Astro 2299

The Search for Life in the Universe
Lecture 5

Last time:

- Redshifts and the Hubble Law
- Hubble law and the expanding universe

This time:

- The cosmic microwave background (CMB)
- The elements and the periodic table

Assignment 1 on course web page (due 15 Feb)

Instructors: Jim Cordes & Shami Chatterjee

http://www.astro.cornell.edu/academics/courses/astro2299/
Main points from last lecture

• Expansion of the universe is described empirically by the Hubble law: \( cz = H_0 d \) where \( H_0 \) = Hubble ‘constant’

• Measurements to greater distances using standard candles like Type Ia supernovae indicate that the universe is accelerating rather than decelerating.

• Gravitational potential energy and kinetic energy are countering forces and underpin much of the physics of the universe (stars, end products of stars, black holes, star formation)

• The cosmic microwave background (CMB) is the remnant blackbody radiation from the big bang. Measurements of it show that it is highly uniform in all directions but shows small deviations due to the Milky Way’s ‘peculiar motion’ with respect to the CMB
Atoms 4.9%

Dark matter 26.8%

Dark energy 68.3%

credit: NASA/WMAP Science Team
Big Bang Cosmology
Matter dilutes as the Universe expands

Steady-State Cosmology:
Matter is constantly created as the Universe expands

Image credit: E. Siegel
Density Evolution (Concordance Model)

Fraction of Total Density

Big Bang

Age (Gyr)

Now

0 1 2 3 4 5 6 7 8 9 10 11 12 13

0 0.2 0.4 0.6 0.8 1

Redshift

0.1 0.2 0.3 0.4 0.5 1

dark matter

dark energy

baryons
A main sequence star’s spectrum is essentially black-body radiation at an effective temperature $T$. 

$$I(\nu) = \left( \frac{8\pi h\nu^3}{c^3} \right) \frac{1}{e^{h\nu/k_B T} - 1}$$ 

Planck curve
https://commons.wikimedia.org/wiki/
File:EffectiveTemperature_300dpi_e.png
Color code: 
green = 2.7K.

Temperature is highly uniform across the whole sky

Constant 2.7K subtracted; yin-yang pattern = “dipole” due to our motion relative to rest frame of the CMB ...
a Doppler effect

Dipole subtracted revealing Galactic plane and temperature fluctuations in the CMB ~ 10^{-5} K
This is where we're coming from...

371 km/s

830,000 mph

September 10th

Virgo

ecliptic

...and this is where we're going to...

CMB Dipole

March 11th

-3354 uK_CMB

3354 uK_CMB
credit: George Smoot/NASA COBE Project
SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND

Wavelength [mm]

Intensity [MJy/sr]

FIRAS data with 400σ errorbars

2.725 K Blackbody
Color coded temperature variations of the cosmic microwave background (CMB)

\[ T_{\text{CMB}} = 2.7 \text{ K} \]

\[ \Delta T/T_{\text{CMB}} \sim 10^{-5} \]

Wilkinson Microwave Anisotropy Probe
The power spectrum of CMB fluctuations is remarkably well understood.

There is structure on many angular scales and it is due to imposed structure from the early universe combined with acoustic waves at the time of recombination.
Isotropy and Structure in the Universe

- Structure in the universe today:
  - Planets, stars, star clusters (globulars), galaxies, galaxy clusters, superclusters
- Why is there structure and why does it have the size and mass scales that we see?
  - Answer: primordial fluctuations + expansion + local gravity + ...
- Primordial fluctuations:
  - Imposed in the big bang as a “scale-free” spectrum of spatial variations in energy
- Inflation era: the universe expanded by a factor of $10^{60}$ in $<10^{-30}$ sec
  - Expansion was at $>>$ speed of light
  - Why is this not a violation of the speed limit of $c = speed$ of light?
  - Why is this required observationally?
The Cosmological Principle

• The cosmological principle is usually stated formally as

• 'Viewed on a sufficiently large scale, the properties of the Universe are the same for all observers.'

• This amounts to the strongly philosophical statement that the part of the Universe which we can see is a fair sample, and that the same physical laws apply throughout. In essence, this in a sense says that the Universe is knowable and is playing fair with scientists. [Credit: W. Keel]

• This is called the cosmological principle: the universe is homogeneous and isotropic

• Recall that the Steady State Theory extends this to include time (universe invariant in time)
The primary reason for why inflation is needed

The “horizon” problem for the homogeneity and isotropy of the universe.

- Horizon = the part of the universe that is visible to us, i.e. the region from which light could have reached us in 13.7 Gyr
- The horizon < the entire universe
- Regions outside our horizon are not causally connected with those that are in our horizon.
- Observational problem: why should the CMB temperature be so nearly the same (to within ~10^{-5} K) from directions that should have been causally disconnected?
- Answer: at one time, they were causally connected
- How: the universe was dramatically smaller so that light (and pressure) could be communicated from one part to any other, allowing the universe to have the same properties everywhere
Inflation: Guth 1980 + others

Chapters: The Cosmic Free Lunch; The Cosmic Vista from Ithaca, NY
Inflation

- Physical models invoke a large reservoir of potential energy in the very early universe that decays to produce the sudden expansion
  - No consensus on the nature of the potential energy (scalar field with a slow-roll downhill or something else?)
- The acceleration of the universe seen currently is a much milder version of inflation
- An over-riding question is why now and why so little acceleration?
Element Formation

Follow the neutrons!
### Periodic Table of the Elements

#### Atomic Properties of the Elements

**Frequently used fundamental physical constants**

For the most accurate values of these and other constants, visit physics.nist.gov/constants.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Atomic Number</th>
<th>Mass Number</th>
<th>Mass (amu)</th>
<th>Density (g/cm³)</th>
<th>Melting Point (°C)</th>
<th>Boiling Point (°C)</th>
<th>Enthalpy of Formation (kJ/mol)</th>
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<td>938</td>
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<td>40.18</td>
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<td>Radon</td>
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<td>222</td>
<td>6.94</td>
<td>74</td>
<td>11</td>
<td>10.00</td>
</tr>
</tbody>
</table>

**For a description of the atomic data, visit physics.nist.gov/atomic**
### "Big Bang" The First Three Minutes

**scenario from** by Steven Weinberg

<table>
<thead>
<tr>
<th>Time</th>
<th>Temp</th>
<th>Energy</th>
<th>Density</th>
<th>What's happening</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 s</td>
<td>10^11 K</td>
<td>8.6 MeV</td>
<td>4 x 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 changed back and forth, so about equal numbers. Only about one neutron or proton for each 10^9 protons.</td>
</tr>
<tr>
<td>1.1 s</td>
<td>3 x 10^9 K</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>10^10 K</td>
<td>860 MeV</td>
<td>4 x 10^8</td>
<td>Primeval 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 x 10^9 K</td>
<td>260 keV</td>
<td></td>
<td>Below pair-production threshold.</td>
</tr>
<tr>
<td>3 m 2 s</td>
<td>10^9 K</td>
<td>80 keV</td>
<td></td>
<td>Electrons and positrons nearly all gone. Protons and neutrons are main constituents of the universe in terms of energy. Neutron decay leaves 90% protons, 14% neutrons but these represent a small fraction of the energy of the universe.</td>
</tr>
<tr>
<td>3 m 48 s</td>
<td>0.9 x 10^6 K</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 8% 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 x 10^6 K</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 8% 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 x 10^5 yrs</td>
<td>3000K</td>
<td>0.26 eV</td>
<td></td>
<td>Cold 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>10^10 yrs</td>
<td>3 K</td>
<td></td>
<td></td>
<td>Living beings begin to analyze this process.</td>
</tr>
</tbody>
</table>
Figure 1. Potential energy surface, as a function of the interdeuteron distance, describing the nuclear fusion reaction $\text{2D} + \rightarrow \text{3He} \ 2^{+} + \text{n}$.
http://physics-database.group.shef.ac.uk/phy303/phy303-4.html
Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei

http://abyss.uoregon.edu/~js/ast123/lectures/lec21.html
Image credit: Frank X. Timmes of http://cococubed.asu.edu/.