Today in Astronomy 142: normal galaxies

- The Hubble sequence for the shapes of normal galaxies
- Distribution of mass and light in normal galaxies
- Dark matter in spiral galaxies

Sa galaxy M104 (the Sombrero), by the Hubble Heritage Team (STScI/NASA).
Galaxies are classified by shape into the so-called Hubble types, listed here in this “tuning-fork” diagram. Different spiral galaxy types are distinguished by the shapes of their disks and bulges; different ellipticals by their ellipticity.

Sloan Digital Sky Survey (SDSS)
Hubble originally thought that the shape of a galaxy indicates evolutionary status, and proposed this arrangement of shapes as the corresponding evolutionary sequence. (We know now that this isn’t right, but the scheme still has utility.)

Sloan Digital Sky Survey (SDSS)
M74 (NGC 628), an Sc galaxy

Color composite image from the Gemini North observatory 8 m telescope. Note the relatively small bulge, very strong spiral structure, very blue color of the spiral arms, and the dust lanes on the trailing edges of the arms.
M33 (NGC 598), an Sc galaxy

Photograph by Tom Davis.

Note the diffuse spiral structure, compared to M74. M74 is a grand design spiral galaxy; M33 is a flocculent spiral galaxy.
NGC 1288, an Sb galaxy

BVI color composite image from the FORS1 camera on the 8.2 m VLT Antu telescope (European Southern Observatory).

Sb galaxies are distinguished from Scs by less-open spiral structure and by more prominent bulge.
M81 (NGC 3031), an Sb galaxy

HST/ACS image by the Hubble Heritage Team (STScI/NASA)
NGC 2681, an Sa galaxy

gri image by D. Hogg and M. Blanton (SDSS).

Sa galaxies have even tighter spiral patterns and yet more prominent bulges. NGC 2681 has two major spiral arms, seen by their extinction, with little evidence for star formation within them.
NGC 3898, an Sa galaxy

gri image by D. Hogg and M. Blanton (SDSS).

The spiral arms are still faint, but have more H II regions to delineate them than NGC 2681 does.
Bulge/disk size in edge-on disk galaxies

NGC 5866: S0

NGC 5907: Sc

(BGR = 1.2, 1.6, 2.2 μm images from 2MASS)

NGC 7814: Sa

NGC 891: Sb

(NGC 7814: Sb)

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NGC 1365, an SBc(s) galaxy

*BRI* image from VLT Antu (European Southern Observatory). The (s) means the arms and bar form a letter S, rather than a closed (r)ing.

Note that it has at least two concentric bars, oriented in different directions.
NGC 1300, an SBb(s) galaxy

HST/ACS image by the Hubble Heritage Team (STScI/NASA)
Spiral structure

- Spiral arms generally trail rotation; there’s only one possible exception so far (see below).
- Spiral arms never wind much more than once around a galaxy.
- Concentration of H II regions and young blue stars is higher in the arms than elsewhere in a galaxy: the star formation rate is higher.
- Dust lanes lie on the trailing edges of arms.
- Molecular cloud complexes tend to be more massive in the arms than elsewhere in a galaxy.

M100 (Sc) by Curt and Sally King/Adam Block/NOAO/AURA/NSF. The disk of M100 rotates counterclockwise in our view.
The exception:
spiral structure in
NGC 4622

Note that the
direction in which the
spiral arms wind is
different inside and
outside the complete
ring. One set of arms
must lead rotation,
and one must trail.

Composite color image by
Buta et al., with the WFPC2
camera on HST (NASA).
The central bulges in nearby spirals usually (65%; Sheth et al. 2008) look at least slightly oval or elliptical, rather than axisymmetric.

Less commonly (30%) the bulge is strongly barred: the SB galaxies.

This is in harmony with computer simulations: initially symmetrical disks always develop quickly – within a few rotation periods – into stable, oval/elliptical or barred shapes (e.g. Hohl 1971), unless given a sufficiently dense bulge or halo (Sellwood 2011).

NGC 1398 (SBb(r)), by Sean and Renee Stecker/Adam Block/NOAO/AURA/NSF
The “bar instability”

$N$-body simulation of an initially exponential disk. Shown are the 3-D positions of particles in the disk as a function of time; a dark halo, also present, is not shown. The central attractions of disk and halo are equal at $R = 2$, at which the orbital period is 15 time units. From Sellwood (2011).
Spiral structure (continued)

- Differential rotation must be important but can’t by itself produce the spiral structure: there are too many spirals seen, and the arms never wrap around multiple times.

- The high star formation rate observed in most spiral arms would exhaust the associated interstellar gas in a time very short compared to the age of the Universe. However, we see lots of spiral galaxies in the sky, so the arms are not material arms: matter must constantly be flowing into and out of them.

- The high abundance of molecular cloud complexes young stars in spiral arms both imply that the interstellar matter there is compressed.

- Thus the explanation for the Milky Way’s spiral structure (lecture, 26 March 2013) works in general.
Elliptical galaxies

Hubble type given as Eq.

- Rotation often not evident: random motions dominate the stellar velocity distribution.
- Very little interstellar matter, compared to mass in stars. Consequently there isn’t much star formation.
- Variety of shapes, ranging from round (E0) to an ellipticity of 0.7 (E7).
  - In terms of the major and minor axes $a$ and $b$ the ellipticity is given by $\varepsilon = 1 - b/a$. The notation Eq, where $q = 10\varepsilon$, is used to denote the shape.
- May be prolate (football-shaped) or oblate (pill-shaped) in 3-D; in general, they are probably triaxial (principal axes all different lengths).
M87 (NGC 4486), an E0 galaxy

We’ll talk about the bright core and the jet in a couple of weeks.

Adam Block/NOAO/AURA/NSF
NGC 1332, an E7 galaxy

...with a smaller or more distant E1 to the southeast.
Lenticular galaxies

That is, Hubble types S0 or SB0.

- Like ellipticals, they have very little interstellar matter, and very little star formation in consequence.
- Like spirals, they have disks, in which rotation dominates the stellar velocity distribution.
- The central bulges tend to dominate the mass in lenticulars; no spiral structure is seen in the disks.
- In early attempts to explain spiral and elliptical galaxies as forming an evolutionary sequence, lenticulars represented the transition between the other two classes.
  - Nobody takes this seriously any more.
- Lenticulars are components of polar ring galaxies, an important class of “interacted” galaxies. (More later.)
NGC 4526, an S0 galaxy

Note the bulge-disk contrast, in comparison to the E7 galaxy NGC 1332, which would otherwise look similar.
NGC 5866, an S0 galaxy

This is why S0s are called lenticular (= lens-shaped) galaxies.

NGC 5866, an S0 galaxy (continued)

They tend not to look quite so obviously lens-like when observed with CCD cameras and presented with a non-photographic stretch, as in this HST/ACS image (STScI/NASA).
Lenticular galaxies viewed (nearly) face on

NGC 4150 (S0)

NGC 2859 (SB0)

HST/WFC3 image (STScI/NASA).

gri image by D. Hogg and M. Blanton (SDSS)
**Bonus lenticular-galaxy images**

NGC 4650A (left, [Hubble Heritage Team](http://www.spacetelescope.org/images/constellations/constellations/heritage/) and NGC 660 (right, [Travis Rector/Gemini Observatory](http://www.gemini.edu/search/science)) are **polar-ring galaxies**: S0 galaxies which have captured disk material from passers-by spiral galaxies into precisely polar orbits.

- Only about 1% of S0s have polar rings.
Irregular galaxies

Usually set between the tines of the fork are the irregular galaxies, types Irr I and Irr II.

- These galaxies are supposed to be amorphous. They have a wide range of masses and luminosities, though they are usually small compared to typical spirals.
- They tend to be rich in ISM and have respectable star formation rates, though most have very small abundances of heavy elements.
- Irr I: hints of regular structure; e.g. the “bar” in the Large Magellanic Cloud.
- Irr II: no regular structure at all. (Note, though: the archetype Irr II, M82, looks amorphous just because of extinction; underneath it’s a spiral galaxy.)
The Large Magellanic Cloud (LMC, Irr I)

Photograph by Weihao Wang (NRAO).
The Small Magellanic Cloud (SMC; Irr I)

Photograph by Weihao Wang (NRAO). The big globular cluster – part of our galaxy, of course, not part of the SMC – is 47 Tucanae.
Bonus Magellanic Cloud image

Also by Weihao Wang (NRAO). Left to right: LMC, SMC, 47 Tuc.
M82 (NGC 3034), archetype of Irr II

BVR image from NOAO.

Its rotation curve reveals that M82 is a nearly edge-on spiral, with heavy foreground extinction: by dusty material stripped from nearby M81 which is accreting onto M82, and by...
... dusty material expelled from M82 due to the burst of massive star formation energized by the accreting material.

*Spitzer* IRAC (mid-infrared) image by Chad Engelbracht and the SINGS team (UAz/JPL/NASA).
Bonus M81-M82 image

Rainer Zmaritsch & Alexander Gross

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Distribution of mass and light in normal galaxies

Most **elliptical galaxies** are found to fit very well this distribution of surface brightness:

\[ \mathcal{L}(r) = \mathcal{L}(0) \exp\left[-\left(\frac{r}{r_0}\right)^{1/4}\right], \]

*(de Vaucouleurs 1948)* where as usual \( \mathcal{L} \), the surface brightness, is the luminosity per unit area projected onto the plane of the sky, and \( r_0 \) is the core radius.

This is an empirical relation. Stellar-dynamical calculations often yield power-law expressions for \( \mathcal{L} \) which resemble the de Vaucouleurs “law,” but none give this result, and such models are very sensitive to stellar population, system age, and many other parameters.
Mass, and the mass $M(r)$ contained within radius $r$, can be deduced from random motions and the virial theorem, as you will show in Homework #7:

$$M(r) = \frac{2rv^2}{G} = \frac{6rv^2}{G}$$

... whence the surface density $\mu(r)$ can be determined. For example, if the galaxy is circularly symmetric in projection (i.e. is an E0 galaxy), the surface density in an annulus at radius $r$ is

$$\mu(r) = \frac{m_{\text{annulus}}}{A_{\text{annulus}}} = \frac{1}{2\pi r \Delta r} \int \frac{d}{dr} M(r) \Delta r = \frac{1}{2\pi r} \frac{d}{dr} M(r).$$
Distribution of mass and light in normal galaxies (continued)

- The **bulges** of spiral galaxies usually fit the de Vaucouleurs law.
- **Disks** of spiral galaxies fit a simpler exponential:

\[
\mathcal{L}(r) = \mathcal{L}(0) \exp\left[ -r/r_0 \right].
\]

- The distribution of mass and surface density is easy to measure, as the motions in disks are dominated by rotation, whether of stars or of interstellar gas:

\[
M(r) = \frac{\nu^2 r}{G}
\]

\[
\mu(r) = \frac{1}{2\pi r \Delta r} \frac{d}{dr} M(r) \Delta r = \frac{\nu^2}{2\pi G r} + \frac{\nu}{\pi G} \frac{d\nu}{dr}
\]
Spiral galaxies have flat rotation curves

It turns out that all spiral galaxies share this property with the Milky Way: the rotation curve is never seen to become Keplerian at large distance from the center, instead staying flat as far as stars and gas can be detected.

Thus, once outside the bulge,

\[ \mu(r) = \frac{v^2}{2\pi Gr} + \frac{v}{\pi G} \frac{d\rho}{dr} = \frac{v^2}{2\pi Gr} \]

\[ \mu = \frac{v^2}{2\pi G \mathcal{L}(0)} \frac{e^{r/r_0}}{r} . \]

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Casertano and van Gorkom 1991
Spiral galaxies have flat rotation curves (continued)

- Since $e^{r/r_0}$ increases faster with increasing $r$ than $r$ itself does, the mass-to-light ratio is very large in the outer parts of spiral galaxies: much too large to explain with overabundant, low-mass stars.

- Discounting the possibility that there’s something wrong with Newtonian gravity, this demands the presence of dark matter.

- A spherical halo of dark matter with $\rho(r) \propto 1/r^2$, in each galaxy, would do it.

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Casertano and van Gorkom 1991