A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

Instructor: Shami Chatterjee

Note: HW 1 posted, due Monday July 1st.
So far: Big Bang cosmology
Next: Large Scale Structure and galaxies
Big Bang Nucleosynthesis

Hot Big Bang Model: about 3 minutes after the Big Bang, the temperature and density were hot and dense enough to allow formation of stable protons and neutrons.
- Hydrogen nuclei formed.
- Some H nuclei fused to form He nuclei.
- A tiny bit of Lithium, Beryllium, and Boron were produced, but no heavier elements.

Quickly, as the universe expanded, the temperature and density dropped so that no more fusion could take place → no more He.

- 90% of atoms are hydrogen (~75% of the mass)
- ~9+% of nuclei are helium (~25% of the mass)
- Trace amounts of Li, Be, B (<0.00007% of the mass)
- Nothing heavier than that!
The Pillars of the Big Bang

• Hubble Expansion.
  \[ V = H_0 \cdot D, \text{ with } H_0 = 72 \text{ km/s/Mpc}. \]

• The Cosmic Microwave Background.
  Uniform, isotropic, 2.73 K black body radiation,
  with \(~200\) microK fluctuations.

• Elemental Abundances.
  Quantitative predictions for ratios of \(H : D, ^3\text{He}, ^4\text{He}, ^7\text{Li}\).
  (Primordial abundances at the end of the Big Bang.)
The history of the universe

The Big Bang happened everywhere 13.8 billion years ago.

Now: the present epoch.
Fate of the Universe

- **Re-collapsing Universe**: the expansion will someday halt and reverse.
- **Critical Universe**: will not collapse, but will expand more slowly with time.
- **Coasting Universe**: will expand forever, with little slowdown.
- **Accelerating Universe?**

Expansion accelerates with time.

Currently favored, but the one with the dark energy problem!

This is the current paradigm: Lambda-Cold-dark-matter, \( \Lambda \text{CDM} \).
96% of the universe is filled with stuff that we don’t really understand (dark matter, dark energy).
The growth of structure

How and when did the filamentary structure we see today form and develop?

Time →

Smoother earlier on

Galaxies, clusters, superclusters and voids today
Galaxies and Galaxy Clusters

LARGE SCALE STRUCTURE
The Cosmic Web

• Density variations of mass-energy led to the formation of a web-like structure in which all galaxies and galaxy clusters formed.
• While the universe expands, local enhancements in mass-energy self-gravitate, increasing the enhancements.
• The web is predominantly structure in dark matter.
• The baryons (~4%) are only along for the ride but they are able to contract into galaxies and stars because they can lose energy through radiation.
• Radiation is needed in order to reduce gas pressure so that gravity can “win”.
• Dark matter evidently does not radiate and cannot contract any further than it has into dark matter halos of galaxies.
Structure in the Distribution of Galaxies and Galaxy Clusters

Sheet

Void

2dFGRS galaxy map

Tuesday, 3 September 13
Simulations of the formation, evolution and clustering of galaxies and quasars

“Millenium Simulation”

Springel et al. 2005
Schematic diagram showing the position of a typical galaxy within the cosmic web

Galaxies grow by mergers...
Redshift

Redshift \( z = (\lambda - \lambda_0)/\lambda_0 \quad [\lambda_0 = \text{rest (laboratory) wavelength}] \)

Redshift means the shift of spectral lines red-ward, i.e. to longer wavelengths.

Physically redshifts occur in three ways:

1. The source of light is moving away from an observer (Kinematic redshift).
2. The source of light is in a gravitational well so that light has to work against gravity to get to the observer (Gravitational redshift).
3. The source of light is at some cosmological distance (Cosmological redshift).
   - This effect is a combination of 1 and 2 + expansion of spacetime.
   - It is not correct to think of galaxy redshifts as measuring only “recession velocities”.

Distances 101

- Speed of light: \( c = 3 \times 10^5 \text{ km s}^{-1} = 3 \times 10^{10} \text{ cm s}^{-1} \).
- Light year: speed of light \( \times \) 1 year;
  \[ 1 \text{ LY} \approx 10^{18} \text{ cm} \approx 10^{13} \text{ km}. \]
- Parsec = parallax arcsecond;
  \[ 1 \text{ pc} \approx 3.09 \times 10^{18} \text{ cm} \approx 3.25 \text{ LY}. \]
- Distance to the Sun \( \approx \) 500 light seconds (1 AU).
- Distance to Pluto \( \approx \) 4 to 5 light hours.
- Next nearest star \( \approx \) 1.3 pc.
- Nearest large galaxy (Andromeda) \( \approx \) 0.6 Mpc.
- Size of Universe \( \approx \) 4.3 Gpc (giga-parsecs)
  (defined in terms of the Hubble constant as \( c / H_0 \)).
Summary

• The universe began as a hot ‘big bang’.
• Olbers’ paradox (dark night sky = fundamental).
• The universe, on average, is expanding; cools down as it expands.
  • Local contraction: galaxy clusters, galaxies, stars.
  • Local heating: stellar winds, supernovae, radiation from stars, galaxy collisions.
• We have detailed quantitative probes of critical ‘milestones’:
  • Large scale structure (cosmic web): imprinted @ t << 1 sec. “Things are as they are because they were as they were” (T. Gold)
  • First elements (t ~ 3 minutes).
  • Cosmic Microwave Background (t ~ 380 kyr, z ~ 1000).
  • First galaxies (t ~ 0.5 Gyr, z ~ 10).
• The universe is evolving in many other ways:
  • Metallicity (Z) increasing.
  • Star formation rate peaked around z = 1 (age ~ 5 Gyr).
  • On very long time scales, star formation will cease.
The Milky Way

Our Milky Way, at radio, IR, optical, X-ray, and gamma-ray wavelengths.

Note: viewed from inside.
Andromeda (M31)
The nearest large galaxy
The Milky Way

Optical

Andromeda
Andromeda (M31)
The nearest large galaxy
Notional image of the Milky Way

Two-arm barred spiral.

~ 30 kpc

Galactic Center
Sgr A* = central source
$4 \times 10^6 \, M_\odot$ black hole

8.5 kpc

$\odot \, \text{Sun}$
The Milky Way

**Stellar Halo**
The Galaxy’s sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about $10^9$ solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.

**Segue 1**
Dwarf galaxy.

**Ursa Major II**
Dwarf galaxy.

**Dark-Matter Halo**
The Galaxy’s largest component is roughly spherical, several hundred kiloparsecs across, about $10^{12}$ times the mass of the Sun — and completely invisible.

**Disk**
This most photogenic part of the Galaxy contains the spiral arms, is 30–40 kiloparsecs across and about $5 \times 10^{10}$ solar masses.

**The Sun**

**Bubbles**
Back-to-back jets of energy erupted from the Galaxy’s central black hole some 10 million years ago, forming two bubbles of hot gas that extend about 7,600 parsecs above and below the galactic plane.

**Dwarf Galaxies**
The Large and Small Magellanic Clouds are the biggest known dwarf galaxies, which probably formed in the denser clumps of the dark-matter halo. About two dozen are known, including Segue 1, Ursa Major II and the Sagittarius dwarf.

**Sagittarius Star Stream**
The Sagittarius dwarf galaxy is being pulled apart by the Milky Way’s gravity, with its stars strung out along its orbit. Many other streams from long-dead dwarfs loop through the outer halo.

**The Big Picture**
Recent data are illuminating the Milky Way’s structure, including its bright disk and the fainter features surrounding it.
Colliding galaxies NGC 5427 and NGC 5426.

Andromeda and Milky Way are expected to collide eventually.

(A few Gyr from now!)
The center of the Milky Way at radio wavelengths

- Sgr B2
- Sgr B1
- Arc
- Sgr A
- New SNR 0.3+0.0
- Threads
- New Feature: The Cane
- Background Galaxy
- Threads
- New thread: The Pelican
- Coherent structure?
- Snake
- Mouse
- SNR 359.0-00.9
- Sgr C
- SNR 359.1-00.5
- Sgr E
This zoom sequence starts with a view of the Milky Way. We zoom in towards the crowded central region, in the constellation of Sagittarius (The Archer). By shifting to an infrared red view we see through the dusty clouds in this direction and get a close up view of the objects orbiting the supermassive black hole that lies at the centre of the Milky Way. The final views show the motion of a newly-discovered gas cloud that is falling rapidly towards the central black hole.

http://www.eso.org/public/videos/eso1151d/
The heart of the Milky Way

- At optical wavelengths, we cannot see the Galactic Center? Why not?
The Galactic Center: A busy place
The Galactic Center: A busy place

The Galactic Center: A busy place

10 light years
Sagittarius A*
Orbits of stars near the Galactic Center

Animation of the motions of stars near the Galactic Center obtained from images and spectroscopy of stars at 2.2 microns (near infrared) using the Keck Telescope on Mauna Kea by Andrea Ghez (UCLA) and her collaborators.

http://www.galacticcenter.astro.ucla.edu/animations.html
Orbits of stars near the Galactic Center

Gillessen et al 2008
The extraordinary star S0-2:
• Maximum observed radial velocity \( \sim 5000 \text{ km/s} \)
• Closest approach at 17 light hours = 120 A.U.

Data: UCLA (Ghez et al) and MPE (Genzel et al) groups
Animation based on observations

http://www.galacticcenter.astro.ucla.edu/animations.html
Sagittarius A*

- Compact, massive.
- At dynamical center.
- Mass: $4 \times 10^6 \, M_\odot$.

Sgr A* →
Supermassive black hole.
Supermassive black holes

A $\sim 50,000 \, M_\odot$ BLACK HOLE IN THE NUCLEUS OF RGG 118

VIVIENNE F. BALDASSARE$^1$, AMY E. REINES$^{1,2}$, ELENA GALLO$^1$, JENNY E. GREENE$^3$

Draft version June 26, 2015

ABSTRACT

Scaling relations between black hole (BH) masses and their host galaxy properties have been studied extensively over the last two decades, and point towards co-evolution of central massive BHs and their hosts. However, these relations remain poorly constrained for BH masses below $\sim 10^6 \, M_\odot$. Here we present optical and X-ray observations of the dwarf galaxy RGG 118 taken with the Magellan Echellette Spectrograph on the 6.5m Clay Telescope and Chandra X-ray Observatory. Based on Sloan Digital Sky Survey spectroscopy, RGG 118 was identified as possessing narrow emission line ratios indicative of photoionization partly due to an active galactic nucleus. Our higher resolution spectroscopy clearly reveals broad H$\alpha$ emission in the spectrum of RGG 118. Using virial BH mass estimate techniques, we calculate a BH mass of $\sim 50,000 \, M_\odot$. We detect a nuclear X-ray point source in RGG 118, suggesting a total accretion powered luminosity of $L = 4 \times 10^{40}$ erg s$^{-1}$, and an Eddington fraction of $\sim 1$ per cent. The BH in RGG 118 is the smallest ever reported in a galaxy nucleus and we find that it lies on the extrapolation of the $M_{\text{BH}} - \sigma_*$ relation to the lowest masses yet.

Compare Sgr A* $\rightarrow 4 \times 10^6 \, M_\odot$. 
Supermassive black holes

Stellar velocity dispersion and galaxy bulge mass scale with mass of central black hole → Mass assembly history of the galaxy.
Active Galactic Nuclei

Inner Structure of an Active Galaxy

- Shock
- Relativistic Jet
- Supermassive Black Hole
- Accretion Disk
- Opaque Torus (Inner Regions)

FR Class I source: radio galaxy 3C31

FR Class II source: quasar 3C175
Radio image with the VLA
Radio image with the VLA

Question to think about:
What powers these jets?