Sep 23, 2015

- Finish elliptical galaxies
- Spiral galaxies overview
  - Dust attenuation
  - Star formation => spectral energy distribution
  - Rotation curves
  - Spiral structure, resonances, bars

HW#4 is due next Monday
- Part of it is to read a paper and answer questions about what you read; if you have questions, ask me!

Mon Oct 05 – there will be an in-class 30 min. test (to give us all feedback). Short answers, quick calculations, definitions. Review the portfolio exercises, assignments, class notes, textbook.

Reading: Chap 2.6: The Galactic Center

Next week: special lectures by Reinhard Genzel speaking on the Galactic Center and its SMBH and on high redshift galaxies

(Hopefully) Arecibo remote observing Fri&Sat Oct 16 & 17
Elliptical galaxies: Summary

• Faint ellipticals (and bulges) are rotationally flattened; bright ellipticals are often anisotropic

• Strong correlation between rotational properties and the shape of the isophotes and core properties:
  - Boxy isophotes, flat core centers: anisotropic, peculiar velocity fields (high L)
  - Disky isophotes, power-law centers: usually rotationally flattened (low L)

• Counter-rotating nuclei show that ellipticals cannot be formed by simple collapse of uniformly rotating gas spheres => formed via merger processes

• Ellipticals contain hot gas (corona); many also have some cool/cold gas, but in smaller amounts than spirals (probably due to recent accretion events/mergers)

• High rotation velocities and velocity dispersions in core regions => SMBH (more later on this...)

• Ellipticals are not simple...
Elliptical galaxies: scaling relations

\[ R_e \propto \sigma_0^{1.4} \langle I \rangle_e^{-0.85} \]

Writing this relation in logarithmic form, we obtain

\[ \log R_e = 0.34 \langle \mu \rangle_e + 1.4 \log \sigma_0 + \text{const} \]

\( R_e \) = "effective radius" (contains \( \frac{1}{2} \) of total light)

\( \langle \mu \rangle_e \) = mean SB within \( R_e \) (mag/sq")

\( \sigma \) = velocity dispersion

\textbf{Fig. 3.23.} Projections of the fundamental plane onto different two-parameter planes. Upper left: the relation between radius and mean surface brightness within the effective radius. Upper right: Faber–Jackson relation. Lower left: the relation between mean surface brightness and velocity dispersion shows the fundamental plane viewed from above. Lower right: the fundamental plane viewed from the side—the linear relation between radius and a combination of surface brightness and velocity dispersion

WHY????
Virial mass: simplest form

The virial theorem in its simplest form says that, for an isolated dynamical system in a stationary state of equilibrium, the kinetic energy is just half the potential energy,

\[ E_{\text{kin}} = \frac{1}{2} |E_{\text{pot}}| . \]  

(1.8)

In particular, the system’s total energy is \( E_{\text{tot}} = E_{\text{kin}} + E_{\text{pot}} = E_{\text{pot}}/2 = -E_{\text{kin}}. \)

For a very simple system of total mass \( M_{\text{tot}} \) of equal mass \( m_i \) objects moving on random orbits:

\[ E_{\text{kin}} = \frac{M_{\text{tot}} \sigma^2}{2} \]

For a uniform sphere of radius \( R \) and density \( \rho \approx \text{constant} \):

\[ M(<r) = \rho \frac{4\pi}{3} r^3 = M_{\text{tot}} \frac{r^3}{R^3} \]

So that the potential energy is:

\[ E_{\text{pot}} = -\frac{3}{5} \left( \frac{GM_{\text{tot}}^2}{R} \right) \]

\[ -2 \left[ \frac{M_{\text{tot}} \sigma^2}{2} \right] = \frac{3}{5} \left( \frac{GM_{\text{tot}}^2}{R} \right) \]

\[ M_{\text{tot}} = \frac{5R}{G} \left[ \frac{\sigma^2}{3} \right] \]
Virial mass for spherical systems

Now consider the total velocity dispersion. For a spherical system, the stellar velocities have three components:

$$\sigma^2 = \sigma_r^2 + \sigma_\theta^2 + \sigma_\phi^2$$

$\sigma_r^2$ is the radial velocity dispersion and is the only one we can measure (the other two are perpendicular to our line of sight). In general,

$$\sigma_r^2 \neq \sigma_\theta^2 \neq \sigma_\phi^2.$$  

However, if $\sigma_r^2 = \sigma_\theta^2 = \sigma_\phi^2$ (isotropic velocity dispersion),

$$\sigma^2 = 3\sigma_r^2$$

and

$$M_{\text{tot}} = \frac{5R\sigma_r^2}{G}.$$  

The mass obtained this way is called the virial mass.
M33

NGC 5194/5
The Spiral Sequence

- Prominence of bulge
- Windy-ness of spiral arms (tight versus open)
The Spiral Sequence

- Prominence of bulge
- Windy-ness of spiral arms (tight versus open)
- Barred versus unbarred
- Degree of development of spiral arms:
  - Flocculent (fleecy)

- Grand design
Spiral galaxies overview:

Dominant motion is **circular rotation** in the disk.
- But seem to be **embedded in dark matter** halos

Multiple components: (thin) disk (+ thick disk) + bulge (+ bar) + halo

“Early” versus “late”
- Sa’s can be small or large-bulged
- SFR declines from Sa to Sd

**Absence from cores of densest clusters**

Sa’s tend to be more luminous than Sc’s

**VCC: Binggeli, Sandage & Tammann**

Most spirals fall in the blue cloud.
Red sequence & Blue cloud

Do galaxies migrate within the CMD? If so, how? why?
2-D B/D decomposition

Best methods: simultaneous fit of inclined exponential disk and Sersic profile bulge in 2-D

Reveals wealth of residual structure which can be described by Fourier modes:

- Lopsidedness (m=1)
- Bars, oval distortions (m=2)
- Spiral arms (m=2,3)

Fig 5.4 (R. Peletier) ‘Galaxies in the Universe’ Sparke/Gallagher CUP 2007
Surface brightness

- **Freeman's (1970) Law**: Luminous spirals have nearly constant disk central surface brightness $\mu_o = 21.65$ (B-band), $21(R\text{-band})$, $20.65$ (I-band) ± 0.65 mag arcsec$^{-2}$
  - Actually a bias => lower L galaxies have lower $\mu_o$ and therefore are harder to see.
- **Central SB** for bulges is 10-100X higher than disks => easier to see!
  - Bulge-to-disk (B/D) luminosity ratio => key parameter in describing disk galaxies
Dust effects on photometry

- Large amounts of dust affect observed surface brightness profile
- Disks optically thick in inner regions; transparent outside
- Hence various components affected differently; depend on geometry.

- Scattering and absorption have competing effects. Which one dominates depends strongly on viewing geometry (both bulge & disk)
- High and low inclination: dimming/reddening
- Intermediate inclination: (forward) scattering

Dust preferentially scatters blue light
- Scattering is not isotropic (dust grains not round) => forward scattering (small angles)

Assume same extinction as seen in MW
Extinction

$\Delta m = -\gamma \log (1-e) = \gamma \log (a/b)$
The nearby spiral galaxy M83 in blue light (L) and at 2.2μ (R)

The blue image shows young star-forming regions and is affected by dust obscuration. The NIR image shows mainly the old stars and is unaffected by dust. Note how clearly the central bar can be seen in the NIR image.
Different views of M104 and M101
Different views of Messier 51

Multiwavelength Whirlpool Galaxy

- **COLD GAS**: Radio waves reveal regions of gas cool enough for CO$_2$ molecules to exist.
- **COOL STARS**: Infrared shows smaller cool red stars that make up most of the galaxy.
- **SOLAR STARS**: Optical light comes from stars around the size of the Sun.
- **HOT STARS**: Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.
- **HOT GAS**: X-rays are emitted from the hottest regions of gas where atoms are ionized.

- **COOL LOW ENERGY RADIATION** — **VISIBLE LIGHT** — **HOT HIGH ENERGY RADIATION**
Different views of Messier 31
HI vs dust

HI: 21 cm spin-flip transition
• Cool (100K) diffuse atomic gas in ISM
THINGS

The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
The starlight ends....

- NGC 2403:
The starlight ends....but the HI doesn't

- NGC 2403:

*Note:* the two images are displayed on the same scale(!)
The interstellar hydrogen extends further out than the starlight(!)
Hα: Massive star formation

- Stars have a cyan-blue appearance.
- Ionized hydrogen traced by Hα emission appears orange-red to yellow.

Hα: 656.3 nm

https://www.noao.edu/image_gallery/html/im1007.html
Star formation in spirals

**Hα emission**
- ionized gas HII regions
- O to early B stars
- $M_{\text{star}} > 17 \, M_\odot$
- timescale $\sim$ few Myr

**UV flux**
- photospheres of O to later B stars
- $M_{\text{star}} > 3 \, M_\odot$
- timescale $\sim$ 100 Myr

Erroz-Ferrer+ 2013
MNRAS 436, 3135
Gas and star formation rate density

The star formation rate (SFR) density (in different regions of a galaxy) is a function of the local density of cool/cold gas.

Schmidt (1959)

Kennicutt (1998) updated the Schmidt relation via a study of star formation in 100 galaxies:

\[ \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^N \]

Most recently, studies have focused on both the molecular and the atomic gas densities => The law holds over an intermediate range in \( \Sigma_{\text{SFR}} \); deviations at very low gas densities and in starbursts.

Roberts' time = Gas consumption time

\[
\tau = \frac{\text{Mass of gas}}{\text{Star formation rate}}
\]
Kennicutt-Schmidt relation

Fig. 3.20 The star formation surface density $\Sigma_{\text{SFR}}$ as a function of the surface mass density $\Sigma_{\text{H}^1+\text{H}_2}$ of the sum of atomic and molecular gas. The colored-shading shows results from subregions of nearby spiral and late-type dwarf galaxies. Symbols show measurements from either regions or radial bins (dots and black circles), or disk-averaged estimates of normal spiral galaxies (asterisks). Open triangles correspond to starburst galaxies, diamonds to low-surface brightness galaxies. The diagonal lines indicate a star-formation rate in which 1, 10 or 100% of the gas is consumed in star formation within $10^8$ yr. The two vertical lines indicate characteristic values of the projected gas density. Source: F. Bigiel et al. 2008, The Star Formation Law in Nearby Galaxies on Sub-Kpc Scales, AJ 136, 2846, p. 2869, Fig. 15. ©AAS. Reproduced with permission

- Star formation closely linked to surface density of molecular gas
- SF becomes more stochastic at low $\Sigma_{\text{gas}}$
Galaxy spectra

Spectral Energy distribution (SED)

- Initial mass function
- Isochrones for different $M$, $T$, $L$, $Z$
- Stellar spectral templates
  ⇒ Synthesized stellar population
- Star formation history and chemical evolution
- Dust model
  ⇒ Composite stellar population
  ⇒ Spectral energy distribution
Rotation curves

Solid body rotation

$$V(R) \propto R$$

Keplerian decline

$$V(R) \propto R^{-1/2}$$

Mass concentrated at center
Rotation curves

The Kepler formula assumes that all the mass is concentrated in a point mass at the center of the system so that

\[ v = \sqrt{\frac{GM}{R}} \]

On the other hand, if the mass is distributed over some geometry, the equation is modified to take that into account. At some radius \( R \), the mass interior to that radius \( M(r<R) \) is

\[ v = \sqrt{\frac{GM(R)}{R}} \]

If we describe a spiral galaxy disk as a cylinder of height \( h \) and with density \( \rho(r) \) so that its mass \( M(r<R) \) becomes:

\[ M(R) = \int_{0}^{R} \rho(r) 2\pi rh \, dr \]

To get \( v(R) \sim \text{constant} \), we need \( \rho(r) \propto \frac{1}{r} \) (not \( \frac{1}{r^3} \))
Implications of a flat rotation curve

Gravitational acceleration

\[ \frac{G \ M(R)}{R^2} = \frac{V^2(R)}{R} \]

Centrifugal acceleration

Solving for the mass interior to \( R \), we get:

\[ M(r<R) = \frac{R \ V^2(R)}{G} \]

If \( V(r) \sim \text{constant} \), then \( M(r) \) increases with \( R \).

Even at the visible edge \( R_{\text{edge}} \), the mass continues to increase.
The starlight ends…. But the gas doesn’t

- NGC 2403: atomic hydrogen image (left) + optical image (right)

Note: the two images are displayed on the same scale(!)
The interstellar hydrogen extends further out than the starlight(!)
The rotation curve measured from the hydrogen gas remains FLAT!
Simulating rotation curves

Let’s see what happens when we vary the ratio of dark matter to stellar mass

http://www.physics.ucdavis.edu/~dwittman/Animations/RotationCurve/GalacticRotation.html
This is as far as I got in lecture.

The remaining slides are related to the origin of spiral structure and its consequences and the stability of disks. This material is also covered in the textbook, but is mainly for the interested.

New material covered in the remaining slides but not elsewhere will not be included in the first prelim (but may be in the 2nd if we discuss it later).
Spiral arm structure

<table>
<thead>
<tr>
<th>m=1</th>
<th>m=2</th>
<th>m=3</th>
<th>m=4</th>
<th>m=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>grand design</td>
<td>flocculent</td>
<td>counter-winding SA</td>
<td>counter-winding SB</td>
<td>anemic</td>
</tr>
</tbody>
</table>
Spiral Galaxy M101

Oval orbits nested to form 2-armed spiral

1-arm spiral

Fig 5.29 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
Density waves: cause and effect

http://ircamera.as.arizona.edu/NatSci102/NatSci102/movies/spiralarms.gif
http://ircamera.as.arizona.edu/NatSci102/NatSci102/movies/spiralarms.gif

web.williams.edu/Astronomy/Course-Pages/104/assignment.html
Rings and bars in real galaxies

Perturbations in the density cause perturbations in the velocity => material piles up

http://heritage.stsci.edu/2001/37/supplemental.html
Orbits in the disk plane

- The motion in the orbit plane can be approximated by the superposition of two motions:
  - Retrograde motion at angular frequency $\kappa$ around a small ellipse (epicycle, with center = guiding center). The length of the semi-major axes of the epicycle are in the ratio $\kappa/2\Omega$.
  - Prograde circular motion of the guiding center at angular frequency $\Omega$.

Example: elliptical orbit of a planet in the Solar System

- Kepler orbit in the Solar System where $\kappa/\Omega = 1$.
- Orbit is closed and elliptical.

In general, the ratio $\kappa/\Omega$ is irrational, so that the orbit is unclosed and forms a rosette figure.

If viewed in a rotating frame with $\Omega_p$, the orbit is closed. This angular pattern speed is chosen as:

$$\Omega_p = \Omega - \frac{n\kappa}{m}$$
Density waves

- **Epicycles**: oscillations (random motions) about circular orbit described as elliptical epicycles with frequency $\kappa$
  - $\kappa^2(R) = -4 \, B(R) \, \Omega(R)$
  - with $B = -\frac{1}{2} \left[ \left( \frac{dV}{dR} \right)_\odot - \frac{V_\odot}{R_\odot} \right]$
  - In the disk plane:

- Spiral is **strengthened** when:
  - $m |\Omega_p - \Omega(R)| < \kappa(R)$
    - where $m$ is the number of arms

- Continuous wave propagates only over a finite range in $R$, i.e. between the inner and outer Lindblad resonances (IRL, OLR)

- Co-rotation (CR) occurs where $\Omega_p = \Omega$

- Beginning and end of spirals arms indicate location of resonances.

**Oort's constant $B$**

There's also a component out of the disk plane ($z$) -- not relevant here.
The Lindblad Resonances

• Gravity forcing from a spiral density wave causes the stellar ellipses to take on a regular pattern. Orbit crowding then creates spiral arms.

• If a star has an angular velocity $\Omega$ and the pattern has an angular velocity $\Omega_p$, then the relative speed of the star wrt the pattern is: $\Omega - \Omega_p$.

• A resonance occurs when this difference is an integral multiple of $\kappa$.

$$\Omega(R) - \Omega_p = \pm \frac{\kappa}{m}$$

for integer values of $m = \#$ of arms

$m=2$ => At ILR & OLR, in the absence of forcing, one epicycle is completed in the time it takes to go from one arm to the next, i.e. in the frame of reference rotating at $\Omega_p$, two epicycles are completed in one revolution.

$$\Omega(R) - \Omega_p = -\kappa/2 \text{ at OLR}$$
$$\text{= } \kappa/2 \text{ at ILR}$$
Tidally driven density waves

Models of the M51 system

Spiral pattern caused by tidal forces from companion

Spiral is a density wave, but the wave is transitory.

“Grand design” spiral

From Earth side view
Disk stability criterion

- “Disk stability” must be low

\[ Q = \frac{3.36 \pi G \sigma_R \kappa}{\kappa(r)} \approx 1 \]

- Random motions
- Epicyclic frequency
- “Toomre’s Q”
- Disk mass surface density
- Ratio of KE/PE
Disk stability: Toomre Q

- Disk stars can reinforce spiral wave and help it to grow only if their random motions are small enough that they do not leave the spiral arms.
- In a thin disk, the axisymmetric (m=0, non-spiral) waves can grow only if the disk is “cold” =>
  - Stellar speeds in the radial direction \( \sigma_r \) must be small relative to the surface density \( \Sigma \) of mass in the disk
- This condition holds if:
  \[
  Q \equiv \frac{\sigma_R K}{3.36 G} \leq 1
  \]
- A spiral pattern grows if \( Q \leq 1.2 \). As it does, the stars developer larger epicyclic motions and Q rises. So we don’t expect to see a stellar disk with \( Q \leq 1 \).

Simulation showing how a disk of 50000 self-gravitating particles develops first a 2-armed pattern and then a bar.