies and clusters: hydrostatic equilibrium of a hot gas
- Velocity dispersions of clusters of galaxies
- Gravitational lenses
- Large-scale velocity fields

7.3 Regularities in DM Halo Properties

- Conspiracy between luminous and dark matter to make flat $V(r)$
- Parameter correlations
    - Rotation curve decomposition into visible and dark matter components
    - Fundamental plane for dark matter halos
    - Evidence for baryonic compression of dark matter halos
    - Implications for galaxy formation

7.4 What is Dark Matter?

- MOND: Modified Newtonian Dynamics?
- Disk dark matter is baryonic: it dissipated
- Primordial nucleosynthesis constraints on baryonic dark matter
- Baryonic halos?
    - Things that won't work: snowballs, M dwarfs, white dwarfs, neutron stars
    - Things that might work: brown dwarfs, black holes of mass $10^{5\pm1}$ $M_\odot$
- Gravitational microlensing surveys
- Hot, warm, and cold elementary particles
- Constraints on neutrino dark matter from dwarf galaxies
- Direct detection of particle dark matter

8. GALAXY FORMATION

Note: The origin and early evolution of fluctuations belongs in the Cosmology course. Some discussion of hierarchical clustering and the formation of large-scale structure is inevitable here, because the study of galaxy formation cannot be removed from its cosmological context. Basically, the aim here is to discuss galaxy formation starting at a time when individual objects are well separated from the expansion of the universe.

8.1 Introduction

- Eggen, Lynden-Bell, & Sandage (1962)
- Hydrodynamic collapse simulations

8.2 Galaxy Mergers: Theory

- Dynamical friction and orbital decay
- Chandrasekhar's formula
- Implications:
  - Toomre's hypothesis that all bulges and ellipticals are merger remnants
  - Galaxy formation must be studied in the context of large-scale structure formation
- Conservation of phase space density

8.3 Simulations of Hierarchical Clustering and Galaxy Formation

- Cold dark matter simulations
  - Properties of the galaxies that form
  - Comparison with observations: successes and failures
- Dissipationless simulations of group and binary mergers
  - Properties of the galaxies that form
  - Comparison with observations: successes and failures
- The need for dissipation
- Dissipational simulations of group and binary mergers
  - Properties of the galaxies that form
  - Comparison with observations: successes and failures

8.4 Observational Constraints on Galaxy Formation

- Observations of mergers in progress
  - Merger sequence from close binary galaxies → violence → remnants
- Starbursts: IRAS galaxies
- Possible connection between ultraluminous IRAS galaxies and quasars
- Recognizing old mergers: tails, shells, and other fine structure
- Recognizing completed mergers: embedded stellar disks
  - Photometric signatures
  - Kinematic signatures
- Small accretion events
  - Not every elliptical with fine structure needs to be a major merger remnant

8.5 Tentative Verdict: Mergers *versus* Dissipative Collapse

- Strengths and weaknesses of the merger picture
- Evidence from high-z galaxies
- Bottom line: both mergers and dissipative collapse were important

8.6 Physical Processes During Galaxy Formation: Origin of the Fundamental Plane

- Dissipation: cooling times and galactic scales
- Complications: energy input during starbursts, etc.
- Formation of ellipticals
- Rotation of disk galaxies
- Late infall of cold gas
- Ongoing problems
- Connections with observations at high z

9. ACTIVE GALACTIC NUCLEI

9.1 Taxonomy

- Radio galaxies
- Quasars and BL Lac objects
- Seyfert 1 galaxies
- Seyfert 2 galaxies
- LINERs

9.2 Demographics

- Number densities compared to galaxy densities
- Evidence for evolution
- Peak in quasar densities at $z \simeq 2 - 3$.

9.3 Emission-Line Physics

- Hydrogen spectrum
- Forbidden lines
- Models of the broad- and narrow-line regions

9.4 Continuum Radiation

- Thermal components; dust scattering
- Nonthermal radiation: synchrotron radiation
- Jets: properties; relativistic beaming
- Gamma rays

9.5 The Unified Model of Nuclear Activity in Galaxies

9.6 Power Sources

- Starbursts: pro and con
- Black holes: pro and con
- The critical observations that imply black hole engines
- The Galactic center