The Search for Life in the Universe
Lecture 3

Last time:
• Drake equation (as continuing intro)
• Our universe = $\Lambda$CDM, originated in hot big bang
• Time scales, distance scales

This time:
• Brief intro to galaxies and their distribution in space-time
• Olber’s paradox
• Redshifts and the Hubble Law
• The elements

Instructors: Jim Cordes & Shami Chatterjee
http://www.astro.cornell.edu/academics/courses/astro2299/
Main Points

• We live in an expanding, evolving universe that began in a hot big bang about 13.7 Gyr ago
• Spacetime geometry appears as 3+1
• Structure in and expansion of the universe are so-far consistent with a Λ CDM cosmology
• Trace elements were produced in the big bang but most in stars after about 0.5 Gyr
• The first planets were formed around second (or Nth) generation stars and the first life could have begun shortly after that (universe about 0.5 to 1 Gyr old)
The Milky Way

optical

infrared
The Milky Way

Radio
(408 MHz)

X-rays
Very Large Array
Cygnus A
Hercules A
Central Black Hole = $2.5 \times 10^9 \, M_\odot$
Radio Galaxy 3C31
NGC 383

VLA 3.6cm radio image on HST WFPC2 optical copyright (c) NRAO 1998

Very Large Array
Plains of San Augustin, New Mexico
Andromeda (M31)
The nearest large galaxy

Fabian Neyer Astrophotography
Notional image of the Milky Way

Two-arm barred spiral
The Milky Way

**THE BIG PICTURE**
Recent data are illuminating the Milky Way’s structure, including its bright disk and the fainter features surrounding it.

**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.

**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.

**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.

**STELLAR HALO**
The Galaxy’s sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about $10^7$ solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.
Colliding galaxies NGC 5427 and NGC 5426

Andromeda and Milky Way are expected to collide eventually

(a few Gyr from now)
Large Scale Structure in the Local Universe

Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004) familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent) Graphic created by T. Jarrett (IPAC/Caltech)
Why is the Night Sky Dark?

• On a moonless night: night sky < $10^{-6}$ daytime brightness

• ‘It takes a genius to realize that the relative weakness of starlight is of great cosmological significance and such a person was Johannes Kepler’

  (E.R. Harrison, Cosmology)

• Possible answers:
  1. Kepler 1610: universe not infinite
  2. Olbers 1823: universe infinite but starlight is absorbed by intervening material
  3. Poe 1848: ‘... by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.’
  4. 20th century: redshifts make distant objects dim at a given wavelength: Hubble law

• Who is correct? Poe

• Because:
  (1) the speed of light is finite ($3 \times 10^5$ km/s)
  (2) the universe has finite age (and stars didn’t exist until > 100 Myr after the BB)
Olber’s “paradox”

Consider a universe made up of stars that have the same luminosity \( L_* = \) their wattage (joules/s or erg/s)

\[
F_\Delta = \frac{L_*}{4\pi D^2}
\]

The flux from all the stars in the shell is

\[
F_D = F_* n_* \Delta V
\]

\[
= \left( \frac{L_*}{4\pi D^2} \right) n_* \ 4\pi D^2 \Delta D
\]

\[
= n_* L_* \Delta D
\]

If we sum over all distances out to some maximum \( D_{\text{max}} \) we get an integral

\[
F = \int_0^{D_{\text{max}}} dD \ L_* n_*
\]

\[
F \to \infty \quad \text{as} \quad D_{\text{max}} \to \infty
\]
## Is the Universe Static or Evolving?

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Theory</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Newton</td>
<td>1600s</td>
<td>Static</td>
<td>Static</td>
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<tr>
<td>Einstein 1.0</td>
<td>1916</td>
<td>Static (“greatest blunder”)</td>
<td></td>
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<tr>
<td>Hubble</td>
<td>1929</td>
<td>Expanding</td>
<td></td>
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<tr>
<td>Einstein 2.0</td>
<td>1929+</td>
<td>Expanding</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Underlying spatial symmetry of the universe (isotropy: it looks the same in all directions, statistically)</td>
<td></td>
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<tr>
<td>Bondi, Hoyle, Gold</td>
<td>1948</td>
<td>Steady State Theory</td>
<td>Static</td>
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<tr>
<td></td>
<td></td>
<td>Based on symmetry in time as well as space (more elegant)</td>
<td></td>
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<tr>
<td>Gamov, Alpher, Herman</td>
<td>1948</td>
<td>Expanding</td>
<td></td>
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<td></td>
<td></td>
<td>Prediction of residual radiation from a hot initial universe</td>
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<tr>
<td>Hoyle</td>
<td>1950</td>
<td>Coined “big bang” as a derogatory term</td>
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<tr>
<td>Refutation of SS Theory</td>
<td>1960s-1970s</td>
<td>Discovery of cosmic background radiation, Galaxy evolution.</td>
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Doppler Effect

- Sound waves
- Electromagnetic waves
- Any kind of wave

Shift in wavelength (simplest form):

\[
\frac{\Delta \lambda}{\lambda} = \frac{V}{c}
\]

- \(V\) = velocity of emitting object
- \(c\) = velocity of light or velocity of sound

But ... motion is not the only cause of wavelength shifts!
Doppler Applications

- Blood flow (speed from acoustical wavelength shifts), artery blockage
- Police radar
- Star motion toward or away from us (as in our rotating galaxy)
- Rotations of stars and planets (one side moves toward us, the other away)
- Detection of planets around stars (the planet perturbs the star’s motion)
- Motions of galaxies relative to us
- Our motion with respect to the cosmic microwave background
But … wavelength shifts are not only about the Doppler effect!

Redshift \( z = (\lambda - \lambda_0)/\lambda_0 \)

\( \lambda_0 = \text{rest (laboratory) wavelength} \)

• Redshift means the shift of spectral lines redward, 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”
Gravitational Redshift

- Light from an atom in a potential well will appear at a longer wavelength than $\lambda_0$ to an observer outside the potential well
- For shallow wells $z_g = \frac{GM}{rc^2} << 1$
- The gravitational redshift was measured in a Harvard lab in the early 1950s and has been measured from atoms in white-dwarf atmospheres and many other astronomical contexts

https://en.wikipedia.org/wiki/Gravitational_redshift

- Important for GPS = global positioning system!
  ‘Relativity in the Global Positioning System,’ Ashby