31 Astro notes 2018/11/9 - Fri - Galaxies, Distance

31.1 Disk galaxies - Mass-Luminosity - Tully-Fisher

One of the major features of spiral galaxies is their rotation curve. (draw example) This increases to some V_{max} toward the edge of the star/gas component, as a result of the surrounding dark matter halo in which all galaxies are imbedded. This is one of the major evidences for dark matter, as the rotation curve should fall off as $1/r$ away from the visible component without dark matter.

A relation between the galaxy's absolute brightness (luminosity) and its V_{max} is observed. Called the Tully-Fisher relation.

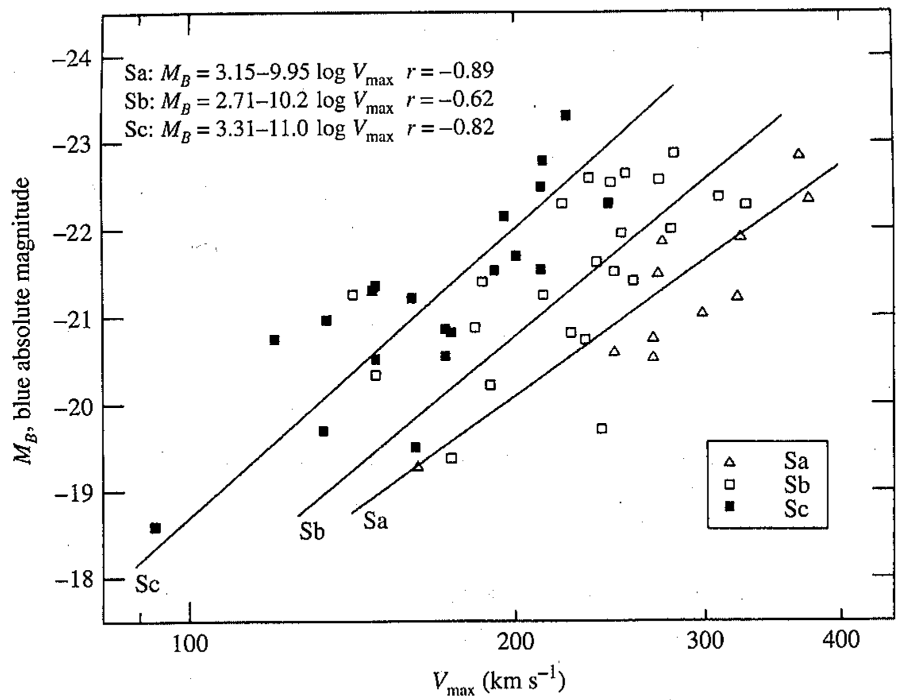


FIGURE 25.10 The Tully–Fisher relation for early spiral galaxies. (Figure adapted from Rubin et al., *Ap. J.*, *289*, 81, 1985.)

from Carroll & Ostlie

A good argument for this relation between the orbital property V_{max} and the overall Luminosity is having them both arise from the overall mass of the galaxy. The virial relation tells us that

$$\frac{GM}{R} \sim V_{max}^2$$

(or just this relation for a keplerian orbit). Where M is the mass of the visible matter and R its radial size. We need to make two assumptions to turn this into a relation to L and eliminate R. First of all, we assume that the mass-to-light ratio is not strongly dependent on galaxy mass

$$\frac{L}{M} \sim C_{ML}, \text{a constant}$$

Also, it is observed (at least for a given class of spiral), that the central surface brightness is relatively universal. From this we can assume

$$\frac{L}{R^2} \sim C_{SB}, \text{a constant}$$

Putting these together we find that
(student: eliminate R and M to get an L-V relation)

$$L \propto M \propto RV_{max}^2 \propto L^{1/2}V_{max}^2$$

which gives

$$L \propto V_{max}^4$$

The observed Tully-Fisher relation in infrared is

$$M_H^i = -9.50(\log_{10} W_R^i - 2.50) - 21.67 \pm 0.08$$

where W_R^i is a measure of the rotation speed from the radial velocity difference across the galaxy in emission lines. Converting L above to magnitudes

$$M = M_{Sun} - 2.5\log_{10}(L/L_\odot) = -2.5\log_{10} V_{max}^4 + ... = -10\log_{10} V_{max} + ...$$

which matches the observed TF relation.

31.2 Spheroidal galaxies mass-luminosity relation - Faber-Jackson, fundamental plane

Elliptical galaxies are generally "simpler" but also follow a relation between their Luminosity and mass. This is much like the relation derived for the spirals, but instead of rotation velocity in the disk, the velocity dispersion σ_0 appears in the virial theorem, so that

$$L \propto \sigma_0^4$$

The observed relation is not quite this well behaved and is more like

$$L \propto \sigma_0^\alpha$$

with α between 3 and 5. This is called the Faber-Jackson relation. A better relation is the fundamental plane, which includes the radial size of the elliptical,

$$L \propto \sigma_0^{2.65} r_e^{0.65}$$

This is fairly well followed, and galaxies live in a "plane" defined by this relation in the space of L, σ_0 and r_e. Some of this additional variation parameterizes the surface brightness, which is not universal as it is for spirals. Also the mass-to-light ratio depends more significantly on overall mass for elliptical, making the exponents slightly different than would otherwise be expected.

31.3 Spiral structure

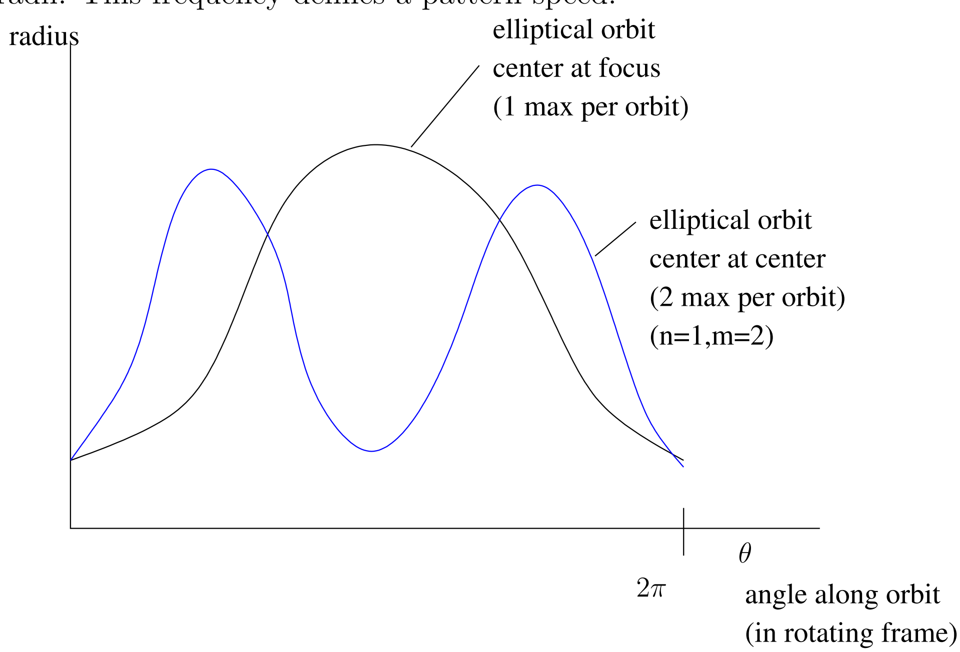
The basic tenet of spiral structure is that the spiral structure is related to spiral density waves in the disk. Stars are formed in the dense regions, and the brightest (high-mass) stars only live for a small fraction of an orbit around the galaxy center. Thus the bright, short-lived stars highlight the regions near the current location of the spiral density wave.

Maintaining a long-lived spiral **pattern** requires that orbits behave in a few particular ways made possible by the non-keplerian potential provided by the presence of the disk itself. This creates a local effective potential in which stars can oscillate in radius (and height above the plane) as they orbit the galaxy.

In general, in a non-rotating frame the orbits of stars will not be closed because the period of their orbit around the galaxy and the period of their oscillation in radius will not be the same. However, orbits turn out to be able to close in a rotating frame over a wide range of distances from the center of the galaxy. This allow a pattern to develop when

$$m(\Omega(R) - \Omega_{\ell p}) = n\kappa(R)$$

where Ω is the local orbital frequency around the galaxy, and κ is the local frequency of oscillations in radius in the effective (non-newtonian) potential of the galactic disk. It turns out that for $n = 1$ and $m = 2$, a single value of $\Omega_{\ell p}$ satisfies this equation over a wide range of radii. This frequency defines a pattern speed.



For this n and m (1 and 2) in the frame of the pattern, each star will oscillate twice in radius for each time it goes around the galaxy. This effectively creates something like an orbit that is elliptical, but with the center of the ellipse at the center rather than its focus. If these ellipses are rotated for different orbits, a spiral pattern will develop.

From our text:

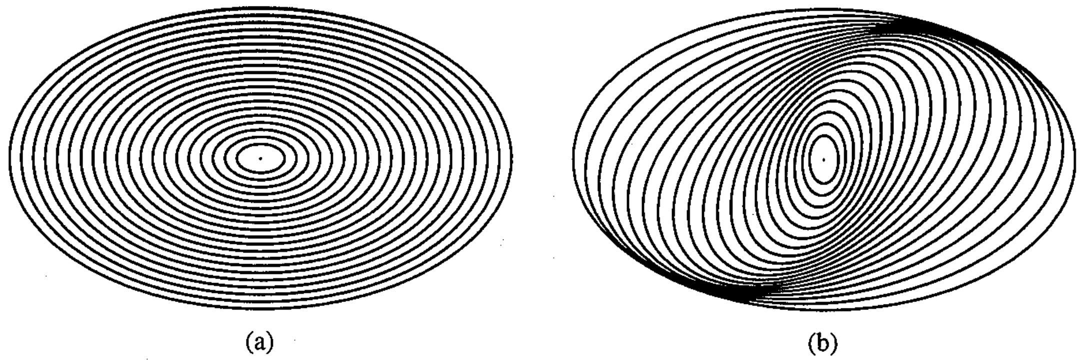


FIGURE 25.28 (a) Nested oval orbits with aligned major axes, as seen in a reference frame rotating with the global angular pattern speed ($n = 1, m = 2$), or $\Omega_{gp} = \Omega - \kappa/2$. The result is a bar-like structure. (b) Each oval is rotated relative to the orbit immediately interior to it. The result is a two-armed grand-design spiral density wave.

Note this is in the frame of the pattern, which is itself rotating at some frequency $\Omega_{gp} = \Omega_{\ell p}$.