Plan of Lecture

Properties of Other Galaxies II

Measurement of galaxy properties.

Spirals: the Tully-Fisher relation.

Ellipticals: the fundamental plane.

Galaxy collisions.

The M-σ relation for black holes in galaxies.

Measuring Distance

As with stars, we need to know how to measure fundamental quantities.

Distance underlies most quantities.

General methods: standard candles (known luminosity); to a lesser extent, standard rulers (known size).

Ideal standard candle: bright, common, well-understood, easily identifiable.

Other than Cepheids (useful to ~ 30 Mpc), what can we use?

Supergiant stars.

Brightest cluster galaxy.

Type Ia supernovae.

Measuring Mass

Straightforward for spirals.

Take spectra at different radii.

Spectrum: redshift $\rightarrow$ blueshift.

Get $M(< r)$.

Similar but more complicated for ellipticals.

No coherent motion.

Spectral lines broadened.

From this, get *velocity dispersion* σ.

$M \propto \sigma^2$.

Can also get masses from binary galaxies.

How does this differ from stars?

Measuring Size and Luminosity

Both are "easy" given a distance measure.

Angular size $\rightarrow$ real size.

Flux $\rightarrow$ luminosity.

However, there are subtleties.

Only measure *projected* size.

Assume flux is unbeamed.

With these caveats, find sizes $\sim 1 - 100$ kpc, and luminosities $L \sim 10^6 - 10^{12}\, L_\odot$.

Mass to Light Ratio

This ratio is helpful in characterizing many systems.

Measure M in solar masses, L in solar luminosities.

$M/L = 1$ **for the Sun.**

For stars in a large range of masses, we have $L \propto M^4$, approximately.

$M/L \propto M/M^4 \propto M^{-3}$.

High-mass stars have low M/L; low-mass stars have high M/L.

Milky Way: $M/L \approx 10$.

Ellipticals: $M/L \approx 10 - 20$.

Another indication of the older stellar population in ellipticals.

The Tully-Fisher Relation

In the 1970s, Tully and Fisher observed a number of spiral galaxies.

By measuring the rotation velocity v and the luminosity L, they found:

$L \propto v^4$.

This relation allows the measurement of distances farther than Cepheids.

Galaxies are brighter than stars!

But why should it hold?

Some answers given, none good.

Baryonic Tully-Fisher

Our own Stacy McGaugh has suggested that the more fundamental relation is between v and baryonic mass:

$M_{\rm tot} \propto v^4$.

$M_{\rm tot} = M_{\rm star} + M_{\rm gas}$.

For low luminosity galaxies, L falls below the usual Tully-Fisher relation.

But why would this hold, either??

Fits with modified gravity.

But, no fundamental theory.

Surface Brightness

Before going on to a similar correlation for ellipticals, we need another measured quantity.

Define *surface brightness* as the flux coming from a given solid angle $d\Omega$.

Units: erg cm^{-2} s^{-1} sr^{-1}.

Flux/solid angle.

Luminosity/(area times solid angle).

Change with distance?

Luminosity is fixed.

Flux$\propto 1/r^2$; $d\Omega \propto 1/r^2$.

Flux/solid angle is constant!

But, $\propto (1+z)^{-4}$.

Fitting Surface Brightness

One problem: unlike luminosity, mass (global quantities), surface brightness varies in galaxy!

High in center, low outside.

Could try as function of radius.

We don't want to just list surface brightness, so fitting forms have been devised.

de Vaucouleurs profile:

$$B \propto \exp[-7.67((r/r_e)^{1/4} - 1)].$$

King profile:

$$B \propto 1/[1 + (r/r_c)^2].$$

Both fit well!

Caveats

Those two profiles (and others) differ radically, but both fit.

Therefore, you need to distinguish carefully between two uses of a particular form:

Getting a concise fit.

Interpreting this physically!

Consider the King model.

"Isothermal sphere".

Derived from physical model.

But, luminosity would be infinite!

Many people get enamoured of fits, thinking they are the real thing; but, easy to fit smooth data!

The Fundamental Plane

Now consider ellipticals fit with a de Vaucouleurs profile.

Measure dV radius r_e, mean surface brightness I within r_e, and velocity dispersion σ.

In principle, three distinct quantities.

In practice, $r_e \propto \sigma^{1.4} I^{-0.9}$.

Therefore, instead of being distributed everywhere in the 3-D parameter space, ellipticals are on a plane!

This is the fundamental plane.

Very tight relation.

Extensions to globulars?

Reason is poorly understood.

Distance Measures

Once calibrated, Tully-Fisher or the fundamental plane can be used to measure distance.

Standard candles.

Galaxies are very bright.

However, these are only *empirical* relations.

Same with Type Ia supernovae.

Unlike Cepheids.

On the one hand, who cares?

If it's good, it's good!

However, for delicate measurements, you'd like to know how things could go wrong.

Evidence for accelerating expansion depends on an empirical distance measure.

The $M - \sigma$ Relation

There is yet another amazingly tight empirical relation.

Measure the mass $M_{\rm BH}$ of a central black hole in a galaxy (how?), and velocity dispersion σ.

$$M_{\rm BH} = 10^8 \, M_\odot (\sigma/200 \text{ km s}^{-1})^4.$$

Discovered recently.

Previous relations: mass to mass.

This relation is consistent with being perfect (meas. errors), and applies across galaxy types.

Might even apply to globulars, but this is disputed.

Plenty of ideas for the relation, but not for how it's so tight.

Summary

Measurement of galaxy properties shows some surprising correlations.

Tully-Fisher relation.

Fundamental plane.

$M - \sigma$ **relation.**

Why? Not clear, but these are important clues to galaxy formation and evolution.