Geometry & Expansion of the Universe

Astronomy 101
Cosmology

• *Cosmology* is the study of the entire Universe:
  – Physics of the Universe.
  – Distribution of objects on all scales.
  – Motions of objects in the Universe.
  – Evolution of the Universe.
  – Age, Origin, and Fate of the Universe.
The Universe in 1917

• 1917: Einstein explored the cosmological implications of General Relativity.

• Observational State in 1917:
  – Kapteyn model of the Milky Way was favored by some (but not all) astronomers.
  – No agreement on the “spiral nebulae.”
  – First good calibrations of the P-L relation for Cepheids and RR Lyrae variables.
The Cosmological Principle

• “The Universe is Homogeneous and Isotropic on the Largest Scales.”

• Critical assumption underlying Cosmology.

• Homogeneous:
  – No special places in the Universe.

• Isotropic:
  – No special directions
Homogeneity

• When viewed on the largest scales:
  – The average density of matter is about the same in all places in the Universe.
  – The Universe is fairly smooth on large scales.

• Does not apply *locally*:
  – We see planets, stars, galaxies in regions nearby in space.
  – The Universe is locally rather “lumpy”.

Isotropy

• When viewed on the largest scales:
  – The Universe looks the same to all observers.
  – The Universe looks the same in all directions as viewed by a particular observer.

• Does not apply *locally*:
  – We see different numbers of local objects in different directions.
The Dynamic Universe

• Einstein applied the Cosmological Principle to General Relativity and got a surprise:
  – The spacetime of the Universe could not be static and unchanging.
  – The Universe *must* either expand or contract!

• Astronomers assured him that no such general motion was observed
The Cosmological Constant

• To make the Universe static, he added a new term in his field equations:

• The Cosmological Constant, $\Lambda$:
  – “Repulsive” gravitation-like force term
  – Arises from empty space.
  – Balances the effects of gravity.
Discovery of Expansion

• **1914-22**: Vesto Slipher, Lowell Observatory
  – Measured radial velocities from spectra of 25 galaxies.

• **Found**:
  – 21 of the 25 galaxies show a redshift.
  – speeds of some >1000 km/sec

• **Most galaxies are rapidly receding** from us.
Hubble’s Discovery

• 1929: Edwin Hubble

• Measured *distances* to 25 galaxies:
  – Used Cepheids and brightest stars.
  – Compared distances with recession velocities.

• Discovered:
  – Recession velocity gets *larger* with distance.
    • *Systematic expansion* of the Universe.
Hubble’s Data (1929)

![Graph showing the relationship between recession velocity and distance.](image)
Refinement

• The 1929 work was very suggestive of an effect, but the uncertainties were large.

• Set about collecting more data:

• By 1931:
  – Added 8 more galaxies with distance estimates
  – Most distant galaxy had a recession velocity of nearly 20,000 km/sec!
  – Showed a stronger, tighter trend with distance
Hubble’s Law

\[ v = H \times d \]

- \( v \): recession velocity in km/sec
- \( d \): distance in Mpc
- \( H \): Hubble’s Constant = 75 km/sec/Mpc

• **In words:**
  The more **distant** a galaxy, the **faster** its recession velocity.
Interpretation

• Hubble’s Law demonstrates that the Universe is expanding in a systematic way:
  – The more distant a galaxy is, the faster it appears to be moving away from us.
  – Rate of expansion = Hubble Constant.

• Comments:
  – Hubble’s Law is empirical - based only on data
  – Not an exact law.
Nature of the Expansion

• General Expansion of Spacetime:
  – All observers in different galaxies see the \textit{same} expansion around them.
  – No center - all observers \textit{appear} to be at the center.

• What is the recession velocity?
  – \textit{NOT} motion \textit{through} space...
  – \textit{Expansion of spacetime}: galaxies carried along.
Systematic Expansion

Universe 2x larger
Galaxies are 2x further apart
Cosmological Redshift

• Most galaxies are receding from us.
• Convenient to express recession velocity as a “redshift” for the galaxy.
• **Redshift** \((z)\):
  – Directly *observable* quantity.
  – Measured accurately from spectral lines shifts.
• Often express cosmic distances as “redshifts”.

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Redshift Distances

\[ d = \frac{v}{H} \]

- Distances estimated using Hubble’s Law even for very distant objects
Mapping the Universe

• Can map the distribution of galaxies using redshifts.

• Largest map includes ~1,000,000 galaxies
  – Reveals sheets and filaments of galaxies surrounding great voids.
  – Depth is ~500 Mpc (or so)
Sloan Digital Sky Survey

• Dedicated 3.5-meter telescope in New Mexico
• Image 1/4 of the sky in 5 colors:
  – 100 Million Galaxies
  – 100 Million Stars
• Redshift Survey:
  – 1 Million Galaxies
  – 100,000 Quasars
What about the Cosmological Constant?

• **1920s:**
  – DeSitter corrects an error in Einstein’s math, showed that the $\Lambda$ Universe was unstable.
  – Friedmann & Lemaître showed that without $\Lambda$, GR predicts that the Universe *expands*.
  – Hubble firmly established cosmic expansion observationally
State of the Art

• Einstein’s guess about the homogeneity and isotropy of the Universe was brilliant and far ahead of the scanty empirical data of his time.

• Modern observations bear out large-scale homogeneity and isotropy:
  – Large-scale galaxy surveys.
  – Maps of the cosmic background radiation.
COBE–DMR Map of CMB Anisotropy

North Galactic Hemisphere
South Galactic Hemisphere

-100 $\mu$K to +100 $\mu$K
Modern Cosmological Constant

• In current cosmological theory, $\Lambda$ reappears in a somewhat modified form:
  – Introduced as the “vacuum energy” of space.
  – Quantum ground-state of empty space.
  – Assumed to be either very very very small or zero.

• Distinction:
  – Its use today is arguably better physically motivated than when Einstein used it in 1917.
Modern Cosmological Constant

• Recent supernova observations suggest a non-zero $\Lambda$
• May mean that there is a form of “dark energy” pushing against gravity
• Form is almost completely unknown and a subject for 21st century astrophysics
• Many projects are planned over the next 10 years to characterize “dark energy”
Summary:

• Cosmological Principle:
  – The Universe is *Homogeneous* and *Isotropic* on *Large Scales*.
  – No special places or directions.

• General Relativity predicts an expanding universe.

• Cosmological Constant
Summary:

• **Hubble’s Law:**
  – Galaxies are receding from us.
  – Recession velocity gets larger with distance.

• **Hubble Constant:**
  – Rate of expansion of the Universe.

• **Cosmological Redshift:**
  – Redshift distances
  – Redshift maps of the Universe.