# Normal Galaxies & Their Distances

Galaxy spectra Distribution of mass and light Dark Matter Standard Candles and Standard Rulers

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University of Rochester

# Normal galaxies & their distances

- Characteristics of galaxy spectra
- Distribution of mass and light in normal galaxies
- Dark matter in spiral galaxies
- Standard candles and standard rulers
- Leavitt's invention of standard candles: Cepheids
- Standard candles: Type Ia supernovae
- The extragalactic distance scale

**Reading**: Kutner Sec. 12.2, 18.1–18.3, & 20.5, Ryden Sec. 20.4

*Right: the SMC, site of the discovery of Leavitt's Law. Photograph by Pablo Carlos Budassi.* 



Galaxy spectra: What else can a galaxy's light tell us?

Most of a galaxy's visible light comes from one of two sources:

Stars which have absorption spectra

- Most of this light comes from the few very luminous stars, not from the huge number of dim M dwarfs.
- In galaxies with active star formation (spirals and irregulars), this light is dominated by the young, hot main sequence O and B stars. In quiescent galaxies (ellipticals and lenticulars), red giants dominate the light.
- The stellar light is the source of a galaxy's color.

Hot gas which produces an emission spectrum

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#### Spectrum of an elliptical galaxy



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#### Spectrum of a spiral galaxy



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#### Spectrum of an active galaxy



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## Gas kinematics from a spectrum

Using the observed wavelength of a spectral line, we can measure the speed of a galaxy relative to ourselves.

With only one spectrum of the galaxy, this gives us the galaxy's overall speed with respect to us: its recessional velocity.

For galaxies that are extended, resolved objects, we can observe spectra across the surface of the galaxy. This allows us to measure the radial velocity as a function of position on the galaxy's surface.



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## Stellar kinematics from a spectrum

Unlike spiral galaxies, elliptical galaxies do not show any significant organized rotational motion. However, the width of the absorption lines is much greater than what would be expected from the effective surface temperatures of the stars.

Stars in an elliptical galaxy move in random orbits, causing a significant spread in the Doppler velocity. These galaxies are pressure supported.



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# Mass and light distribution in elliptical galaxies

The surface brightness distribution of most **elliptical galaxies** are fit very well by the de Vaucouleurs profile (de Vaucouleurs 1948):

$$\mathcal{L}(r) = \mathcal{L}(0) \exp\left[-\left(rac{r}{r_0}
ight)^{1/4}
ight]$$

where  $\mathcal{L}$ , 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 relationship. Stellar-dynamical calculations often yield power-law expressions for *L* which resemble the de Vaucouleurs profile, but none give this exact result.
- Calculations are very sensitive to details of the stellar population, system age, and many other parameters.

# Mass and light distribution in elliptical galaxies

▶ The mass, and the mass *M*(*r*) contained within radius *r*, can be deduced from random motions and the virial theorem:

$$M(r) = \frac{2r\overline{v^2}}{G} = \frac{6r\overline{v_r^2}}{G}$$

where  $\overline{v_r^2}$  is the mean square random component of radial velocity.

From this we can determine the surface density  $\mu(r)$ . For example, if the galaxy is circularly symmetric in projection — i.e., it is an E0 galaxy — the surface density in an annulus of radius *r* is

$$\mu(r) = \frac{m_{\text{ann}}}{A_{\text{ann}}} = \frac{1}{2\pi r \Delta r} \frac{d}{dr} M(r) \Delta r = \frac{1}{2\pi r} \frac{d}{dr} M(r)$$

# Mass and light distribution in spiral galaxies

- The **bulges** of (unbarred) spiral galaxies are usually also well fit by the de Vaucouleurs profile.
- ► The **disks** of spiral galaxies follow a simpler exponential:

$$\mathcal{L}(r) = \mathcal{L}(0) \exp\left(-\frac{r}{r_0}\right)$$

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

$$M(r) = \frac{v(r)^2 r}{G} \qquad v(r) \text{ is orbital speed at radius } r$$
$$\mu(r) = \frac{1}{2\pi r \Delta r} \frac{d}{dr} M(r) \Delta r = \frac{v(r)^2}{2\pi G r} + \frac{v(r)}{\pi G} \frac{dv}{dr}$$

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# Spiral galaxies have flat rotation curves

It turns out that **all** spiral galaxies are like the Milky Way; v(r) never becomes Keplerian at large distances from the center but stays flat as far as stars and gas can be detected (Rubin et al. 1980).

Thus, once outside the bulge,

$$\mu(r) = \frac{v^2}{2\pi Gr} + \frac{v}{\pi G}\frac{dv}{dr} = \frac{v^2}{2\pi Gr}$$
$$\frac{\mu}{\mathcal{L}} = \frac{v^2}{2\pi G\mathcal{L}(0)}\frac{e^{r/r_0}}{r}$$

v(r) from a selection of dwarf galaxies and large bright galaxies (Casertano & van Gorkom 1991).



# The galaxy rotation problem



Persuasive evidence for the galaxy rotation problem came from Vera Rubin and Kent Ford at Georgetown during the 1970s. Possible solutions to the galaxy rotation problem:

- 1. Galaxies have dark matter halos.
- 2. Newtonian gravity is not correct on large scales (deviations from  $1/r^2$ ; MOND).
- 3. Gravity is not the only force holding galaxies together.

Hypotheses 2 and 3 were taken seriously through the early 2000s, but we now favor the dark matter hypothesis.

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# Spiral galaxies have flat rotation curves

- Since e<sup>r/r<sub>0</sub></sup> increases faster than r as a function of r, the mass-to-light ratio is very large in the outer parts of spiral galaxies.
- This µ/L is much too large to explain with overabundant low-mass stars.
- Discounting the possibility that something is wrong with Newtonian gravity, this demands the presence of dark matter.
- A spherical halo of dark matter with ρ ∝ r<sup>-2</sup> in each galaxy would correct the discrepancy.



## The distance ladder

Distances from galactic to extragalactic scales.



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#### Standard candles & standard rulers

There is only one **direct** distance measurement for objects beyond a few light-hours away: **trigonometric parallax**, and it only works on relatively unextinguished objects within about 100 kpc of us (e.g., *Gaia*). To measure distances beyond this, we use standard candles or rulers.

Standard Candle An object with a well-determined luminosity *L* known *a priori*, and measurable flux *f*, whose distance is therefore

$$r = \sqrt{rac{L}{4\pi f}}$$
 or equivalently  $r = 10^{0.2(m-M)+1}$  pc

Standard Ruler An object with length *d* perpendicular to the line of sight known *a priori*, and measurable angular size  $\theta$ , whose distance is

$$r = \frac{d}{\sin \theta} \approx \frac{d}{\theta}$$

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Cepheid variables were the first standard candles. Today,  $> 10^4$  are known. A large fraction of them (2400) were identified by **Henrietta Leavitt**, who worked as a "computer" in Edward Pickering's group at Harvard College Observatory.



- 969 of Leavitt's Cepheid variables are in the SMC (Leavitt 1908), so they are all ~60 kpc away.
- Leavitt noticed in the first few sets of photographic plates that many of the brightest stars were variable and that the brighter variables had longer periods.
- She also noticed that the light curve *shapes* resemble those of "cluster variables," the stars we now call RR Lyrae variables. The Milky Way globular cluster 47 Tuc was in all of her SMC plates.

After noticing the brightness-period relation, Leavitt acquired  $\sim 100$  more plates on the SMC, taken over a period of 16 years, from the Harvard archives. She then worked out the light curves and periods of many of the variables.

Choosing 25 objects with particularly good light curves and a large range of magnitudes, Leavitt determined their periods and showed that the **magnitudes are proportional to the logarithm of the periods** (Leavitt & Pickering 1912).

Conclusion: The variables are **standard candles** —

Since the variables are probably at nearly the same distance from Earth, their periods are associated with their actual emission of light [luminosity], as determined by their mass, density, and surface brightness.

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- Period–apparent magnitude relation for the bright variables in the SMC, from Leavitt & Pickering (1912).
- The upper (lower) curve represents each star's maximum (minimum) brightness in its pulsation cycle.
- The linear fits have the same slope: 1 mag per 0.48 in log ( $\Pi/day).$



Today, we know that Leavitt's stars are classical Cepheids (not RR Lyraes) and the period–average magnitude relation for her LMC stars is (Monson et al. 2012)

$$\overline{m_V}(\text{LMC}) = -2.77 \log\left(\frac{\Pi}{\text{day}}\right) + 17.58$$

Since the absolute and apparent magnitudes differ only by the constant distance modulus and the *V* extinction — 18.48 and 0.39 mag, respectively, for the LMC — we have a relation between the period and absolute magnitude (Leavitt's Law):

$$\overline{M_V}(\Pi) = -2.77 \log\left(\frac{\Pi}{\mathrm{day}}\right) - 1.69$$

and the distance to a new Cepheid with period  $\boldsymbol{\Pi}$  is given by

$$5\log\left(\frac{r}{10\,\mathrm{pc}}\right) = \overline{m_V} - \overline{M_V}(\Pi)$$

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Leavitt's Law for 23 galaxies (Riess et al. 2016)



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# Hindsight on the pulsating stars

Classical Cepheids belong to Pop I: high metallicity, low random velocity.

W Virginis stars and RR Lyraes belong to Pop II: low metallicity, high random velocity.

Right: H-R diagram of pulsating stars from Cox (1974), with the **Instability Strip** indicated by the dashed line.





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The ladder by which distances to celestial objects are currently determined. Each rung depends on the previous result, inheriting its uncertainty and adding its own.

- 1. Distances at the scale of AU are measured using **radar** reflection from Venus and Mars, and now time-stamped spacecraft radio transmissions.
  - ▶ It would be tempting to measure stellar distances by radar, but the reflected signal decreases as  $r^{-4}$ , so it does not work for objects more than a few light-hours away.
- 2. Use **trigonometric parallax** to determine the distances to as many variable stars (e.g., classical Cepheids, RR Lyr) as possible, and work out the terms in Leavitt's Law (for the classical Cepheids).
  - With Gaia, there are about 200 Cepheids with decent parallax measurements in DR2 (Groenewegen 2018).
  - More than 20 times as many as can have distances measured by main-sequence fitting (An et al. 2007), and more accurate besides.

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- 2b. RR Lyr are not as bright as classical Cepheids, so we observe as many globular clusters as possible, measuring their distances with RR Lyr stars as standard candles.
- 2c. Measure the HR diagram of each globular cluster, and from these, calibrate a new standard-candle luminosity, the **tip of the red giant branch** (TRGB).
  - Unlikely as it seems, the luminosity of the TRGB is remarkably uniform.



Freedman (2021)

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3. Observe classical Cepheid periods and fluxes, or the TRGB, in galaxies, get their luminosities from their periods (Cepheids), and determine their distances (and therefore distances to their host galaxies) using

$$r=\sqrt{rac{L}{4\pi f}}$$

 This works until it is impossible to isolate individual stars in the galaxy disks. For ground-based telescopes, the limit is about 3 Mpc. For the HST, the distance limit is about 40 Mpc.



NGC 3370 has at least 93 Cepheids (Hoffmann et al. 2016)

- 4. Near the end of the Cepheid & TRGB range, several empirical relations are used to calibrate galactic luminosity and distance:
  - Tully-Fisher relation Power law relation between the rotation speed of a spiral galaxy and its mass or intrinsic luminosity (Tully & Fisher 1977).
  - Faber-Jackson relation Power law relation between the velocity dispersion of elliptical galaxies and their intrinsic luminosity (related to "fundamental plane" relations for ellipticals) (Faber & Jackson 1976).



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