Plan of Lecture
Hubble's Law and Galaxy Clusters

Measurements of recession.

Hubble's law and interpretation.

Clusters of galaxies.

Advising Appointments

Remember that to register, you need an advising appointment.

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Also see her if you want to add astronomy as a major.

Galaxy Redshifts

Slipher, 1914:

11 of 15 spiral nebula redshifted!

Definition: $z = (\lambda - \lambda_0)/\lambda_0$.

Later measurements showed that virtually all galaxies display a redshift.

In 1929, Edwin Hubble showed using Cepheid measurements that z is linear with distance.

Hubble "constant" H_0.

Original: $H_0 \approx 500$ **km s**$^{-1}$ **Mpc**$^{-1}$.

From H_0, can get rough measure of age of universe.

$T \propto 1/H_0 \sim 2 \times 10^9$ **yr.**

Oops! Shorter than age inferred from geology.

Refined Measurements

What caused the problem?

Redshift measured easily.

Distance underestimated.

Hubble: Pop I Ceph, Pop II W Vir.

Also confused H II regions w/ stars.

When corrected, measurements by two groups:

Sandage, SNe Ia, $H_0 \approx 50$.

de Vaucouleurs, T-F, $H_0 \approx 100$.

Later, much better Cepheid measurements with the Canada France Hawaii Telescope (followed by Hubble) gave $H_0 \approx 72 \pm 3 \pm 7$.

Systematic errors are tough to deal with!

Galaxy Clusters

Dropping H_0 for the moment, consider clusters of galaxies.

Galaxies tend to congregate.

Some in tens (Local Group).

Some in thousands (e.g., Virgo).

For the big clusters, typical properties are:

Radius $\sim 1 - 2$ **Mpc.**

Mass $\sim 10^{14-15}\,M_\odot$**.**

Luminosity $\sim 100 - 1000\,L_{\rm MW}$**.**

Higher fraction of ellipticals.

Now let's go into these in more detail.

Membership in a Cluster

First, how do you determine if a galaxy is a member of a cluster?

Simple way: galaxy has same redshift as cluster, and is in same direction on sky.

But there are complications...

Galaxies in clusters move ~ 1000 km s^{-1}.

(1000/70)=14 Mpc of Hubble flow!!

Cluster is spread out in redshift.

Also, nearby but unassociated galaxies feel gravity of cluster.

Farther ones fall towards us.

Nearer ones fall away.

"Finger of God".

The Matter Content of Clusters

How do you determine the mass of a cluster?

Positions, redshifts of galaxies.

Need to take average redshift, determine individual z relative to it.

Total mass of big cluster $\sim$few$\times 10^{14}\,M_\odot$.

What is the stellar mass?

Get optical luminosity.

Apply typical M/L ratio.

Result: $M_* \sim 10^{13}\,M_\odot$.

What is the rest of the mass?

Full of Hot Air

Well, hot gas, actually.

Look at a typical cluster in X-rays.

Diffuse glow; why?

Consider a gas molecule in the cluster. What is its temperature?

Speed $v \sim 1000$ **km s^{-1}.**

$v = \sqrt{3kT/m}$**,** $T \approx$**few**$\times 10^7$ **K.**

Blackbody peak in X-rays.

This motion is an independent measure of the cluster mass.

But even this is only 10-20% of the total mass!

Dark Matter

We are therefore again left with mass we can't see.

$\sim$80-90% of total.

Can we corroborate the existence of this mass?

Independent measure: gravitational lensing.

Mass deflects light.

Clusters are $\sim$transparent.

See background galaxies, quasars.

Map distribution of mass.

Indeed, mass is same as estimated from galaxies and gas.

Nature of dark matter? Not clear.

Origin of the Gas

Where did the hot gas originate?

Clue: the fraction of ellipticals is much higher in clusters.

In clusters, galaxies are closer.

Collisions are more frequent.

Computer simulations are essential to understanding collisions.

Dynamics: tidal tails.

Hydrodynamics: shocks, stars form.

Products look like ellipticals.

Therefore, gas from inside galaxies might be distributed through cluster.

Cooling Flows

Suppose we look at the gas more closely.

As gas cools down from few$\times 10^7$ K, it accelerates its cooling.

Cooling is especially fast between 10^6 K and 10^4 K.

But where is this cool gas in clusters?

Don't see it in optical.

Don't have lots of star formation.

Part of this discrepancy could be resolved by observations in last few years.

Not as much "flow" as thought.

But there seems to be a need for heating of gas.

The Sunyaev-Zeldovich Effect

Clusters can be used as probes, as well.

Think about radiation from the microwave background.

Low-energy photons.

Equivalent temperature: ~ 3 K.

The electrons in the cluster gas are a lot hotter.

When a photon scatters off a fast-moving electron, the photon tends to gain energy.

This shifts that patch of the microwave background to a higher temperature.

Use to detect clusters; also gives "secondary anisotropy" to background.

Detect equally at all z!

Back to the Hubble Constant

The SZ effect can be used to estimate the Hubble constant.

From SZ effect, measure T times number of electrons in line of sight.

From X-ray spectrum, measure T, and separately the number density n of electrons.

Combine to get size of cluster.

Assume cluster is spherical. Then, know true width of cluster.

From angular diameter, get distance.

Combine with z to get H_0.

Result? Lower H_0, ~ 50, than other methods.

Biases?

Summary

The Hubble constant H_0 is one of the fundamental parameters of cosmology.

$H_0 \approx 70$ **km s^{-1} Mpc^{-1}.**

Galaxies are often grouped into clusters.

Thousands of galaxies.

Most baryons in hot gas.

Most mass in dark matter.

Challenge: how could an active galaxy influence a cluster?