The Big Bang Theory & Expansion of the Universe
Example: the Sun's Spectrum
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Distinct energy levels lead to distinct emission or absorption lines.

Emission: atom loses energy

Absorption: atom gains energy
Doppler Shift

Observer 1

Car traveling toward the right

Observer 2

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Definition: Redshift

• The measure of the amount a spectral line is shifted in wavelength
<table>
<thead>
<tr>
<th>Cluster nebula in</th>
<th>Distance in light-years</th>
<th>Redshifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgo</td>
<td>78,000,000</td>
<td>H + K</td>
</tr>
<tr>
<td>Ursa Major</td>
<td>1,000,000,000</td>
<td>1,200 km s⁻¹</td>
</tr>
<tr>
<td>Corona Borealis</td>
<td>1,400,000,000</td>
<td>15,000 km s⁻¹</td>
</tr>
<tr>
<td>Bootes</td>
<td>2,500,000,000</td>
<td>22,000 km s⁻¹</td>
</tr>
<tr>
<td>Hydra</td>
<td>3,960,000,000</td>
<td>39,000 km s⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>61,000 km s⁻¹</td>
</tr>
</tbody>
</table>
Hubble Law - 1929

Originally $H_0 \sim 500 \text{ km/s/Mpc}$
Known galaxies within 8,000 km/s of us
• Galaxies are all moving away from each other, so every galaxy sees the same Hubble expansion, i.e. there is no center.

• The cosmic expansion is the unfolding of all space since the big bang, i.e. there is no edge.

• We are limited in our view by the time it takes distant light to reach us, i.e. the universe has an edge in time not space.
Hubble Constant Determinations

The graph shows the evolution of the Hubble constant ($H_0$) since 1920. The graph plots $H_0$ (km/s/Mpc) against the date, indicating changes in the rate of expansion of the universe over time.
Cosmology: What We Know

1. Redshift – it’s cosmic expansion, *not* Doppler
1. If the Universe is expanding, then reversing that expansion (going backwards in time) indicates that the Universe must have been smaller in the past.
Blackbody (Thermal) Radiation
Two Properties of Thermal Radiation:

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.
Infrared Light – Human Body Glows!
2. Discovery of the Cosmic Microwave Background

1964

Bob Wilson

Arno Penzias
Cosmic Microwave Background:
The farthest we can see back…
Radiation signature from 300,000 years after the Big Bang
2. Background Radiation – thermal, at 2.73K
The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

We can only see the surface of the cloud where light was last scattered.
Measuring the Cosmic Microwave Background

$T = 2.725 \text{ K}$

$\Delta T = 3.35 \text{ mK}$

$\Delta T = 18 \mu\text{K}$

$\Delta T = 18 \mu\text{K}$

WMAP
An image of quantum fluctuations blown up to the size of the universe
3. Galaxies in past look younger (smaller and more irregular)
Galaxy Formation Simulation
Courtesy Charlotte Christensen
4. Abundance of the Lightest Elements

The lightest elements — hydrogen, helium, and a smattering of deuterium (heavy hydrogen isotope) and lithium — were from the big bang itself, produced by fusion in the first three minutes when the universe was as hot as the core of a star like the Sun!
Big Bang Fusion

Nuclear fusion in first 3 minutes
The predictions match observations!

- WMAP measured this ratio of matter/photons
- Horizontal bands are observed abundances
- Solid lines are theory predictions

Abundance

Density of Matter / Photons
There is evidence for expansion, and the universe was hotter and denser in the distant past.

The microwave background and the helium abundance cannot easily be explained in any other way.

There are hundreds of thousands of big bang photons in every breath you take: the big bang is all around us.

It is a theory, but a theory with a web of evidence to support it. The theory is mute about the cause of the cause.
A Schematic Outline of the Cosmic History

- **The Big Bang**
  - The Universe filled with ionized gas

- **The Universe becomes neutral and opaque**
  - The Dark Ages start

- **Galaxies and Quasars begin to form**
  - The Reionization starts

- **The Cosmic Renaissance**
  - The Dark Ages end

- **Reionization complete, the Universe becomes transparent again**

- **Galaxies evolve**

- **The Solar System forms**

- **Today: Astronomers figure it all out!**
How do our lifetimes compare to the age of the Universe?

- The Cosmic Calendar: a scale on which we compress the history of the universe into 1 year.
- This is a time scale model where 14 billion years equals 1 year, i.e. 14,000,000,000:1.
- Our lives would scale similarly, so 80 years goes down by a factor of 14 billion too.
- In the scale model, a human life is about 2 tenths of a second!
The Cosmic Calendar: January-November

January 1 (15 bya): Big Bang

March 20 (12 bya): Galaxies form

October 6 (3.6 bya): Life established, first fossils, photosynthesis (?)

September 2 (5 bya): Formation of our solar system

September 14 (4.5 bya): Earth formed

October

November

November 14 (2 bya): Complex single cells

November 19 (1.8 bya): Free oxygen

November 21 (1.7 bya): Evidence of multicellular organisms (?)
Now home in on the more recent span of the history of life and of humans and civilization.
The Raw Material for Astrobiology

• **Space:** the potential habitable worlds around ten thousand billion billion stars; ours is just one.

• **Time:** a cosmic history of nearly 14 billion years; life took less than \( \frac{1}{2} \) billion years to start here.

“If they not be inhabited, what a waste of space.”

Thomas Carlyle, Scottish Essayist (1795-1881)