Active Galaxies and Galactic Structure
Lecture 22
April 18th
• FINAL Wednesday 5/9/2018 6-8 pm
• 100 questions, with ~20-30% based on material covered since test 3.
• Do not miss the final!
The Nature And Demographics of Small Exoplanets

Dr. Diana Dragomir (MIT)

Abstract:

One of the most significant recent discoveries in the exoplanet field is that planets smaller than Neptune are more common than larger ones in our galaxy. These planets can theoretically have a wide range of compositions which we are just beginning to explore observationally. Meaningful constraints on their atmospheres, masses and radii - and thus their density and composition - are generally feasible only for those planets that transit bright, nearby stars. I will present the small ensemble of known sub-Neptune exoplanets that are amenable to mass measurements and atmospheric characterization. I will discuss what we have learned about these systems until now, and how they inform our understanding of this population of exoplanets. I will conclude by describing how the Transiting Exoplanet Survey Satellite (TESS), due to launch this month, will revolutionize this understanding by significantly increasing the number of known small exoplanets orbiting nearby stars. This new ensemble of well-characterized small exoplanets can then be statistically leveraged to uncover new trends and gain deeper insights into their composition, and ultimately their formation.
Hubble's Law

Hubble's Data (1929)

Hubble and Humason (1931)
Three Steps to Measuring the Hubble Constant

Stellar Parallax Measurement of Cepheid Variable

1. Earth (June) - Sun - Cepheid - Earth (December)

Galaxies hosting Cepheids and Type Ia supernovae

Distant galaxies in the expanding universe hosting Type Ia supernovae

Light redshifted (stretched) by expansion of space

- Short-period Cepheid
- Long-period Cepheid

0 - 10,000 Light-years
10,000 - 100 Million Light-years
100 Million - 1 Billion Light-years
Expanding Universe

• All galaxies are in motion away from us, with more distant galaxies moving faster.

• Newton’s second law -> changing velocity implies an force.

• Is some force is accelerating galaxies away from us?!
  • Are we the center of the universe?

• Cosmological principle- the universe is isotropic and homogenous

• If galaxies are not accelerating, then the space between them must be expanding!
The Expanding Ruler
Expanding Universe

• If the Universe were infinite, static, and filled with a uniform distribution of stars, then the sky would be very bright.
• In an expanding, finite universe, distant objects become dimmer as time progresses.
• Eventually, the night sky will be starless!
• A finite universe that is expanding implies that we had a beginning (Big Bang).
• Turns out the expansion of the universe is accelerating!
Quasars

• Quasars—quasi-stellar objects—are starlike in appearance, but have very unusual spectral lines.
• They are very bright in the radio and visible spectrum.
• The first quasar was discovered in 1963 and was thought to be an unremarkable blue star, but with a nonstellar spectrum.
Quasar Stellar Spectrum

- Eventually, it was realized that quasar spectra were normal, but enormously redshifted (37% redshift).
Quasars and host galaxies

- The Hubble telescope was able to resolve the host galaxies.
- Quasars are 10-100 times brighter.
- Galaxies obey Hubble’s law, so do quasars/
- Quasars are incredibly far away!
Size and Mass

- Quasars brightness fluctuates (~30%) on a short time scale $10^{10} - 10^{3}$ days.
- The time scale of these fluctuations allows astronomers to measure the size of the quasars.
- Quasars are typically a few light months in size (about the size of our Solar System).
If rotational speed of objects in orbit around the quasar can be measured, we can use Kepler's laws to calculate the mass.

For normal galaxies, we can measure the orbital speed of bright stars or globular clusters to weigh the galaxy.

Quasars outshine any star or globular cluster, so astronomers measure the Doppler shift of gas near the quasar.

Quasars weigh between ~ million to 50 billions of solar masses.
What are quasars

• Quasars are hugely powerful, emitting more power in radiated light than all the stars in our Galaxy combined.
• Quasars are tiny, about the size of our solar system (to astronomers, that is really small!).
• Because quasars put out so much power from such a small region, they can’t be powered by nuclear fusion the way stars are; they must use some process that is far more efficient.
• Quasars are really far away, thus they are more common in the early universe.

They must be super massive black holes
• When objects fall into a black hole, they form into an accretion disk.
• As the object falls, it converts its gravitational potential energy into kinetic energy.
• When in falling matter experiences any kind of friction on its way down, heat is produced.
• The accretion disk is whole clouds of interstellar gas and dust; they may radiate away as much as 10–20 percent of their mass before disappearing (E=mc²).
Quasar Stellar Spectrum

• Quasars are among the most luminous objects in the galaxy to be visible over such enormous distances.
• Oldest quasar created ~700 million years after the big bang. ~13 Billion light years away from Earth.
• Today, why are most super massive black holes quiescent?
The black hole mass gape

• The minimum mass for a black hole is about 5 solar masses, while the most massive supernova leave can leave behind ~30 solar mass black hole.

• Galactic black holes have a mass of millions to billions of solar masses.

• We do not find black holes with masses in between these two regions.

• Why? No one knows for sure, but the formation of super massive black holes may give some clues.
Super Massive Black Hole Formation.

• Once a black hole is in place in the center of a galaxy, it can grow by accretion of matter and by merging with other black holes.

• If a super massive star (~100 solar masses) went supernova, the explosion would push much of the needed material away causing the black hole to form much slower.

• Super massive black holes could have been seeded during the big bang when the universe was much denser. The initial mass would be about the same as the moon.

• Quasar prove that super massive black holes formed very early in our universe.
Galaxy Evolution

• The further away a galaxy is, the younger it is.

• 13.8 billion years since the big bang
  • If a galaxy is ~6 billion light years away, 8 billion years old.

• The Doppler shifts of a galaxy’s spectral lines can tell us how fast the galaxy is rotating and hence how massive it is

• Analysis of such lines can also indicate the types of stars that inhabit a galaxy

• The younger the galaxy, the dimmer it is. Sometime only the shape can be measured.
Galaxy Evolution

• Nearly all the galaxies at distances greater than 11 billion light years are extremely blue.
• Young galaxies are smaller and less massive.
• Over time, these smaller galaxies collided and merged to build up today’s large galaxies.
• Spectra indicates an abundance of ‘metals’ in stars as young as 1 billion years old!
• Galaxies grow by merging and cannibalizing.
Mergers and Cannibalism

• Stars rarely collide when their host galaxies collide because the space between stars is very large.
  • Orbits will change though

• Gas clouds, which are much larger than stars, can compress and trigger rapid star formation. Phenomenon called “starburst”.

• Merger: When two galaxies of equal size collide.

• Galactic cannibalism: When a small galaxy is consumed by a much larger one.
  • Large elliptical galaxies probably formed from cannibalism.
  • Have multiple nuclei.
Nonstellar Radiation

• About 20–25 percent of galaxies are not well characterized by a blackbody spectrum— they are far too luminous.

• Such galaxies are called active galaxies. They differ from normal galaxies in both the luminosity and type of radiation they emit.

• The radiation from these galaxies is called nonstellar radiation.
M–sigma relation

• M–sigma relation is a strong correlation between the average rotational velocity and the mass of the host black hole.
• This points to a feedback between star formation and black hole accretion.
• The black hole has to evolve with the galaxy.
Dark Matter and Star Clusters

• Recall Escape Velocity:
  • speed needed to completely escape the gravity of a massive object.

• Comma Cluster:
  • Mass in visible matter (galaxies and intracluster gas) $2 \times 10^{14}$ solar masses. Size 3 Mpc. Escape speed then 775 km/s.

• Typical velocity of galaxy within cluster observed to be 1000 km/s, and many have 1000-2000 km/s

• Must be more mass than is visible (85% dark matter inferred).
Gravitational Lensing

Remember from Einstein’s Theory of General Relativity that gravity causes light to follow curved paths, e.g.

So gravity acts like a lens.  
Saturn-mass black hole
Clusters of galaxies also bend the light of more distant galaxies seen through them.
From the lensed galaxy images, you can figure out the total mass of the cluster. Results: much greater than mass of stars and gas => further evidence for dark matter!

All the blue images are of the same galaxy!
The Bullet Cluster

Dark matter predicted not to interact with ordinary matter, or itself, except through gravity. Gas clouds, by contrast, can run into each other. A collision of two clusters provides dramatic evidence for dark matter:
Super Clusters - Laniakea Supercluster

[Diagram showing the Laniakea Supercluster with various clusters and groups labeled.]
More Super clusters – note the filamentary shapes
• There are at least 2 trillion galaxies in the observable universe.

• Each galaxies has billions of stars.

• Where in the Universe are we?

1801 Mountain Rd NW,
Albuquerque, NM 87104
United States of America
Earth
The Solar System
The Milky Way Galaxy
The Local Group
The Virgo Supercluster