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

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Note: HW 1 posted.
So far: Measuring the Universe, the Big Bang
Next: Cosmology
Olbers’ Paradox

Why is the sky dark at night? (Heinrich Olbers, 1823)

If the universe were infinite, then every line of sight would eventually intercept a star (or galaxy) and hence the whole night sky should look like the surface of a star.

Solution: universe must be finite in space, in age, or both.
Fundamental Observations

• The night sky is dark. (Olbers’ paradox; the universe must be finite in size and age.)

• There have been no obvious visitations from extraterrestrials (microbes or aliens).

• The Earth and the solar system are middle-aged: 4.6 Gyr vs. ~12 Gyr (MW) vs. 13.7 Gyr (U).
Fundamental Observations

The laws of physics:

- **The good news:** can extrapolate back to $<<1$ sec after Big Bang … for describing matter and radiation.

- **The bad news:**
  - Matter is only 4% of the universe.
  - The structure of the universe was largely determined by physics that goes beyond our ability to extrapolate backwards – the action was at $10^{-43}$ sec (the Planck time).
As far as we know, it doesn’t have to be this way!

- There may be other universes with entirely different properties.
- We find ourselves in this one because it has the right properties to produce us.
  - Is this statement profound or obvious?
  - Described as the “anthropic principle”.
COSMOLOGY MARCHES ON

WHERE THE HELL DID IT ALL COME FROM?

WHERE THE HELL DID IT ALL COME FROM?
Looking back to the dawn of time

UNDERSTANDING THE BIG BANG
The Pillars of the Big Bang

• Hubble Expansion.
• The Cosmic Microwave Background.
• Elemental Abundances.
In 1923, Hubble identified Cepheid variable stars in the Andromeda galaxy. P=31.45 days \( \Rightarrow \) 7000 times brighter than Sun. Implied that Andromeda was 300 kpc away.

Follow-up: Distances to many other galaxies…

(Velocities from Doppler shifts of spectral lines; Distances from Cepheids.)

Edwin Hubble observing at the 100-inch telescope at Mt. Wilson, early 1920s.
In spite of many systematic errors, the basic trend is clear:

Galaxies that are further away are moving away from us faster.

“A relation between distance and radial velocity among extra-galactic nebulae”
- E. Hubble (1929)

\[ V = H_0 \times D \]

V: Recession velocity, from Doppler shift of spectral lines.
D: Distance, as estimated using distance ladder.
H_0: The “Hubble constant”.
The Cosmic Microwave Background

- The CMB is isotropic and uniform – the Big Bang happened “everywhere”.
- Essentially perfect black body radiation, $T = 2.72548 \pm 0.00057\ K$ (peak at 160 GHz or 1 mm).
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- Earth’s orbit around Sun: subtract Doppler shift.

- Milky way: subtract local structure.
Wilkinson Microwave Anisotropy Probe (WMAP) 9-year data: 13.77 billion year old temperature fluctuations ➞ the seeds that grew to become galaxies. Plot temperature range is ± 200 microKelvin. Our galaxy signature was subtracted using multi-frequency data.
Aside: The Accelerating Universe

Distant supernovae are fainter than they should be, if they are standard candles.

= First evidence for an accelerating (not just expanding) Universe.

“Dark Energy”
Aside: The Accelerating Universe

Different lines of evidence back this overall picture:

- Type Ia supernovae.
- CMB fluctuation spectrum.
- Large-scale structure in the distribution of galaxies ("baryon acoustic oscillations").
- Elemental abundances.
96% of the universe is filled with stuff that we don’t really understand (dark matter, dark energy).
How the universe works

Density = Destiny

Because the theme for many processes is Gravity vs. Kinetic Energy.

(The universe, formation of galaxy clusters and galaxies, stars, planetary systems, …)
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 \(~20\) microK fluctuations.

• Elemental Abundances.
To make an apple pie from scratch, you must first invent the Universe – Carl Sagan

BIG BANG NUCLEOSYNTHESIS
“The elements were cooked in less time than it takes to cook a dish of duck and roast potatoes.”

— George Gamow, theoretical physicist (1904-1968)

(Elements formed early in the big bang, that is.)
### "Big Bang" scenario from The First Three Minutes by Steven Weinberg

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature (°K)</th>
<th>Energy (MeV)</th>
<th>Density (water~1)</th>
<th>What’s happening</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 s</td>
<td>$10^{11}$</td>
<td>8.6 MeV</td>
<td>$4 \times 10^{-7}$</td>
<td>The universe is mostly light. Electrons and positrons are created from light (pair-production) and destroyed at about equal rates. Protons and neutrons being created back and forth, so about equal numbers. Only about one neutron or proton for each $10^9$ photons.</td>
</tr>
<tr>
<td>1.1 s</td>
<td>$10^5$</td>
<td>2.6 MeV</td>
<td></td>
<td>Free neutrons decaying into protons, so there begins to be an excess of protons over neutrons.</td>
</tr>
<tr>
<td>1.09 s</td>
<td>$10^9$</td>
<td>950 keV</td>
<td>$4 \times 10^{-5}$</td>
<td>Primordial fireball becomes transparent to neutrinos, so they are decoupled. It is still opaque to light and electromagnetic radiation of all wavelengths, so they are still contained. Electron-positron annihilation now proceeding faster than pair-production.</td>
</tr>
<tr>
<td>13.8 s</td>
<td>$3 \times 10^9$</td>
<td>260 keV</td>
<td></td>
<td>Below pair-production threshold.</td>
</tr>
<tr>
<td>3 m</td>
<td>$10^9$</td>
<td>86 keV</td>
<td></td>
<td>Electrons and positrons nearly all gone. Photons and neutrinos are main constituents of the universe in terms of energy. Neutron decay leaves 99% protons, 14% neutrons but these represent a small fraction of the energy of the universe.</td>
</tr>
<tr>
<td>5 m 46 s</td>
<td>$0.9 \times 10^7$</td>
<td>78 keV</td>
<td></td>
<td>Deuterium is now stable, so all the neutrons quickly combine to form deuterium and then helium. There is no more neutron decay since neutrons in nuclei are stable. Helium is about 26% by mass in the universe from this early time. Nothing heavier formed since there is no stable produce of mass 5.</td>
</tr>
<tr>
<td>34 m 40 s</td>
<td>$3 \times 10^8$</td>
<td>26 keV</td>
<td>10</td>
<td>Deuterium is now stable, so all the neutrons quickly combine to form deuterium and then helium. There is no more neutron decay since neutrons in nuclei are stable. Helium is about 26% by mass in the universe from this early time. Nothing heavier formed since there is no stable produce of mass 5.</td>
</tr>
<tr>
<td>7 yr</td>
<td>3000 K</td>
<td>0.26 eV</td>
<td></td>
<td>Cool enough for hydrogen and helium nuclei to collect electrons and become stable atoms. Absence of ionized gas makes universe transparent to light for the first time.</td>
</tr>
<tr>
<td>10¹⁰ yr</td>
<td>3 K</td>
<td></td>
<td></td>
<td>Living beings begin to analyze this process.</td>
</tr>
</tbody>
</table>
The Big Bang

1 second from the Big Bang
Protons, neutrons emerge from the cooling quark soup
250 seconds from the Big Bang
Simple atomic nuclei are formed:
74% H  25% He  1% other
300,000 years from the Big Bang
Electrons combine with H, He and other nuclei to form neutral atoms
Billions of years
Gravity causes the diffuse H$_2$/He gas to form clouds which collapse into stars
Billions of years
Stars ignite by burning $^1$H to $^4$He. The cosmos lights up
Millions of years
Nucleosynthesis
Heavy stars, late in their lives, burn to form isotopes up to $^{56}$Fe before exploding as supernovae. Isotopes heavier than $^{56}$Fe are produced during the explosion.
Years to Seconds
Nucleosynthesis
Hot radioactive fallout explodes into the interstellar medium where it rapidly cools.
Millions of years
The fallout’s activity decays until it consists of 266 stable isotopes, 18 or so very long lived isotopes and small zoo of short lived daughter isotopes.
Millions of years
This rich stardust (clinker) incorporates into emerging solar systems...
Millions of years
where it forms planets...
Millions of years
and biology begins...
Note: no elements heavier than Beryllium, due to a bottleneck: no stable nucleus with 8 or 5 nucleons.
Element Formation in the Early Universe

- The abundances of elements with atomic numbers > H depend on the density of matter when the universe was ~ 3 minutes old.
- High matter density implies faster reactions.
- A cosmic race was taking place: the universe had to cool down enough for heavier atoms to form.
- But meanwhile, free neutrons were decaying: half life ~882 s (~15 minutes).
- \( n \rightarrow p + e^- + \nu' \) (anti-neutrino)
- When all the free neutrons are gone, reactions cease.
Big Bang Nucleosynthesis

• The abundances of elements with atomic numbers > H depend on the density of matter when the universe was ~3 minutes old.

• Rapid production of Deuterium, $^3$He, $^4$He, $^7$Li – we can calculate the primordial production ratios.

• Observed abundances agree (very well!) for $^3$He, $^4$He.

• Abundance of $^7$Li is more problematic.
  - Theoretical understanding of reaction rates?
  - Observations?

• … Where do all the other elements come from?
Johnson 2019, Science: Nucleosynthetic sources of elements in the Solar System. Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources, scaled to the time of Solar System formation. Artificially made elements and elements produced only through radioactive decay of long-lived nuclei are shown in gray.
The Pillars of the Big Bang

• Hubble Expansion.
  $V = H_0 D$, with $H_0 = 72$ 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, $^3$He, $^4$He, $^7$Li.
  (Primordial abundances at the end of the Big Bang.)
Metallicity

- Metallicity is often denoted by $Z$. ($X = \text{abundance of hydrogen}, \ Y = \text{abundance of helium}$.)
- The metallicity of the Sun is approximately 1.8% by mass.
- Across the Milky Way, metallicity is higher in the galactic center and decreases as one moves outwards.
- Primordial (Population III) stars are estimated to have a metallicity of less than $-6.0$, that is, less than a millionth of the abundance of iron which is found in the Sun.

$$[\text{Fe/H}] = \log_{10} \left( \frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\text{star}} - \log_{10} \left( \frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\text{sun}}$$
Galaxies and Galaxy Clusters

LARGE SCALE STRUCTURE
Structure in the Distribution of Galaxies and Galaxy Clusters

Sheet

Void

2dFGRS galaxy map
Redshift

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

Redshift means the shift of spectral lines red-ward, i.e. to longer wavelengths.
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.
Simulations of the formation, evolution and clustering of galaxies and quasars

“Millenium Simulation”

Springel et al. 2005