Galaxies  Astro 530
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Tully-Fisher Relation (finish)
& Spiral Structure (start)
Tully-Fisher relation

Traditional Tully-Fisher relation:
Good correlation between galaxy’s stellar luminosity (absolute magnitude) and its maximum rotation velocity (or linewidth, corrected for inclination)

Importance of TF relation:
1. Method of determining distance
2. Tight correlation between stellar luminosity and maximum rotation velocity has important implications for galaxy structure & formation (implies poorly-understood coordination between dark matter and baryonic matter)
4 different versions of TF relation

Tightest “TF relation” is with baryonic mass (stars & gas)

There is tight correlation between a galaxy’s baryonic mass and its non-baryonic mass & mass distribution

Scatter and slope of TF are of great interest

Scatter -- accuracy as distance indicator, galaxy structure & evolution

slope -- galaxy structure & evolution
TF relation yields $L \sim v_{\text{max}}^4$

\[ M_H = c - s \log v_{\text{max}} \]
\[ 2.5 \log L_H = c_1 + s \log v_{\text{max}} \]
\[ \log L_H^{2.5} = c_1 + s \log v_{\text{max}} \]
\[ L_H^{2.5} = 10^{c_1} v_{\text{max}}^s \]
\[ L_H \sim v_{\text{max}}^{s/2.5} \]
\[ L_H \sim v_{\text{max}}^b \]
\[ b \approx 3.5 \text{ in } B \text{ band} \]
\[ b \approx 4.0 \text{ in } I,J,H \text{ bands} \]
\[ \rightarrow L \propto v_{\text{max}}^4 \]

**NOTE:** not all studies find $b=4$
range of values found $b \approx 3-4$

c = intercept or ‘zero-point’
s = slope (for TF in magnitudes)
b = slope (for TF in luminosity)
b = s/2.5

Difference in slope comes from the color-luminosity or color-mass relation: TF is less steep at B since low mass/lum galaxies are bluer on average, since they are both more metal poor and younger (larger fraction of young stars, which emit lots of light in the optical)
**Tully-fisher mystery**

Why does $v_{\text{max}}^4 \propto L$?

Why do LSB galaxies obey the TF relation?

Let’s predict what relation we might expect between $L$, $v_{\text{max}}$ for disk galaxies …

Assume: virial theorem, exponential disk

Result:

$v_{\text{max}}^4 \propto Y_{\text{OR}}^2 I_0 L$ is predicted

$v_{\text{max}}^4 \propto L$ is observed

$\Rightarrow Y_{\text{OR}}^2 I_0 \approx \text{constant}$  
*but why should this be??*

$Y_{\text{OR}}$ = total mass-to-light ratio within observable radius $R_{\text{OR}} = xR_d$

$I_0$ = central disk surface brightness
2 galaxies with same total stellar luminosity
one is high surface brightness (compact stellar distribution)
other is low surface brightness (diffuse stellar distribution)
TF relation & rotation curves vs. surface brightness

Rotation curves of HSB and LSB spirals with \textit{same stellar luminosity and same } $v_{\text{max}}$!

The TF relation doesn’t depend on central surface brightness!

Implication of TF relation not depending on surface brightness

correlation of central surface brightness $I_0$ (or $\mu_0$ in magnitudes) and mass-to-light ratio $Y_{OR}$ needed to have all galaxies obey TF relation:

Higher $M/L$ in LSB galaxies

$Y_{OR}^2 I_0 \approx \text{constant}$
MOND
Modified Newtonian Dynamics

invented to “explain” flat rotation curves, but not to explain that HSB and LSB galaxies both obey TFR

\[ a = \sqrt{g_N a_0} \] modified gravitational acceleration in MOND

\[ a = \text{acceleration} \]

\[ g_N = \text{normal Newtonian acceleration} = \frac{GM}{R^2} \]

\[ a_0 = \text{universal constant} \]

\[ a = \frac{V_c^2}{R} = \frac{\sqrt{GM a_0}}{R^2} \]

\[ \Rightarrow V_c^4 = a_0 GM \quad \text{i.e. observed TF relation} \]
are LSB galaxies evidence for MOND? not strong evidence...

• slope of TFR may not be exactly 4 (e.g. Bradford+2017)

• many rotation curves not perfectly flat, but increase or decrease a bit at outermost measured points (MOND predicts FLAT rotation curves ... and what V do you pick?)

• other evidence for dark matter (e.g., Bullet cluster)

the tightness of the TFR should instead be considered a strong constraint on galaxy formation & evolution
slope of TF relation depends on how you measure velocities

can get slopes between 3.0-4.3
2 galaxies with same dark matter distributions, very different baryon distributions, same stellar luminosity and same $v_{\text{max}}$!

FIG. 1 (color online). The rotation curves of two galaxies, NGC 2403 and UGC 128, of similar mass but very different size. The contributions of the baryonic components (stars plus gas: solid lines) are very different even though the dark matter halos (dashed lines) are similar. Lines for the baryons and dark halo of NGC 2403 end with its velocity data at 20 kpc while those of UGC 128 continue to 40 kpc. Arrows mark the radius $R_p$ where the peak of the baryonic rotation occurs.
As baryons infall toward center of halo, DM halo should get compressed

adiabatic infall in spherical halo model

Rotation curve and mass model of the luminous high surface brightness galaxy NGC 2903. The rotation curve data are plotted as circles with error bars. The contribution to the rotation by the baryonic component (stars plus gas) is denoted by squares. Large squares are for the modeled mass-to-light ratio specified in Table 1. Also shown as small squares are the limiting cases of the minimum (gas only, with $\phi = 0$) and maximum disk. The dashed line shows the adiabatically formed exponential disk used to approximate the observed baryon distribution. The solid line is the total rotation due to disk plus compressed halo. The primordial NFW halo (with parameters given in Table 1) is shown by the dotted line, and the compressed halo is shown by the dot-dashed line.
Offset between spirals and S0s in traditional TF (velocity-light) relation

Best-fit lines for spirals and S0s have the same slope, but are offset by $\Delta I \approx 1.5$. Thus both follow a Tully-Fisher relation but with different constants (zero-points). Can use TF to estimate distances to both spirals and S0s, if you know zero-points for both.
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**Both follow same baryonic TF with no offset but have different stellar populations.** M/L$\sim$1.5 for spirals and M/L$\sim$6 for S0s ($\Delta I = 1.5$ corresponds to a factor of 4 in luminosity). This suggests that S0s were once spiral galaxies but are now dominated by old, red stars.
Evolution of Tully-Fisher relation

Stellar mass TF relation
Black points & line: galaxies $z=1.0-1.7$
Grey line: galaxies at $z=0.2-1.0$

No change in TF relation between $z=0-1.7$
(maybe more scatter at $z=1.7$?)

Evolution of Tully-Fisher relation

At high $z$, different studies find different results (it’s hard to measure accurate stellar masses and velocities for high $z$ galaxies), but best work (e.g. Miller etal 2012) finds no evolution in TF out to $z=1.7$
Summary of key points on TF relation

Tightest TF-type relation is with baryonic mass \((M_{\text{baryon}} - v_{\text{max}})\) better than \((M_{\text{star}} - v_{\text{max}})\) better than \((L_{\text{star}} - v_{\text{max}})\), \(M_{\text{baryon}} \sim v_{\text{max}}^4\)

TF relation is a statement that galaxies obey virial theorem, but that something in addition to the virial theorem is important in determining spiral galaxy structure \(Y_{OR}^2 I_0 \approx \text{constant}\)

TF relation provides tight constraints on how baryonic and dark matter get radially rearranged during galaxy formation and evolution
Spiral structure in galaxies

something interesting that happens in a disk

can reveal physical conditions in that disk

can transfer angular momentum outwards

otherwise doesn't greatly affect formation & evolution of galaxy
does this represent a spiral galaxy?
does this represent a spiral galaxy?

solid body rotation
material arms
With a solid body rotation curve there is no differential rotation

but galaxies with spiral arms do not have solid body rotation!
does this represent a spiral galaxy?
does this represent a spiral galaxy?

differential rotation
material arms
With a nearly flat rotation curve, there is significant differential rotation in the disk.
Differential rotation naturally makes spiral patterns in disk

But! differential rotation makes material arms wind up too fast!

Material arm: stuff in arm stays in arm

Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.
does this represent a spiral galaxy?
does this represent a spiral galaxy?

differential rotation
density wave arms
**density waves**: stuff moves in and out of arms (unlike material arms)
there are different types of spiral structure, but spiral structure requires:

**differential rotation** *(for all)*

**gas** *(for all but tidal arms)*
evidence that differential rotation needed for spiral structure...
M101

large spiral
galaxy

- Stellar mass 1-2X that of Milky Way
- Classified as Sc spiral (c-> small bulge)
- **Strong spiral structure**
M33 – medium-size spiral galaxy

- Stellar mass ~1/3 that of Milky Way
- Classified as Sc spiral (c → small bulge)
- Strong spiral structure
Large Magellanic Cloud

- Stellar mass ~1/10 that of Milky Way
- Classified as *magellanic irregular galaxy* or *large dwarf galaxy*
- In class of gas-rich, star-forming galaxies, has mass near transition between spiral galaxies (large) and dwarf irregular galaxies (small)
- **Weak spiral structure**

Pink: Hα emission from ongoing star formation
Small Magellanic Cloud

- Stellar mass $\sim 1/30$ that of Milky Way
- Classified as *dwarf irregular*
- No spiral structure

Pink: H$\alpha$ emission from ongoing star formation
Low mass galaxies have little or no spiral structure

• WHY?
Low mass galaxies have little or no spiral structure

• **WHY?**

• Massive disk galaxies have *strong differential rotation*, so can have *strong spiral structure*

• Low mass galaxies have *little differential rotation*, so have *weak spiral structure*
Rotation curves of M33, LMC, SMC

M33  mass \(\sim 1/3\) MW

LMC  mass \(\sim 1/10\) MW

SMC  mass \(\sim 1/30\) MW

close to solid body rotation in low mass galaxies!
Why low mass galaxies have weak spiral structure

Rotation curves of high & low mass galaxies

High mass disk (spiral galaxy)
Large $V_{\text{max}}$ and flat at large $r$

Low mass disk (dwarf galaxy)
small $V_{\text{max}}$ and close to solid body rotation
Why low mass galaxies have weak spiral structure

Rotation curves of high & low mass galaxies

- High mass disk (spiral galaxy)
  - Large $V_{\text{max}}$ and flat at large $r$
- Low mass disk (dwarf galaxy)
  - Small $V_{\text{max}}$ and close to solid body rotation

Angular speed curves of high & low mass galaxies

- High mass disk (spiral galaxy)
  -Lots of differential rotation ($\Omega$ varies a lot with radius)
  -$\rightarrow$ strong spiral arms
- Low mass disk (dwarf galaxy)
  -Little differential rotation ($\Omega$ nearly constant with radius)
  -$\rightarrow$ weak spiral arms
What is the mass of this galaxy?

Morphology often gives a rough constraint on galaxy mass.
What is the mass of this galaxy?

Morphology often gives a rough constraint on galaxy mass

any galaxy with strong spiral structure is more massive than the LMC, i.e.,

\[ M_{\text{star}} > 3 \times 10^9 \, M_{\odot} \]
Gas needed for (most) spiral structure

→ show video of simulation of development of gas & stellar spiral features in disk

→ https://astro3.sci.hokudai.ac.jp/~alex/research_SP_en.html
Gas needed for (most) spiral structure

- In order to have structures in a disk, the stuff making up the structure needs to have sufficiently small random motions. If random motions are too large, the stuff doesn’t stay in the structure.
- Gas can have small random motions. It is *collisional* and can therefore dissipate energy & dynamically cool (reduce motions).
- Stars are *collisionless*. They can be dynamically heated (increase motions) but not cooled.
Trend of increasing velocity dispersion with age of stars in MW disk

Gravitational interactions between stars and either GMCs or spiral arms transfer energy to the stars, “heating them up” dynamically, thereby increasing their vertical motions and their average height above the disk. An internal, continuous process. Stars gain random motions over time, they don’t lose them!
Gas needed for spiral structure

- In order to have structures in a disk, the stuff making up the structure needs to have sufficiently small random motions. If random motions are too large, the stuff doesn’t stay in the structure.
- Gas can have small random motions. It is collisional and can therefore dissipate energy & dynamically cool (reduce motions).
- Stars are collisionless. They can be dynamically heated (increase motions) but not cooled.

- Young stars have the small random motions of the gas they formed from. But stars get dynamically heated over time, so older stars have larger random motions.
- Spiral structure can exist in disk of young-ish, dynamically cool stars but not in disk of older, dynamically hot stars
simulation showing development of gas & stellar spiral features in disk:

- gas concentrates much more strongly than stars, since gas is collisional and dissipates energy

- stellar orbits are perturbed by the (initially gas only) lumps in the mass distribution, perturbed stellar orbits act to concentrate stars in arms

- get spiral arms with higher densities of both stars and gas
S0 galaxies: *Disk galaxies without gas & therefore no spiral structure*
3 types of spiral structure
physically 3 different things happening although common physical elements

1.
2.
3.

characterize the spiral structure in the following images & identify differences
3 types of spiral structure
physically 3 different things happening although common physical elements

1. Grand design spirals (density waves)
2. Flocculent spirals (stochastic)
3. Tidal material spiral arms

Can have multiple types of spiral structure within 1 galaxy

Critical common elements:
**differential rotation** (for all),
**gas** (for all but tidal arms)
Grand design spirals

M100 = NGC 4321 Grand design

NGC 1300 Grand design with bar

M51 grand design + tidal material arm?
Grand design spirals

Observed properties:

- Arms can be traced continuously for >1/2 revolution
- Often clear symmetry
- Spiral pattern exists in old stars as well as gas & young stars $\rightarrow$ an enhancement in mass density of disk
Grand design spirals

Observed properties:
• Arms can be traced continuously for >1/2 revolution
• Often clear symmetry
• Spiral pattern exists in old stars as well as gas & young stars → an enhancement in mass density of disk

Physical interpretation:
• Due to density waves, through which gas and stars pass (wave of enhanced mass & gravity)
• Due to a global process – gravitational instability in disk
How is spiral structure different in these galaxies?
Flocculent spirals

NGC 4414

NGC 2841 zoom-in HST

NGC 2841
Flocculent spirals

Observed properties:
- Arm segments short, can’t be traced far
- No clear symmetry
- Spiral pattern seen in gas & young stars, but not in older stars
Flocculent spirals

Observed properties:
• Arm segments short, can’t be traced far
• No clear symmetry
• Spiral pattern seen in gas & young stars, but not in older stars

Physical interpretation:
• Due to local process
• Material arm, not a wave
• Short-lived gas concentrations which get sheared out into spiral shape by differential rotation
• Each gas lump eventually get ripped apart by shear, but new ones form to replace them
How is spiral structure different in these galaxies?
Tidal material spiral arms

M51: inner arms grand design, Outer arms tidal?
Tidal spiral arms can exist in stars only

Virgo galaxy NGC 4488
SDSS image (Hogg)
tidally disturbed galaxy
Tidal spiral arms

Observed properties:
- Strong 1 or 2-arm pattern, can be symmetric
- Spiral pattern in old stars, young stars, & gas
- Material arm, not wave

Physical interpretation:
- Due to global process – tidal interaction
- Material pulled together by tidal interaction, differential rotation turns it into spiral
- May connect to density waves in inner galaxy
HW 1 extra credit

how can you judge a galaxy’s mass from its image?

2 ways …
What is the mass of this galaxy?

Morphology often gives a rough constraint on galaxy mass. Any galaxy with strong spiral structure is more massive than the LMC, i.e., $M_{\text{star}} > 3 \times 10^9 \, M_{\odot}$.
one of these galaxies is nearby & the other is much further away
one of these galaxies is nearby & the other is much further away

how easily individual stars (or star clusters) can be seen in an image depends on distance
nearby – image resolved into individual stars (or star clusters)
distant – image smooth -- can’t identify individual stars (or star clusters)
this is basis of *surface brightness fluctuation technique* for measuring distance
HW 1 extra credit

how can you judge a galaxy’s mass from its image?

2 ways ...

1. **mass – morphology relation** (some types of galaxies only exist in small range of masses)

2. **distance clues** – ability to resolve individual stars in image depends on distance (if you know distance and measure flux, you get luminosity which correlates with mass)